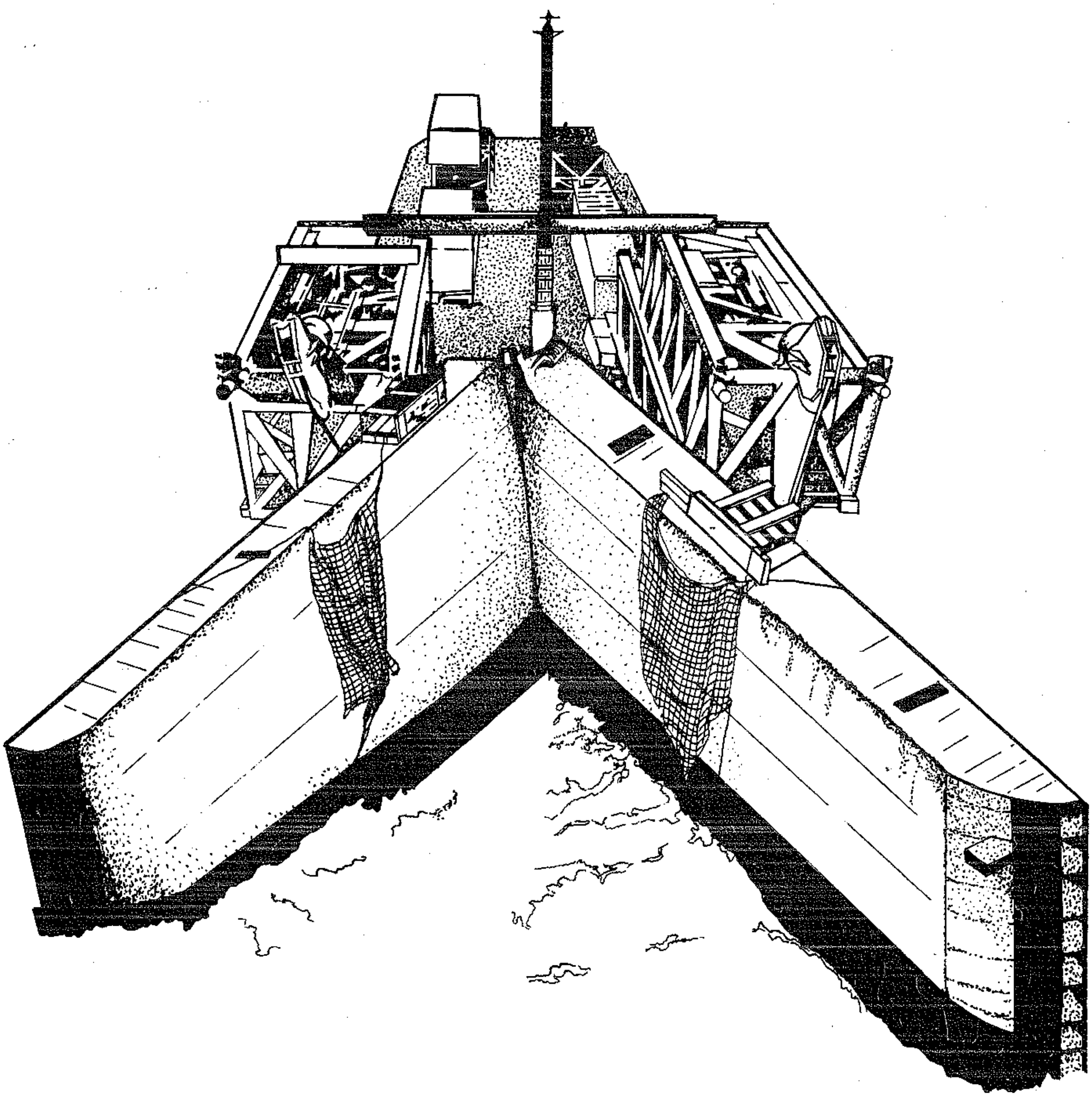
BARGE 45 SALVAGE OPERATIONS
BUFFALO, NEW YORK
SEPTEMBER - DECEMBER 1986



SL740-AB-RPT-010/SUPSALV

19 DECEMBER 1988

SL740-AB-RPT-010/SUPSALV

0910-LP-272-6400

BARGE 45 SALVAGE OPERATIONS
BUFFALO, NEW YORK
SEPTEMBER - DECEMBER 1986

PUBLISHED BY DIRECTION OF COMMANDER, NAVAL SEA SYSTEMS COMMAND

19 DECEMBER 1988

TABLE OF CONTENTS

SUPERVISOR OF SALVAGE
U.S. NAVY

19 December 1988

FOREWORD

The December 1986 removal and disposal of Barge 45 from the Peace Bridge, in the middle of New York's Niagara River, was a unique wreck removal operation where current velocity both restricted and dictated the salvors' options. The perseverance of the salvage crew in effecting the successful removal and disposal of Barge 45, despite several major setbacks and the threat of winter ice causing layup of expensive equipment, is a typical example of the persistence and tenacity demanded of a professional salvor. The job was very difficult. It was also very successful.

This case study of the Barge 45 salvage operation is intended to provide an educational vehicle for salvors who are not engineers. Furthermore, it is intended to provide salvage engineers with a reference document in situations where the effects of current velocity must be quantified. The discussion in Appendix B reflects the state of the art in hydrodynamic force prediction where time does not permit more exhaustive computer analysis or model testing.

C. A. Bartholomew
Captain, USN
Supervisor of Salvage

BARGE 45 LIST OF ILLUSTRATIONS

CHAPTER 1 ABSTRACT/EXECUTIVE SUMMARY

On 7 August 1986 an unidentified tug and Barge 45 were transiting the vicinity of the entrance to the Niagara River at the most northeasterly point of Lake Erie. The barge measured 175 feet long by 40 feet wide by 9.5 feet deep, and weighed approximately 300 short tons. Instead of entering the Black Rock Canal, running parallel to the river, the tow entered the swift-running Niagara. Having lost tug control, the tow collided with the concrete ice knife of pier 4 of the Peace Bridge, which spans the Niagara River between Buffalo, N.Y., and Fort Erie, Canada. The tug capsized downriver and sank. The barge became impaled broadside against the ice knife by the force of the strong river current, in excess of 11 knots. (See Figures 1-1 and 1-2).

The U.S. Navy was tasked to conduct the salvage in September. In late December, the barge wreckage was disposed of at the southeastern edge of Buffalo Harbor, in the vicinity of the former Bethlehem Steel Mill.

The successful removal of Barge 45 represents one of the more difficult and complex salvage projects in the history of U.S. Navy salvage. Mitigating against expeditious salvage were problems related to:

- High (over 11.0 knots) river current

- Large lifting loads
- Marginal equipment
- Wreck integrity.

Persistent work by salvors and various participating support agencies ultimately overcame these problems.

Significant lessons learned pertain to the design of load-bearing systems; analyzing current directional components; dewatering in critical situations; rigging; load monitoring and public relations.

Appendix A summarizes calculations and data pertinent to the operation. Appendix B is a basic reference document for salvors working in high currents, where calculation of hydrodynamic forces is critical to execution of the salvage plan.

FIGURE 1-1
AERIAL VIEW OF PEACE BRIDGE

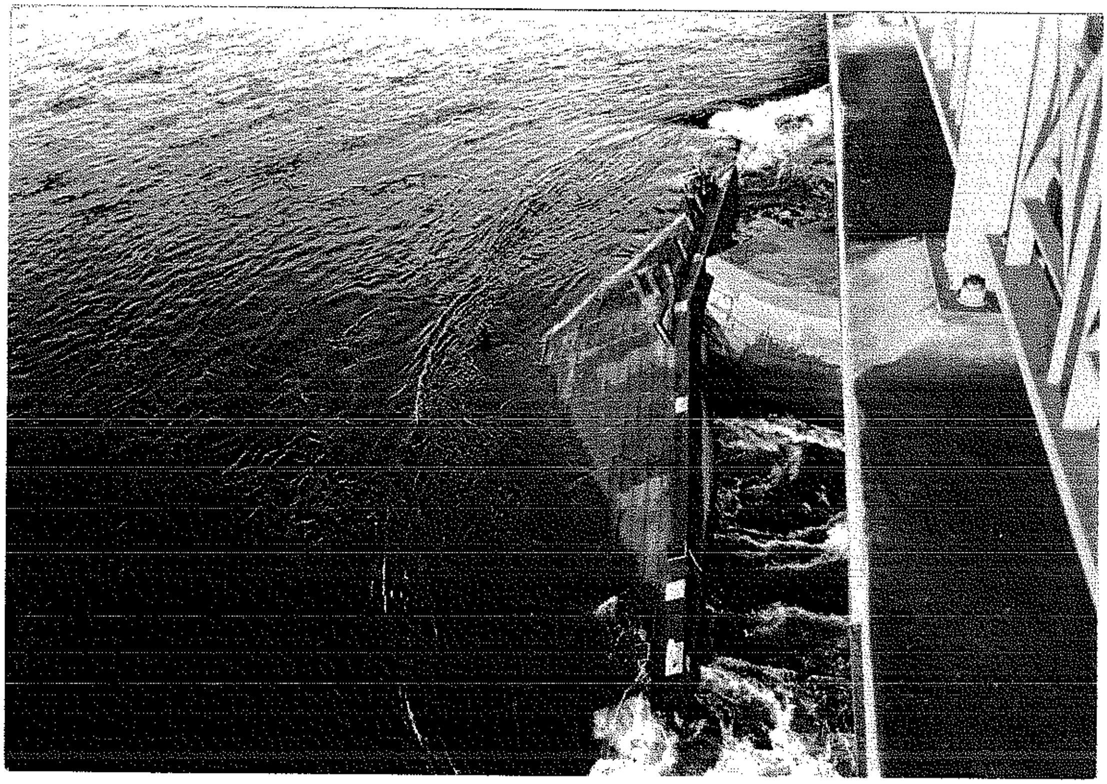


FIGURE 1–2
PRE–OPERATION CONDITION OF WRECK OF BARGE 45

CHAPTER 2 INTRODUCTION/CHRONOLOGY

Barge 45 wrecked on Pier 4 of the Peace Bridge on 7 August. Its owner abandoned it. Its removal, therefore, became the responsibility of the Buffalo District of the U.S. Army Corps of Engineers (COE), who has responsibility for maintaining safety of marine structures in waterways.

The barge had been declared a hazard to navigation by the Buffalo Captain of the Port. The impaled vessel threatened not only the structural integrity of the Peace Bridge and the International Railroad Bridge located 1.5 miles downriver but also small boat safety in the immediate vicinity. Morever, by restricting approximately 7,000 cubic feet per second of Lake Erie's outflow, the derelict barge also had caused a two-inch increase in the Lake's water level over approximately sixty days. This equates to an annual rate of one foot. Thus, the threat of local flooding and erosion during the fall increased, with measurable effects on Lakes Michigan and Huron. The typical Great Lakes winter threatened to make the barge an accumulation point for ice, thereby increasing the potential for damage to Bridge Pier 4. Another fear was that ice pressure could break the barge into two separate parts, with residual buoyancy in one or both sections. This could cause the barge to remain afloat as the current carried it toward downstream structures. Clearly the COE had to act to remove the barge.

After seven weeks of legal and administrative negotiations, the COE formally requested that the Commander, Naval Sea Systems Command (NAVSEA) undertake the wreck removal. Because the Navy had no organic assets available to operate in the unique environment of the Niagara River, the Supervisor of salvage (SUPSALV) tasked its East Zone salvage contractor, DONJON MARINE CO., INC., to conduct the operation under Contract N00024-86-D-4266.

After an accelerated and complex mobilization phase, the on-site salvage operation began on 27 November. The barge was successfully removed from the Peace Bridge on 19 December and deposited in a designated backwater site on 21 December.

Throughout the course of this operation, the U.S. Coast Guard (USCG), Group Buffalo, provided logistics and safety support. Their outstanding attitude and "can-do" spirit were essential to the salvage operation's success.

CHRONOLOGY

August	7	Barge 45 impacts Peace Bridge Pier 4
September	17	Technical analysis of wreck and removal methods begins, culminating in initial salvage proposal

	24	Initial salvage plan presented to COE, USCG and Peace Bridge Authority; plan accepted by COE
	25	COE tasks SUPSALV with removal and disposal of the wreck
October	9-17	Niagara River core testing completed; work continues to drill holes, fabricate pins, test grout material and install pins
	18-25	Anchor pin holes drilled; upon completion, concrete blocks are placed over holes to prevent backfilling
	29	Final salvage plan submitted to all cognizant parties
	30-31	Anchor pins grouted into place and pronounced ready for testing

November	6-14	Mobilization of Barges 251, 252 in Montreal includes welding, installation of living modules, generators, stores and salvage equipment
	22-24	Barge 252 tests anchor pins in Niagara River
	27	Barge 251 commences warping downriver from pins to wreck
December	2	Barge 251 strays into Peace Bridge span
	3	Barge 251 is hauled out from bridge span
	7	Tugs EL GATO GRANDE and ANDREW B., in Black Rock Canal, assist Barge 251 in lateral positioning
	10	Barge 251 starboard lift truss roller disintegrates during first lift attempt

13 Barge 45 rotated upright during second lift attempt, set back down due to weather and load conditions. Starboard lift wire parts

19 Barge 45 successfully lifted; warp upriver commences

20 All salvage vessels removed from river; Barges 251 and 45 shifted to COE-designated dumping ground in southeast corner of Lake Erie

21 Barge 45 dumped in COE-designated area.

CHAPTER 3 CASUALTY SITE AND WRECK CONDITIONS

After SUPSALV tasked them with removal, on 7 October salvors conducted a detailed survey of the barge. They found the barge in a partially-submerged condition, resting against the mid-channel ice knife of the Peace Bridge Pier 4, at an angle of approximately 19.5 degrees (See Figure 3-1).

Barge 45 was constructed of steel in 1933 in Ambridge, Pennsylvania. It weighed approximately 300 short tons, and featured welded seams and butts. Frames and bulkheads were riveted to the hull plating. Sideshell plating was connected to the deck and bottom plating by a riveted, inverted, internal angle. A doubled deck over the original deck would complicate attachment of lifting gear.

The barge had grounded against the upper edge of the ice knife, approximately 12.5 feet forward of midships. It was believed that the forward and aft starboard rake tank corners were still in contact with the river bottom. The current's hydrodynamic pressures against the barge's inclined submerged deck area caused a downward moment around the starboard edge of the barge, where the barge had made contact with the lower ice knife edge, and broke the back of the barge. The horizontal force against the barge's submerged deck area was transmitted to the bridge pier.

The Niagara river bottom is at an elevation of 550 feet above International Great Lakes Datum, 1955 (IGLD, 1955). The water level at the Peace Bridge normally is 573 feet above IGLD on calm days, corresponding to water depth of approximately 23 feet (See Figure 3-2). However, water levels can be higher when winds come out of the south and west.

During a 21 August survey of the local area, salvors had measured currents at various locations upstream from the Peace Bridge (See Figure 3-3). Recorded current speed of approximately 11 knots at the bridge corresponded to a recorded water flow rate of 265,000 cubic feet per second, and a water gauge level of 573 feet above the IGLD. Data from the COE showed that a severe storm could raise the water gauge level by 8 feet and cause the water to flow at a rate of 400,000 cubic feet per second, producing current velocity in excess of the normal 11 knots. Throughout the project, current velocity would be the major consideration.

Time also was critical. The COE estimated that the St. Lawrence Seaway would be closed to traffic by 25 December. Because most of the mobilized assets were being staged from the Atlantic Seaboard and the Gulf of Mexico, their return prior to the Seaway's closing was a major cost consideration.

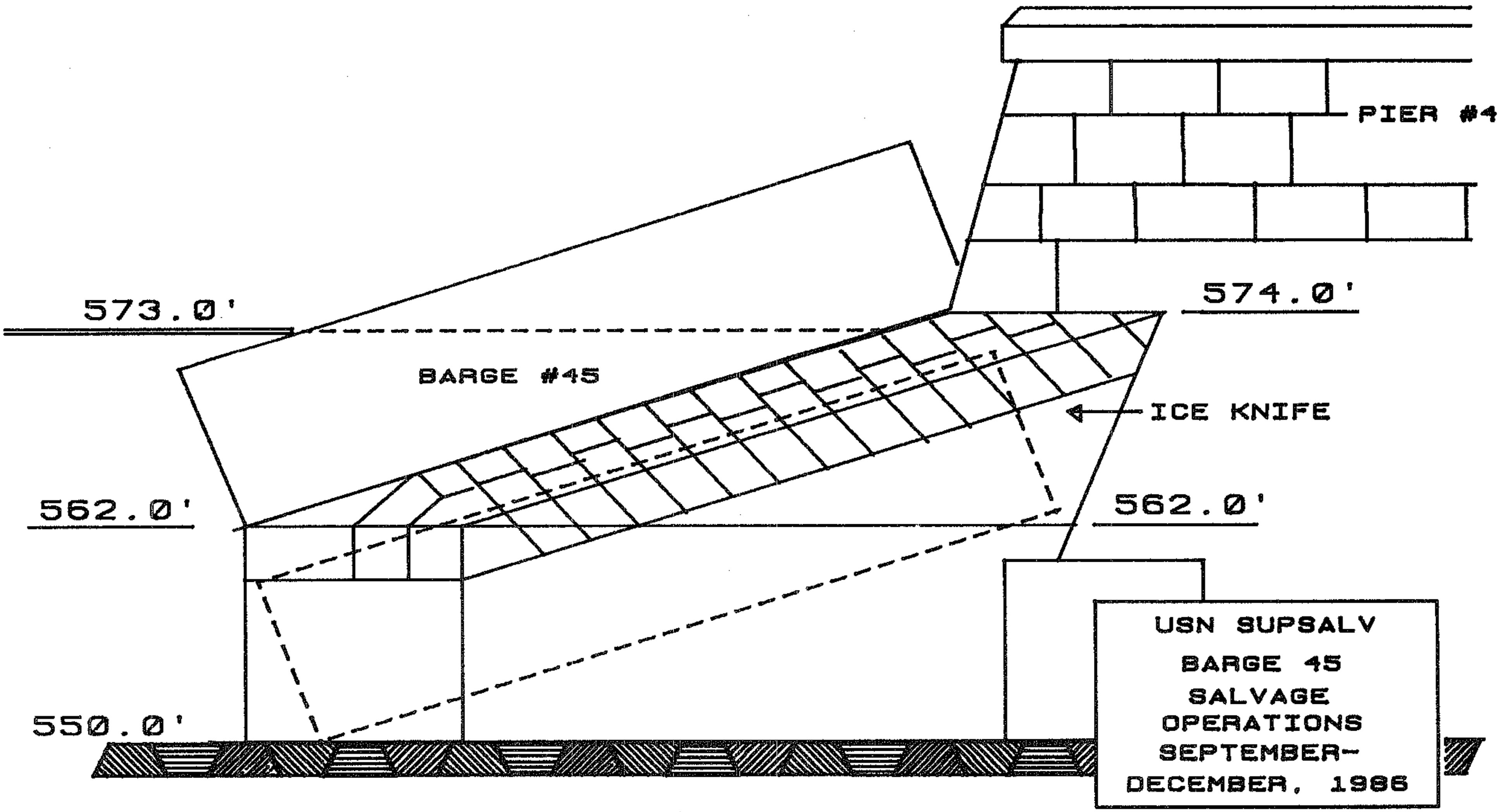


FIGURE 3-1
TRANSVERSE VIEW, BARGE 45 AGAINST PEACE BRIDGE PIER 4

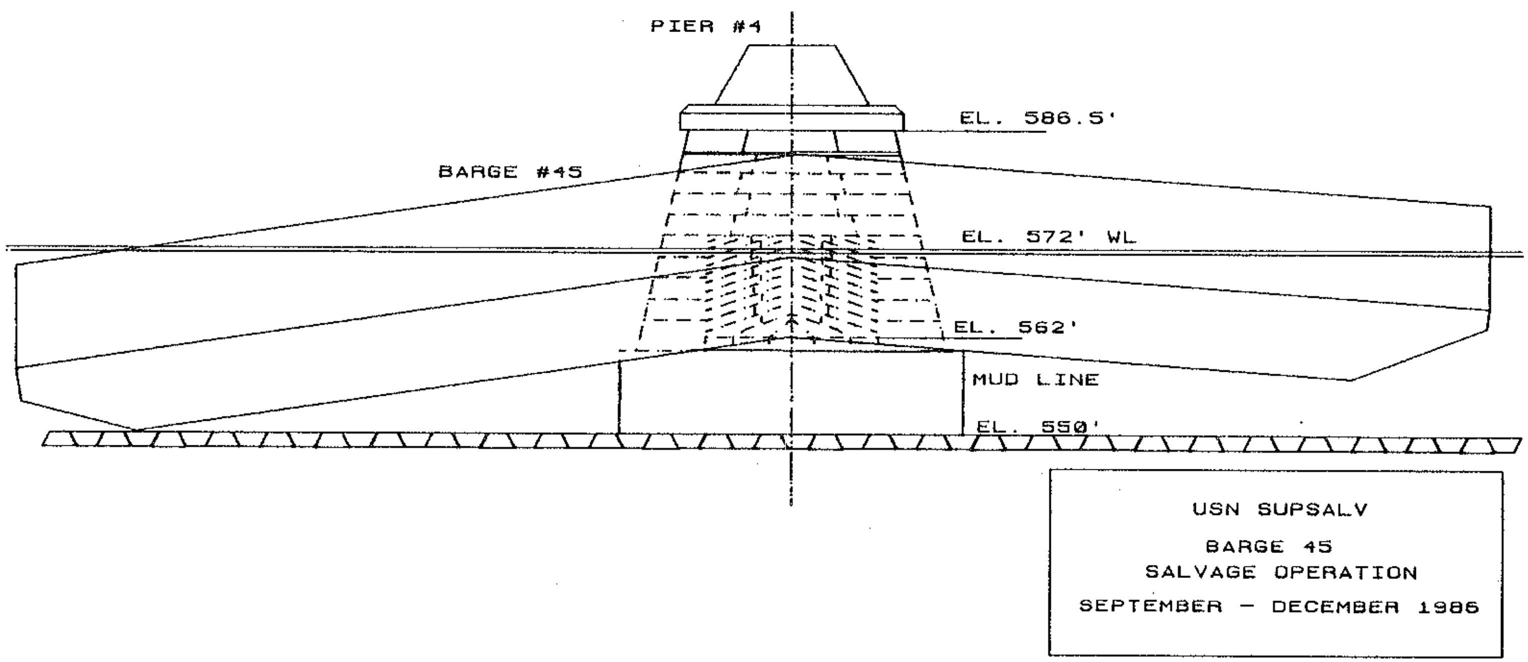
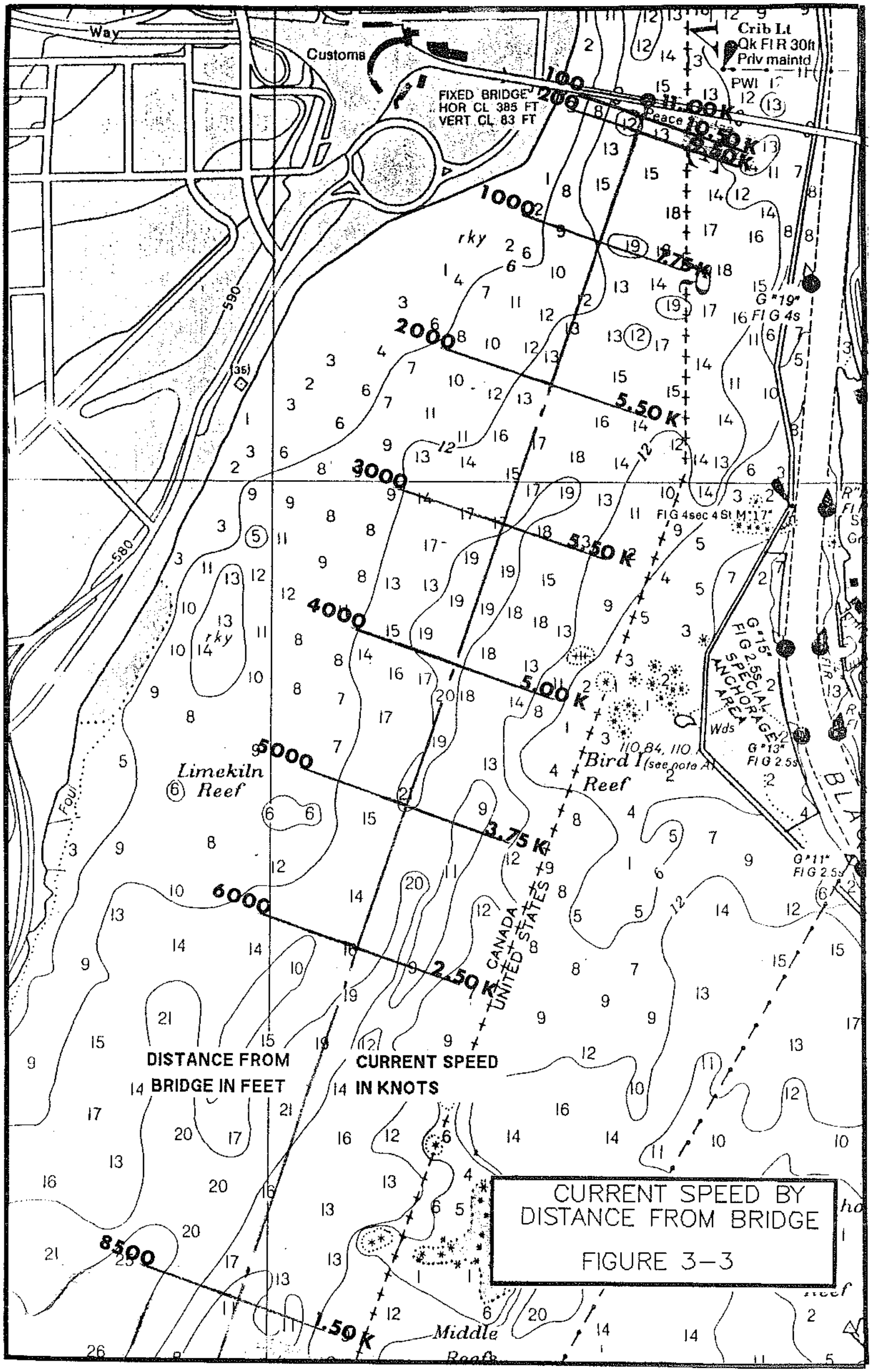


FIGURE 3-2
ELEVATION VIEW, BARGE 45 AGAINST PEACE BRIDGE PIER 4



CURRENT SPEED BY DISTANCE FROM BRIDGE

FIGURE 3–3

CHAPTER 4 SALVAGE PLAN DEVELOPMENT

Salvors had to develop a detailed salvage plan to remove Barge 45 from its impaled condition; mobilize and configure all equipment; complete on-site preparatory work; perform tests, and conduct the operation--all in fewer than 80 days. Conducting salvage operations in Niagara River ice conditions, which historically commenced in mid-December, was considered unacceptable.

Current velocity at the Peace Bridge and the barge's structural condition led salvors to conclude that the wreck could not be dragged from the bridge pier. The hydrodynamic force upon the impaled wreck was calculated to require a horizontal pulling force in excess of 1,000 tons for removal by dragging. While this capability was available in the marine lifting and pulling market, using this approach would have been impractical, especially considering bottom irregularities and pulling vessels' draft limitations. Installing pulling anchors to achieve the required pulling force was not feasible, given the time constraint. Because divers could not work safely in the high current, dismantling in place also was not feasible.

Next, salvors analyzed lifting the wreck vertically from the ice knife. They determined that required equipment would have to be able to lift approximately 650 tons. This figure was obtained after considering the 300-ton barge weight; estimated residual water trapped within the barge; and the vertical component of hydrodynamic force imposed by the river current. The question of equipment availability and configuration became the next consideration.

High-capacity lifting equipment was available in the Gulf of Mexico oil field support industry. High-capacity line pull winches encased in truss structures frequently had been utilized to lower platform structures. In such operations trusses were cantilevered over the ends of barges to control a structure's descent. Salvors procured eight of these winch/truss combinations especially for the Barge 45 salvage. The pulling power of two winches was harnessed to rotate and lift the wreck from the ice knife, via a configuration which would provide sufficient hoist and outreach. Six winch/truss units were used to warp Lift Barge 251 downriver from the anchor pins to the wreck. Two mooring winch/truss units were installed on Barge 251 (See Figure 4-1) and four on Mooring Barge 252 (See Figure 4-2).

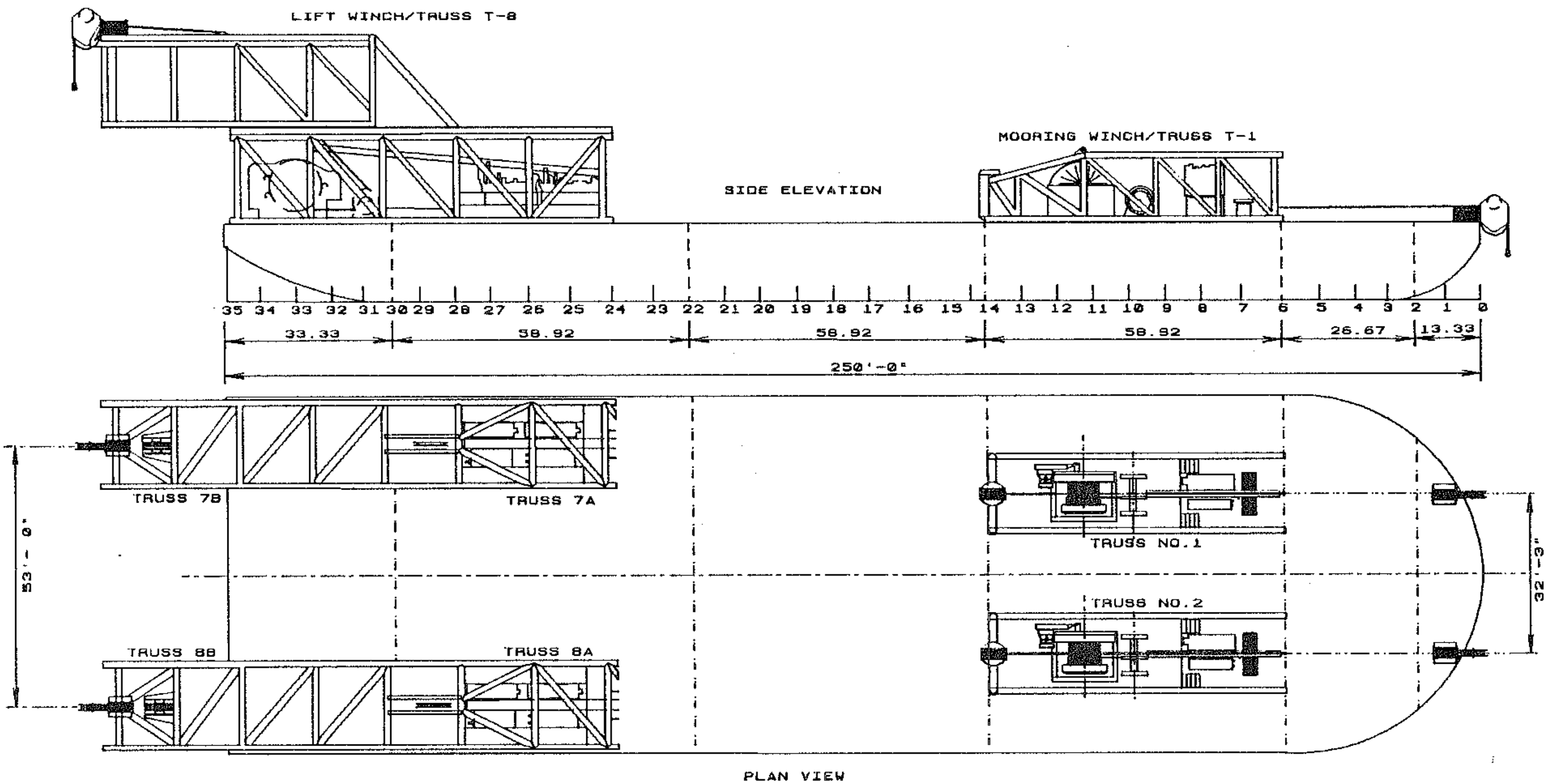
Critical factors involved in design of the lifting apparatus included the calculated resistance caused by the current force; the wreck's structural integrity; and the vertical hoist necessary to clear the bridge ice knife. The wreck's longitudinal strength was insufficient to prevent the hydrodynamic force of the current from bending the wreck.

However, the wreck structure exhibited enough ductility to rule out the possibility of an instantaneous brittle failure. In designing the lift system, salvors contended with the possibility of the wreck's separating into two pieces during or after the lift. The system of two lifting winch/truss combinations allowed for rotating and lifting the wreck on either side of the point where it had bent over the bridge ice knife. If the wreck broke apart, the system would revert to two separate lifting components.

Equipment positioning required analysis of current conditions and corresponding forces at various points in the Niagara River. It was determined that the appropriate starting point was approximately 7,500 feet from the bridge. A minimum of three-inch diameter wire was required. This necessitated using multiple sets of winches, since no available single winch drum stored the desired cable length and thickness. Mooring Barge 252, equipped with two sets of mooring winches, helped position the lift barge approximately 6,000 feet downriver from the pins. The remaining pair of winch/truss units fixed to the bow deck of the lift barge allowed for the remaining 1,500 foot transit. The entire system was analyzed to verify loads on the mooring system. Determination of the expected load led to the design of steel anchor pins whose shafts were embedded nine feet into the river bedrock (See Figure 4-3). The location of anchor pins in the river is shown in Figure 4-4.

Design of the anchor pins considered the anticipated load on the entire system, as well as local topography--including bottom contour, bedrock strength and overburden. The load was spread among four pins to ensure the safety of personnel and equipment in the Niagara River, providing a total safety factor of 4:1. Appendix A provides a summary of pertinent calculations and data.

Time was a critical factor throughout the decision-making process for system design and installation. Equipment had to be mobilized and salvage completed before icing conditions prevented further work.

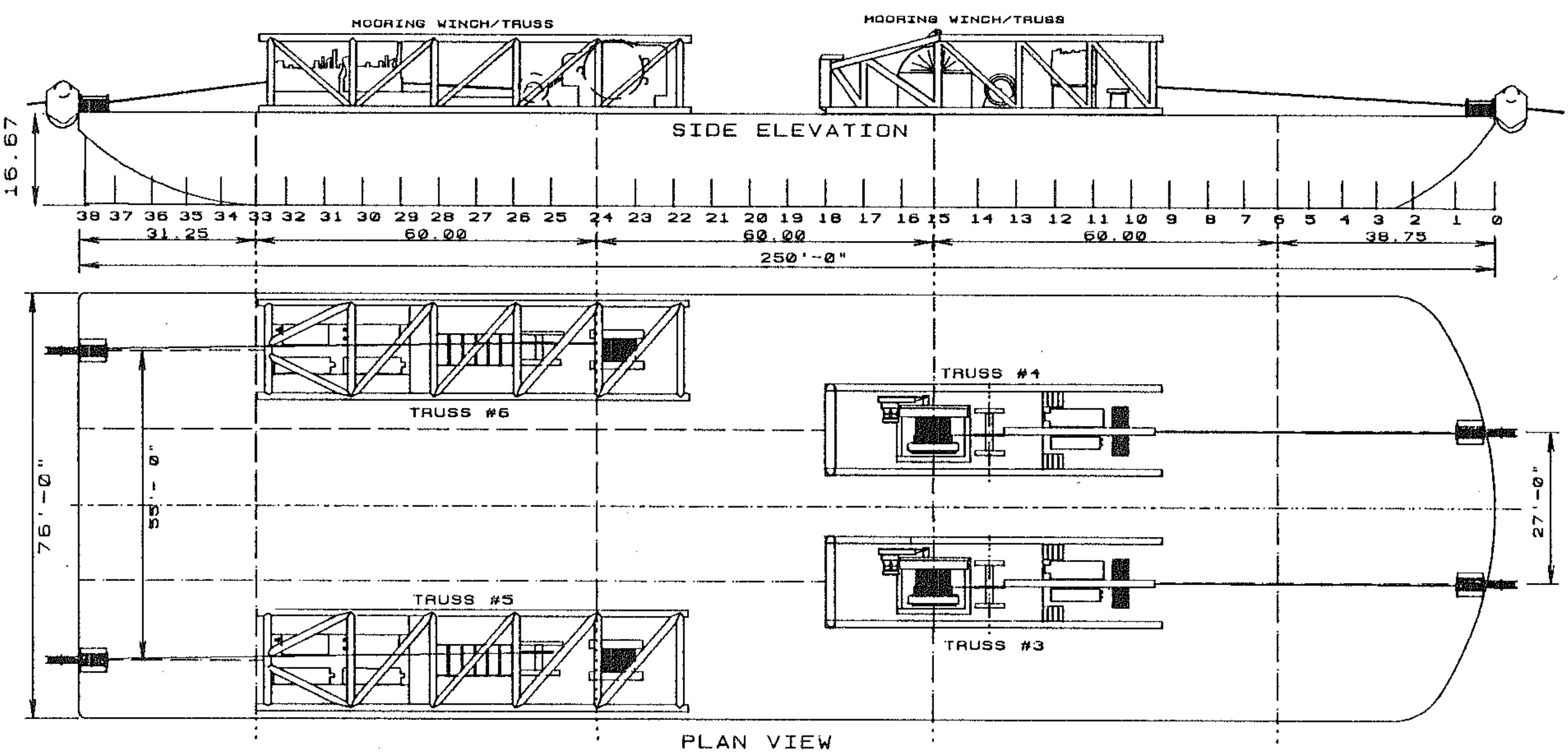


BARGE NPR 251
LIFT BARGE
PARTICULARS

LOA	250'- 0"
BREADTH	72'- 0"
DEPTH	16'- 0"

FIGURE 4-1
LIFT BARGE 251

USN SUPSALV
BARGE NPR 251
LIFT BARGE
SALVAGE OPERATION
SEPTEMBER - DECEMBER 1986

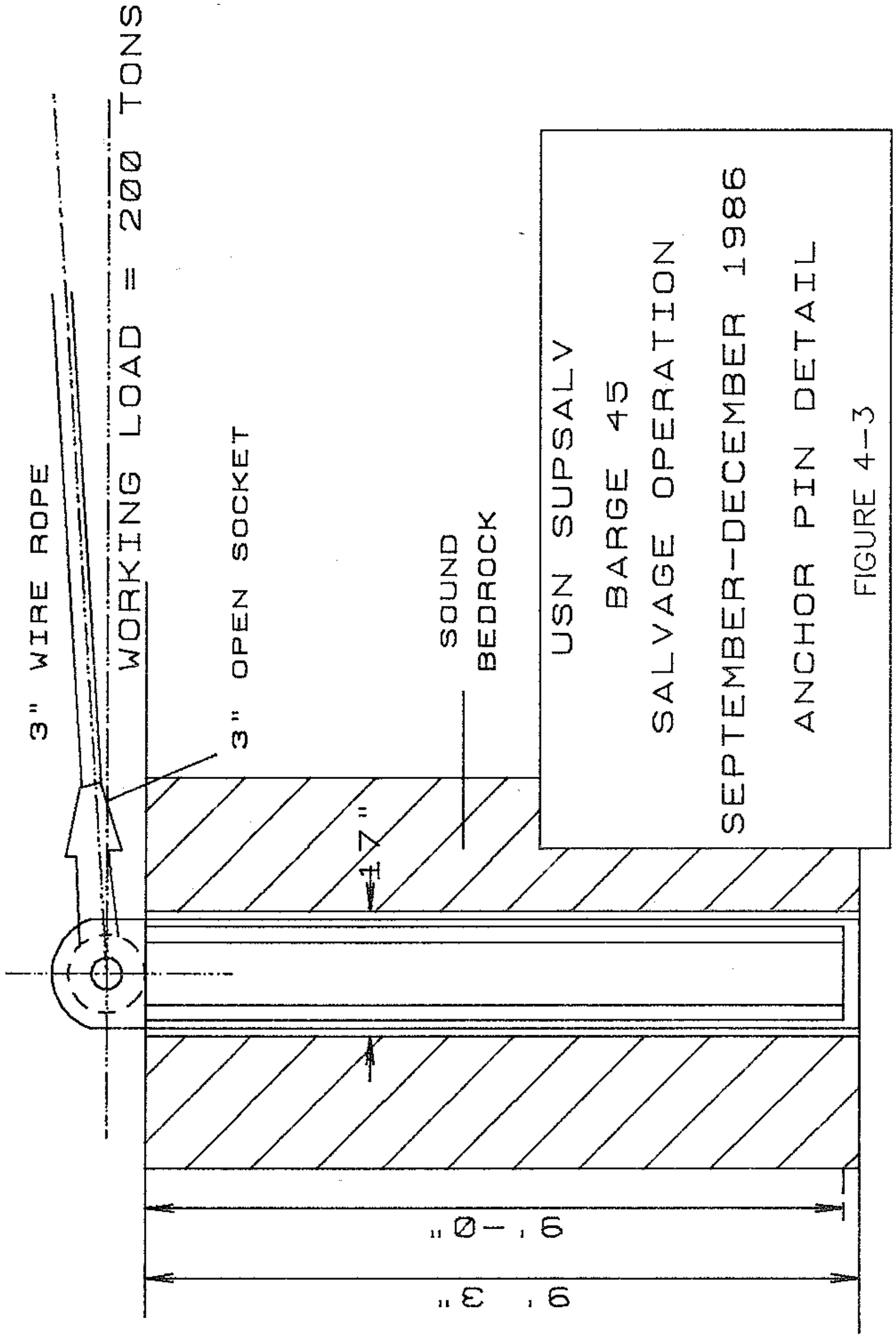


BARGE McALLISTER 252
MOORING BARGE
PARTICULARS

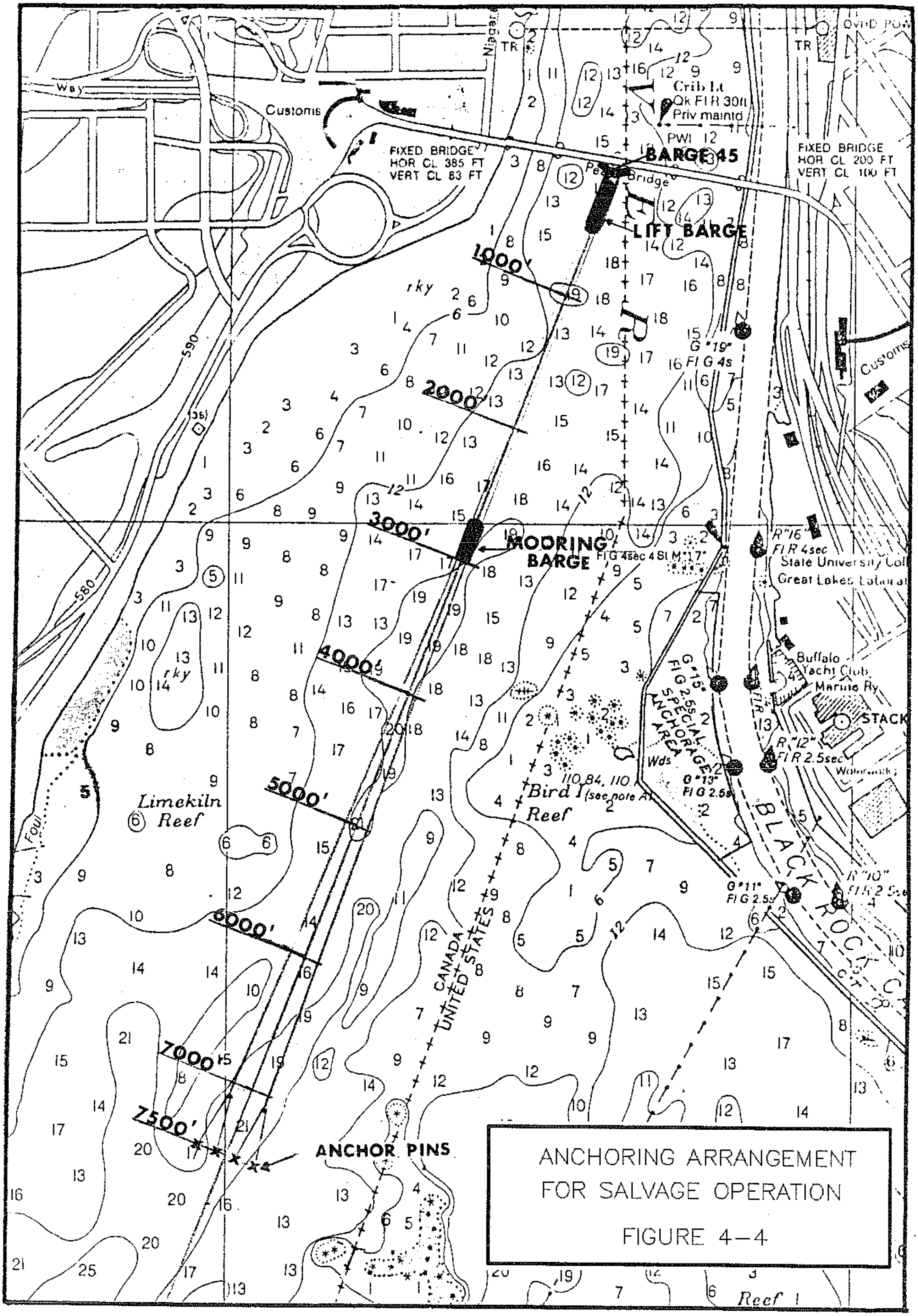
LOA	250' 0"
BREADTH	76' 0"
DEPTH	16' .67"

FIGURE 4–2
MOORING BARGE 252

USN SUPSALV
BARGE McALLISTER 252
MOORING BARGE
SALVAGE OPERATION
SEPTEMBER – DECEMBER 1986



3" WIRE ROPE
WORKING LOAD = 200 TONS
3" OPEN SOCKET
SOUND BEDROCK
7"
9' -0"
9' 3"
USN SUPSALV
BARGE 45
SALVAGE OPERATION
SEPTEMBER-DECEMBER 1986
ANCHOR PIN DETAIL
FIGURE 4-3



ANCHORING ARRANGEMENT
FOR SALVAGE OPERATION

FIGURE 4–4

CHAPTER 5 ASSET MOBILIZATION, MOORING INSTALLATION AND TESTS

The following section discusses mobilization of assets, installation of moorings and testing prior to commencing salvops. The section is divided into the following parts:

- o Transport of winch/trusses
- o Modification and configuration of winch/trusses
- o Design, fabrication and installation of wreck lifting saddles
- o Design, fabrication and installation of bridge pier protection
- o Anchor pin location, design and installation
- o Testing of anchor pins, mooring wires and winches

5.1 Transport of Winch/trusses

After determining winch/truss availability, salvors arranged for their transport to Port Newark, N.J. An ocean tug, M/V EL GATO GRANDE, and an oceangoing deck barge were chartered. Barge NPR 251 was chartered to transport the winch/trusses and to serve as the lift barge for salvops. Although slower, marine transport of the winch/trusses was the only feasible alternative, because of their size and weight. The largest of these weighed 350 tons and measured 75 ft. long x 20 ft. high x 19 ft. wide.

5.2 Modification and Configuration of Winch/trusses

Criteria used to select Barge 251 as the lifting platform for salvops included an open deck area, load line rating and construction. Construction was a critical parameter, considering longitudinal and torsional stresses that the barge would experience during the salvage operation.

Barge 251 transited from Morgan City, La., to Port Newark, N.J., between 4 and 14 October. After major modifications and configurations were completed in Port Newark (See Figures 5-1 through 5-5), it was towed to Montreal, Canada, between 28 October and 6 November (See Figure 5-6). Modifications continued after the transfer of four winch/trusses to the Montreal-based, chartered Barge 252 (See Figures 5-7 and 5-8). Both barges were outfitted with living and galley modules, 100 KW generator sets, lights, sanitary systems, rigging cranes and welding support equipment. The transit from Montreal to Buffalo was completed from 13 to 19 November.

The lifting trusses were assembled from offshore erection trusses originally built to lift 450 tons each. The diesel-driven hydraulic pump units, hydraulic winches, control units and fairleads all were mounted on or inside the truss structure as originally built. However, the winch/truss control systems were considerably modified for this salvage project.

Modification and configuration of the lift trusses considered the horizontal overhang, or cantilever, necessary to make an unobstructed lift of the wreck. A 34-foot outreach and a structure capable of supporting a maximum load of 800 tons were necessary. Salvors considered the required vertical hoist of 37 feet to rotate and lift the wreck, and designed a stacked configuration. The design took into account directional components of the maximum expected load in various planes. For this reason, fairleads capable of swiveling were installed to permit transmission of vertical, horizontal and torsional stresses into the truss and barge structures. Stiffening doubler plates were welded to the deck of Barge 251 to absorb expected loads. Installation of boxes around the barge's stern end mooring bitts, which were recessed into the hull, compensated for column loads and provided continuity of deck structure. This construction ensured that the column loads would be transmitted inward to the barge's sideshell and headlog.

Welding schedules were developed and implemented throughout, considering bending moments and shear forces expected during the maximum lift, and less-than-ideal conditions under which salvors worked during the mobilization period.

Approximately seven tons of welding rod were expended in reconfiguring the lift and mooring barges.

The fairleads' design meant that they overhung the ends of the barges, resulting in localized stress. Doubler plates were incorporated to reinforce the barge structure so that it could absorb the corresponding vertical load.

In order to ensure control of both ends of the wreck during the lift, the two-truss system was employed as described above.

5.3 Design, Fabrication and Installation of Wreck Lifting Saddles

Two lifting saddles outfitted with a rotating padeye were fabricated in Montreal and installed on Barge 45. Installation work commenced on 24 October and took approximately 10 days (See Figures 5-9 through 5-12). The saddles were welded to the wreck's deck and sideshell plating. Installation of two lifting saddles was necessary, since the wreck's back was broken and total separation of the two halves was probable. The saddles were designed with heavy, one-inch base plating, four-inch thick main girders, and heavy framing so that the structure would not deflect when loads transferred between the deck and sideshell. The design converted pulling loads on the deck plating into shear and tensile loads in the wreck plating. Secondly, the design ensured that where the plating was expected to plastically deform in the deck, the loads would be transferred in a bending mode from the deck edge to the bilge area on the sideshell. Due to saddle rigidity, the plating was not expected to deflect locally without rotating or shearing in the perpendicular plane. The saddle design area was such that shear loads and stresses were low, while stresses in the base materials were less than three tons per square inch. (See Figure 5-13.)

5.4 Design, Fabrication and Installation of Bridge Pier Protection

A steel sheath, called a "nose piece," was installed around the protruding portion of the bridge pier. The nose piece was constructed of 1/4" thick, 10-pound plate. It was fitted against timber supports, which in turn rested against the pier face. Grouting was poured to preclude deformation. The nose piece was intended to mitigate the large friction forces acting on the wreck as it was lifted up the face, possibly causing further damage to the bridge pier itself.

5.5 Anchor Pin Location, Design and Installation

Salvors needed to determine where the salvage barges could be positioned safely and moored to a secure point in the river.

Drift tests indicated general current directions. The information on current direction available from charts was not detailed, since the area's water depth and current speed preclude its use by all but pleasure craft. Criteria for choosing the tentative anchor site included:

- Low current velocity to permit diving operations and ensure safety of tugs and barges during their entry into the river
- Sufficient water depth for safe navigation of the vessels (i.e., minimum of 18 feet)
- Anticipated submersion of the wreck during the extraction operation, and
- Local overburden for efficient drilling of the holes and installation of the anchor pins.

Salvors conducted exploratory drilling to determine rock character and compressive strength at the proposed anchor pin site. The drilling, or core testing, entailed sinking eight boreholes into the bedrock to depths ranging from seven to 21 feet. The rock's general character was confirmed as a fine-grained, cherty limestone with thin shale zones throughout the length of the core. Compressive strength tests were performed for composite samples to confirm that use of a rock yield of 11,000 pounds per square inch (PSI) was prudent for design of the anchor pins.

The anchor pins were designed and installed to take full account of the bedrock to the surface. The design disregarded the top six inches of the bedrock as a load-bearing zone. It also satisfied two load conditions--the test load which resulted in an upward lift component on the anchor, and the horizontal loading expected during salvage operations. The pins were installed without incident, over a two-day period. Care was taken to ensure that the grouting material fully filled the cavity in the 17.5-inch diameter bore hole, and that the pins were properly centered and protected from grout washout.

5.6 Testing of Anchor Pins, Mooring Wires and Winches

Each anchor pin's designed holding capacity was 200 short tons. Tests on pin holding power involved hauling on each of the pins while holding to a test pin, which had been installed approximately 600 feet farther downriver. The test used Barge 252 with a stern winch connected to the respective anchor pin and a bow winch connected to the test pin. In the absence of a capable load cell, the winches were slowly loaded and stalled to the selected pump pressure corresponding to the proof line pull for the wrap present on the winch drum. This value was determined by linear extrapolation of the winches' designed performance. The average proof load held during the test periods was approximately 225 tons. The calculated line pulls were verified and calibrated against a 300,000 pound dynamometer. Divers inspected the condition of the pins and their stabilizing grout before and after the test. The winch "pump pressure/line wrap" technique was used throughout the salvage operation to estimate wire rope tensions. For amplifying details, see Figures 5-14 and 5-15.

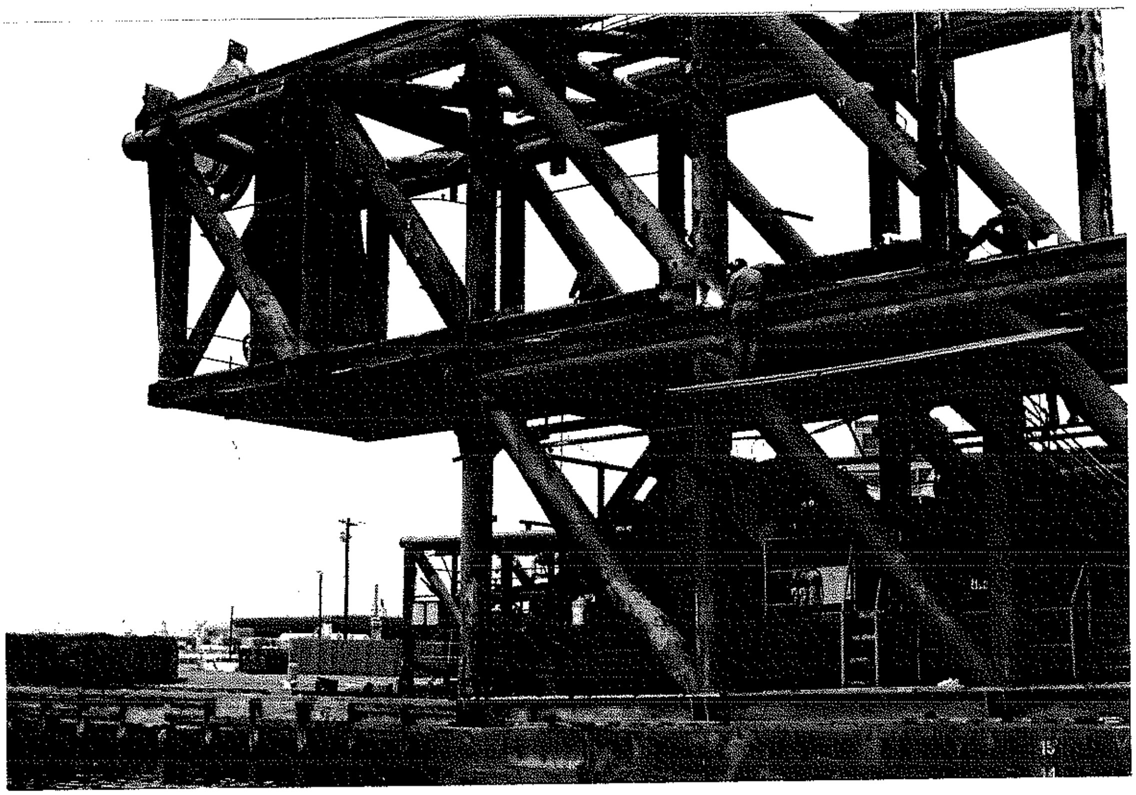
The breaking strength of the three-inch diameter wire was tested at the U.S. Navy Emergency Ship Salvage Material (ESSM) warehouse at Cheatham Annex, Williamsburg, Va. The two test wires failed at loads of 867,400 and 874,400 pounds respectively, both breaks being in excess of the ultimate anticipated salvage load of 800,000 pounds. With two 3-inch wires, the mooring system would have a total capacity of 800 tons. Because the four anchor pins, tested to 225 tons each (900 tons total) were stronger, factors of safety were based upon the nominal 800-ton combined breaking strength of the two three-inch diameter wires.

The total hydrodynamic resistance of Barge 45 (1056.2 short tons, per page A3-8), in addition to that of Barges 251 and 252, exceeded the combined breaking strength of the mooring wires. Thus, it was imperative that Barge 45 not be shifted from the pier 4 ice knife until it was lifted out of the water sufficiently to lower hydrodynamic forces to acceptable levels. If the salvors' actions had inadvertently accepted the full Barge 45 hydrodynamic load, wires would fail and, in the worst-case scenario, the three-barge armada could have gone over Niagara Falls!

The two 3.5-inch diameter wires on the Barge 251 lift trusses, having an advertised breaking strength of 555 tons each (i.e., 1,110 tons total), were not tested. However, the initial maximum calculated lifting force was 296.24 ST (per page A3-11) for a factor of safety of 3.75. In reality, a significantly greater load was anticipated and SUPSALV had agreed in advance to accept a factor of safety of 2.0 (555 tons). During execution, lift loads up to 650 tons were achieved, lowering the factor of safety to 1.7. While this was undesirably small, the practicality of the situation and realistic size of wire available mitigated against a more conservative solution.

Because time was insufficient to conduct a test lift, salvors tested winch performance by locking winch drums in place and backing the winch off in payout mode to the full hydraulic pressure of 3,100 PSI for each winch. Winch brakes were tested by locking them and attempting to turn the winch drums at approximately 90% of full hydraulic pressure. All machinery was test-run for five days to ensure reliability of diesel units, oil pressure gauges, temperature and RPM gauges, turbochargers, water pumps, belts and hoses.

FIGURE 5-1/5-2
CONSTRUCTION OF BARGE 251 LIFTING ARRANGEMENT
IN PORT NEWARK, N.J.



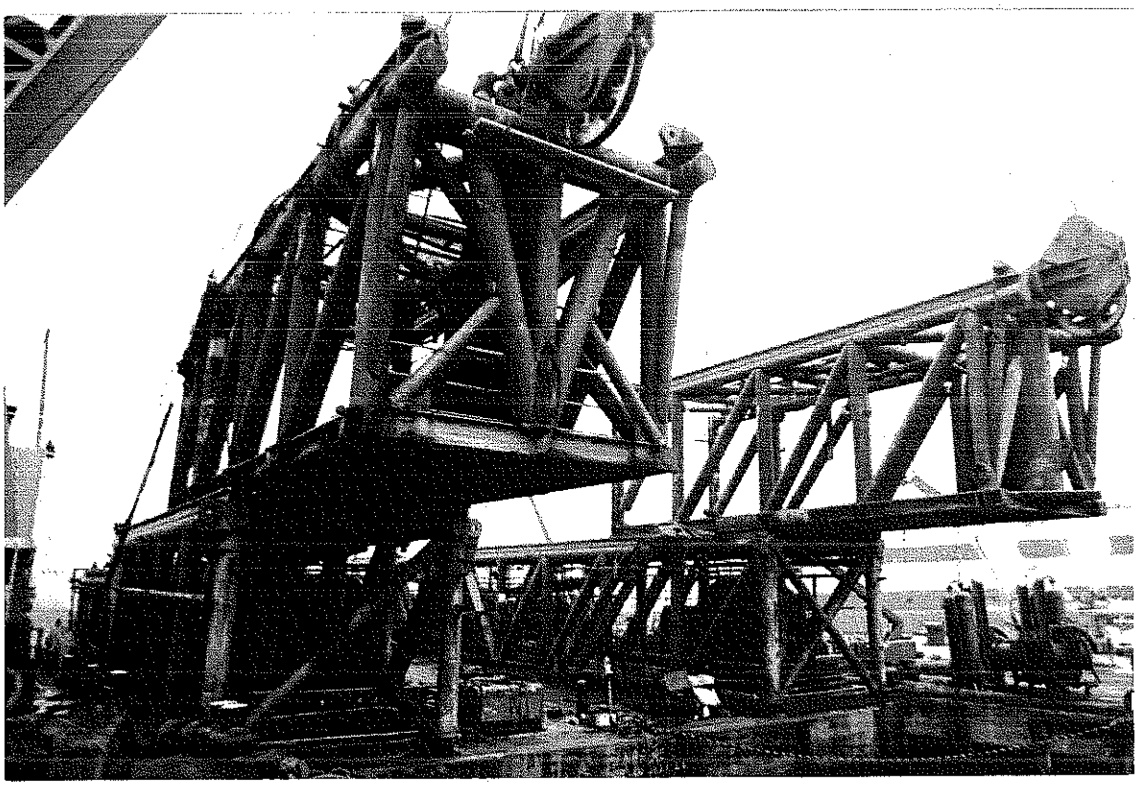
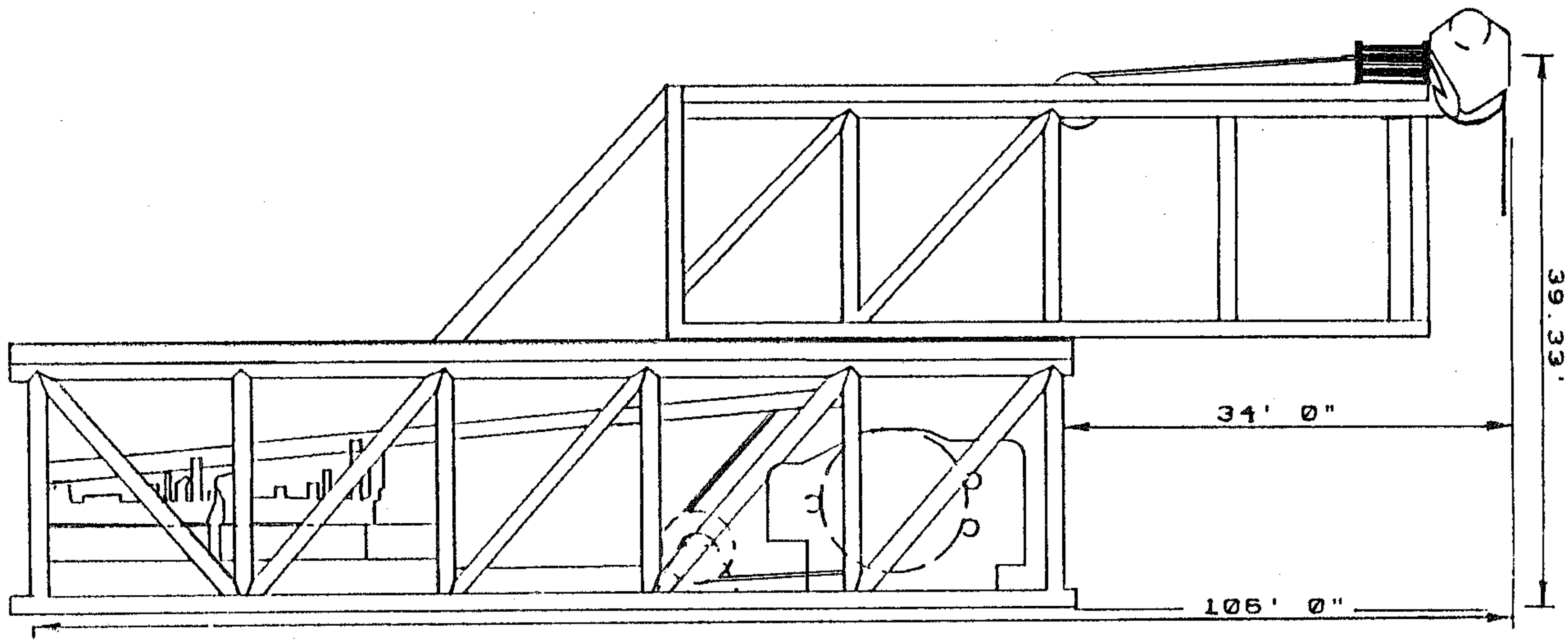


FIGURE 5–3/5–4
CONSTRUCTION OF BARGE 251 LIFTING ARRANGEMENT



USN SUPSALV
BARGE 45 SALVAGE OPERATION
SEPTEMBER - DECEMBER 1986
LIFT TRUSS SIDE ELEVATION
T-7 & T-8

FIGURE 5-5

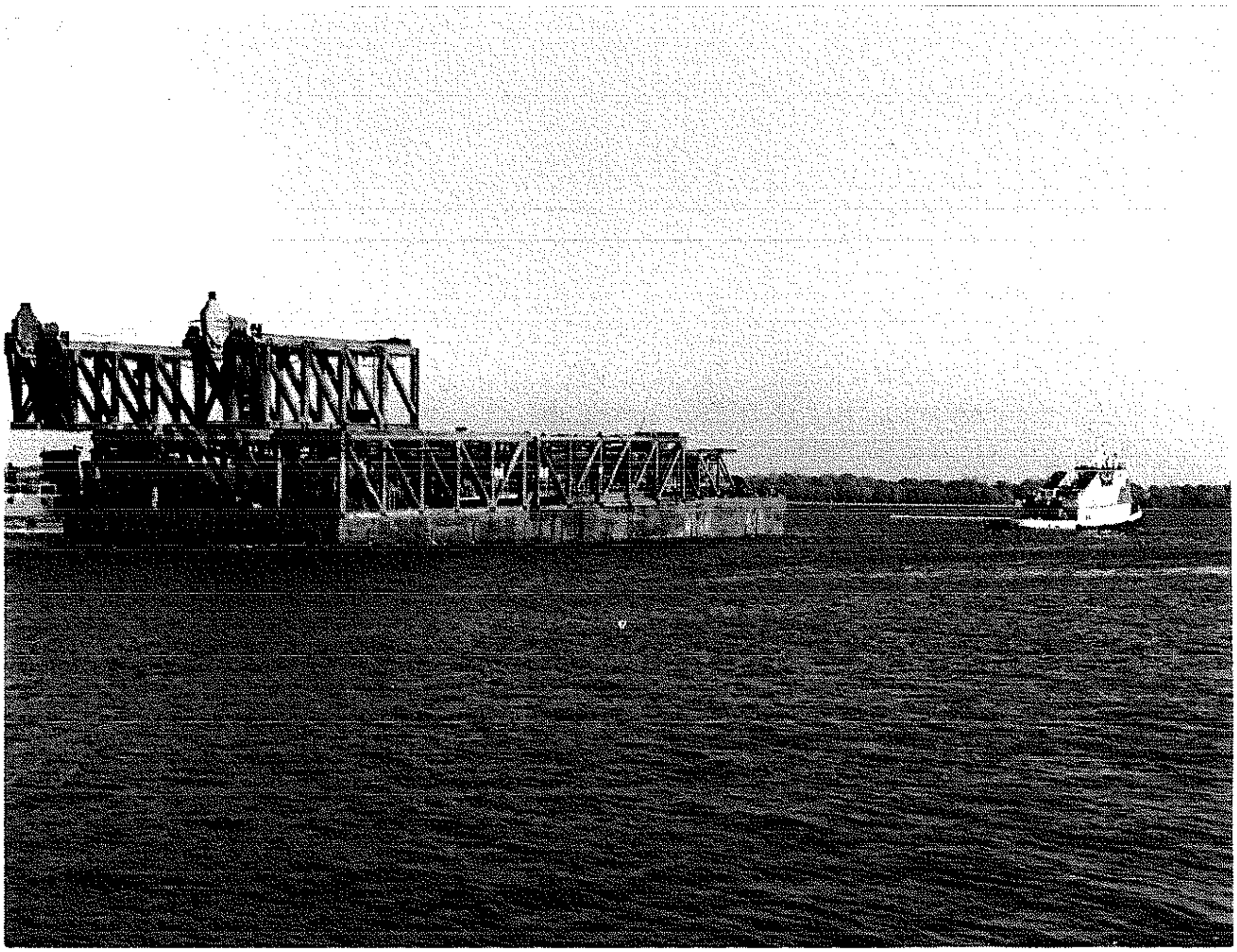
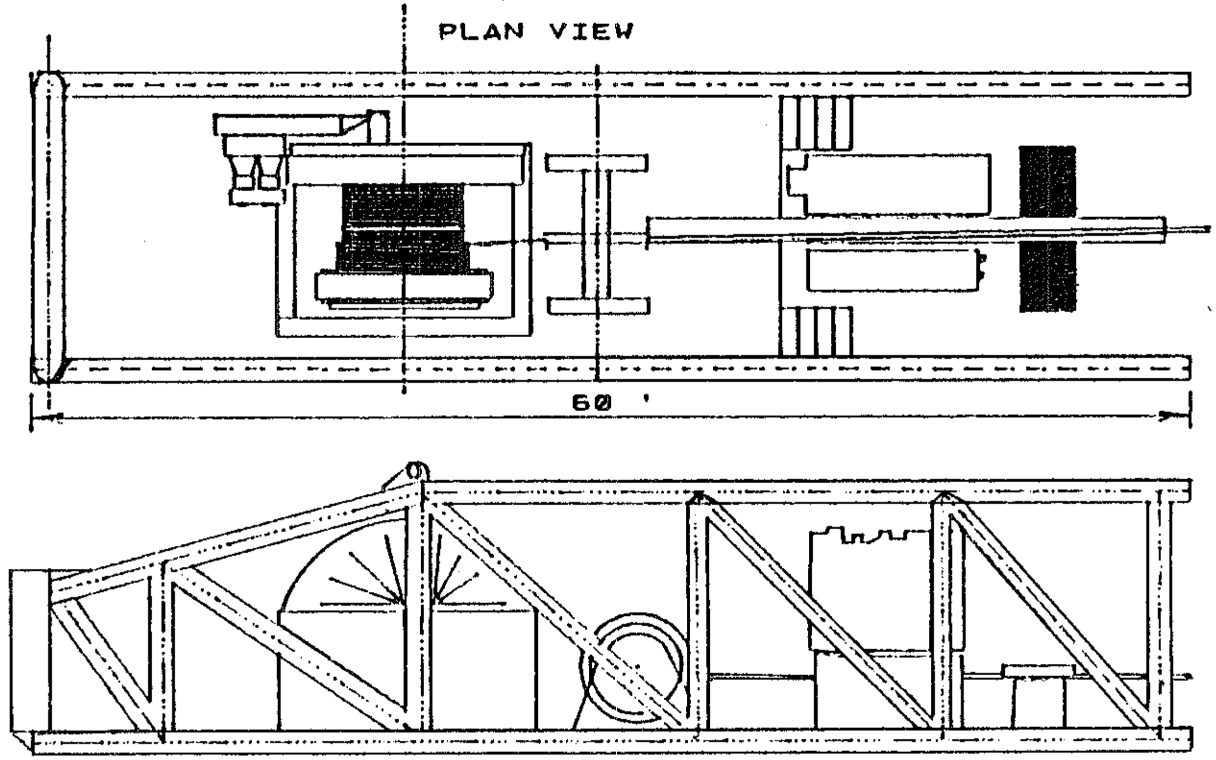
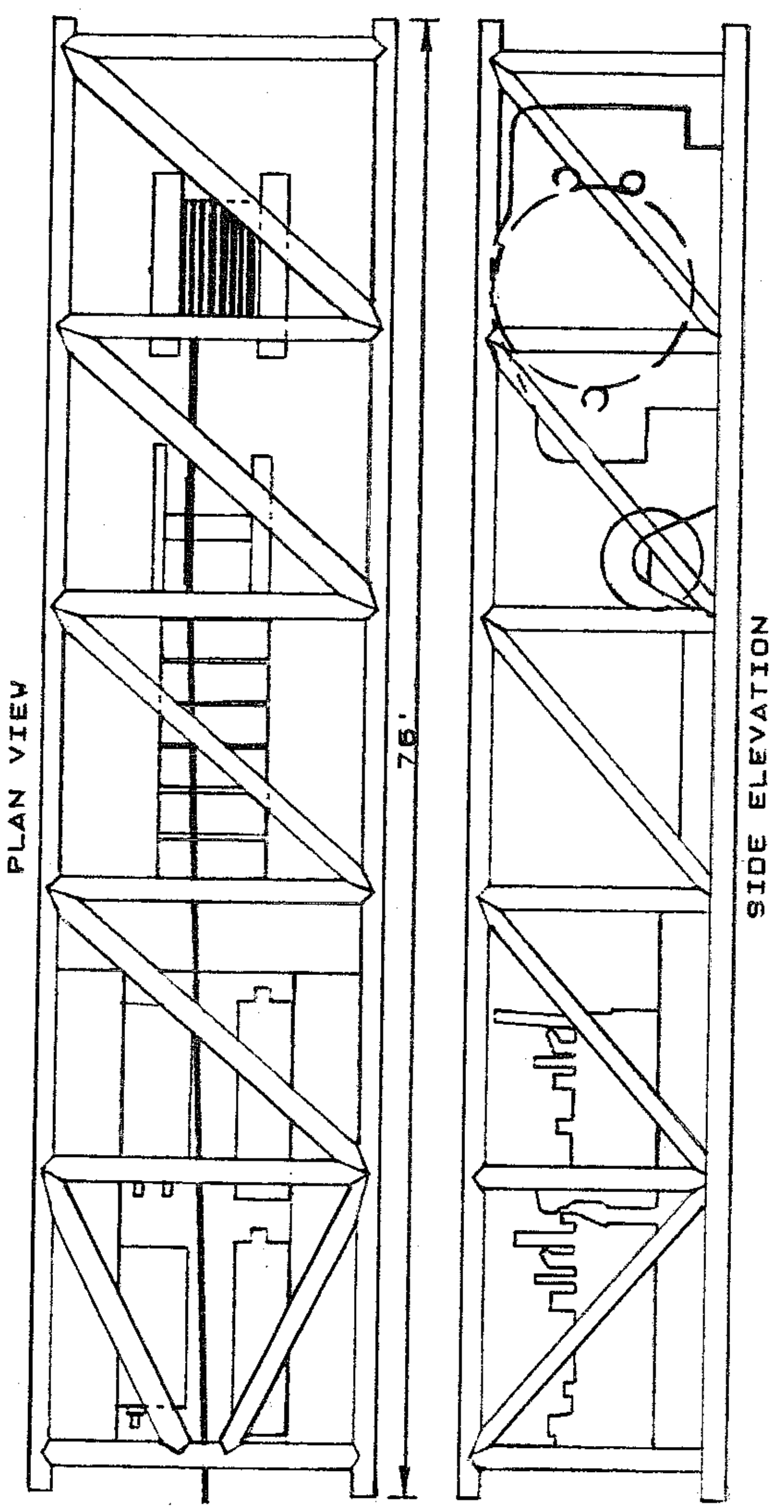


FIGURE 5–6
TUG EL GATO GRANDE TOWING BARGE 251 TO MONTREAL



USN SUPSALV
BARGE 45 SALVAGE OPERATIONS
SEPTEMBER - DECEMBER 1986
WINCH TRUSSES
T-1, T-2, T-3, T-4

FIGURE 5-7



USN SUPSALV
BARGE 45 SALVAGE OPERATIONS
SEPTEMBER - DECEMBER 1986
WINCH TRUSS T-5, T-6

FIGURE 5-8

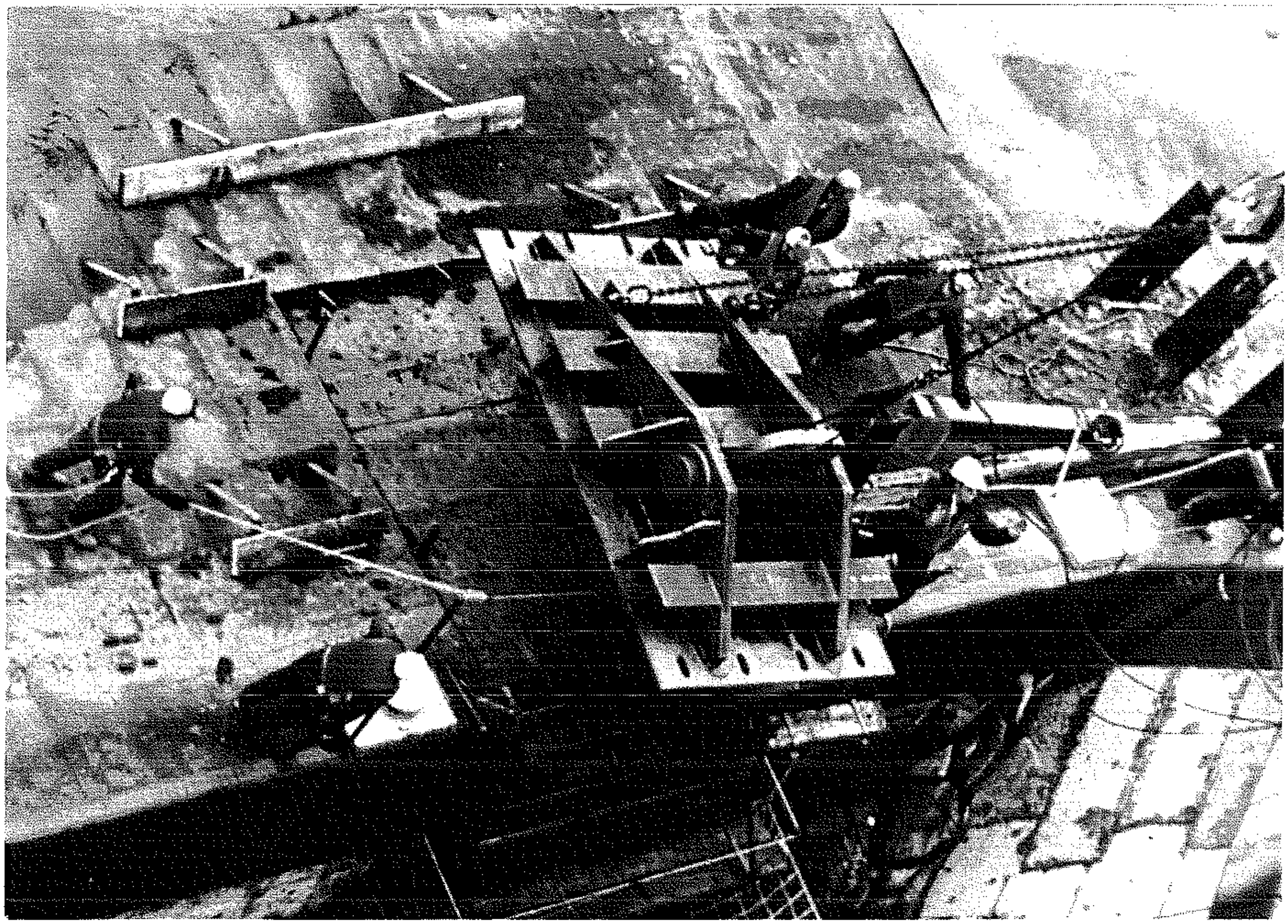


FIGURE 5–9
OPERATIONS TO INSTALL LIFTING SADDLES ON BARGE 45

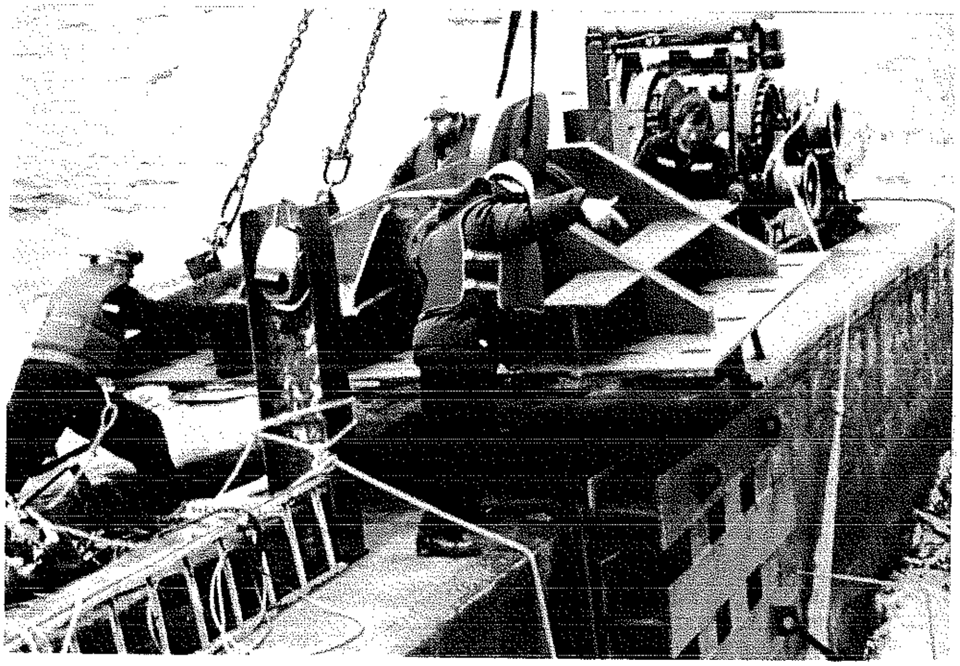
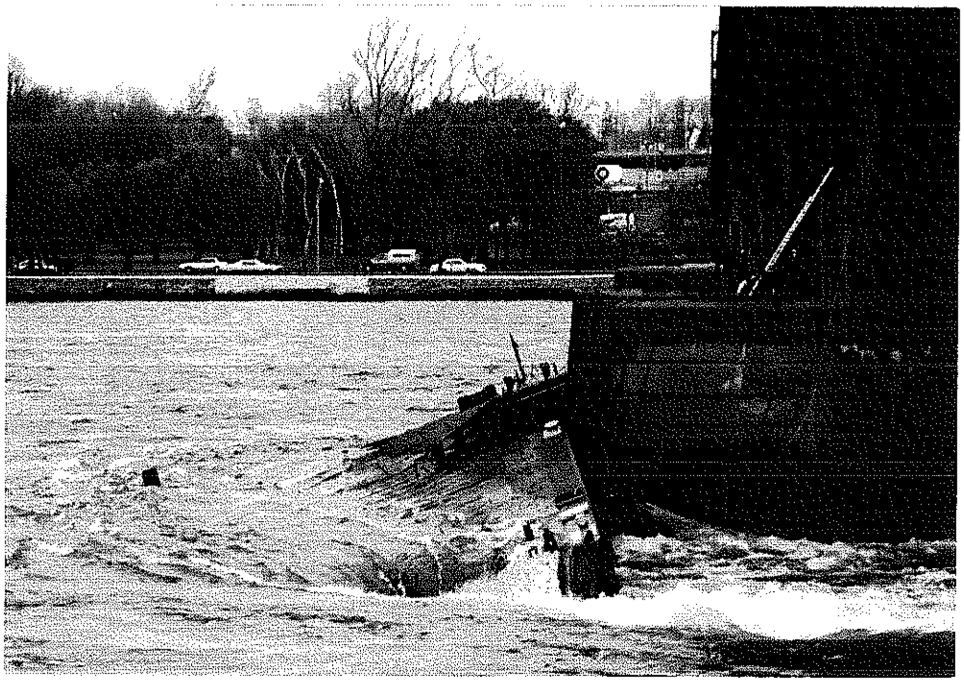


FIGURE 5-10
OPERATIONS TO INSTALL LIFTING SADDLES ON BARGE 45



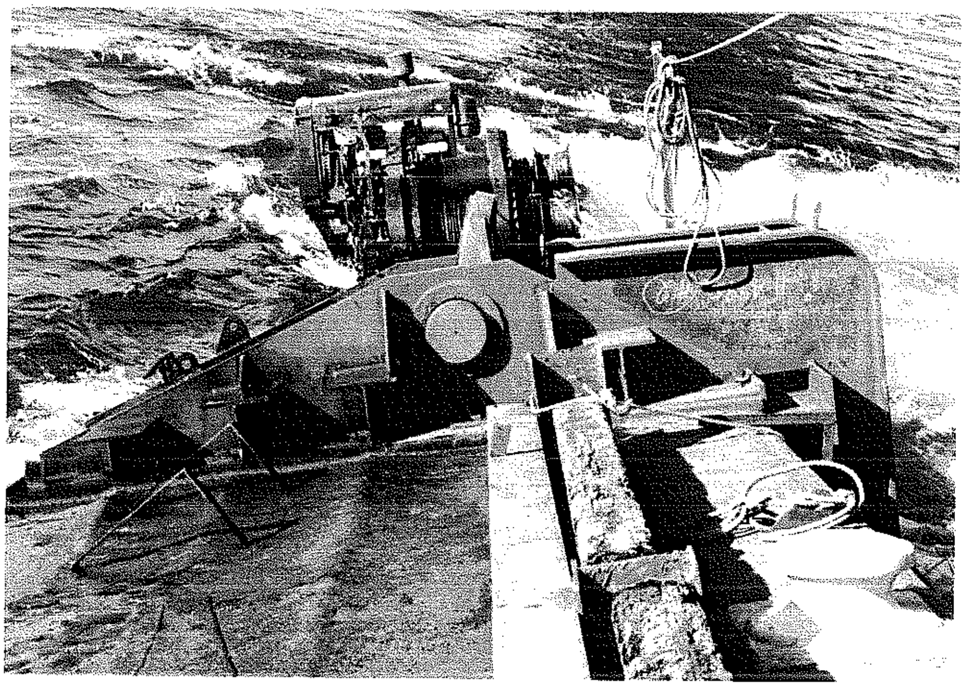
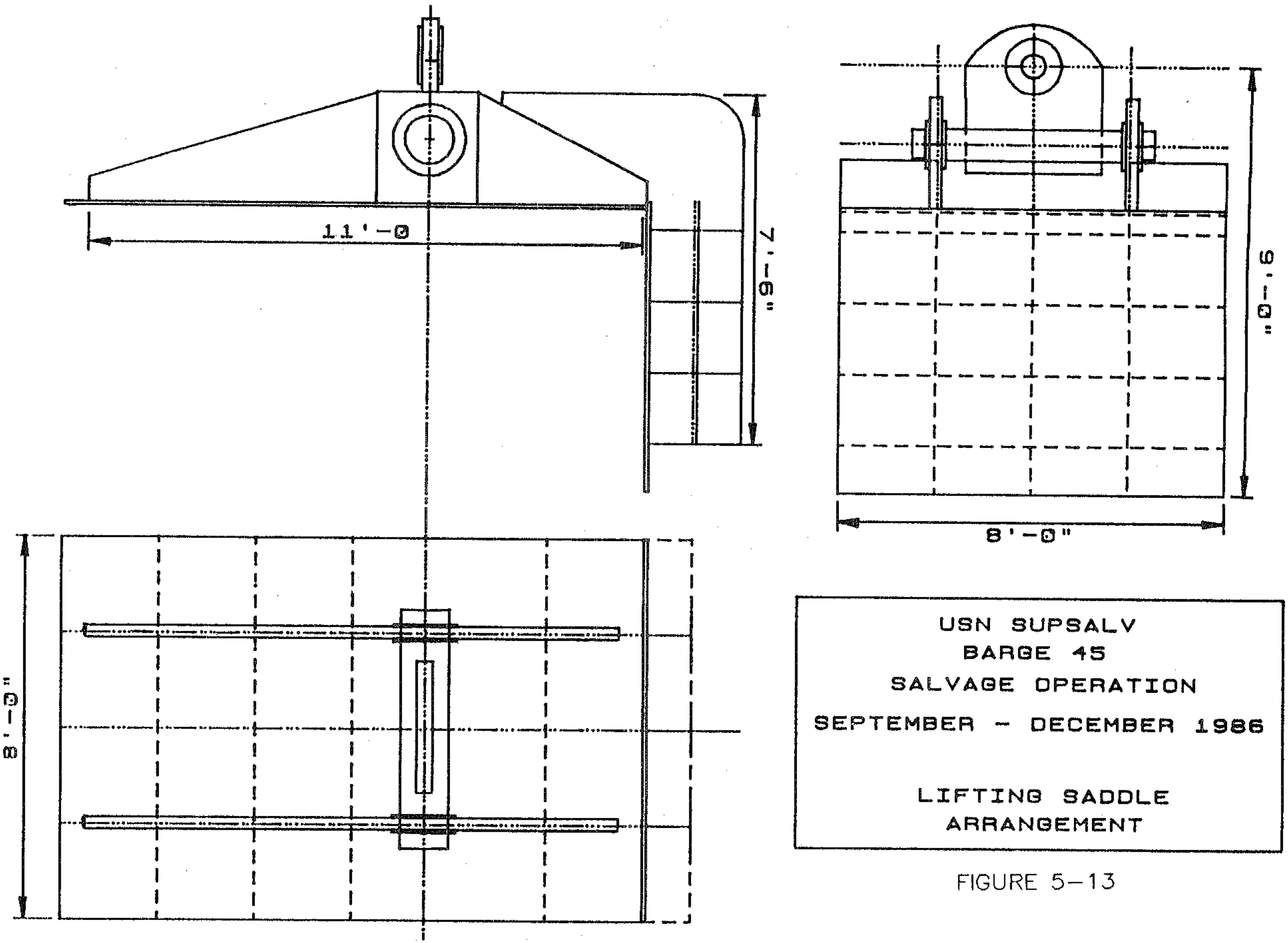


FIGURE 5-11/5-12
LIFTING SADDLES INSTALLED ON BARGE 45



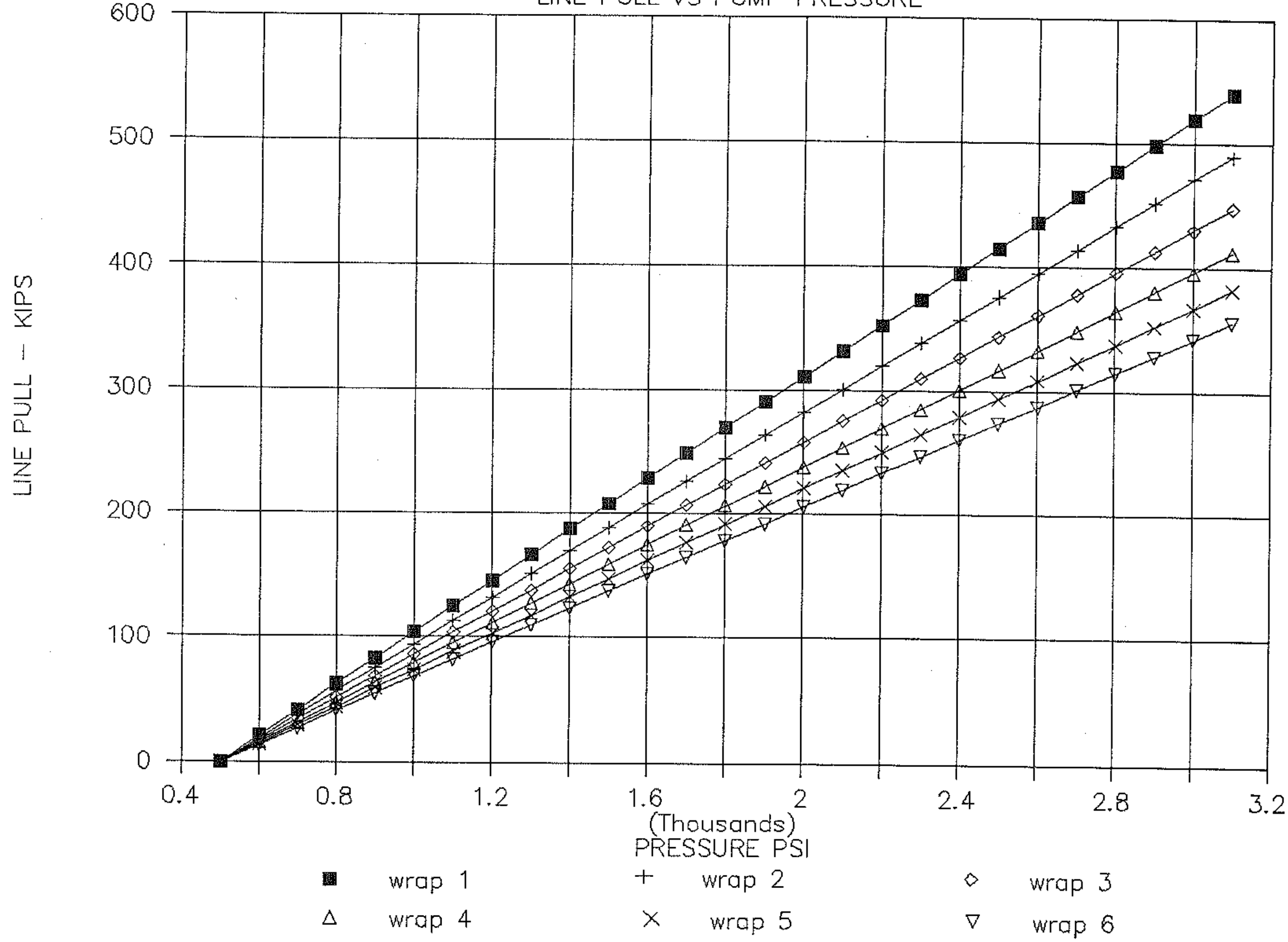
USN SUPSALV
BARGE 45
SALVAGE OPERATION
SEPTEMBER - DECEMBER 1986

LIFTING SADDLE
ARRANGEMENT

FIGURE 5-13

WINCHES T1- T4

LINE PULL VS PUMP PRESSURE



WINCHES T5 – T8

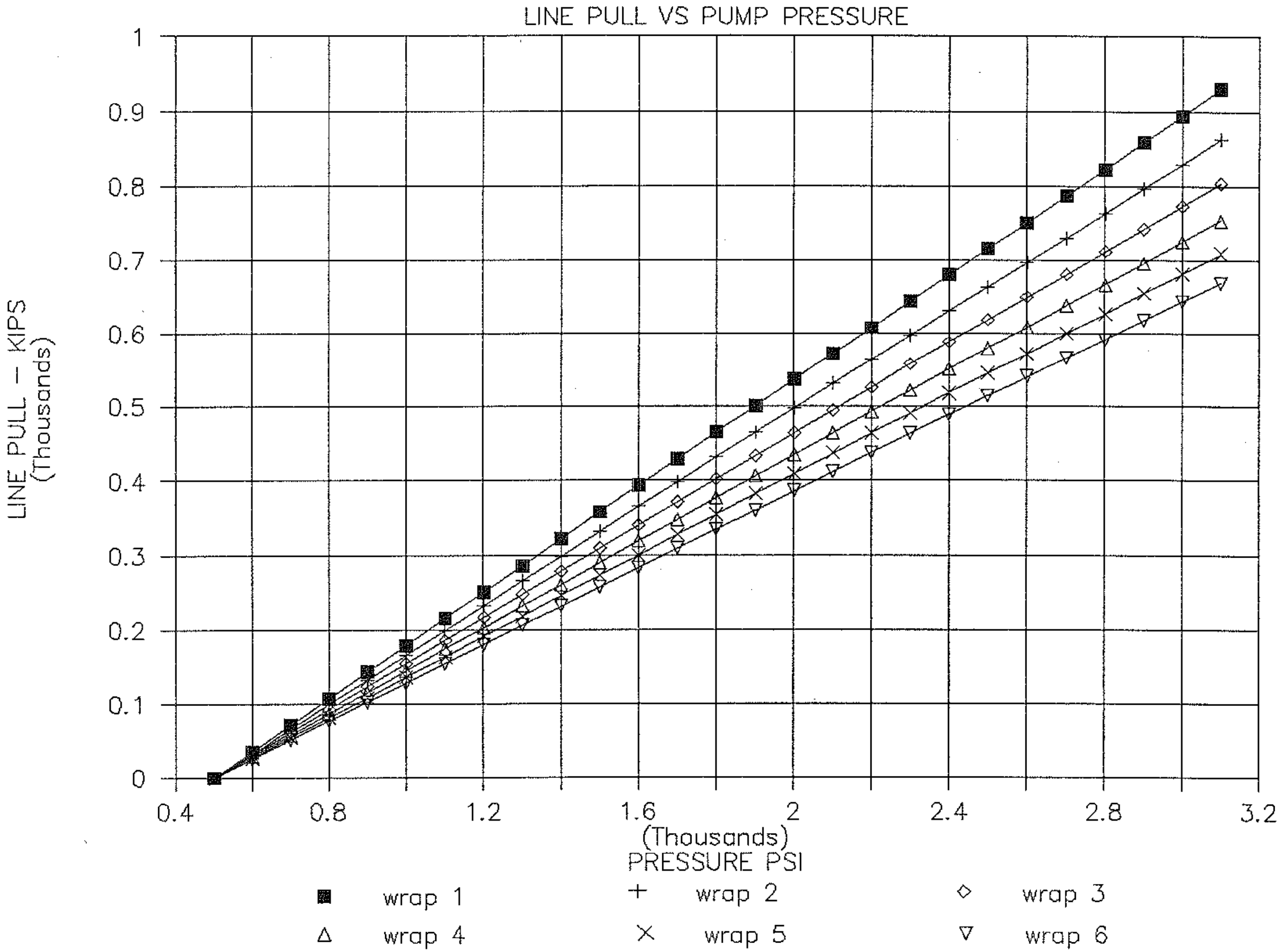


FIGURE 5–15

CHAPTER 6 EXECUTION OF SALVAGE PLAN

SUMMARY OF MILESTONE EVENTS

MILESTONE	EVENT
ALPHA	Mooring rigging installed and barges positioned
BRAVO	Barge 251 approaches wreck and strays into Peace Bridge span
CHARLIE	Barge 251 laterally positioned using tug's tow wire
DELTA	First lift attempt; lift wire parts
ECHO	Second lift attempt; lift wire parts
FOXTROT	Third lift attempt; Barge 251 hauled upriver
GOLF	Vessels removed from river; wreck disposal

6.1 MILESTONE ALPHA Mooring Rigging Installed and Barges Positioned

Execution of the salvage plan commenced on 25 November after completion of anchor pin testing. Salvors worked off Barge 252 and the spud dredge ANDREW B. to connect a 400-foot-long, three-inch diameter pennant wire to each of the four pins. On 26 November, after installation of the pennant wires, Barge 252 was towed back to the dock. The ANDREW B. crew then connected equalizer sheaves to the corresponding pennant wires, forming two bridle-like assemblies for connection to the next section of mooring wire. Divers ensured that no fouling occurred. Pennants and equalizers were installed by day's end. Dredge ANDREW B. remained on standby in the river during the night with the equalizers lashed to its deck.

Lift Barge 251 was towed out into the river at 0700 local time on 27 November. Because the cumulative length of wire on three sets of mooring winches was insufficient to allow the lift barge to reach the wreck, the 3.5-inch diameter wire from each lift truss was connected to the respective equalizer assemblies, and approximately 1,000 feet of wire was spooled off the winch drums as Barge 251 was allowed to drift downriver in the current. This offered a dual advantage. It compensated for the wire shortage and satisfied SUPSALV's requirement to obtain maximum winch line pull, which normally occurs with the first layer of wire rope on the drum. The wires were cut and stoppered off on the deck of Barge 251. Sockets were installed on the dead ends of the wires in preparation for connection to the next section of wire.

At approximately 1230 on 28 November, Barge 252 was towed into the Niagara River and brought alongside Barge 251. The stoppered-off wires on the deck of Barge 251 were connected to the wires passed from the respective stern winches on Barge 252. With Lift Barge 251 alongside, Barge 252's stern winch wires were slackened until the wires were almost completely off their winch drums. At this point, one of the wires was cut and passed to Barge 251 where a socket was installed on the wire's bitter end. After socketing, the wire was connected to a previously-installed padeye on Barge 251. The mooring load was then transferred to this wire. A similar procedure was used for the second wire. Barge 252 was towed to the dock at 0900 on 30 November, to spool an additional of 2,500 feet of 3.5-inch diameter wire onto each of its stern mooring winches.

On 1 December Barge 252 was towed back into the Niagara River and tied up alongside Lift Barge 251. The latter passed over the bitter ends of the two mooring wires. Barge 252's crew connected the transferred wires to its own stern mooring winches, and resumed slackening. The barges were kept in proximity to each other as Barge 252 spooled off wire (See Figure 6-1). The barges were swept toward the bridge by the ever-increasing current. When Barge 252 had spooled off approximately 1,560 feet of wire from its stern winches, those winch drums were dogged. Her bow winch wires were slackened until approximately 1,400 feet of wire had been spooled from the drums. As before, the winch dogging mechanisms were set so that slackening of the Barge 251 bow winch wires could begin.

6.2 MILESTONE BRAVO Barge 251 Approaches Wreck and Strays into Peace Bridge Span

At approximately 0600 on 1 December, after 66 days of extensive preparation, Barge 251 was allowed to warp downriver to a point approximately 1,000 feet from the wreck. As the lift barge proceeded to this point, the barge drifted from the baseline measured from the centerline of the anchor pins to the center of Bridge Pier 4. Attempts to compensate for the drift toward the Buffalo shoreline by alternately slackening port and starboard wires proved unsuccessful, so at approximately 2300 the operation was secured for the night.

On 2 December, selective hauling of the three sets of mooring winches allowed Lift Barge 251 to move back to the baseline and proceed downriver toward the wreck of Barge 45 (See

Figure 6-2). When the lift barge was within 50 feet of the wreck, it began to oscillate transversely from one end of the wreck to the other. The high-speed current forked at the wreck and diverted off either end with considerable velocity. The combination of this oscillation and the current velocity was sufficient to draw the mooring wires taut and cause Barge 251 to surge through the arch of the Peace Bridge between piers 4 and 5. The upper fairlead on the starboard side lifting truss jammed under the bridge span, near pier 5 (See Figure 6-3).

Salvors worked throughout the rest of 2 December and until approximately 1600 on the following day to free Barge 251. They hauled the port lifting wire up onto the deck of the Peace Bridge and dragged it along the bridge roadway to a point where it could be lowered to Pier 4 and connected to a 1.5-inch diameter wire which previously had been choked around the pier structure. Selective ballasting of the lift barge and hauling on the lift wire enabled salvors to haul Barge 251 toward the center of the span and finally clear of the bridge. It then could be warped upriver to assess damage.

6.3 MILESTONE CHARLIE Barge 251 Laterally Positioned Using Tug's Tow Wire

Weather worsened during the period 4-6 December. Strong southwesterly and westerly winds caused the water level at the bridge to increase, with corresponding current velocity increase. During this period, careful inspection revealed no significant damage to Barge 251's starboard lift truss as a result of hitting the bridge. Efforts to maintain lateral position relative to the bridge, using one-inch diameter wires running from the stern of Barge 251 to bridge piers 3 and 5, were unsuccessful. Salvors had underestimated the river's transverse flow components.

At this point salvors implemented a contingency plan. The ocean tug M/V EL GATO GRANDE was moored alongside the Canadian Dredge and Dock Co. dredge ANDREW B., in the Black Rock Canal (See Figure 6-4). The canal was deep enough to accommodate the tug, and had no significant current. The dredge acted as a stakeboat for the EL GATO GRANDE so the tug's two-inch-diameter tow wire could be run out and attached to a set of double bitts on the port side, amidships of the lift barge. Hauling or slackening the tow wire enabled lateral control of the lift barge during its final approach to the wreck.

6.4 MILESTONE DELTA First Lift Attempt; Lift Wire Parts

On 9 December salvors positioned the lift barge adjacent to Bridge Pier 4 and connected the 3.5-inch-diameter lift wires to the wreck. A major setback occurred the following morning as the starboard upper roller fairlead disintegrated while being cycled under load, causing the 3.5-inch lift wire to part. Barge 251 subsequently was hauled away from the bridge pier for repairs.

The failed fairlead roller was not part of the original winching machinery, but had been furnished, along with its companion port roller, from the salvor's yard. Although they appeared sound, in retrospect they should not have been used, since they were constructed of cast steel. The roller diameter was only 14 inches--too small for a 3.5-inch wire under high load. The absolute minimum recommended roller diameter for that size wire in limited salvage use is 21 inches. (See PROBLEMS ENCOUNTERED AND LESSONS LEARNED, Section 7.3).

6.5 MILESTONE ECHO Second Lift Attempt; Lift Wire Parts

During the period 10-12 December, the salvage crews fabricated and installed two new rollers, and removed and re-socketed the damaged section of the starboard lift wire. Because of the need for expediency these new fairlead rollers were flat and only 11 inches in diameter. (See PROBLEMS ENCOUNTERED AND LESSONS LEARNED, Section 7.3).

At approximately 0900 on 13 December, salvors attempted another lift. The wreck of Barge 45 began to rotate upright as the lift progressed. Portable pumps were used to dewater the wreck as it emerged from the river. Concurrently, men lowered by a crane from the bridge cut drainage holes into the wreck using oxy-thermal lances. At 1900, the load on the lifting arrangement was calculated at approximately 650 tons, and it appeared that the wreck's water drainage was inadequate. At this point strong winds began to blow out of the southwest. Due to increased water level and current speed at the bridge, salvors decided to set the wreck back down, cut more water drainage holes and wait for better weather. While the wreck was being set down, the load became unevenly distributed and the starboard lift wire parted once again, with subsequent irreparable damage to the newly-installed upper truss lift roller. The lift barge was warped upriver for repairs. The port lift wire remained connected to the wreck (See Figure 6-5).

6.6 MILESTONE FOXTROT Third Lift Attempt; Barge 251 Hauled Upriver

Salvors spent the next four days fabricating and installing new 21-inch diameter rollers for both upper lift trusses, replacing and socketing a new starboard lift wire and dewatering the wreck. The dewatering procedure involved using divers to cut access holes from inside the wreck, including holes in transverse bulkheads between tanks (See Figures 6-6 and 6-7). By 18 December, all was ready for another lift attempt. Salvors stood by until the next morning waiting for improved weather. On 19 December vertical rotation and lifting were resumed. Soon the lift wires were taut with 650 tons combined pull. The wreck remained immobile, and by now the salvors knew that the wreck contained little entrained water. Even as the salvage crews were considering the next best step, Barge 45 groaned, shivered and suddenly raised about five feet. The wreck somehow had caught on the base of the ice knife. This had caused the wreck to rotate, instead of sliding up the nose piece, temporarily making it seem inordinately heavy. The holding force had been exerted not by water, but by steel embedded in the hidden underwater portion of the concrete ice knife. The liftoff then proceeded without incident, and the wreck was lifted clear of Pier 4 ice knife at approximately 1100. The warp upriver commenced immediately. The force of the current, compounded by periodic contact with the bottom, progressively caused the wreck to fold in half as the lift barge was cautiously hauled upriver (See Figures 6-8 and 6-9).

6.7 MILESTONE GOLF Vessels Removed From River; Wreck Disposal

On 20 December a total of seven tugs assisted in the disconnect from the mooring arrangement and the shift of the lift barge to the dump site. The urgency of completing the work and transporting equipment through the St. Lawrence Seaway System before its winter closure necessitated leaving the intermediate lengths of mooring wires and the equalizer assemblies in the river. On 21 December the wreck was dumped at the COE Confined Dike Disposal Area #4 in the vicinity of the abandoned Bethlehem Steel plant located at the southeast corner of Buffalo Harbor (See Figure 6-10). Mooring Barge 252 and Lift Barge 251 were demobilized in Buffalo on 21 December EL GATO GRANDE and Barge 251 safely transited the Seaway System, while Barge 252 remained at a safe berth in Hamilton, Ontario, for the winter months.

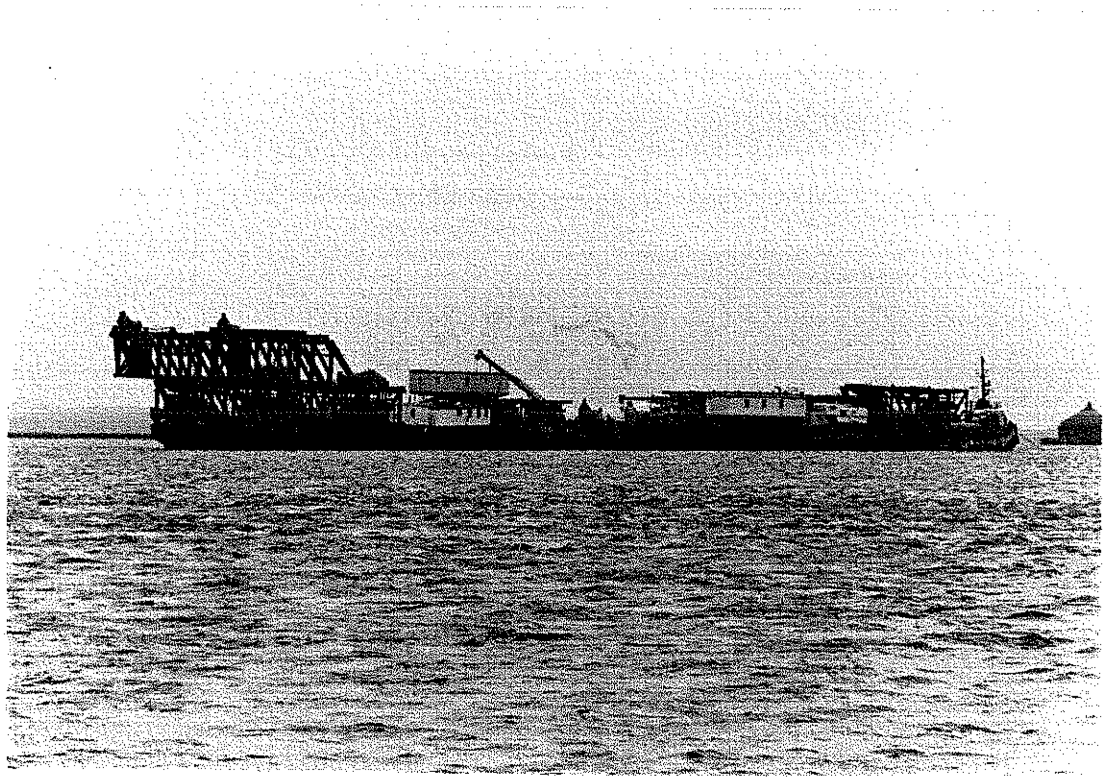


FIGURE 6–1

LIFT AND MOORING BARGES BEFORE SLACKENING OF WIRES, 1 DECEMBER

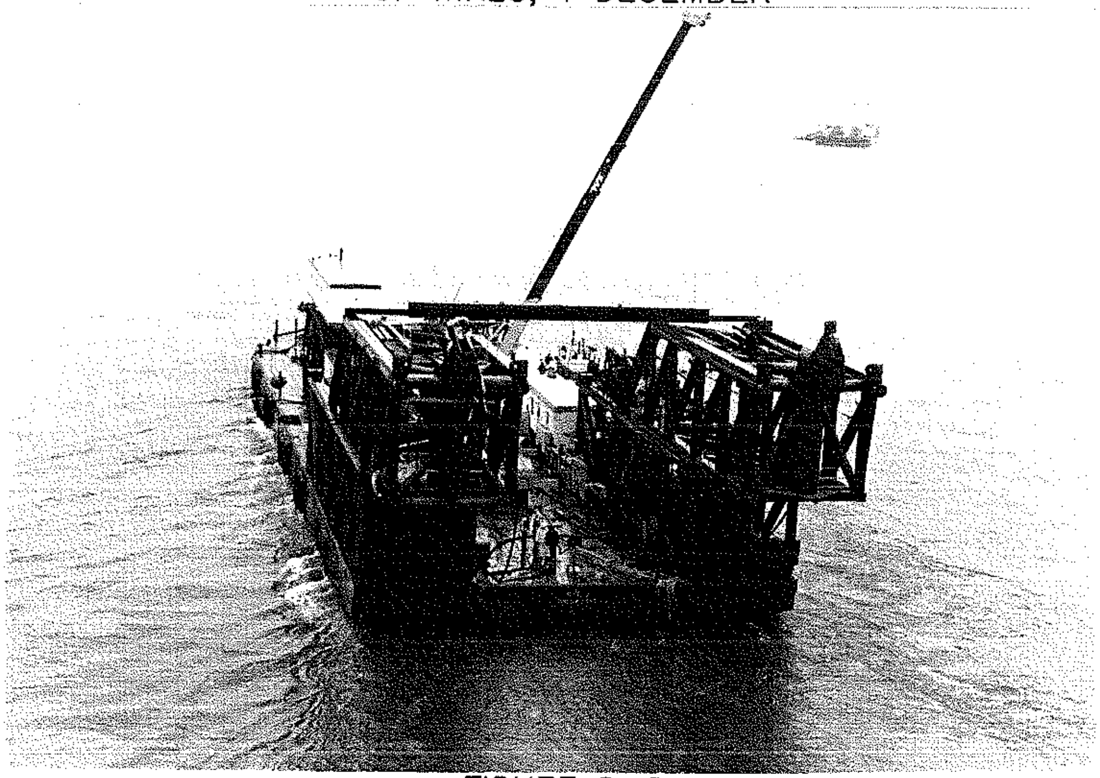


FIGURE 6–2

LIFT BARGE APPROACHING WRECK, 2 DECEMBER

FIGURE 6–3
LIFT BARGE JAMMED UNDER PEACE BRIDGE SPAN, 2 DECEMBER

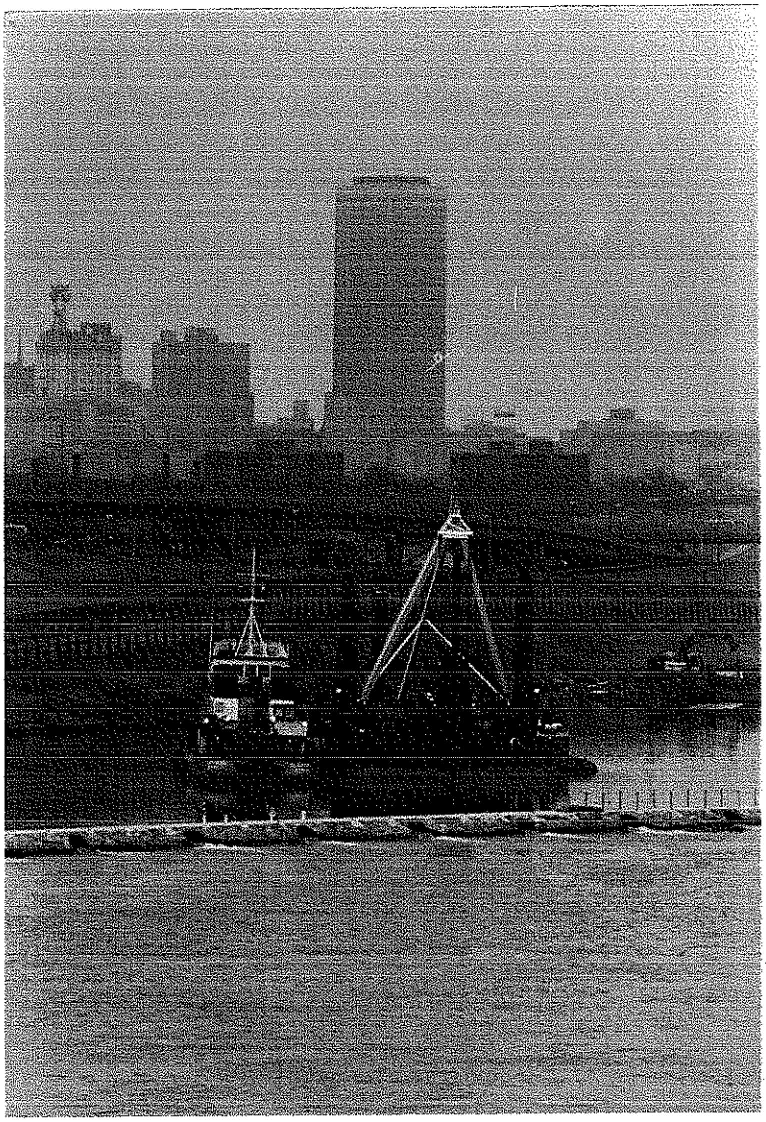


FIGURE 6–4
TUG EL GATO GRANDE AND DREDGE ANDREW B.
IN BLACK ROCK CANAL, 7 DECEMBER

FIGURE 6–5
BARGE 45 AFTER LIFT WIRE PARTED, 14 DECEMBER

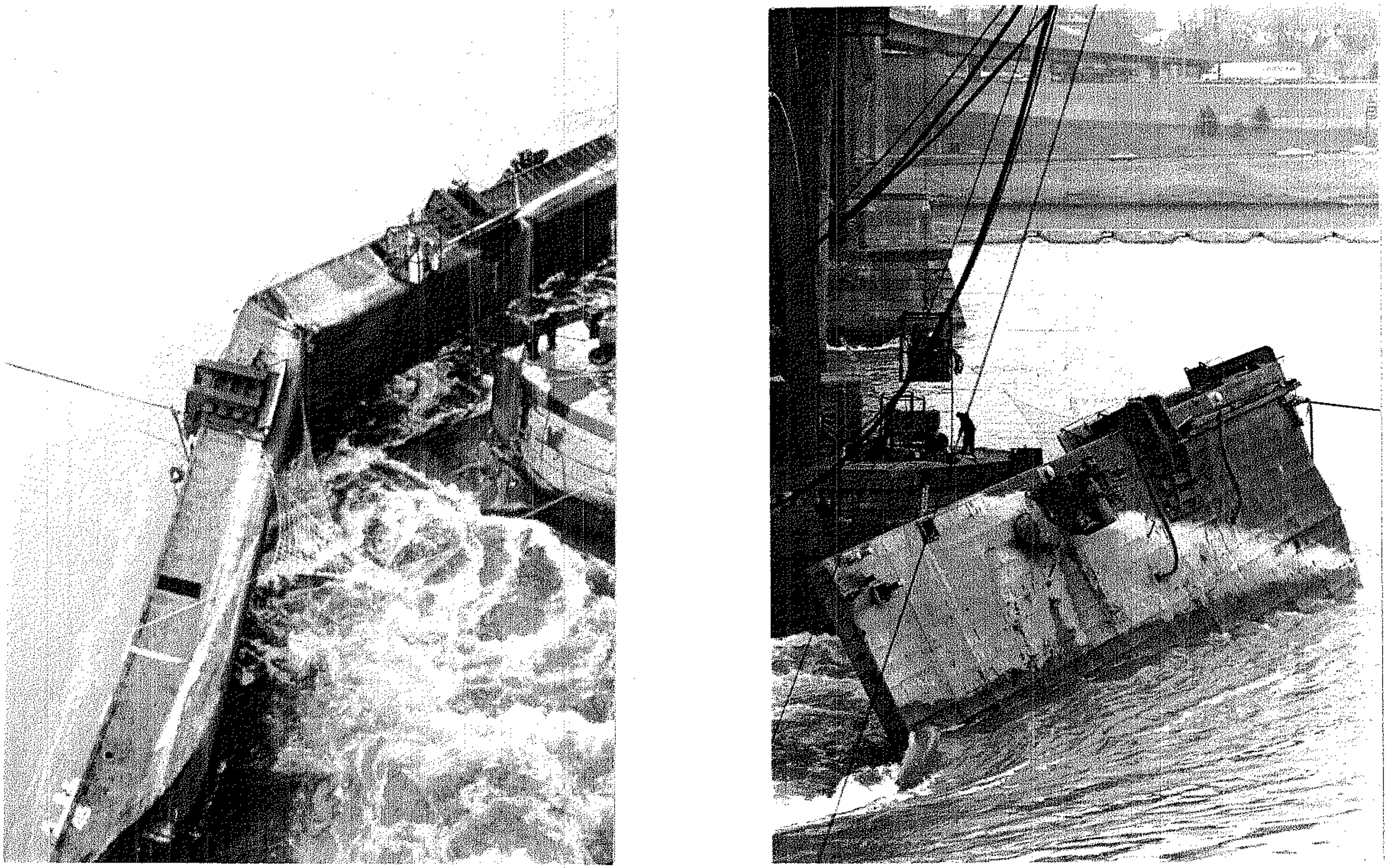


FIGURE 6-6/6-7
FINAL DEWATERING PROCESS COMPLETED, 17 DECEMBER

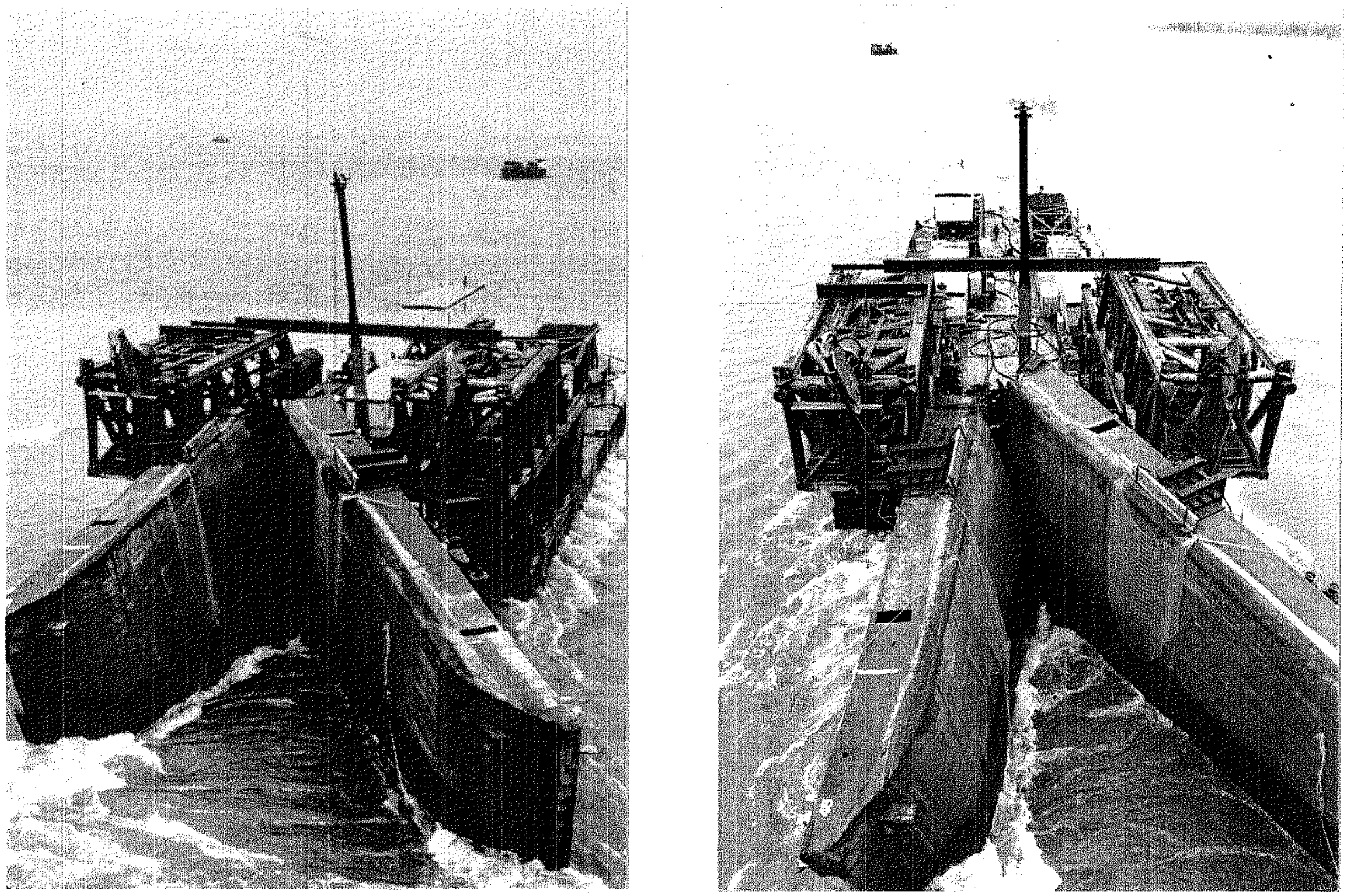


FIGURE 6–8/6–9
BARGE 45 HAULED UPRIVER, CURRENT CAUSING PROGRESSIVE
HULL GIRDER COLLAPSE, 19 DECEMBER

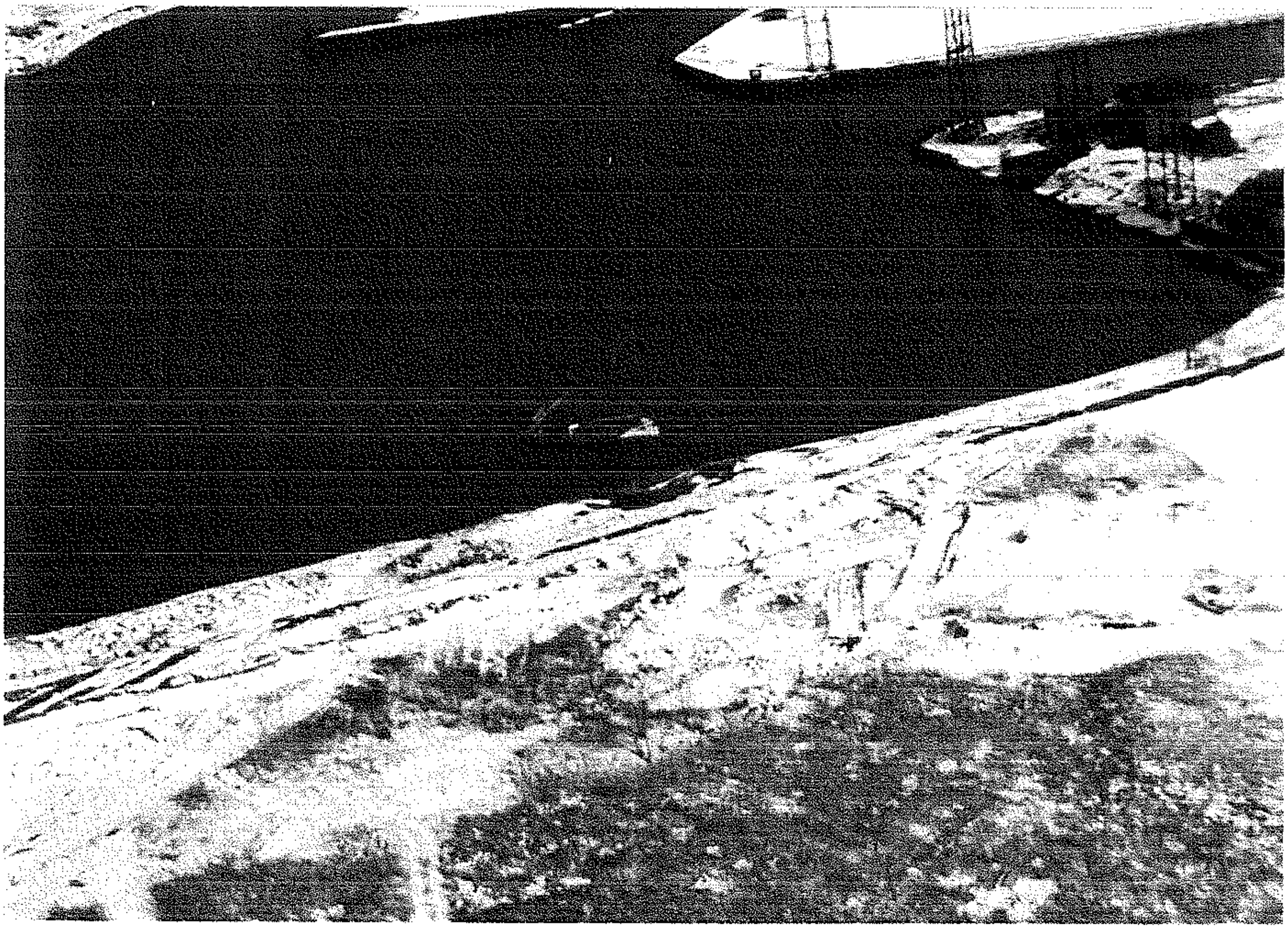


FIGURE 6-10
BARGE 45 AFTER DISPOSAL, 21 DECEMBER

CHAPTER 7 PROBLEMS ENCOUNTERED AND LESSONS LEARNED

The Barge 45 operation involved considerable technical difficulty. Salvors had to mobilize assets hastily and accept low safety factors, driven by the urgency of completion before the arrival of unacceptable winter weather. As with any complex salvage job, salvors experienced and ultimately overcame problems, delays and setbacks. The following discussion of these problems addresses:

- Time available to complete the task
- Simultaneous mobilization in three locations
- Lift wire roller and sheave diameter
- Wire available on winch drums
- Transverse hydrodynamic loads
- Availability and use of measurement instrumentation
- Dewatering the wreck during the lift operation
- Public affairs and communications among activities.

7.1 Time Available to Complete the Task

Time available for salvors to complete the project was estimated at approximately 80 days. Tasking occurred on 25 September, and the ice barrier historically had been installed at the mouth of the Niagara River around the middle of December. The problem was clear: salvors had to locate suitable equipment, configure and install it for the job at hand, transport the equipment to the casualty site, complete required safety tests and remove the wreck in order to demobilize from Buffalo before the St. Lawrence Seaway closed for the winter. The cost of a winter layup of salvage assets was considered unacceptable.

SUPSALV did not become involved in the casualty of Barge 45 until mid-September, as the COE had felt it necessary first to allow the owner to procure a salvor and solve the problem on his own. Navy salvors presented an initial plan after locating the winch/truss combinations in the Gulf of Mexico. COE legal procedures resulted in a 25-day delay before they tasked SUPSALV at the end of September. However, this delay proved critical, because during the delay the owners commenced scrapping the winch/truss units.

Dismantling caused a time and cost increase in four separate areas. The truss bottom suffered deformation, most evident at the bottom truss girders. The deformation produced a gap between the truss weldment points, increasing by approximately 150% the amount of welding necessary to attach the trusses to the salvage barges' decks. Internal machinery also was affected by the cutting. Hydraulic and cooling systems had to be repiped in order to restore them to their pre-dismantling configuration. In some winch/trusses the cutting had caused a considerable loss of wire. Extensive mechanical modifications and maintenance were necessary because the winch/trusses had not been operable since the mid-1970s, and because the machinery had been through numerous storms during the transit from the Gulf of Mexico to New York.

The lesson learned here is that salvors continuously must make customers aware of the impact of delays in the decision-making process. The salvor must understand and convince all parties that lost time and subsequent efforts to compensate for it will cause additional expense, especially with the advent of adverse environmental conditions.

7.2 Simultaneous Mobilization in Three Locations

The fact that salvors mobilized assets and coordinated major work in three separate locations led to significant inefficiencies which impacted cost and schedule.

Major modifications to trusses and machinery commenced upon the barges' arrival in Port Newark, N.J. Simultaneously, work began to design and install lifting saddles on the wreck; conduct core tests; drill holes; and grout anchor pins. Salvors transported to their subcontractor's base in Montreal the winch/truss combinations that would be used in the mooring system. Once the major modifications were complete, salvors left their home base in Port Newark. The anticipated production in Montreal never materialized.

Salvors experienced a similar situation upon arrival in Buffalo, in that local labor unions and contractors did not honor prior verbal agreements nor provide required services.

The lesson learned here is that salvors should expect a loss of continuity and reduced negotiating leverage when industrial work is to be completed away from home base. As much of the work as possible should be completed at home, where the contractor has absolute control of assets. If premature departure is mandatory, binding contractual commitments should be obtained in advance.

7.3 Lift Wire Roller and Sheave Diameter

The upper lift truss roller fairleads caused two major setbacks during salvops. During preparation for a lift on 10 December, and again during the first lift on 13 December, the starboard side lift wire and roller fairlead failed.

During the urgent mobilization salvors had installed roller fairleads in the upper lift trusses for guiding the lift wire from the winch drums in the lower trusses to the cantilevered fairleads at the end of the upper trusses. To expedite the mobilization phase, two rollers were obtained from the salvor's yard instead of having support structures specifically constructed for the 72-inch diameter sheaves, which were part of the miscellaneous inventory purchased with the winch/truss combinations.

Available wire rope manuals, including the "Wire Rope Users Manual, Committee of Wire Rope Producers, American Iron and Steel Institute," provide data to salvors on wire and sheave specifications. The specifications on the lift wires include:

Wire diameter	3.5 inch
Nominal strength	1,100,000 pounds
Wire classification	6 x 49 extra improved plow steel

For nominal service, the 3.5-inch diameter lift wires were rated with a safety factor of 5:1 at 222,000 pounds while for salvage work the same wire rope was rated as capable of a lift load of 900,000 pounds.

Table 7-1 indicates that wire cable having a classification of 6 x 41 requires a sheave diameter corresponding to a D/d ratio equal to 21:1 for reasonable service life, where:

D = thread diameter of the sheave in inches

d = nominal wire diameter in inches.

TABLE 7-1

SHEAVE AND DRUM RATIOS

Construction*	Suggested D/d Ratio***	Minimum D/d Ratio**
6 x 7	72	42
19 x 7 or 18 x 7 Rotation Resistant	51	34
6 x 19 S	51	34
6 x 25 B Flattened Strand	45	30
6 x 27 H Flattened Strand	45	30
6 x 30 G Flattened Strand	45	30
6 x 21 FW	45	30
6 x 26 WS	45	30
6 x 25 FW	39	26
6 x 31 WS	39	26
6 x 37 SFW	39	26
6 x 36 WS	35	23
6 x 43 FWS	35	23
6 x 41 WS	32	21
6 x 41 SFW	32	21
6 x 49 SWS	32	21
6 x 43 FW (2 op)	28	18
6 x 46 SFW	28	18
6 x 46 WS	28	18
8 x 19 S	41	27
8 x 25 FW	32	21
6 x 42 Tiller	21	14

* WS - Warrington Seale
FWS - Filler Wire Seale
SFW - Seale Filler Wire
SWS - Seale Warrington Seale
S - Seale
FW - Filler Wire

**D = tread diameter of sheave
d = nominal diameter of rope
To find any tread diameter from this table, the diameter for the rope construction to be used is multiplied by its nominal diameter (d). For example, the minimum sheave tread diameter for a 1/2" 6 x 21 FW rope would be 1/2" (nominal diameter) x 30 (minimum ratio) or 15".

NOTE: These values are for reasonable service. Other values are permitted by various standards such as ANSI, API, PCSA, HMI, CMAA, etc. Smaller values affect rope life (Fig. 7-1).

For a wire of 3.5-inch nominal diameter, the thread diameter of a normal service sheave used in a fairlead would be 73.5 inches.

Higher bending and tensile stresses are permissible when the service life of a wire is limited to one or two cycles, where fatigue would not be a factor. A minimum service life factor approximating unity would suggest a D/d ratio of 6:1. Thus, the minimum sheave thread diameter for this restricted condition then would be 21 inches for the 3.5-inch diameter lift cable. Figure 7-1 provides a graph of the relationship between service life and D/d ratios.

The service life curve only takes into account bending and tensile stresses. Its applicability can be illustrated by the following example: a rope working with a D/d ratio of 26 has a relative service life of 17. If the same rope works over a sheave that increases its D/d ratio to 35, the relative service life increases to 32. In short, this rope used on a larger sheave, increases its service life from 17 to 32, or by 88%.

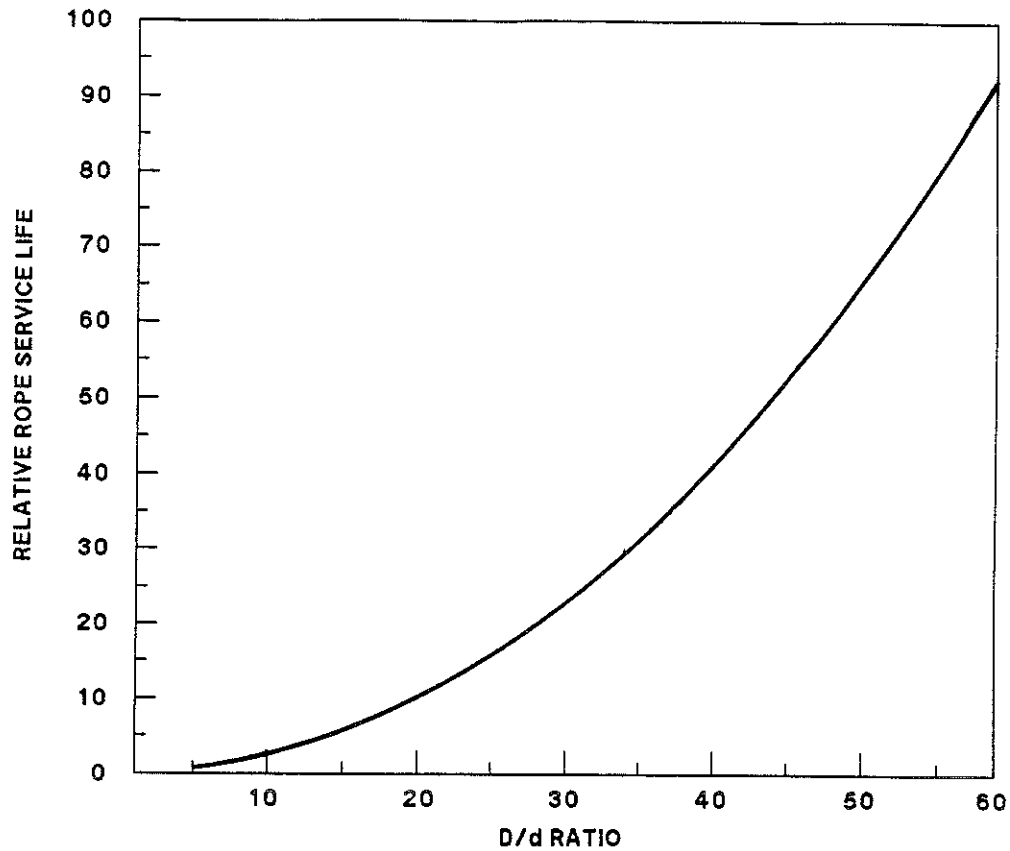


Figure 7-1
Service Life Curve for Cables With Certain D/d Ratios

In salvage situations where the salvor will operate at near maximum capacity, the wire rope is expected to be highly stressed and minimal sheave diameters normally will be used. In this case it is important that the sheave be provided with a groove having optimal geometry to properly support the shape of the wire and to prevent the wire's deformation or flattening under load. Table 7-2 provides information on minimal sheave and drum-groove dimensions for various size ropes under a range of conditions.

This page intentionally left blank

TABLE 7-2

MINIMUM SHEAVE-AND DRUM-GROOVE DIMENSIONS*

Nominal Rope Diameter		Groove Radius			
		New		Worn	
1 inches	2 mm	3 inches	4 mm	5 inches	6 mm
1/4	6.4	.135	3.43	.129	3.28
5/16	8.0	.167	4.24	.160	4.06
3/8	9.5	.201	5.11	.190	4.83
7/16	11	.234	5.94	.220	5.59
1/2	13	.271	6.88	.256	6.50
9/16	14.5	.303	7.70	.288	7.32
5/8	16	.334	8.48	.320	8.13
3/4	19	.401	10.19	.380	9.65
7/8	22	.468	11.89	.440	11.18
1	26	.543	13.79	.513	13.03
1 1/8	29	.605	15.37	.577	14.66
1 1/4	32	.669	16.99	.639	16.23
1 3/8	35	.736	18.69	.699	17.75
1 1/2	38	.803	20.40	.759	19.28
1 5/8	42	.876	22.25	.833	21.16
1 3/4	45	.939	23.85	.897	22.78
1 7/8	48	1.003	25.48	.959	24.36
2	52	1.085	27.56	1.025	26.04
2 1/8	54	1.137	28.88	1.079	27.41
2 1/4	58	1.210	30.73	1.153	29.29
2 3/8	60	1.271	32.28	1.199	30.45
2 1/2	64	1.338	33.99	1.279	32.49
2 5/8	67	1.404	35.66	1.339	34.01
2 3/4	71	1.481	37.62	1.409	35.79
2 7/8	74	1.544	39.22	1.473	37.41

TABLE 7-2 (continued)

MINIMUM SHEAVE-AND DRUM-GROOVE DIMENSIONS*

Nominal Rope Diameter		Groove Radius			
		New		Worn	
1 inches	2 mm	3 inches	4 mm	5 inches	6 mm
3	77	1.607	40.82	1.538	39.07
3 1/8	80	1.664	42.27	1.598	40.59
3 1/4	83	1.731	43.97	1.658	42.11
3 3/8	87	1.807	45.90	1.730	43.94
3 1/2	90	1.869	47.47	1.794	45.57
3 3/4	96	1.997	50.72	1.918	48.72
4	103	2.139	54.33	2.050	52.07
4 1/4	109	2.264	57.51	2.178	55.32
4 1/2	115	2.396	60.86	2.298	58.37
4 3/4	122	2.534	64.36	2.434	61.82
5	128	2.663	67.64	2.557	64.95
5 1/4	135	2.804	71.22	2.691	68.35
5 1/2	141	2.929	74.40	2.817	71.55
5 3/4	148	3.074	78.08	2.947	74.85
6	154	3.198	81.23	3.075	78.11

*Values given are applicable to grooves in sheaves and drums; they are not generally suitable for pitch design since this may involve other factors.

Further, the dimensions do not apply to traction-type elevators; in this circumstance, drum- and sheave-groove tolerances should conform to the elevator manufacturer's specifications.

Modern drum design embraces extensive considerations beyond the scope of this publication. It should also be noted that drum grooves are now produced with a number of oversize dimensions and pitches applicable to certain service requirements.

In this instance the salvor accepted a lower-than-recommended safety factor for sheave diameter and wire support. In retrospect, this was a major mistake, costing additional time and expense, which can be explained only by the urgency of the salvage. The third set of rollers, fabricated and installed after the 13 December lift attempt, had a thread diameter of 21 inches and were grooved properly to accommodate the worst-case load.

Technical data appearing in Table 7-1, Figure 7-1 and Table 7-2 are drawn from "Wire Rope Users Manual, Committee of Wire Rope Producers, American Iron and Steel Institute."

7.4 Wire Available on Winch Drums

Considering the anchor pins' position relative to the bridge, the lift barge had to transit approximately 7,500 feet to arrive at the wreck. The salvor experienced a problem in that the cumulative amount of wire on the three sets of mooring winches was insufficient to allow the lift barge to reach the bridge. Because calculations had led the salvor to believe that there would be a 1,000-foot shortage, the salvor's final salvage plan compensated for this shortage by including 1,000 feet of wire spooled off from the lifting trusses. This length of wire was intended to avert a mooring shortfall. The remaining wire on the lift winch drums satisfied SUPSALV's requirement for lifting Barge 45 on the first wire wrap (i.e., the point at which maximum single line pull could be obtained). The calculation for length of wire available on each drum utilized the following formula:

$$L = \sum_{i=1}^{i=N} \Pi d_i * W$$

where: i = layer number, from 1 to n
W = number of wire lays per layer
d_i = diameter at any layer

During anchor pin testing, it became apparent that the wraps on the winch drums were not tight--and, in fact, the cumulative length available still was insufficient. The salvor then utilized intermediate-length pennant wires procured from inventory (See Section 6, EXECUTION OF SALVAGE PLAN, MILESTONE ALPHA) to make up the required distance.

The lesson learned here is that every attempt should be made to verify wire lengths and other supplies on hand, where a specific quantity is required. A project can be shut down if supplies of critical components are insufficient to do the job. In this instance, the salvor had additional three-inch and 3.5-inch wire rope in stock. However, such wire and other high-capacity components are not instantaneously available in all salvage situations. The salvor must plan for loss and replacement of components in order not to jeopardize the continuity of a critical task.

7.5 Transverse Hydrodynamic Loads

Dealing with the transverse component of the Niagara River's current presented a major problem. Lateral positioning of the lift barge was a critical element of the operation. Drift tests and local topography had provided the data necessary to determine the required position of anchor pins to allow the barges to plumb downriver to the wreck site. However, data available on current direction was insufficient to allow the salvors to calculate accurately what should be the lift barge's exact position relative to the wreck of Barge 45. Salvage engineers underestimated the effects of transverse components of current adjacent to the wreck, and compounded this mistake by using a lateral positioning winch of inadequate capacity and condition. The final salvage plan had called for installation of wires running to the pier immediately adjacent to the wreck, for use in lateral positioning. One inch diameter wire was used by the salvors because it was readily available. A wire of this diameter was too small for the job and easily parted on several occasions. A contingency plan subsequently was devised and implemented on scene to use the on-site tug EL GATO GRANDE, with its two-inch diameter towing wire and winch with additional backup available via the U.S. Navy-supplied hydraulic pullers to solve the lateral positioning problem.

The lesson learned is that the salvor's plan should utilize only proven and tested auxiliary equipment with sufficient capacity to deal safely with worst-case loads. A system's overall performance can be jeopardized by any marginal component. In highly unusual operations such as this one, case histories may provide insufficient local environmental data. Therefore, when specifying equipment under these conditions, salvors should include a generous safety margin.

7.6 Availability and Use of Measurement Instrumentation

Among parameters measured during the operation were current velocity, anchor pin test loads and wreck condition and attitude. During initial site surveys, salvors measured current velocity at various points in the river. The accumulated data were matched against the river gauge level for the survey date to establish a baseline. This baseline measurement was used to extrapolate data for the specific salvops date to obtain estimated current speed, which was the fundamental parameter used to calculate the hydrodynamic force applied to the wreck. The resultant force value was the most important factor in the decision-making process during execution of the salvage plan. The salvor was directed to procure a current meter to measure and record current velocity during the operation, since a current change of a few knots could have affected hydrodynamic drag by hundreds of tons. With the meter installed alongside the lift barge, the readings were inaccurate, due to the lift barge's attitude and hull geometry, which caused a localized flow.

Another measurement and instrumentation problem occurred during testing of the anchor pins. The design load for each pin was 200 tons, and salvors desired to test the pins to 110% of their design capacity. Salvors procured the only known portable dynamometer in North America capable of measuring loads in excess of 200 tons while submerged. The load cell failed upon submersion, and a substitute measurement method was necessary. Salvors interpolated the performance of the hydraulic winch (i.e., line pull vs hydraulic pressure for various wraps). Calculated line pulls were verified and calibrated against a 300,000 pound dynamometer, which the salvor procured from another supplier.

Other important considerations included design and installation of a measurement system to monitor the vertical, horizontal and rotational movement of the wreck, and the angle of the lift wire relative to vertical. Measuring such variables would have allowed the salvors to understand better what was happening to the wreck by continuously monitoring conditions during the lift and comparing observations to the various predictions that emerged from the pre-salvage analysis. Unfortunately, when the salvor finally was directed to design and install a practical measurement system, the time required was prohibitive. In a salvage operation such as this where there are so many unknown or uncertain factors, the salvor should continuously attempt to install measurement instrumentation so that the salvage master has available as much relevant information as possible.

The lesson learned is that although accurate extrapolation and/or interpolation of available data may be sufficient to determine current velocities and loads, critical parameters should be actually measured if practical.

7.7 Dewatering the Wreck During Lift Operation

Dewatering Barge 45 during the lifting procedure was critical. The 300 ton estimate of the wreck's weight was derived by analysis of the hull form and structural configuration. This clearly was an estimate, since original plans and data for the 53-year-old barge were unavailable. Additionally, salvors had no information regarding possible additional weight due to rock or concrete ballast which may have been added during the life of the barge. Safety considerations precluded diver inspection of the wreck. Because the weight of entrained water during the lift would be additive to an already uncertain barge weight, it was mandatory that every possible step be taken to maximize the flow of water from within the wreck.

Salvors expected the barge to partially dewater itself during the lifting operation, because the barge was visibly holed and breached in numerous locations. The salvage survey and analysis showed that the barge was raked at both ends, with three main tanks divided into six compartments by a longitudinal, centerline bulkhead. The survey also allowed salvors to gain access to the center compartment on the high side of the wreck and the bow rake tank. Water levels in these tanks, which were inaccessible, were tidal, except in the bow rake tank. Water in this tank was observed to be higher than the river level, indicating that the tank was watertight.

Salvors planned to increase the dewatering rate by using underwater thermal lances. Men working from a man-basket deployed by a crane on the Peace Bridge roadway could operate the lances and punch numerous holes into the wreck. After the unsuccessful 13 December lift attempt, it was believed that the dewatering rate was insufficient and/or large pockets of water remained trapped. The thermal lances cut very small holes, and the salvage crews' area of operation was limited by the crane's reach. Subsequently, when the wreck's near-vertical attitude rendered it more accessible, divers made the compartments common by cutting holes into transverse bulkheads. Large holes also were cut in the side plating. This procedure left no doubts concerning excessive water weight. Salvors could then proceed with another lift attempt, assured that the wreck was draining properly.

In retrospect, the entrained water was not the primary cause of salvops' inability to lift the wreck on 13 December. During the successful lift on 19 December a point again was reached where the wreck could be lifted no further. While salvors applied a lift force of approximately 650 tons, the wreck suddenly dislodged itself from the ice knife. Thus, during the prior unsuccessful lift attempt, the contribution of entrained water to the total load will never be known.

The lesson learned in this instance is that all attempts should be made to verify the possibility of excess water within a casualty. If the amount cannot be verified, salvors should assume the worst case and systematically dewater the casualty. This approach may eliminate a potentially disastrous unknown.

7.8 Public Affairs and Communications Among Activities

As with all high-visibility salvage projects, the Navy salvage team was confronted with negotiating, communicating and working hand-in-hand with various government agencies, subcontractors and media personnel. In dealing with numerous groups having diverse interests, salvors often encounter problems with which they must deal on a case-by-case basis.

During a contracted salvage operation it is standard procedure for SUPSALV to insulate the contractor from other Government activities. Usually salvors also are discouraged from talking directly with media groups, because to do so distracts them from their primary responsibilities. Therefore, SUPSALV dealt with the COE, Buffalo District, who in turn handled all communications with the Peace Bridge Authority, USCG and media groups. The salvage contractor was expected to handle communications with all subcontractors, local collective bargaining units and the Peace Bridge Authority's consulting engineers.

During this task the flow of information went from the U.S. Navy to the COE and/or the USCG, and then to the eager news media. This information flow did not work well at times, and the television reports and newspaper articles frequently bore little resemblance to fact. As an example, after the 3.5-inch diameter lift wire parted due to a load shift on 13 December, the media were advised that winds gusting to 40 knots had parted the wire. The COE spokesman, being apparently unaware of the true story, seemed to have improvised and missed the mark.

The lesson learned is that periodic press conferences to provide media groups with clear and concise information are advisable. For high-visibility salvage operations with local or national media interest, the U.S. Navy should provide a public affairs officer to handle public affairs matters and to ensure the maximum positive Navy exposure.

APPENDIX A

METHODOLOGY FOR DETERMINATION OF BARGE 45 LIFT FORCES

A1. SYMBOLS AND ABBREVIATIONS

SYMBOL	DESCRIPTION	UNITS	NOTATION
A	Angle of Collapse	degrees	(°)
B	Angle of Rotation	radians	(rad)
B(x)	Barge Buoyancy as Function of Barge Length	long tons	(LT)
BN	Net Buoyancy Force	long tons	(LT)
$B_N(x)$	Net Buoyancy as Function of Barge Length	long tons	(LT)
C_d	Drag Coefficient		
C_{da}	Drag Coefficient of Aft Section of Barge		
C_{df}	Drag Coefficient of Forward Section of Barge		
d	Distance Dimension	feet	(ft)
F_f	Friction Force	short tons	(ST)
F_p	Pivot Point Force	short tons	(ST)
FS	Free Surface Effect	feet	(ft)
H_p	Draft of Barge	feet	(ft)
H_{pa}	Projected Draft of Aft Section of Barge	feet	(ft)
H_{pf}	Projected Draft of Forward Section of Barge	feet	(ft)
H_{pm}	Projected Draft of Midships Section of Barge	feet	(ft)
K	Shallow Water Coefficient		
K_a	Shallow Water Coefficient, Aft		
K_f	Shallow Water Coefficient, Forward		
KG	Keel to Center of Gravity	feet	(ft)
KM	Keel to Metacenter	feet	(ft)
L	Length of Barge	feet	(ft)
L	Lift Forces	short tons	(ST)
L_a	Length Aft	feet	(ft)

SYMBOL	DESCRIPTION	UNITS	NOTATION
LCB	Longitudinal Center of Buoyancy	feet	(ft)
LCG	Longitudinal Center of Gravity	feet	(ft)
L_f	Length Forward	feet	(ft)
M	Moment	foot-short tons	(ft-ST)
O	Origin of Coordinate System		
R	Distance Vector, Origin to Point of Interest	feet	(ft)
R_c	Current Drag in Deep Water	short tons	(ST)
R_{ct}	Current Drag in Shallow Water	short tons	(ST)
SM	Section Modulus	$feet^3$	(ft^3)
T_m	Mean Draft	feet	(ft)
u	Friction Coefficient		
V_c	Current Speed	feet/sec	(ft/sec)
VCG	Vertical Center of Gravity	feet	(ft)
W(x)	Barge Weight as Function of Barge Length	long tons	(LT)
W_b	Weight of Barge	short tons	(ST)
X	Longitudinal Coordinate Axis, Global System	feet	(ft)
X'	Transverse Coordinate Axis, Rotated System	feet	(ft)
X'	Longitudinal Coordinate Axis, Rotated System	feet	(ft)
Y	Transverse Coordinate Axis, Global System	feet	(ft)
Z	Vertical Coordinate Axis, Global System	feet	(ft)
Z'	Vertical Coordinate Axis, Rotated System	feet	(ft)
θ	Lift Line Angle, Relative to Vertical	radians	(rad)
ρ	Mass Density	pounds-sec^2/ft^4	(lbs-sec^2/ft^4)

A2. INTRODUCTION

This appendix treats the mechanics of the barge lift itself, as distinct from the problem of positioning both the lift and mooring barges in tandem. For purposes of this appendix, Lift Barge 251 is assumed to be moored a fixed distance from Mooring Barge 252. Figure A3-1 shows the lift arrangement at the outset of the evolution as lift tension is developed. The wreck is assumed to be supported all along its bottom by the sloping ice knife. Table A-1 provides information on Barge 45 which is particularly important to developing lift calculations. Figure A3-2 shows an elevation and plan view of Barge 45 as found at the start of salvage operations.

Table A-1
Particulars of Barge 45 as Found
at Start of Salvage Operations

L Aft	75 ft	Angle of Repose	20°
L Fwd	100 ft	Barge Light Ship Weight	302 ST
Angle of Midship Collapse			
Fwd	10°	Barge VCG	12.5 ft (below main deck)
Aft	10°		
Breadth of Barge = 40 ft			
Breadth of Deck Submerged:			
at Midship	2 ft	Current Speed	11 kts
at Bow	40 ft	Current Speed	18.58 ft/sec
at Stern	40 ft	Water depth	23 ft

Assumptions

The boundary conditions and other assumptions which frame the mechanics of the problem as presented here include:

a. Barge 251 is restrained in surge by the two mooring wires' catenary (surge motion is assumed to be negligible because Barge 252 can adjust tension in the mooring catenary to hold the lift barge stationary).

b. Lateral static and hydrodynamic forces are ignored, thereby rendering the lift problem two-dimensional.

c. Barge 251 is free to trim under the lift load.

d. The lift barge's added resistance due to trim under lift load is assumed to be small.

e. Current is a steady 11 knots throughout the entire water depth (i.e., there is no velocity gradient).

f. The barge is free to flood and drain (i.e., there is no net buoyant force or added weight of entrapped water).

g. The actual angle of repose of the barge was 19.5°. For simplicity of calculations, a 20° angle was used throughout.

A3. ROTATIONAL PHASE

Using the information supplied in Figure A3-1, and bearing in mind the foregoing assumptions, each force which comes into play during the initial lift will be discussed in turn.

F_p - Pivot point reaction. At the instant of rotation, the starboard bilge of Barge 45 bears against the lower ice knife. This point of contact becomes the point of rotation during the first moment of the wreck lift. It serves as a suitable point, "O", about which to sum moments of all forces.

R_{ct} - Current force in shallow water (See Appendix B9 for a full discussion). The current force of 11 knots of water flowing past the stationary wreck keeps the barge pinned to the bridge pier's lower ice knife. The magnitude and centroid of the current force is difficult to predict because of the barge's folded position over the lower ice knife and the fact that the deck is submerged. Figure A3-2 shows the barge's projected area exposed to the river's current, and reveals that its starboard side, close to the river bottom, constricts water flow, and thus greatly influences the free-stream flow.

As seen the horizontal plane, Figure A3-2 also shows that the barge's midsection collapse has swept back the bow and stern halves, permitting fluid acceleration along the deck. At each end of the barge, vortices form from the abrupt loss of fluid momentum associated with fluid deceleration at the ends. To further complicate the analysis, the water level has risen over the barge, forming wave drag in addition to the current force (i.e., viscous drag due to flow separation).

Of the two components of current force present, wave and viscous (pressure) drag, the viscous component clearly dominates. This dominance can be gauged intuitively from Figures 1-1 and 1-2 in the text of this report. The bow and stern eddies so apparent in Figure 1-1 indicate the strength of viscous drag, while the absence of a clearly-defined system of transverse waves in Figures 1-1 and 1-2 indicates that wave drag is not the dominant feature of current force. Therefore, it is convenient to neglect wave drag and concentrate on determining the current drag force.

Estimation of the current force for this situation must take into account the following effects:

- Free surface of the water
- Flow restrictions due to proximity of the barge's starboard side to the bottom
- Sweep of the barge ends due to midship collapse
- Free-stream eddies at the bow and stern
- The barge's 20-degree angle of repose on the pier's lower ice knife.

A detailed hydrodynamic analysis of this situation, using potential flow theory and the method of images to establish a plausible flow field around the wreck, is perhaps the most rigorous approach to a general solution of the problem. However, in this application, estimating the current viscous drag force is useful only to size salvage equipment and to ensure that sufficient capacity exists in the system to overcome the maximum current force pinning the barge to the pier's lower knife edge. As a conservative estimate, salvage engineers chose the British Ship Research Association empirical formula, discussed in Appendix B9, to calculate drag on the wrecked barge. This resistance formula incorporates hydrodynamic effects due to inertia, friction, roughness, and angle of attack to current.

$$R_c = C_d \cdot \rho/2 \cdot L \cdot H_p \cdot v_c^2$$

WHERE:

- R_c = current force in deep water (pounds)
- C_d = current drag Coefficient (figure B9-1)
- L = actual submerged length of either the bow or stern portion of the barge (i.e., 75 ft or 100 ft)
- H_p = projected submerged depth (average of depth at collapse point and either the bow or stern depth)
- v_c = current speed in ft/sec
- ρ = mass density of the water in slugs/ft^3

The constriction of water flow, also discussed in Appendix B9, is treated as a correction factor, K, which is a function of the ratio of depth of water to ship draft (see Figure B9-2). The total resistance formula in shallow water is written as follows:

$$R_{ct} = K \cdot R_c$$

W_b - Barge weight. With the barge open to free flooding, the weight of entrapped water counteracts buoyant forces of the submerged volume, so the two cancel each other. Thus, the barge lift weight equals the weight of barge steel and deck gear, including the lifting saddles welded to the deck. The barge's total lift weight was determined to be 302 ST. Once the barge lifts and rotates, there is a quantity of entrained water that must drain from the barge. This takes some time. The difference between water levels within the barge and at the water surface represents a net increase in barge weight, which is ignored in the equilibrium calculations for lift. If the lift is made too quickly to allow the entrapped water to drain out, this additional weight places a sizable additional load on the wire during the lift evolution.

The barge's center of gravity in its folded position is calculated as 12.5 feet below the deck level on the centerline. This center of gravity calculation assumes that weight distribution was homogeneous that the VCG of the undeformed barge was located at mid-depth and mid-length, and finally that the initial collapse angle was 10 degrees at each end. The VCG is calculated as follows:

$$VCG = \frac{9.5}{2} + \frac{\left(\frac{75}{2} \cdot \cos 10 \cdot \frac{75}{175} \cdot 302 + \frac{100}{2} \cdot \cos 10 \cdot \frac{100}{175} \cdot 302\right)}{302}$$

F_f - Frictional force. Until the barge initially moves and begins to rotate about the pivot point, O, frictional forces along the contact surfaces on the bottom of the barge act to restrain horizontal barge motion. Since the direction of initial impending motion is normal to the ice knife, the bottom contact friction force does not come into play in the initial lift. However, an initial vertical coefficient of static friction exists between the port bilge and the pier nose piece, which is assumed to be 0.10 R_{ct}.

Once the port side and bottom of the barge open a gap with the pier's knife edge, the horizontal current force will press the hull against the vertical pier ice knife, and vertical frictional forces will develop along the knife edge between the port side of the barge and the nose piece. As the barge works up the ice knife it will skid along on its starboard and port bilges, which are in contact with the ice knife. Forces developed during this stage of the evolution are addressed in the impending motion calculation.

Lift Tension Calculation

Calculation of the initial lift force is accomplished by summing moments about O, using the information provided in

Table A-1 and the geometry shown in Figures A3-1 and A3-2. To find the current drag force it is necessary to estimate the average projected draft of the bow and stern portions of the wreck, H_p. Then, following the discussion presented in Appendix B9, the empirical curves in Figures B9-1 and B9-2 can be used to account respectively for angle heading to the current and the effects of draft restriction. In this case, the information in Table A-1 can be used in conjunction with Figure A3-3 to determine the average draft and moment of submerged area. This calculation is accomplished as follows:

Calculation of R_{ct}

$$R_{ct} = R_{ct(fwd)} + R_{ct(aft)}$$

$$= C_{df} \cdot \quad /2 \cdot L_f \cdot H_{pf} \cdot v_c^{2} \cdot K_f + C_{da} \cdot \quad /2 \cdot L_a \cdot H_{pa} \cdot v_c^{2} \cdot K_a$$

$$= \quad /2 \cdot v_c^2 \; (C_{df} \cdot L_f \cdot H_{pf} \cdot K_f + C_{da} \cdot L_a \cdot H_{pa} \cdot K_a)$$

$= 1.9379$ for fresh water at 35° F

$v_c = 11 \cdot 1.689 = 18.58$ ft/sec

$L_f = 75$ ft

$L_a = 100$ ft

$$R_{ct} = 334.5\;(75 \cdot C_{df} \cdot H_{pf} \cdot K_f + 100 \cdot C_{da} \cdot H_{pa} \cdot K_a)$$

To calculate H_{pf} and H_{pa} from the data presented in Table 1, use the transform provided in Figure A3-3 as follows:

at midship, Y' = 2 and Z' = 9.5, therefore:

$$Z = Y' \sin 20 + Z' \cos 20$$

$$Z = 2 \sin 20 + 9.5 \cos 20 = 9.61 \text{ ft}$$

at bow and stern, Y' = 40 and Z' = 9.5 (note $H_{pf} = H_{pa}$)

$$Z = 40 \sin 20 + 9.5 \cos 20 = 22.61 \text{ ft}$$

$$H_p = \frac{9.61 + 22.61}{2} = 16.11 \text{ ft projected draft}$$

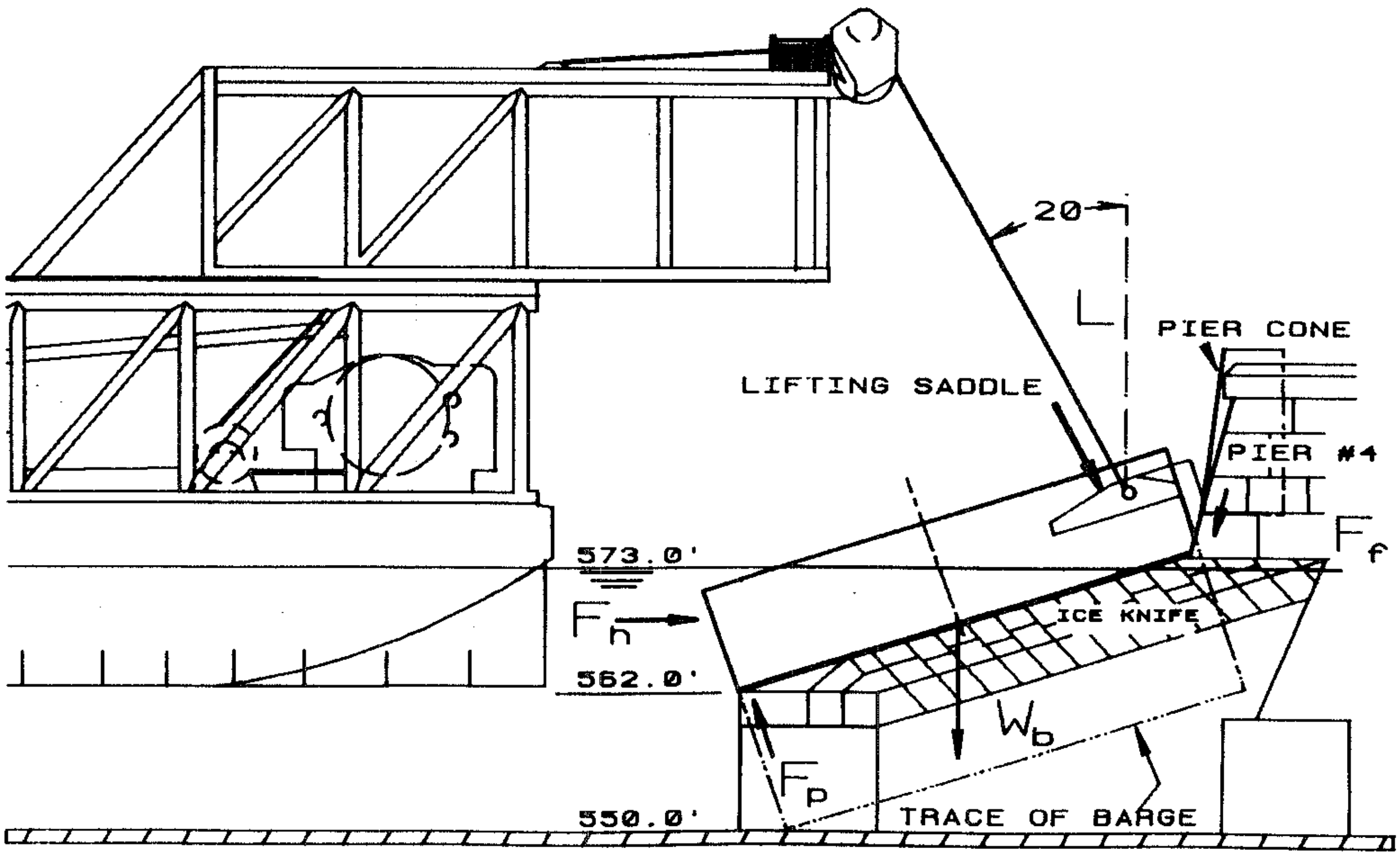
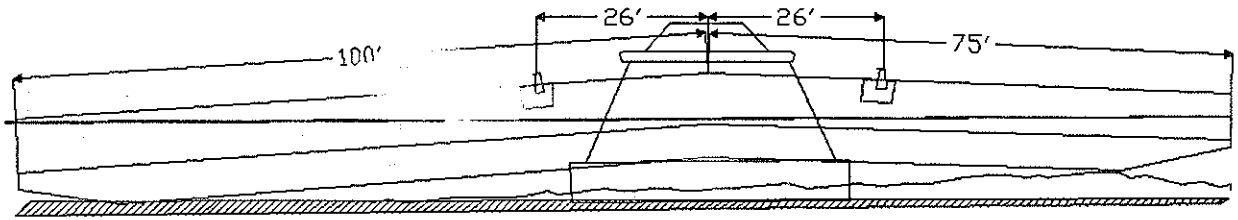
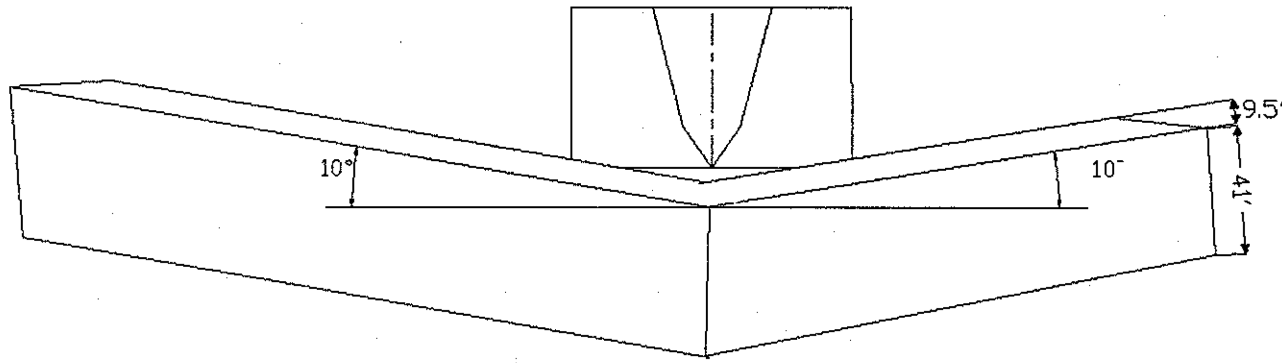


FIGURE A3-1
BARGE 45 LIFT ARRANGEMENT



BARGE 45 PROJECTED AREA
(X-Z PLANE)



BARGE 45 HORIZONTAL PLANE
(X-Y PLANE)

FIGURE A3-2

Calculation of C_d (Note $C_{df} = C_{da}$ since the angle of attack is 80 degrees for each part of the barge). Reading from Figure B9-1 for 80°, $C_d = 0.56$.

Calculation of the depth correction factor K for the depth/draft ratio of 1.43 (i.e., $23/H_p$) merely involves looking up the value of K in Figure B9-2 for 1.43 which is approximately 4.0.

R_{ct} is now expressed as:

$R_{ct} = 334.5\ (75 \cdot 0.56 \cdot 16.11 \cdot 4 + 100 \cdot 0.56 \cdot 16.11 \cdot 4)$
$R_{ct} = 2112407.67$ pounds
$R_{ct} = 1056.2$ ST

The centroid of the submerged area is calculated readily from the data by subdividing the area into a rectangle and a triangle.

Centroid of area:

Dimension	Area	d(from "O")	Moment
$9.61 \cdot 175$	1681.75	$+ 9.61/2$	8080.81
$\frac{(22.61 - 9.61)}{2} \cdot 175$	1137.50	$- 13 \cdot 1/3$	-4928.67
	2819.25		+3152.14

$$\frac{\text{Moment}}{\text{Area}} = \frac{3152.14}{2819.25} = 1.12 \text{ ft}$$

The location and magnitude of this force is indicated in Figure A3-3. The Y coordinate of the barge's 302 LT weight, which acts vertically, is:

$$Y = Y' \cos 20 + Z' \sin 20$$
$$Y = 20 \cos 20 + (12.5 - 9.5) \sin 20 = 19.85 \text{ ft}$$

The frictional force, F_f, appropriate for this stage of the lift is assumed to act at the intersection of the port bilge

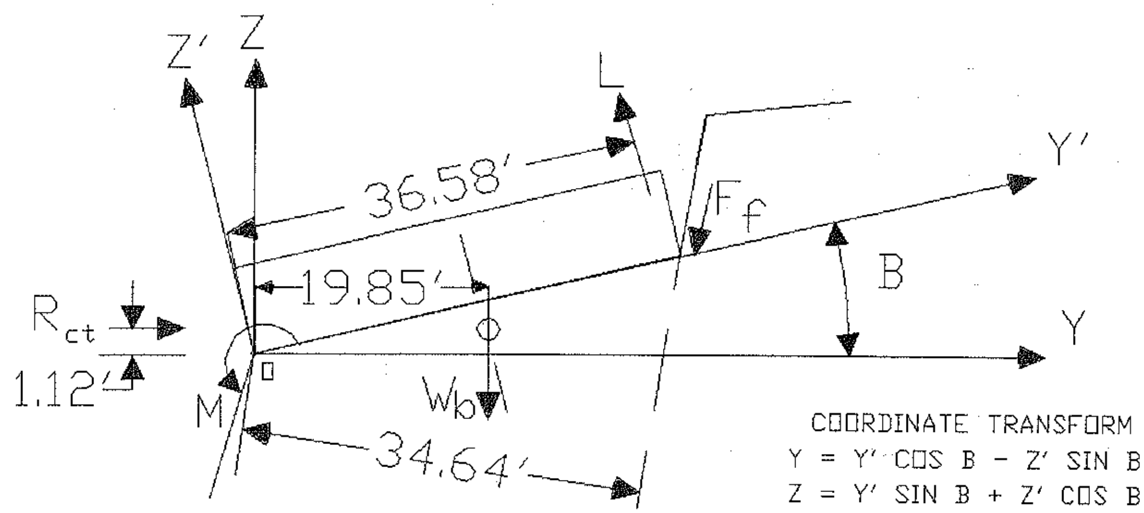


FIGURE A3-3
BARGE 45 Y-Z PLANE

and the nose piece. F_f is assumed to equal 0.1 of R_{ct}. Therefore, F_f is 105.62 ST. Friction acts <u>against</u> the instantaneous direction of motion, in this case downward at an 80-degree angle to the horizontal, along the nose piece. By inspection the moment arms of this force is computed as:

$$40 \sin 60 = 34.64 \text{ ft}$$

The lifting saddle location coordinates appear in Figure A-2. Y' and Z' coordinates are established for the 10-degree collapse angle as Y' = 36.0, Z' = 6.49 (Note Z' = 9.5 + 1.5 - 26 sin 10) relative to the origin at point "O". Using the transform these coordinates correspond to:

$$Y = Y' \cos 20 - Z' \sin 20$$
$$Y = 36 \cos 20 - 6.49 \sin 20 = 31.61 \text{ ft}$$
$$Z = Y' \sin 20 + Z' \cos 20 = 18.41 \text{ ft}$$

The lift vector, assuming a 30-degree angle from the vertical as shown in Figure A3-1, has Y and Z elements of -0.5L, and 0.866L, respectively. Using the cross-product rule, **R x L**, the moment is computed as:

$$\mathbf{R} \times \mathbf{L} \quad \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & 31.61 & 18.41 \\ 0 & -0.5L & 0.866L \end{vmatrix} = 36.58L$$

positive being counter-clockwise about "O".

For convenience Figure A3-3 shows the calculated moment arm distances from the pivot point.

Collecting all terms and using the convention that positive rotation is counter-clockwise (right-hand rule) the summation of moments is written:

$+ \nwarrow M_o = 0;$

$$- 34.64\ F_f - 19.85\ W_b - 1.12\ R_{ct} + 36.58\ L = 0$$

Applying previously-computed or known values given in Table A-1 of W_b, R_{ct} and using the fact that F_f is assumed to be a function of R_{ct} ($F_f = 0.1 \cdot R_{ct}$), gives the lift force L as:

$$L = [(34.64)(105.62) + (19.85)(302) + (1.12)(1056.2)]/36.58$$

$$L = 10836.32/36.58$$
$$= 296.24\ ST$$

A4. CONTROL LIFT FORCE

Once the initial friction force is overcome the barge starts to rotate and F_f goes to zero along the bottom of the barge. The consequent horizontal and vertical force imbalance in the system due to the loss of friction between the barge's bottom and the ice knife will permit the barge to be shoved horizontally against the ice knife's steel nose piece under the force of the 11-knot current.

In the second phase of the lift evolution, therefore, the geometry of motion combines translation and rotation, with the port bilge of the barge sliding nearly vertically up the pier nose cone, and the starboard bilge of the barge sliding along the lower ice knife. Figure A4-1 depicts this sequence at four angles. The essential determination to make during this phase of the salvage operation is whether sufficient lift capacity exists to overcome the friction forces of impending motion.

Sample Impending Motion Calculation

Barge 45 rests against the lower ice knife and pier at a 25° angle from the horizontal, as shown in Figure A4-2. Determine the lift force necessary to overcome friction and continue motion.

In this example, using the same method employed in the previous example to calculate R_{ct} and its moment arm requires only an adjustment for the decrease in average draft. From inspection of Figure A4-2 it is clear that the Law of Sines can be used to determine the draft change by first determining the distance the port bilge slides along the upper ice knife as it is dragged up the nose piece, evolving from a 20- to a 25-degree angle of repose. From the geometry of Figures A4-2 and A4-3, respectively,

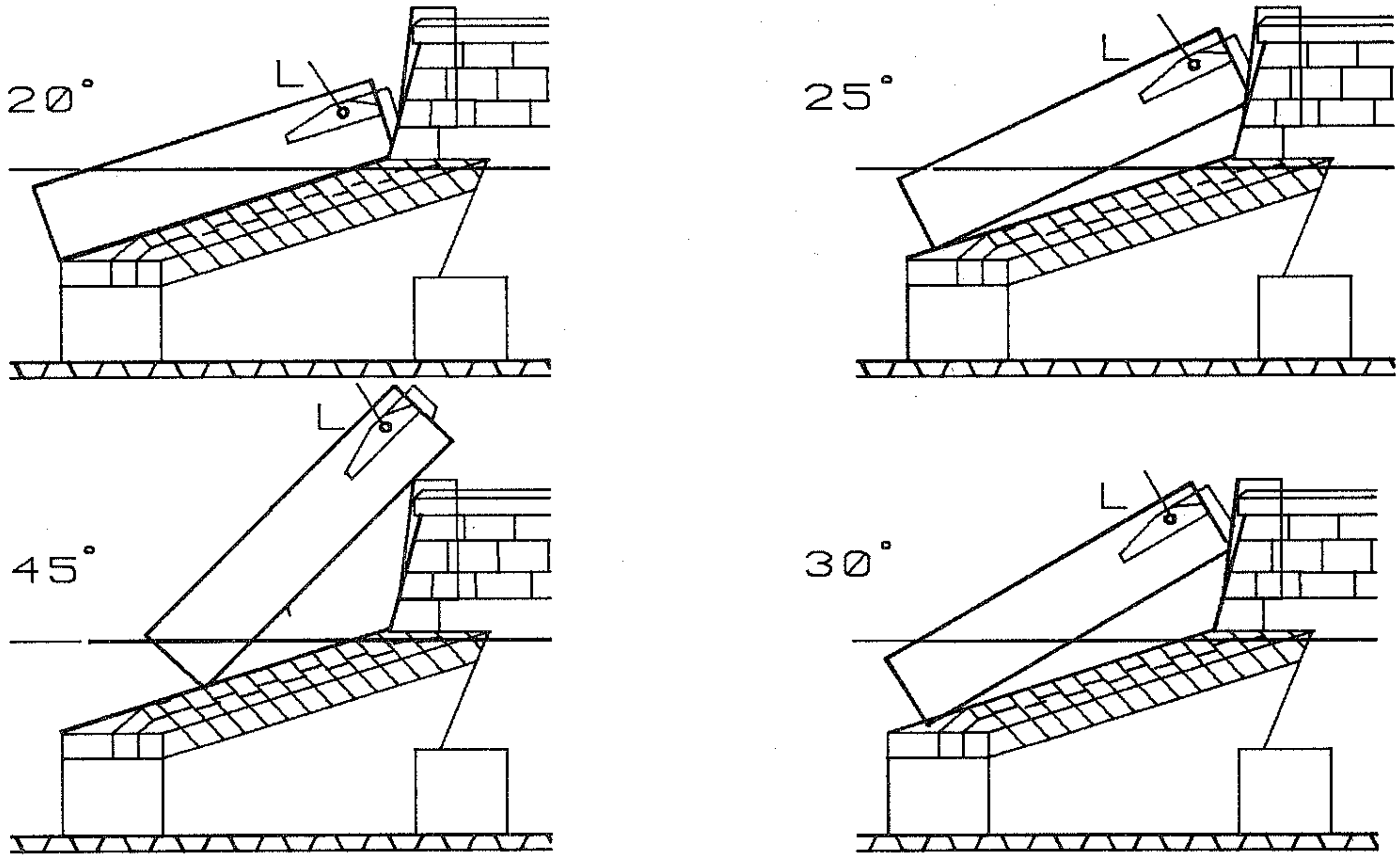


FIGURE A4-1
LIFT SEQUENCE FOR IMPENDING MOTION CALCULATIONS

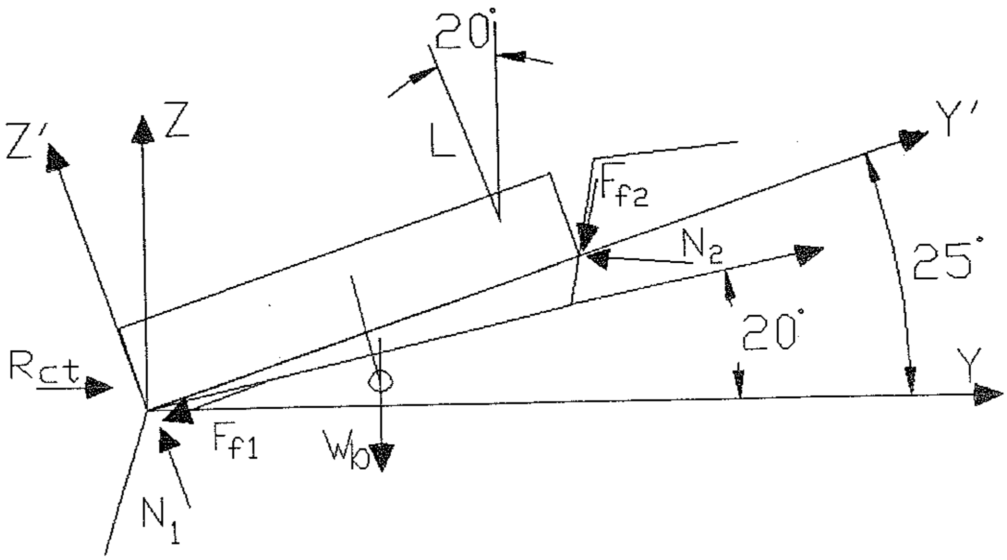


FIGURE A4–2
FORCE SYSTEM FOR 25 – DEGREE LIFT

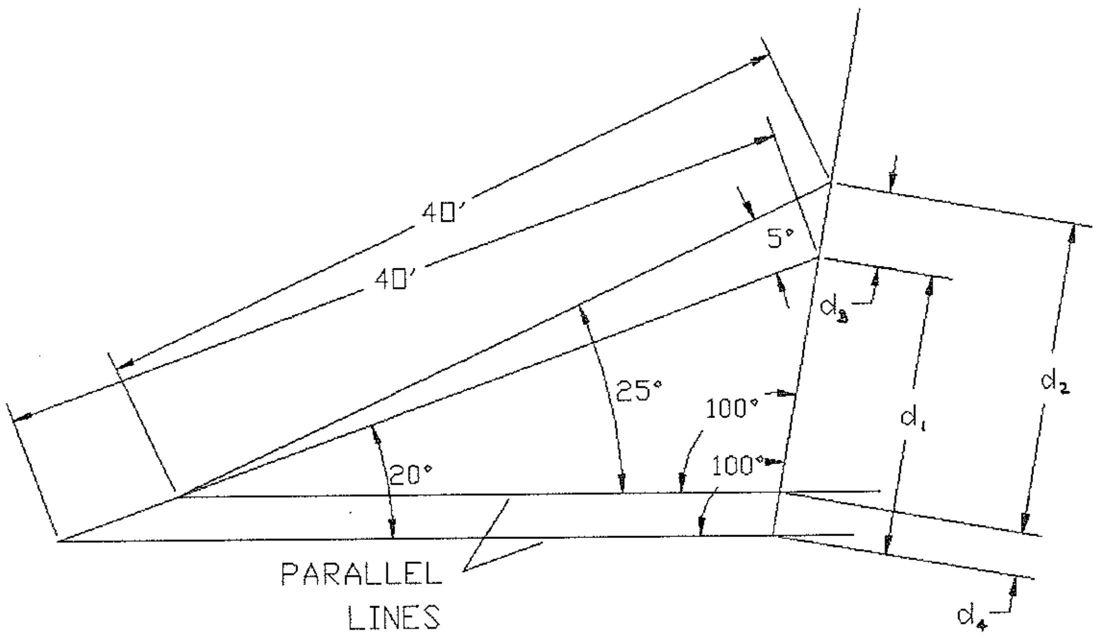


FIGURE A4–3
REDUCED DRAFT WITH TRANSLATION
AND ROTATION

$$\frac{40}{\sin 100} = \frac{d_1}{\sin 20} \qquad d_1 = 13.89 \text{ ft}$$

$$\frac{40}{\sin 100} = \frac{d_2}{\sin 25} \qquad d_2 = 17.17 \text{ ft}$$

$$\frac{40}{\sin 120} = \frac{d_3}{\sin (25-20)} \qquad d_3 = 4.03 \text{ ft}$$

The distance along the ice knife is then computed as:

$$d_4 + 17.17 = 13.89 + 4.03$$
$$d_4 = 0.75 \text{ ft}$$

The change in barge draft must take into account both the change in elevation as the barge is pulled up the lower ice knife and the additional draft change due to rotation from 20° to 25°.

The draft at midship is then: $H_p = 9.61 - .75 \sin 80 = 8.87$ ft. Draft at the ends will be $8.87 + 13.0 \cos 5 = 21.82$ ft. The new mean draft is then: $(21.82 + 8.87)/2 = 15.35$ ft. Since ΔH_p is small, 0.76 ft, the depth-to-draft ratio, K, is not expected to change and R_{ct} can be regarded as linear in draft. Thus R_{ct} will be conveniently expressed as:

$$\frac{H_p - \Delta H_p \cdot R_{ct}}{H_p} = 0.95\ R_{ct}$$
$$= 0.95 \cdot 1056.2$$
$$= 1003.39 \text{ ST}$$

The centroid of the area will be calculated using the method shown in the previous problem.

Centroid of area:

Description	Area	d(from "O")	Moment
$8.87 \cdot 175$	=1552.25 ·	+ 8.87 · 1/2=	+6884.23
$\frac{(21.82 - 8.87)}{2} \cdot 175$	=1133.13 ·	- 12.95 · 1/3=	4891.30
	2685.38		+1992.93

$$\frac{\text{Moment}}{\text{Area}} = \frac{1992.93}{2685.38} = 0.74 \text{ ft}$$

Since motion is impending at both surfaces, the coefficient of static friction at each bilge contact with the ice knife will be at its limit. Therefore, the frictional forces can be written as functions of the normal reaction forces N_1 and N_2.

$F_{f2} = u_d \cdot N_2 = 0.74\ N_2$

$F_{f1} = u_w \cdot N_1 = 0.24\ N_1$

u_d = coefficient of static friction, dry steel on steel

u_w = coefficient of static friction, wet steel on stone

Using the geometry shown in Figure A-5, it is necessary to write three equilibrium equations for the three unknowns N_1, N_2 and L, sum moments about the starboard bilge, and balance forces.

$+ \rightarrow \Sigma F_Y = 0$

$$R_{ct} - N_1 \sin 25° - L \sin 20 - N_2 \cos 10 - F_{f2} \sin 10 - F_{f1} \cos 25 = 0$$

substituting $F_{f1} = 0.24N_1$ $F_{f2} = 0.74N_2$ and applying known values for R_{ct}, the equation reads:

$$1003.39 - 0.42N_1 - 0.22N_1 - 0.98N_2 - 0.13\ N_2 - 0.34L = 0$$

or,

$$0.64N_1 + 1.11N_2 + 0.34L = 1003.39$$

$+ \uparrow \Sigma F_Z = 0$

$$-W_b + N_1 \cos 20 - F_{f1} \sin 20 + N_2 \sin 10$$
$$-F_{f2} \cos 10 + L \cos 20 = 0$$

Performing similar substitutions for W_b, F_{f1} and F_{f2} the equation reads:

$$-302 + 0.94N_1 - 0.08N_1 + 0.17N_2 - 0.73N_2 + 0.94L = 0$$

or,

$$0.86N_1 - 0.56N_2 + 0.94L = 302$$

Summing moments about the starboard bilge contact with the ice knife yields. (Note bold face indicates vectors)

$+ \nwarrow \Sigma M_o + 0$

$$(\mathbf{R}_L \times \mathbf{L}) + (\mathbf{R}_{N2} \times \mathbf{N}_2) + (\mathbf{R}_{N2} \times \mathbf{F}_{f2}) + (\mathbf{R}_w \times \mathbf{W}_b) + (\mathbf{R}_h \times \mathbf{R}_{ct}) = 0$$

For $\mathbf{R}_L$ $\quad X = 0$

$$Y = 36 \cos 25 - 6.49 \sin 25 = 29.88$$
$$Z = 36 \sin 25 + 6.49 \cos 25 = 21.10$$

$$\mathbf{L} = (0, -0.34L, 0.94L)$$

$$\mathbf{R}_L \times \mathbf{L} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & 29.88 & 21.10 \\ 0 & -0.34L & 0.94L \end{vmatrix} = 35.26L$$

For $\mathbf{N}_2$ and $\mathbf{F}_{f2}$ the vector sum can be used since $\mathbf{F}_{f2}$ is a function of $\mathbf{N}_2$ and then the cross product can be taken.

$$\mathbf{N}_2 + \mathbf{F}_{f2} = (0, -1.21N_2, -0.56N_2)$$

$$X = 0$$

$\mathbf{R}_{N2}$ $\quad Y = 40 \cos 25 \quad 36.25$

$\quad Z = 40 \sin 25 \quad 16.90$

$$\mathbf{R}_{N2} = (0, 36.25, 16.90)$$

$$\mathbf{R}_{N2} \times (\mathbf{N}_2 + \mathbf{F}_{f2}) = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & 36.25 & 16.90 \\ 0 & -1.21N_2 & -0.56N_2 \end{vmatrix} = 0.15N_2$$

$\mathbf{R}_w =$ $X = 0$ ft

$\mathbf{R}_w =$ $Y = 20 \cos 25 - 4 \sin 25 = 16.44$ ft

$Z = 20 \sin 25 + 4 \cos 25 = 12.08$ ft

$\mathbf{W}_b = (0, 0, -302)$

$$\mathbf{R}_w \times \mathbf{W}_b = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & 16.44 & 12.08 \\ 0 & 0 & -302.00 \end{vmatrix} = -4964.88$$

$$\mathbf{R}_H \times \mathbf{R}_{ct} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & 0 & 0.74 \\ 0 & 1003.39 & 0 \end{vmatrix} = -742.51$$

Collecting these cross products gives

$+\nwarrow \Sigma M_o = 0$

$$35.26L + 0.15N_2 - 4964.88 - 742.51 = 0$$

or,

$$35.26L + 0.15N_2 = 5707.39$$

There are now three equations with three unknowns:

$$.47N_1 + 1.21N_2 + .34L = 1003.39 \quad (1)$$
$$.86N_1 - .56N_2 + .94L = 302.00 \quad (2)$$
$$-0.15N_2 + 35.26L = 5707.39 \quad (3)$$

The equations which are solved simultaneously by matrix elimination by multiplying equation (1) by -0.86 and equation (2) by 0.47 and adding the results:

$$.40N_1 - 1.04N_2 - .29L = -862.92$$
$$-.40N_1 + 0.26N_2 - .44L = -141.94$$
$$\overline{\quad - 1.30N_2 + .15L = -720.98 \quad}$$

Multiplying the resulting equation by the ratio 0.15/1.30 and adding it to equation (3) yields:

$$
\begin{array}{rrcl}
 & -0.15N_2 + .017L & = & -83.19 \\
+ & -0.15N_2 + 35.26L & = & 5707.39 \\
\hline
 & 0 \quad + 35.28L & = & 5624.20 \\
 & L & = & 159.42 \text{ ST} \\
 & N_2 & = & 572.67 \text{ ST} \\
 & N_1 & = & 545.23 \text{ ST}
\end{array}
$$

Similarly, calculations can be performed for all angles shown in Figure A4-1. Results appear in Table A4-1.

Table A4-1

Results of Impending Motion Calcuations

Angle (DEG)	L (ST)	N_1 (ST)	N_2 (ST)
20	249.02	474.99	618.42
25	159.42	545.23	572.67
30	76.27	576.56	479.12
45	-67.59	586.22	247.52

In inspecting these results, it is important to keep the following in mind:

- o As the barge rotates and slides along the ice knife, the hydrodynamic force magnitude and moment will diminish (reference point is the starboard bilge, 0)

- o The normal reaction and friction vectors do not change in reference to the Y-Z coordinate system

- The moment arm vectors R_L, R_{N2}, R_w and R_H will change in reference to the Y-Z coordinate system

- The lift angle is always assumed to be 20 degrees from the vertical.

The calculation merely estimates the lift tension required to overcome friction and keep the control lift in progress.

Two things should be apparent from an inspection of Table A4-1. First, the lift tension, L, will diminish as the lift and rotation continue. Second, the fact that L is shown to be negative at a 45-degree angle should warn the salvage team that under the assumed conditions the hydrodynamic moment eventually will act counter-clockwise (i.e., the moment arm will be below the starboard bilge), causing the barge to auto-rotate. This could cause a dangerous situation if control is lost. From the results shown, it is estimated that the barge would auto-rotate at about 40 degrees. The obvious correction is to gradually make the lift tension more nearly vertical as the process continues, by warping the lift barge farther downstream.

A5. DETERMINATION OF WRECK FORCES AFTER LIFTOFF

After the barge was lifted to its maximum height, the salvage plan called for warping Barge 251 upriver with the wreck of Barge 45 suspended from the lifting fairleads. Determination of the forces acting on the wreck in this condition calls for balancing gravity and current forces about the center of lift. The current force and its centroid are treated as functions of the angle of collapse and the suspended barge's draft. The barge's center of gravity is also a function of the collapse angle. Figure A5-1 depicts the suspended barge's geometry and provides a transformation matrix to convert from the barge's undeformed coordinate system (X', Y', Z') to the global coordinate system (X, Y, Z) as a function of collapse angle A, and angle of rotation B. To linearize the computations, the small radian angle approximations are made for the angle B such that the cos B is construed as 1 and the sin B as B. Thus angular measure of B must be in terms of radians.

For any given lift height above the waterline, h, and any collapse angle, A, it is possible to solve for the lift forces, L, and equilibrium angle, B, using a linearized representation of the problem. A more complex representation of the transform would result in a more complex solution without any practical benefit.

Sample Suspended Load Calculation.

For a lift height of 34 feet and a collapse angle, A, of 20 degrees, the force equilibrium is determined by first computing the global coordinates of the barge lift center as a function of B, assuming a small angle of rotation. Both local and generalized coordinates appear along with their transformation matrix in Figure A5-1. Using the local coordinates (26, -1.5, 36) of the lift center, and the small

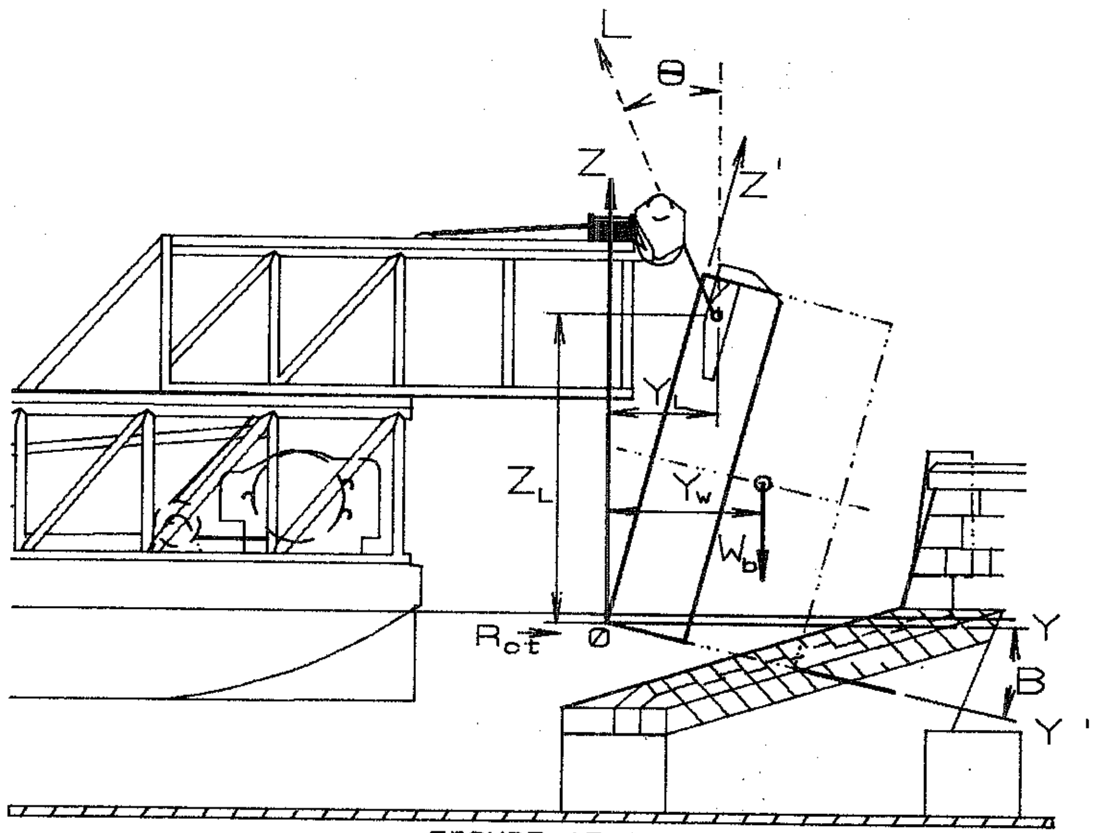


FIGURE A5-1

SMALL ANGLE TRANSFORM FOR B

$$\begin{Bmatrix} X' \\ Y' \\ Z' \end{Bmatrix} \begin{bmatrix} \text{COS A} & -\text{SIN A} & 0 \\ \text{SIN A} & \text{COS A} & -\text{B} \\ \text{B SIN A} & \text{B COS B} & 1 \end{bmatrix} = \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix}$$

A = COLLAPSE ANGLE
B = EQUILIBRIUM ANGLE

angle approximation, the formulae for the generalized coordinates (X_L, Y_L, Z_L) from the origin at the main deck starboard shell (Point "O") to the lift center for A=20 degrees are:

$$X_L = 26 \cos 20 + 1.5 \sin 20 = 24.95 \text{ ft}$$
$$Y_L = 26 \sin 20 - 1.5 \cos 20 - 36 B = 7.48 - 36 B \text{ ft}$$
$$Z_L = 26 \sin 20 \cdot B - 1.5 \cos 20 \cdot B + 36 = 7.48 B + 36 \text{ ft}$$

The total projected draft at midship $H_p(B)$ is the projected depth of submerged deck plus the change in draft due to rotation of the barge's 9.5 ft side depth. Therefore, the total draft at midship for a <u>negative</u> rotation of B, in <u>radians</u> is expressed as follows:

$$H_{pm}(B) = Z_L - h - 9.5 B$$
$$H_{pm}(B) = 36 + 7.48 \cdot B - 34 \text{ ft} - 9.5 B$$
$$H_{pm}(B) = 2 - 2.02 \cdot B \text{ ft}$$

Similarly, the projected draft at each end of the barge can be treated as vertical projections of transverse distances along the deck formed by the local vectors (X', Y', Z') from midship to the ends of the main deck (100, 0, 0) and (75, 0, 0) transformed to the global coordinate system:

$$H_{pf}(B) = 2 - 25.65 \cdot B$$
$$H_{pa}(B) = 2 - 34.20 \cdot B$$

The mean draft $H_p(B)$ for the suspended wreck taken as a whole is the average of the average drafts of the bow and stern. This mean draft is the computed as follows:

$$\frac{\dfrac{H_{pf}(B) + H_{pa}(B)}{2} + H_p(B)}{2}$$

The mean draft is then substituted into the current force formula.

$$K \cdot v_c^2 \cdot C_d \cdot L \cdot H_p(B) = 175 \cdot (2 - 15.98B) \cdot v_c^2 \cdot C_d \cdot K$$

The depth correction factor K and the current force coefficient C_d, which is a function of the collapse angle A, must be established before R_{ct} can be computed. These curves appear in Appendix B9. In reference to Figure B9-2 note that for all practical purposes K is equal to approximately 1 when the barge is lifted to warping height. With reference to Figure B9-1 the current force coefficient, C_d, for a 20-degree collapse angle (i.e., 70-degree angle of attack) is about 0.53. If the collapse angle is uneven (as was the case in MILESTONE FOXTROT), then a different coefficient should be used for the bow and stern and two calculations are required. Using the current force formula for A = 20 degrees and the assumed values, R_{ct} can be made a linear function of B.

$$R_{ct} = 175\ (2 - 15.98 \cdot B) \cdot v_c^2 \cdot 0.53 \cdot 1$$

$$R_{ct}\ (B) = 32.01 - 255.80 \cdot B$$

For convenience, the moment arm from the lift center, L, to R_{ct} will be estimated at 36 feet, which in effect means that the current force is assumed to act through the point 0. With a more rigorous representation of the problem, the equation becomes cubic in B, with a correspondingly more complex solution.

The distance to the barge's center of gravity is computed as a function of collapse angle, assuming that the barge is homogeneous in structure with an undeformed VCG at mid-depth. The VCG of the deformed barge is computed as follows:

$$VCG = (50 \cdot 100/175\ W_b \sin A + 37.5 \cdot 75/175 \cdot W_b \cdot \sin A)/W_b + 4.75$$

$$VCG = 44.64 \sin A + 4.75$$

Therefore, $VCG = 20.02$ ft when A = 20 degrees

The vector to the barge's VCG from the origin at 0 in the barge's local coordinate system (X', Y', Z') is (0, 20, 20). Multiplying the vector by the coordinates transform matrix gives the vector to the VCG, as a function of B in the generalized coordinate system.

$$X_w = -20 \sin A$$
$$Y_w = 18.79 - 20B$$
$$Z_w = 18.79 \cdot B - 20$$

It is now necessary to equilibrate forces vertically and horizontally and sum moments about 0 to solve for the lift force, L, and the approximate angle of equilibrium B, and the lift line angle, θ.

$$+ \uparrow \Sigma F_z = 0;$$
$$L \cdot \cos\theta = W_b$$
$$+ \rightarrow \Sigma F_y = 0;$$
$$L \cdot \sin\theta = R_{ct}$$
$$+ \nwarrow \Sigma M_o = 0;$$
$$Y_L \cdot L \cdot \cos\theta + Z_L \cdot L \cdot \sin\theta = Y_w \cdot W_b$$

Substituting known values for W_b (the barge is assumed to be free-flooding, so the total weight is only the weight of steel) and functional expressions for R_{ct}, Y_L, Z_L and Y_W, developed above, a quadratic equation in B results. For vertical forces,

$$L \cos\theta = 302$$

and for horizontal forces,

$$L \sin\theta = 32.01 - (255.80 \cdot B)$$

Substituting their expressions into the moment equation,

$$(7.48 - 36 \cdot B) \cdot L \cdot \cos\theta + (7.40B + 36) \cdot L \cdot \sin\theta$$
$$= (18.79 - 20B)302$$

$$(7.48-36B)302+(7.48B+36)(32.01-255.80B) = (18.79-20B)302$$

collecting terms,

$$(7.48B+36)(32.01-255.8B)=302[(18.79-20B)-(7.48-36B)]$$

simplifying,

$$-8969.37B + 1152.36 - 1913.38B^2 = 3415.62 + 4832B$$

or,

$$-1913.38B^2 - 13801.37B - 2263.26 = 0$$

and finally,

$$B^2 + 7.21B + 1.18 = 0$$

The negative root of B (B = -0.17 radians) is selected, and L and θ are computed.

$$B = -0.17 \text{ rads} = -9.74 \text{ degrees}$$
$$L \cdot \sin\theta = 32.01 - 255.8(-0.17)$$
$$L \cdot \sin\theta = 75.50; \quad \sin\theta = 75.50/L$$
$$L \cdot \cos\theta = 302; \quad \cos\theta = 302/L$$

Therefore,
$$\theta = \tan^{-1} 75.50/302 = 14.04 \text{ degrees}$$
$$L = 311.30 \text{ LT}$$

A6. LATERAL EQUILIBRIUM CALCULATION

After the 13 December lift attempt failed, Barge 45 settled in a new equilibrium position on the ice knife as shown in Figures 6-6 and 6-7 in the text. Instead of an angle of collapse symmetrically distributed forward and aft of the collapse line (10 degrees both forward and aft) exposed to the current flow, the barge's midship had collapsed further and the entire barge had rotated so that the aft part lay at a 38-degree angle to the current, and the forward part lay at a 5-degree angle. See Figure A6-1. The major concern was whether the barge would rotate catastrophically off the ice knife during the course of the next lift attempt and place uneven loads on the lift wires. The following calculation shows how to estimate the lateral equilibrium of the Barge 45 wreck.

In this case, the current force moment in the horizontal plane about the collapse line will be determined by applying different coefficients to the forward and aft portions of the wreck (i.e., considering the wreck as two shapes).

Using the B of -0.17 radians computed in the previous example, and following formulae developed in the previous example to compute draft:

$$H_{pm} = 2 - 2.02\ B$$
$$H_{pf} = 2 - 25.65\ B$$
$$H_{pa} = 2 - 34.20\ B$$

the forward and aft hydrodynamic forces can be computed as:

For forward portion of the hull, the mean draft is:

$$\uparrow H_p = \frac{2 - 2.02\ (-0.17) + 2 - 25.65(-0.17)}{2}$$

$$\uparrow H_p = 4.35$$

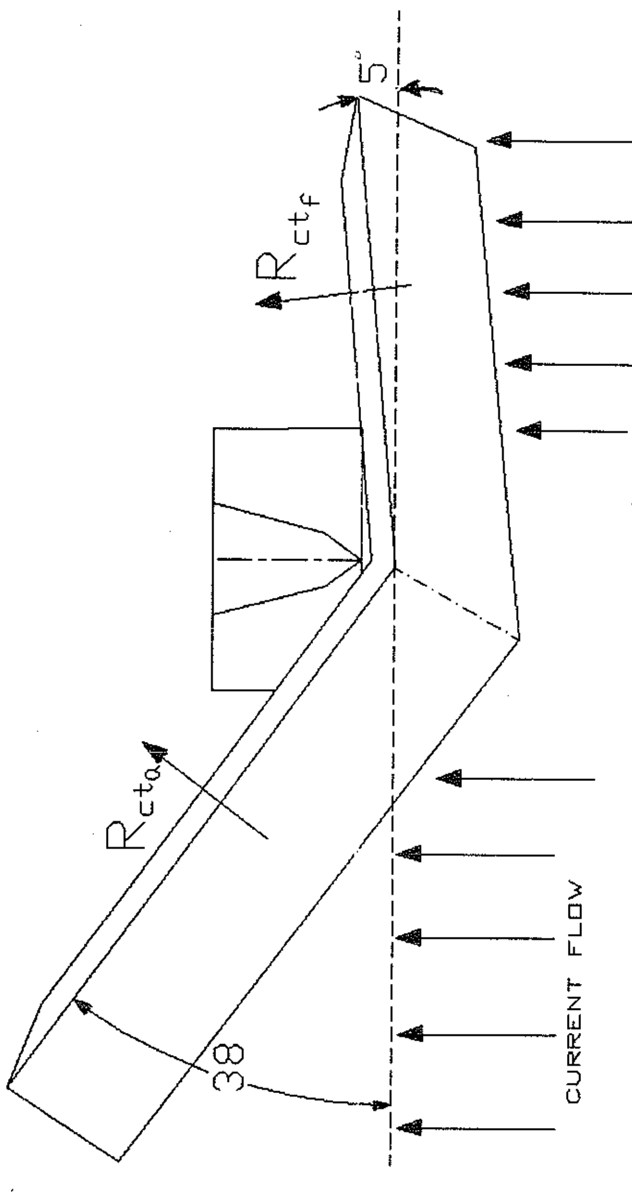


FIGURE A6-1
LATERAL EQUILIBRIUM

$$R_{ct_f} = \frac{75 \cdot 4.35 \cdot (18.58)^2 \cdot (.58)(1)}{2000} = 32.66 \text{ ST}$$

the moment about the collapse line is

$$M_f = 75/2 \cdot 32.66 = 1224.75 \text{ ft-ST}$$

For the aft portion of the hull:

$$H_P = \frac{2 - 2.02(-.17) + 2 - 34.2 \cdot B}{2}$$

$$H_P = 5.08$$

$$R_{ct_a} = \frac{100 \cdot 5.08 \cdot (18.58)^2 \cdot (.45)(1)}{2000}$$

$$R_{ct_a} = 39.46 \text{ ST}$$

$$M_a = 100/2 \cdot 39.46 \text{ ST} = 1972.91 \text{ ft-ST}$$

A7. LIFT BARGE SHEAR FORCE AND BENDING MOMENTS

As tension is developed in the lift wires attaching Barge 251 to Barge 45, Barge 251 will trim and sink under the applied load. The general effect of a vessel's heavy lift weight on strength and stability is covered in reference 2, in the chapters on strength and stability. For this illustration of the salvage operation it is necessary only to consider Barge 251 to be a prismatic beam of variable weight supported by water pressure buoyancy forces, as shown in Figure A7-1. The lift barge will be in static equilibrium when its summation and moment of weights and buoyancy forces are equal and opposite. At this equilibrium condition the internal forces and moments in the hull of Barge 45 will produce shear and bending stresses. Simple beam theory is utilized to compute the magnitude of stresses within the hull's plating. The objective of this analysis is to evaluate the strength of Barge 251 for the maximum possible wire load at breaking strength (i.e., 800 ST) to determine if the lift barge's strength are adequate to withstand the maximum lift forces.

Table A-2 contains the summation of weights and moments used to establish the locations of the longitudinal and vertical centers of gravity of the barge. At equilibrium the distribution of buoyancy forces will be such that its magnitude and longitudinal center align with total barge weight and longitudinal center of gravity. Table A-3 contains the hull's hydrostatic properties when in equilibrium with the weights and moments.

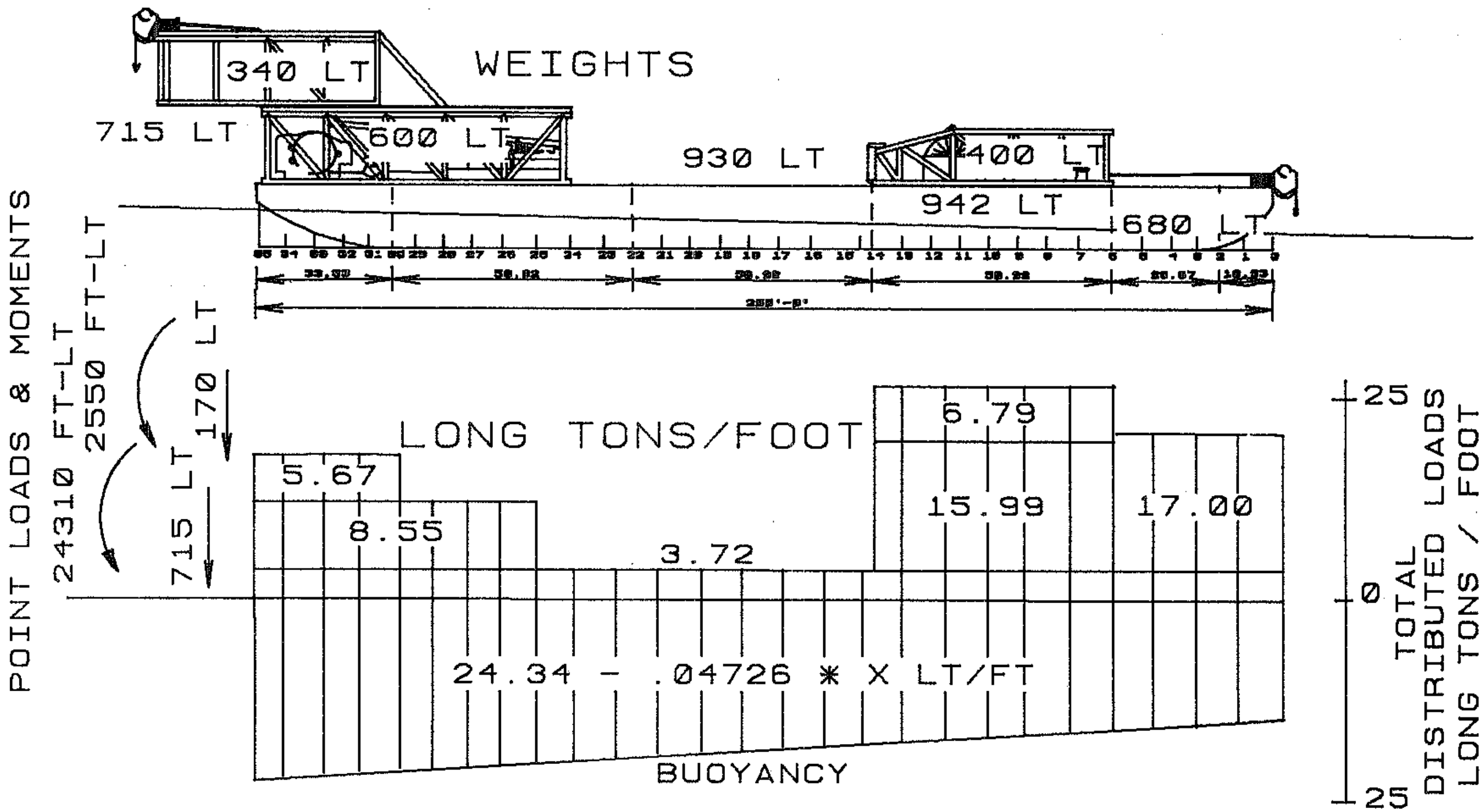


FIGURE A7-1
WEIGHTS, MOMENTS AND BUOYANCY

800 ST LIFT

Table A-2
Barge 251 Weights and Moments at 800 ST Lift

Item	Wt (LT)	VCG (ft)	Vert. Moment (ft-LT)	LCG (ft)	Long'l Moment (ft-LT)	MFS* (ft-LT)
Lightship	930.00	8.00	7440	-1.8	-1627	
Truss 7a	300.00	26.35	7905	-88.0	-26400	
Truss 7b	170.00	45.25	7693	-125.0	-21250	
Truss 8a	300.00	26.35	7905	-88.0	-26400	
Truss 8b	170.00	45.25	7693	-125.0	-21250	
Winches	350.00	26.35	9223	45.0	15750	
Misc	50.00	21.00	1050	45.0	2250	
FWD RAKE	680.00	9.40	6392	104.1	70774	5300
No 1 cp	471.33	8.00	3771	55.6	26215	
No 1 cs	471.33	8.00	3771	55.6	26215	
Lift	715.00	55.67	39804	-159.0	-113685	
Total	4607.66	22.27	102645	-15.1	-69407	5300

*Moment of Free Surface

Table A-3
Barge 251 Hydrostatic Properties at Equilibrium with 800 ST Lift

Displacement	4607.66 LT
Mean draft at midships (T_m)	10.20 ft
Transverse metacenter above keel (KM)	49.50 ft
Vertical center of gravity above keel (KG)	22.28 ft
Static transverse stability (KM-KG)	27.22 ft
Free surface effect (FS) 5300/4607.66	1.15 ft
Net static transverse stability (GM)	26.07 ft
Longitudinal center of buoyancy (LCB) (+ fwd of midship)	-1.70 ft
Longitudinal center of gravity (LCG) (+ fwd of midship)	-15.06 ft
Trimming lever arm (LCG - LCB)	-13.36 ft
Trimming moment (LCG-LCB) · 4607.66	-61574.00 ft-LT
Moment to change trim 1 Foot	9420.00 ft-LT
Trim -61574/(12 x 785)	-6.54 ft
Draft forward	6.93 ft
Draft aft	13.47 ft

The longitudinal locations of maximum bending moment will occur where the shear passes through zero. To establish these points, a consolidated beam equation is written for the combined weights and buoyancy. Using the drafts forward and aft, and hull hydrostatic properties, a buoyancy-per-unit length formula, expressed in long tons per foot (LT/ft) incorporating both uniform and triangular force distribution is written as a function of barge length, moving from aft forward.

$$B(x) = 24.34 - .04726 \cdot x$$

The barge's lightship weight distribution, also expressed in LT/ft, can be regarded as a constant function of length and written as follows:

$$W(x) = 3.72$$

Net buoyancy is then defined as B(x) - W(x) or:

$$B_N(x) = 20.62 - .04726 \cdot x$$

Other weights are non-continuous functions of length and must be incorporated by piecemeal integration. Figure A7-2 shows consolidated deck and lift weights, and net buoyancy curves for the barge's hull girder. Inspection of the figure suggests that the first point of zero shear will occur forward of frame 24 when the cumulative net upward buoyancy force will first exceed the sum of deck and lift weights. Assuming this to be the case, the sum of deck and lift loads will be constant from Frame 24 forward to Frame 14 and will not have to be integrated. Thus the integral of net buoyancy (i.e., the buoyancy function minus the hull's uniformly-distributed light ship weight) must equal the sum of deck and lift weights over the interval.

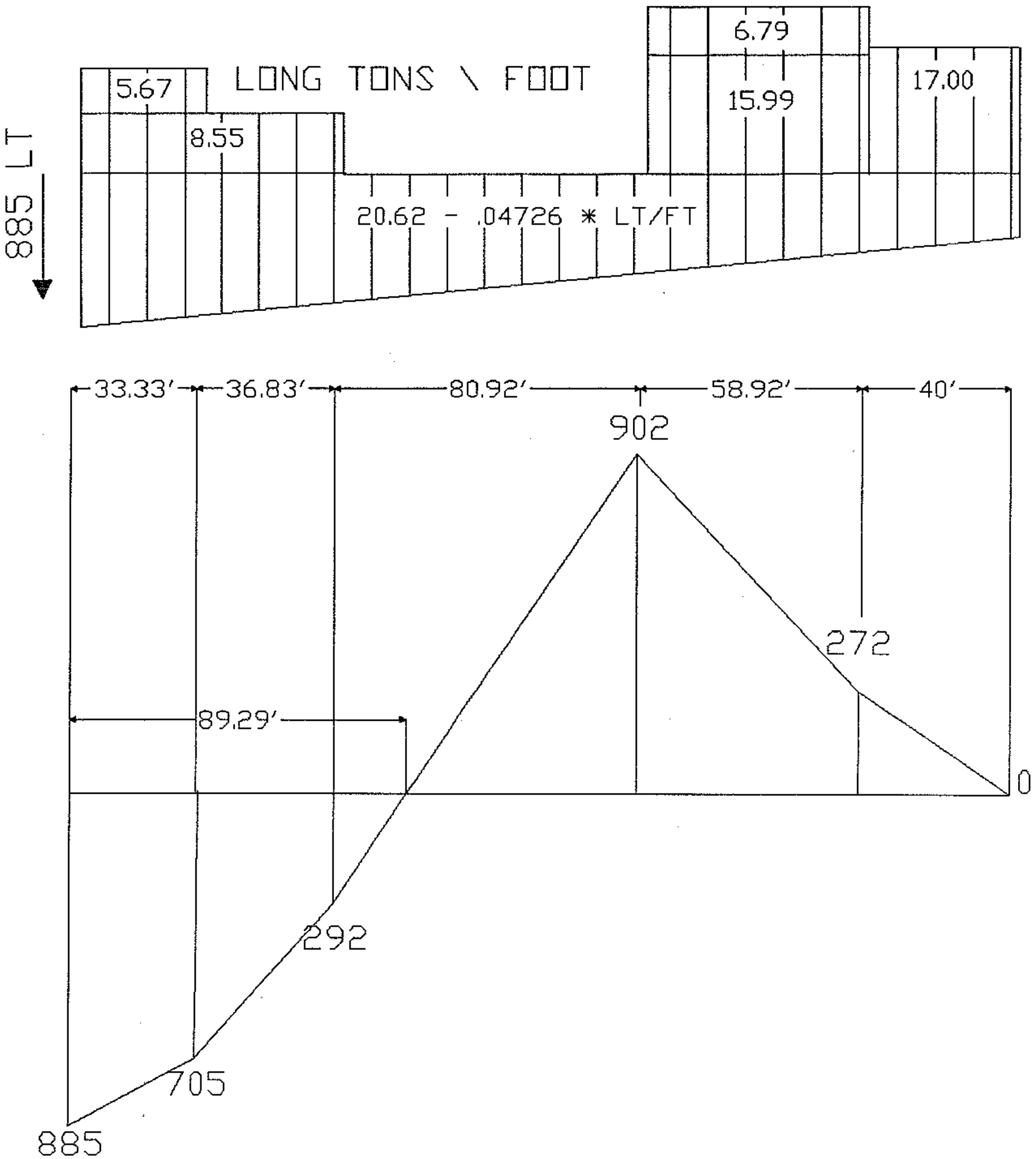


FIGURE A7-2
SHEAR CURVE, 800 ST LIFT

$$\int_{o}^{x} 20.62 - .04726 \cdot x \cdot dx = 1654$$

$$x = 89.29 \text{ ft}$$

This is the only point where the shear crosses zero; by definition, it is also the location of the maximum bending moment in the hull girder. The net moment of forces, taken about the point 89.29 feet forward of the stern, provides the maximum bending moment. This integration can be completed without involved computation by using the center of gravity of deck and lift weights shown in Table A-2 and the moment of force provided in the net buoyancy equation. The moment expression is as follows:

$$M = -715 \cdot 123.29 - 340 \cdot 89.29 - 600 \cdot 52.29 + 16.40 \cdot 89.29 \cdot \frac{89.29}{2} + \frac{4.22 \cdot 89.29}{2} \cdot \frac{2}{3} \cdot 89.29$$

$$M = -73294 \text{ ft-LT}$$
$$M = -879528 \text{ in-LT}$$

The hull girder's section modulus is calculated in Table A-4 with an assumed neutral axis at mid-depth. The calculated section modulus of 117767 $in.^3$ is divided into the maximum moment to evaluate maximum midship bending stress.

$$\frac{M}{SM} = -\frac{879528}{117767} = -7.46 \text{ LT/in}^2$$

Allowable working stress is 10 LT/in^2 so the hull girder is satisfactory to support the maximum lift loads under the assumed ballast conditions.

Table A-4
Barge 251 Midship Section Modulus Calculation

Item	width (in)	t (in)	A (in^2)	d (in)	A · d (in^3)	A · d^2 (in^4)	i_o (in^4)
Above na							
Deck	432.0	0.50	216.00	96.3	20790	2001037	5
Side sh	96.0	0.50	48.00	48.0	2304	110592	36864
Long bhd	96.0	0.38	36.00	48.0	1728	82944	27648
5 cl bhd	96.0	0.19	18.00	48.0	864	41472	13824
Dk long	0.0	0.00	54.72	92.0	5034	463150	206
Sh long	0.0	0.00	10.83	48.0	520	24952	41
Bhd long	0.0	0.00	10.26	48.0	492	23639	39
Below na							
Bottom	432.0	0.50	216.00	-96.3	-20790	2001037	5
Sidesh	96.0	0.50	48.00	-48.0	-2304	110592	36864
Long bhd	96.0	0.38	36.0	-48.0	-1728	82944	27648
.5 cl bhd	96.0	0.19	18.00	-48.0	-864	1472	13824
Bot long	0.0	0.00	54.72	-92.0	-5034	463150	206
Sh long	0.0	0.00	10.83	-48.0	-520	24952	41
Bhd	0.0		10.26	-48.0	-492	23639	39
Total			786.62	0.0	0	5495573	157252

Total inertia for one side	5652826 in^4
Total inertia	11305652 in^4
Total depth of structure	192 in
Maximum distance from neutral axis	96 in
Section modulus minimum 11305652/96	117767 in^3
Maximum allowable bending stress	10 LT/in^2

APPENDIX B

METHODOLOGY FOR DETERMINATION OF HYDRODYNAMIC FORCES

B1. SYMBOLS AND ABBREVIATIONS

SYMBOL	DESCRIPTION	UNITS	NOTATION
A	Projected Area of Body	$feet^2$	(ft^2)
A_p	Pressure Area	$feet^2$	(ft^2)
B	Beam	feet	(ft)
C_b	Block Coeff.		
C_d	Current Drag Coeff.		
C_f	Frictional Resistance Coeff.		
C_{ft}	Total Friction Coeff.		
C_r	Residual Resistance Coeff.		
C_{rgh}	Roughness Coeff.		
C_t	Total Resistance Coeff.		
D	Depth	feet	(ft)
Dspl	Displacement	long tons	(LT)
D_w	Water Depth	feet	(ft)
F_n	Froude's Number		
R_n	Reynolds' Number		
H	Draft	feet	(ft)
H_m	Mean Draft	feet	(ft)
H_p	Projected Draft	feet	(ft)
K	Shallow Water Coeff.		
L	Length on Waterline, Distance	feet	(ft)
M_h	Longitudinal Moment	foot-pounds	(ft-lbs)
M_v	Transverse Moment	foot-pounds	(ft-lbs)
R	Resistance or Drag	pounds	(lbs)
R_c	Current Force or Drag	pounds	(lbs)
R_{ct}	Current Drag in Shallow Water	pounds	(lbs)
R_{ts}	Current Drag in Shallow Water	pounds	(lbs)
R1	Reaction	pounds	(lbs)
R2	Reaction	pounds	(lbs)
S	Wetted Surface	$feet^2$	(ft^2)

SYMBOL	DESCRIPTION	UNITS	NOTATION
V	Current or Vessel Speed	knots	(kts)
V_c	Current Speed	knots	(kts)
d	Depth of Water	feet	(ft)
f	Freeboard	feet	(ft)
f	Proportionality Coeff.		
f(x)	Function of x		
f_p	Freeboard Port	feet	(ft)
f_s	Freeboard Starboard	feet	(ft)
g	Acceleration of Gravity	feet/sec^2	(32.2 ft/sec^2)
lcp	Long. Center of Pressure	feet	(ft)
s	Station Spacing	feet	(ft)
s_m	Simpson Multiplier		
v	Vessel Speed	feet/sec	(ft/sec)
v_c	Current Speed	feet/sec	(ft/sec)
vcp	Vert. Center of Pressure	feet	(ft)
x	Point on Long. Axis of Vessel		
θ	Angle of Heel	degrees	(deg)
ν	Kinematic Viscosity	$feet^2$/sec	(ft^2/sec)
ρ	Density	pounds-sec^2/ft^4	(lbs-sec^2/ft^4)

Coeff. - Coefficient

Vert. - Vertical

Long. - Longitudinal

B2. INTRODUCTION

The intent of this section is to present hydrodynamic principles and empirical formulae which will help the salvage engineer determine the drag or resistance of a vessel or barge exposed to a strong water current in a waterway.

Resistance of ships through water has preoccupied engineers ever since the time of Leonardo da Vinci in the 15th century. In North America D.W. Taylor, upon graduation from the U.S. Naval Academy in 1885, pioneered research and development in tank testing techniques and formulation of empirical data on ship resistance based on the hydrodynamic principles formulated by Froude and Reynolds. The efforts of Admiral D.W. Taylor led to the construction of the Experimental Model Basin (EMB) about 1900 in Washington, D.C., and later the David Taylor Model Basin, still the leading model testing facility in the world. Naturally, the efforts to determine ship resistance or drag were focused on developing optimal or lower resistance hull forms, combined with good seakeeping qualities in forward-moving vessels.

The advent of larger vessels since the 1960s has diversified testing and development efforts in determining resistance characteristics for vessels in restricted or shallow draft seaways, and for vessels moored or anchored against strong current. These developments have led to formulation of empirical formulae tested against models and full-size vessels.

After colliding with bridge pier #4 of the Peace Bridge, Barge #45 was pinned transversely against the pier ice knife by the high-velocity current of the Niagara River. Powerful hydrodynamic forces caused the barge hull structure to fail in a hogging mode and bend about the axis of the ice knife such that at least one end of the barge was touching the river bottom. The barge's perpendicularity to the current flow and its bent and asymetrically-submerged attitude represented an exception to the normal hydrodynamic methods of prediction of resistance and flow around hull forms.

On the other hand, the mooring and lift barges' resistance or drag against the current of the Niagara River could be determined by the traditional methods to determine hull form resistance using model tank testing data and full-size correlation.

B3. HYDRODYNAMIC RESISTANCE - NEWTON'S RESISTANCE LAW

Hydrodynamic resistance or drag of an object moving through water, or stationary with water flowing past it, was originally determined by Newton, the founder of mechanics (Ref. 1). The textbook version of Newton's Resistance Law is expressed in Equation 1.

EQUATION 1

$$R = f \cdot A \cdot \rho \cdot v^2 \quad \text{(Ref. 1)}$$

WHERE:

R = Resistance or Drag

A = Projected Area of Body in Direction of Flow

ρ = Density of the Fluid

f = Proportionality or Resistance Coefficient

Newton's Law was derived from the momentum theorem and still applies where the total drag of a body consists exclusively of pressure drag. In this instance the resistance coefficient is practically a constant. This is the case with plates moving perpendicularly to their plane. Generally, the law also applies to bodies with sharp edges, where the fluid breaks away at definitely determined points of the body.

B4. GENERAL RESISTANCE LAW

Newton's Resistance Law assumes that the resistance forces are caused by dynamic pressures. Experimental results do not always agree with this theory, especially for ship forms running ahead. This is because other factors, such as friction due to viscosity, and wave-making, are as important or more important than the dynamic pressures associated with flow separation which dominates in the case of the Newton theory. In this light, the drag or resistance of a body in a viscous, incompressible fluid with a free surface is a function of two dimensionless numbers, titled the Reynolds' and Froude's numbers, which govern the viscous and wavemaking resistances respectively. The resistance coefficient (C_t) is now defined as:

$$C_t = \text{Function } (R_n,\ F_n)$$

$$R_n = \text{Reynolds' Number} = v \cdot L/\nu$$

$$F_n = \text{Froude's number} = v \cdot (Lg)^{\frac{1}{2}}$$

The expression of resistance is given in Equation 2.

EQUATION 2

$$R = C_t \cdot \rho/2 \cdot S \cdot v^2$$

WHERE:

R = Resistance

C_t = Total Resistance Coefficient

r = Density of Fluid

S = Wetted Surface of Body

v = Velocity = $1.69 \cdot V$

ρ = Density, Salt Water = 1.99*

ρ = Density, Fresh Water = 1.94*

ν = Kinematic Viscosity, (Fresh Water = $1.211 \quad 10^{-5}$)
(Salt Water = $1.264 \cdot 10^{-5}$)

F_n = Froude's Number = $v/(Lg)^{\frac{1}{2}}$

g = Gravity = 32.2 ft/sec^2

R_n = Reynolds' Number = $v \cdot L \cdot \nu$

C_f = Frictional Resistance Factor
= $0.075 \cdot (\log 10(R_n)-2)^{2*}$

C_{rgh} = Roughness Coeff. = 0.001 for Dirty Hull Bottoms

C_{ft} = $C_f + C_{rgh}$

C_r = Residual Resistance From Model Test Data

C_t = $C_r + C_{ft}$

* At 60° F, variations of ρ and ν with temperature and tabular values of C_f vs. R_n are given in Ref. 2.

The Principles of Naval Architecture, published by the Society of Naval Architects and Marine Engineers (Ref. 3), along with many other treatises on hydrodynamics, deal at length with the theory and formulation of dimensional analysis and the various elements contributing to hydrodynamic resistance.

B5. SHIP AND BARGE RESISTANCE

The resistance coefficients for ship and barge hull forms are determined by model tank testing. The coefficients are often expressed as in Equation 3.

EQUATION 3

$$C_t = C_{ft} + C_r$$

WHERE:

C_t = Total Resistance Coefficient

C_{ft} = $C_f + C_{rgh}$

C_f = Frictional Resistance Coefficient

C_{rgh} = Surface Roughness Coefficient

C_r = Residual Resistance Coefficient

C_t is measured during model testing experiments for specific geometries, hull forms and appendages. Determination of the frictional resistance coefficient has been agreed upon at various International Towing Tank Conferences (ITTC). The 1957 ITTC definition of frictional resistance is given in Equation 4 (Ref. 2).

EQUATION 4

$$C_f = .075/(\log 10(R_n) - 2)^2$$

WHERE:

R_n = Reynolds' Number = $v \cdot L/\nu$

v = Velocity

L = Length

ν = Kinematic Viscosity of Water

The roughness coefficient for new and clean hull bottoms is generally taken as 0.0004 but may increase to 0.001 for old and dirty hull bottoms.

The residual resistance coefficient is determined from measurements of model test data leading to the determination of the total resistance coefficient from Equation 5.

EQUATION 5

$$C_r = C_t - C_{ft}$$

The residual resistance coefficient includes form resistance, wavemaking resistance, wake separation resistance and appendage resistance.

Modern hydrodynamic theory has yet to postulate methods to determine accurate values of the residual resistance coefficient. Experiments through model tank testing represent the only accurate method of determining the residual resistance of a ship or barge. However, series of ship and barge forms have been tested and can give guidance for a particular case not tested. (See Refs. 4, 5, and 6)

The large amount of data obtained and published on the resistance of all types of ships and barges should be the salvage expert's most reliable source of information in determining resistance of a ship or barge proceeding, towed or moored against a strong water current.

B6. DETERMINATION OF RESISTANCE FOR SHIPS TOWED OR MOORED, AND HEADING INTO A HIGH-SPEED CURRENT

The resistance of ships towed or moored with their bows heading into the current can be determined with the use of model test tank data, where the residual resistance coefficient is given for a geometrically similar vessel. For the purposes of this exercise, a geometrically similar hull form has the same length/breadth (L/B) and breadth/draft (B/H) ratios. The geometrically similar hull form also has the same block coefficient.
The particulars, parameters and relationships are developed below.

L = Length on Waterline

B = Beam Molded

D = Molded Depth Above Baseline

H = Draft Corresponding to Loading Condition

C_b = Block Coefficient at Loaded Depth

Dspl = Displacement as given or calculated by:
$C_b \cdot L \cdot B \cdot H/36$ (for fresh water)

S = Wetted Surface as given or estimated within 1% by:
$((Dspl \cdot 36)/H) + (1.69 \cdot L \cdot H)$ (Ref. 3)

V = Resulting Speed of Vessel Against Current

SAMPLE CALCULATION NO. 1

During the course of a salvage operation, a work barge must be towed and moored in a specific location characterized by a 7.9

knot water current. The salvage engineer must determine the resistance of the barge and advise the salvage master, who will determine tug powering and mooring requirements.

RESISTANCE FOR A BARGE MOORED IN A 7.9 KNOT CURRENT
BARGE MOORED IN DEEP WATER

Known Parameters:

Barge Particulars

L	= Length on Waterline	250.00 ft
B	= Beam	73.00 ft
D	= Depth	16.00 ft
H	= Draft Loaded	12.17 ft
C_b	= Block Coefficient	0.84
L/B	= Length/Breadth Ratio	3.43
B/H	= Breadth/Draft Ratio	6.00

Current Particulars

V_c	= Current Velocity	7.900 kts
d	= Water Depth	85.000 ft
ρ	= Density of Fresh Water	1.938 lbs-sec^2/ft^4 @ 60° F
ν	= Kinematic Viscosity	1.211 ft^2/sec @ 60° F

Model resistance test data for a barge of similar geometry is published by the Society of Naval Architects and Marine Engineers (Ref. 6).

Based on the above data the salvage specialist can determine the resistance of the barge by using the equations and relationships established for hydrodynamic resistance.

Displacement	= Dspl	$= C_b \cdot L \cdot B \cdot H/36$
		$= 0.84 \cdot 250 \cdot 73 \cdot 12.17/36$
		= 5182.4 LT
Wetted surface	= S	$= (Dspl \cdot 36/H) + (1.69 \cdot L \cdot H)$
		$= 20472\ ft^2$
Velocity	= v	$= 1.69 \cdot V = 1.69 \cdot 7.90$
		= 13.35 ft/sec
Gravity	= g	$= 32.20\ ft/sec^2$
Froude's No.	$= F_n$	$= v/(Lg)^{\frac{1}{2}}$
		$= 13.35/(250 \cdot 32.2)^{\frac{1}{2}}$
		= 0.149
Reynolds' No.	$= R_n$	$= v \cdot L/$
		$= 13.35 \cdot 250/(1.211 \cdot 10^{-5})$
		$= 2.76 \cdot 10^8$
Frictional Coeff.	$= C_f$	$= 0.075/(\log10(R_n)-2)^2$
		= 0.001808 (Ref. 2)
Roughness Coeff.	$= C_{rgh}$	= 0.0008
Total Frictional Coeff.		$= C_{ft} = C_f + C_{rgh} = 0.002608$

Residual resistance must be interpolated for the calculated Froude's number from the tank test data of the parent barge hull form (Ref. 6).

Model No. MU-361-A

$V(L)^{\frac{1}{2}}$	Froude's No. (F_n)	C_r
0.50	0.149	0.00252

Residual Resistance Coeff. for $F_n = 0.149$, $C_r = 0.00252$

Total Resistance Coeff. $= C_t = C_r + C_{ft}$

$$= 0.002608 + 0.00252 = 0.005128$$

Total Resistance (lbs) $= R = \rho/2 \cdot S \cdot v^2 \cdot C_t$

$$R = 0.5 \cdot 1.938 \cdot 20472 \cdot 13.35^2 \cdot 0.005128 = 18130 \text{ lbs}$$

B7. DETERMINATION OF THE INCREASE IN RESISTANCE IN SHALLOW WATER

The effect of shallow water on the speed and powering of ships is treated at length in Ref. 3, which specifically reports on investigations carried out at the David Taylor Model Basin. This shallow water effect on typical commercial ship hull forms has been investigated at The Model Basin by running resistance and propulsion tests on models.

The increase in resistance and shaft horsepower, together with sinkage and trim were measured over a range of speeds in depths of water from 22 feet to deep water. The increase in shaft horsepower or resistance relative to a base of the ratio of water depth-to-ship draft for various "speed over the square root of the length" ratios are shown in Table B-1 and further illustrated in Figure B7-1.

TABLE B-1

INCREASE IN RESISTANCE IN SHALLOW WATER
PERCENTAGE INCREASE IN RESISTANCE

RATIO OF WATER DEPTH TO DRAFT d/H	$V(L)^{\frac{1}{2}}$ .2	$V(L)^{\frac{1}{2}}$ .3	$V(L)^{\frac{1}{2}}$ .4	$V(L)^{\frac{1}{2}}$ .5
1.10	96	104	110	125
1.20	56	66	76	90
1.30	35	45	55	65
1.40	23	31	38	46
1.50	14	20	26	32
1.60	8	13	17	22
1.70	4	7	10	14

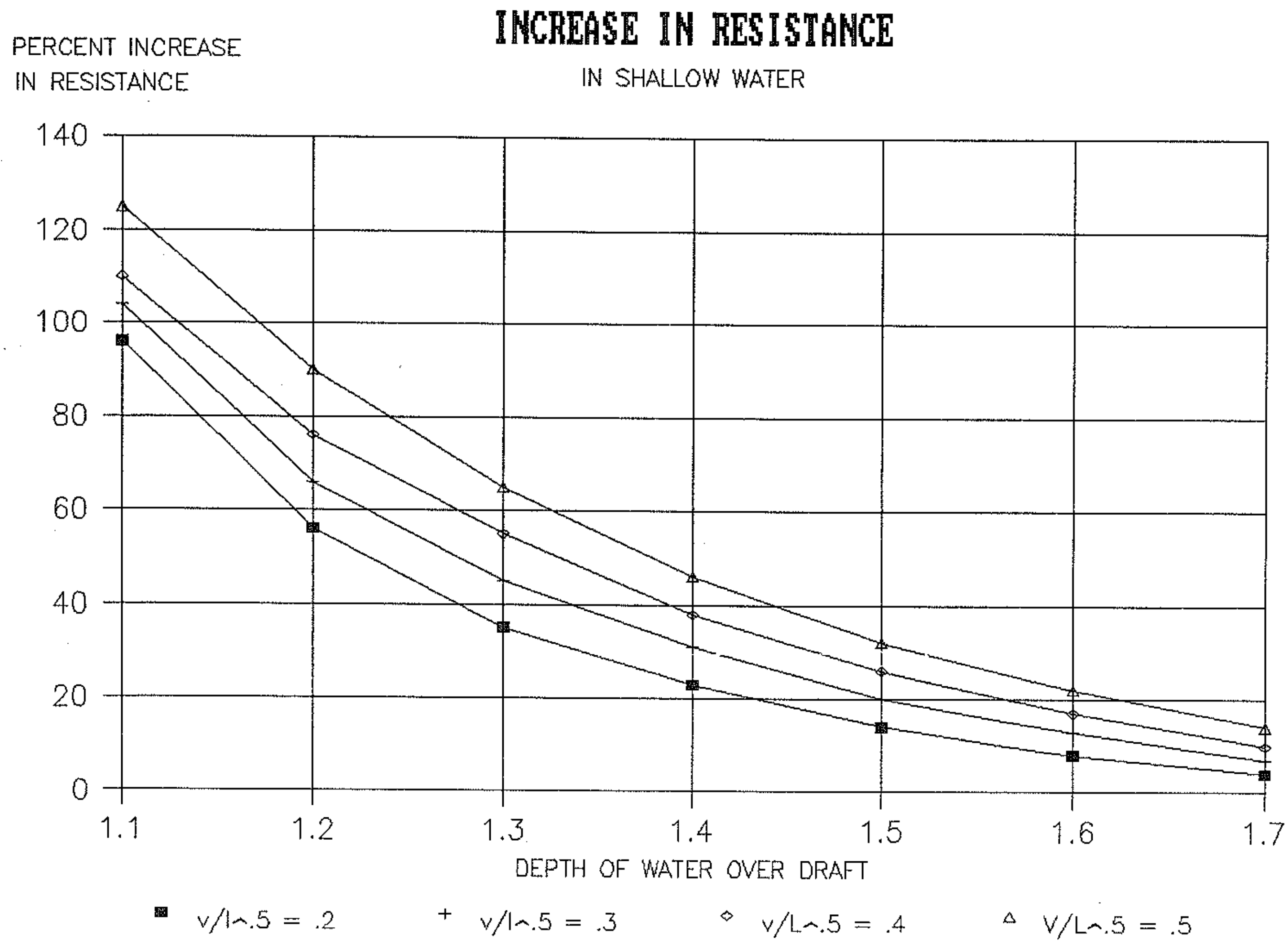

INCREASE IN RESISTANCE
IN SHALLOW WATER
PERCENT INCREASE
IN RESISTANCE
140
120
100
80
60
40
20
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
DEPTH OF WATER OVER DRAFT
v/l^.5 = .2
v/l^.5 = .3
v/L^.5 = .4
V/L^.5 = .5

FIGURE B7-1

In Sample Calculation No. 1, the ratio of water depth-to-draft is equal to 7. The "speed over the square root of the length" ratio is equivalent to 0.50 and would result in no increase in resistance.

However, the same barge exhibiting an identical loading condition in the 7.9 knot current, but in a water depth of 17.50 feet, would experience an increase in resistance of 41% due to the shallow water effect, as shown in Sample Calculation No. 2.

SAMPLE CALCULATION NO. 2

RESISTANCE FOR A BARGE MOORED IN A 7.9 KNOT CURRENT BARGE MOORED IN SHALLOW WATER

Shallow Draft Parameters

Barge Draft	= H	=	12.20 ft
Water Depth	= d	=	17.50 ft
Water Depth / Draft Ratio	= H/d	=	1.44
Speed / Length Ratio	= $V(L)^{\frac{1}{2}}$	=	0.50

Percentage Increase in Drag Due to Shallow Water Effect from Figure B7-1 or Table B-1 = 41.00

R_{ts} = Total Resistance of Barge in 17.50 ft Water Depth

$$R_{ts} = R \cdot 1.41 = 18130 \cdot 1.41 = 25563 \text{ lbs}$$

B8. DETERMINATION OF CURRENT RESISTANCE FOR VESSELS PERPENDICULAR OR WITH A DIVERGING ANGLE TO HIGH-SPEED WATER CURRENTS IN A RESTRICTED WATERWAY

When a ship or barge is perpendicular to, or at large angles to, the current direction, the shape of the hull form has little effect on the resistance, since the side of the vessel approaches the shape of a flat plate opposing the current. This, in turn, approaches Newton's basic theory.

In this condition the dynamic pressure forces are predominant, while the frictional and form resistances will be relatively small. The free surface is still present, causing cresting along the impact surface of the vessel while a trough would appear on the vessel's lee side.

The lack of clearance between the vessel's bottom and the waterway bed in a grounding situation also will greatly obstruct the flow around the vessel and increase the hydrodynamic resistance. The bow and stern of the vessel present sharp edges against the current and create large eddies downstream.

Early research on the resistance of flat plates perpendicular to the water flow were oriented to the fully submerged and unobstructed conditions, where the influence of free surface, side walls and bottom would not influence the experimental results. Research on the resistance of grounded vessels in a strong current has never been published and may never have been carried out.

Partial elements of research on flat surface resistance, shallow water effect, ram pressure effect and sharp edge vortex formation have been carried out. The U.S. Navy has led some of the research in the field of current resistance.

The British Ship Research Association (Ref. 7) carried out the first and only widely-published effort to formulate a practical methodology for determining resistance of vessels moored in variable current directions in shallow water. This endeavor coincided with the increasing size of vessels calling at overcrowded or developing ports, where mooring system adequacy was critical and where the accuracy of information on mooring forces was a requirement.

The situation and condition of a vessel aground and perpendicular to the current can be considered analogous to that of a vessel moored perpendicular to the current in shallow water, where $d/H = 1$.

B9. CURRENT FORCES

In the 1970s, the British Ship Research Association, based on research carried out by the U.S. Navy, developed empirical data and formulae which enabled naval architects to determine accurately the resistance or drag of vessels or barges against currents of variable velocity and direction. This work led to reasonably accurate estimating of the total resistance coefficients and included the following.

- Dynamic Pressure
- Friction
- Roughness
- Viscosity
- Angle of Attack to Current
- Depth of Water vs. Submerged Hull Depth

The total current resistance or drag coefficient is defined as follows in Equation 6.

EQUATION 6

$$C_d = R_c / (\rho/2 \cdot L \cdot H_p \cdot v_c^2)$$

WHERE:

- C_d = Current Drag Coefficient
- R_c = Current Force in Deep Water
- L = Actual Submerged Length
- H_p = Projected Submerged Depth From Submerged Geometry
- v_c = Current Speed in ft/sec
- ρ = Water Density

Alternatively, the current resistance or drag in deep water can be calculated by using Equation 6A.

EQUATION 6A

$$R_c = C_d \ \rho/2 \cdot L \cdot H_p \cdot v_c^2$$

Current resistance coefficients are plotted against angle of attack in Figure B9-1, as derived from Ref. 7. The angle of attack is defined as the angle of current relative to a ship's head.

The above relationship is true only in deep water or water depths equal to at least seven times the vessel's draft. When this ratio is less than seven, a correction factor (K) must be applied to the deep water current force as follows.

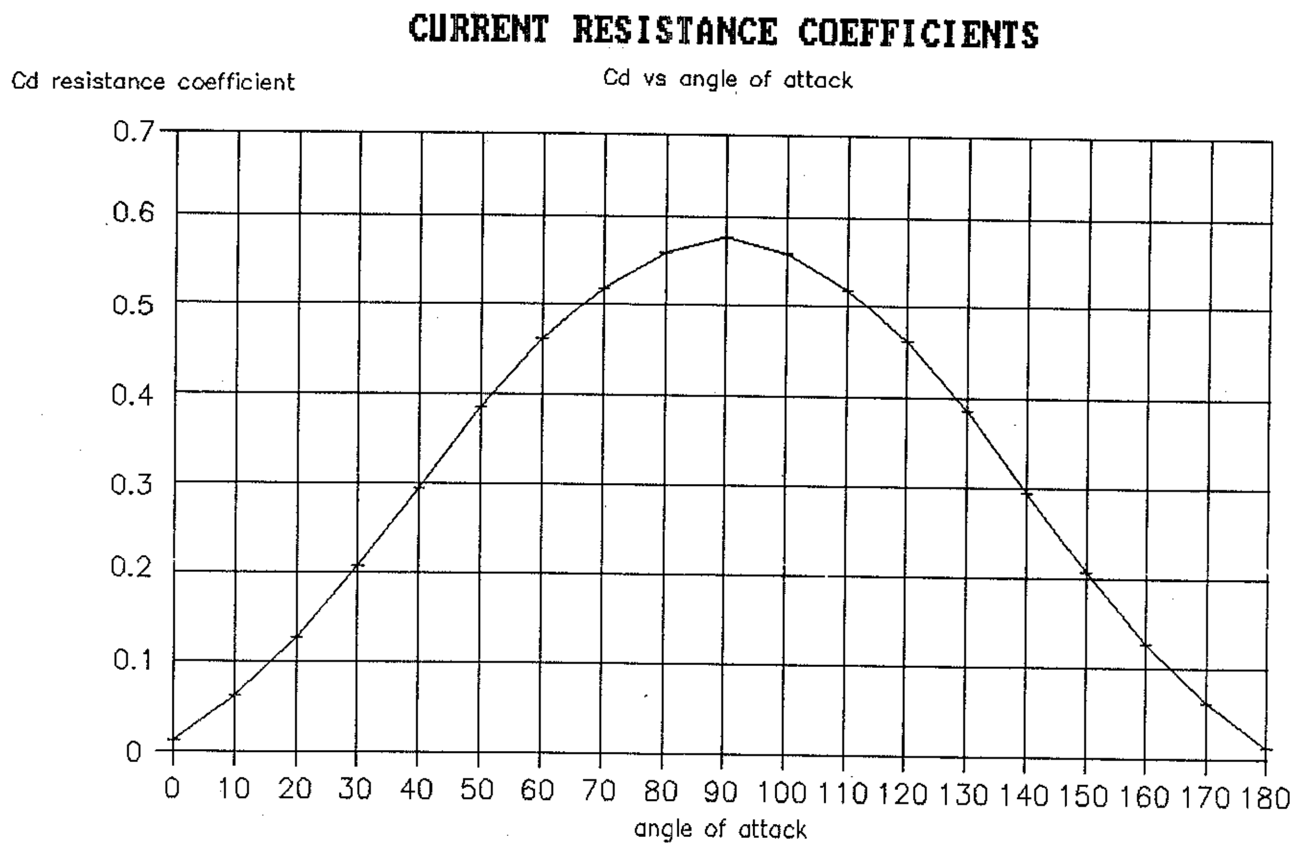

CURRENT RESISTANCE COEFFICIENTS
Cd resistance coefficient
Cd vs angle of attack
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
angle of attack

FIGURE B9-1

EQUATION 7

$$R_{ct} = K \cdot R_c$$

WHERE:

K = Shallow Water Correction Coefficient

R_{ct} = Total Current Force in Shallow Water

Depth correction factors (K) as given in Ref. 7 are plotted against the ratio of water depth-to-ship draft in Figure B9-2.

CURRENT RESISTANCE

depth correction factor

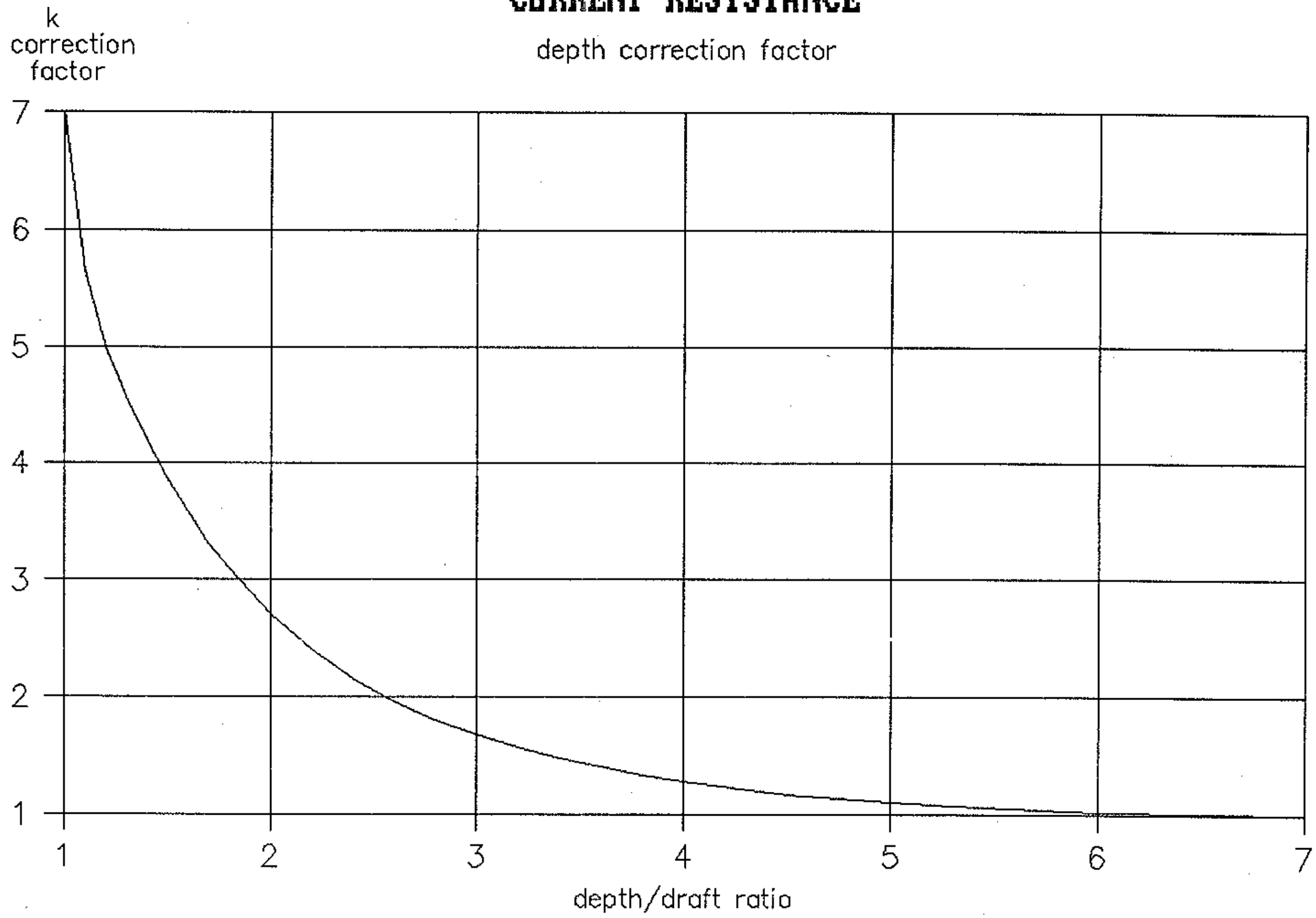


FIGURE B9–2

In order to illustrate the application of the empirical resistance data applicable to barges and vessels resting at an angle to high velocity currents, sample calculations are presented as listed below.

Sample Calculation No. 3

Barge immobilized at 90° to current flow in deep water

Sample Calculation No. 3A

Barge immobilized at 90° to current flow in shallow water

Sample Calculation No. 4

25,000 DWT ocean-going vessel stranded at 45° to current flow in a trimmed condition, and in variable water depth

Sample Calculation No. 5

Barge grounded, partially flooded and submerged, at 70° to current flow, presenting a complex geometry in the high speed current.

SAMPLE CALCULATION NO. 3

BARGE PERPENDICULAR TO A HIGH-SPEED CURRENT IN DEEP WATER

An out-of-control barge is carried downriver by a high-speed current to rest against piles abreast the current at an angle of

90 degrees. A determination of the hydrodynamic current drag must be carried out before a salvage plan can be formulated.

The principal particulars of the barge and current are listed as follows:

Barge Particulars

Length	= L	= 250 ft
Beam	= B	= 73 ft
Depth	= D	= 16 ft
Draft Loaded	= H	= 10 ft

Current Particulars

Current Speed	= V_c	= 7.9 kts
Depth of Water	= d	= 75.0 ft
Angle of Attack of Current Against Barge		= 90.0 deg

The attitude and condition of the barge and current are illustrated in Figure B9-3.

Barge Particulars

Length	= L	= 250 ft
Beam	= B	= 73 ft
Depth	= D	= 16 ft
Draft Loaded	= H	= 10 ft

Current Particulars

Current Speed	= V_c	= 7.9 kts
Depth of Water	= d	= 20.0 ft
Angle of Attack of Current Against Barge		= 90.0 deg
d/H		= 2.0
K (from Figure B9-2)		= 2.75

From Equation 7:

$$R_{ct} = K \cdot R_c$$

From Sample Calculation No. 3:

$$R_c = 253865$$

$$R_{ct} = 2.75 \cdot 253865 = 698129 \text{ lbs}$$

SAMPLE CALCULATION NO. 4

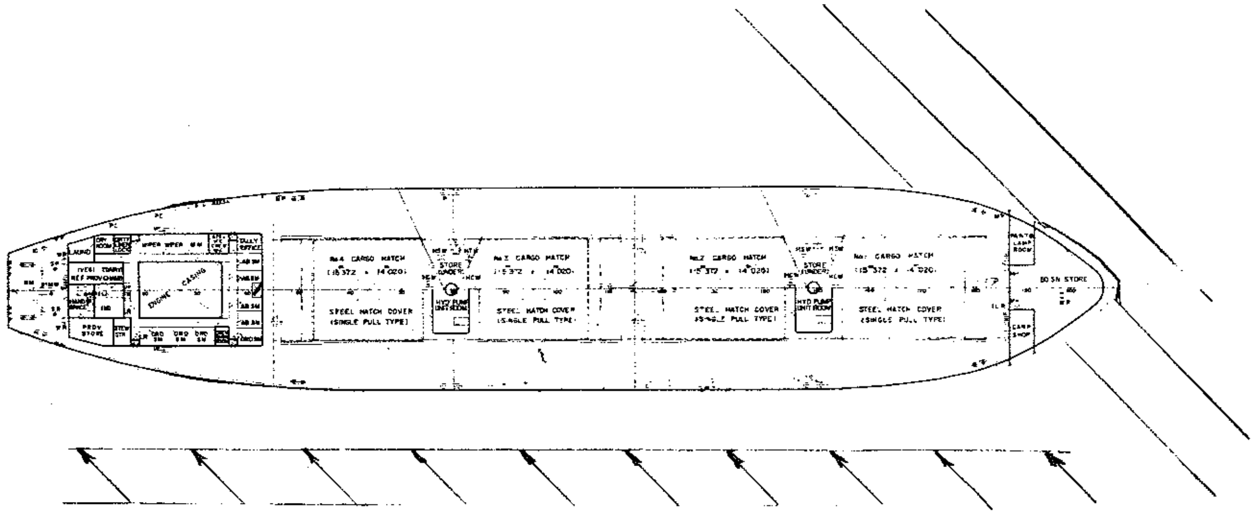
25,000 DWT FREIGHTER IS AGROUND IN A FAST-FLOWING RIVER AT 45 DEGREES TO THE CURRENT IN VARIABLY SHALLOW WATERS

The vessel lost control in a ten-knot current and finally came to rest with her bow aground in 25 feet of water. The vessel's stern is afloat in deeper water but pinned against a bridge pier by the strong current. In this wedged position, the vessel was pointing its bow 45 degrees to the direction of the current.

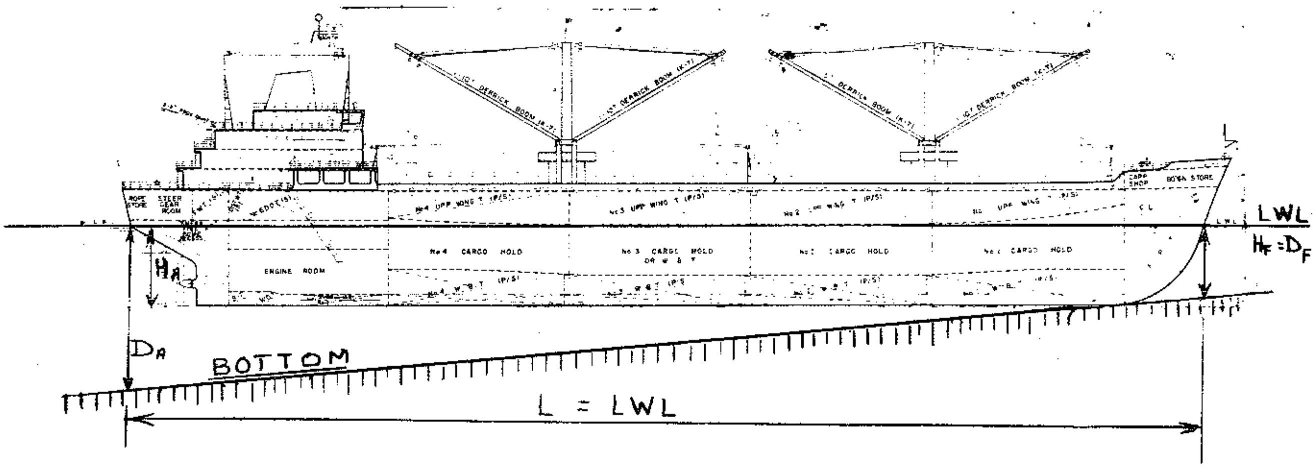
The attitude of the vessel to the current and river bottom is illustrated in Figure B9-4.

A survey of the vessel produced changing drafts and water depths along the length of the vessel. The drafts and water depths taken at 10 equidistant stations along the length of the vessel are listed in Table B-2.

Also shown in Table B-2 are the corresponding water depth-to-draft ratios and depth correction factors (K) for each station. (See Figure B9-2)



V CURRENT VELOCITY 10 KNOTS
AT 45° TO SHIP AXIS



L LWL	500′
B BEAM	80′
H_F	25′
H_A	30′
D_F	25′
D_A	50′

FIGURE B9-4

TABLE B-2

Station		Draft ft H	Water Depth ft d	d/H	K
Aft perp.	0	30.00	50.0	1.67	3.40
	1	29.50	47.5	1.61	3.55
	2	29.00	45.0	1.55	3.75
	3	28.50	42.5	1.49	3.90
	4	28.00	40.0	1.43	4.08
	5	27.50	37.5	1.36	4.33
	6	27.00	35.0	1.30	4.57
	7	26.50	32.5	1.23	4.90
	8	26.00	30.0	1.15	5.30
	9	25.50	27.5	1.08	5.70
fwd perp.	10	25.00	25.0	1.00	7.00

DETERMINATION OF CURRENT RESISTANCE BASED ON MEAN DRAFT & WATER DEPTH

The mean draft of the vessel in this partially aground condition is 27.5 feet (i.e., (25+30)/2). The mean water depth is 37.5 feet (i.e., (25+50)/2).

As shown in Table B-2 for station 5 (amidships), the water depth-to-draft ratio is 1.36 and the corresponding depth correction factor K is 4.33, for the mean draft and mean depth values. (See Figure B9-2)

A first approximation of the current drag or resistance on the grounded vessel can be calculated while using the values and coefficients corresponding to these mean values of draft and water depth.

By combining Equations 6A and 7, the total current resistance of the vessel aground in shallow water is expressed as follows in Equation 8.

EQUATION 8

$$R_{ct} = C_d \quad \rho/2 \cdot L \cdot H_m \cdot v_c^2 \cdot K_m$$

WHERE:

H_m	= Mean Draft = 27.5 ft
d_m	= Mean Water Depth = 37.5 ft
d_m/H_m	= 37.5/27.5 = 1.36
K_m	= Mean Shallow Water Coefficient = 4.33
C_d	= 0.352 (from Figure B9-1) Angle of Attack = 45°
L	= 500 ft
V_c	= 10 kts
v_c	= 16.9 ft/sec
ρ	= 1.938

$$R_{ct} = (1.938/2) \cdot 0.352 \cdot 500 \cdot 27.5 \cdot 16.9^2 \cdot 4.33$$

$$R_{ct} = 5800033 \text{ lbs}$$

DETERMINATION OF CURRENT RESISTANCE BY USE OF INTEGRATION

Since the drafts and water depths vary along the length of the vessel, the water depth correction factors also vary in a non-linear fashion. The variables along the length of the vessel are the draft (H) and the water depth correction coefficient (K).

The total current resistance would then be represented as follows in Equation 9.

EQUATION 9

$$R_{ct} = C_d \quad \rho/2 \cdot v_c^2 \quad \int_O^L (H \cdot K \cdot d \cdot x)$$

By using Simpson's rule of integration (Ref. 3), the equation is expressed as follows in Equation 10.

EQUATION 10

$$R_{ct} = C_d \quad \rho/2 \cdot v_c^2 \quad (1/3 \cdot s \cdot \Sigma(H \cdot f \cdot K)$$

WHERE:

s = Station Spacing = L/10 = 50

f(K) = K · sm

sm = Simpson Multiplier

K	=	Water Depth Correction Factor at Station x
C_d	=	Current Drag Coefficient = 0.352 at 45 degrees
V_c	=	Current Speed = 10 knots
v_c	=	16.9 ft/sec
H	=	Draft at Station x
ρ	=	1.938

The numerical integration process for determining current resistance and longitudinal center of pressure is shown in Table B-3.

TABLE B-3

Station x	Draft ft H	K	sm	f(K)	Hf(K)	xHf(K)
0	30.00	3.40	1	3.40	102	0.0
1	29.50	3.55	4	14.20	419	418.9
2	29.00	3.75	2	7.50	218	435.0
3	28.50	3.90	4	15.60	445	1333.8
4	28.00	4.08	2	8.16	228	913.9
5	27.50	4.33	4	17.32	476	2381.5
6	27.00	4.57	2	9.14	247	1480.7
7	26.50	4.90	4	19.60	519	3635.8
8	26.00	5.30	2	10.60	276	2204.8
9	25.50	5.70	4	22.80	581	5232.6
10	25.00	7.00	1	7.00	175	1750.0
Sums				135.32	3686	19787.0

R_{ct} $= 1/3 \cdot \Sigma(H \cdot f(k)) \cdot s \quad C_d \cdot \rho/2 \cdot v_c^2$

$= 1/3 \cdot 3686 \cdot 50 \cdot 0.352 \cdot 1.938/2 \cdot 16.9^2$

= 5984721 lbs

lcp = Longitudinal Center of Pressure from AP

$= \Sigma(x \cdot H \cdot f(k)) / \Sigma(H \cdot f(k)) \cdot s$

$= 19787/3686 \cdot 50 = 268.41$ ft

A comparison of the results using Equation 10 (Integration Method) versus Equation 8 (Mean Average Method) indicates a variation of 3% (i.e.; (5984721-5800033)/5984721). Under most circumstances, 3% accuracy is well within the salvor's goals. Thus, the mean average calculation method is sufficiently rigorous.

SAMPLE CALCULATION NO. 5

BARGE GROUNDED, PARTIALLY FLOODED & SUBMERGED, AT A 70° ANGLE TO A HIGH-SPEED CURRENT

HYDRODYNAMIC FORCES AND MOMENTS

The hydrodynamic forces and moments produced by the current and acting on a barge with a complex geometry as shown in Figures B9-5 to B9-7 are listed as follows:

- o Total Horizontal Force
- o Horizontal Reaction Against Pier
- o Horizontal Reaction Against Rock
- o Transverse Moment About Lower Grounding Point
- o Longitudinal Moment About Grounding Point

These hydrodynamic forces and moments can be combined with buoyancy and gravity forces and moments, by the salvage engineer in order to determine the total order of magnitude of forces and moments present in the salvage situation.

SURVEY

A survey of the barge around and against the rock and pier shows the condition of the barge as follows: (See Figures B9-5, B9-6)

Barge Particulars

L	= Length on Waterline	250.00 ft
B	= Beam	72.00 ft
D	= Depth	16.00 ft

The barge has three transverse and two longitudinal bulkheads. The forepeak and #1 compartments are tidal. The #2 and aft peak compartments are watertight and contain residual bilge water.

	Barge Freeboard		Depth of Water (d)	
Location	Port	Stbd	Port	Stbd
Forward	0.00	-24.62	14.00	39.65
Amidships	12.31	-12.31	30.00	30.00
Aft	24.62	0.00	25.00	25.00

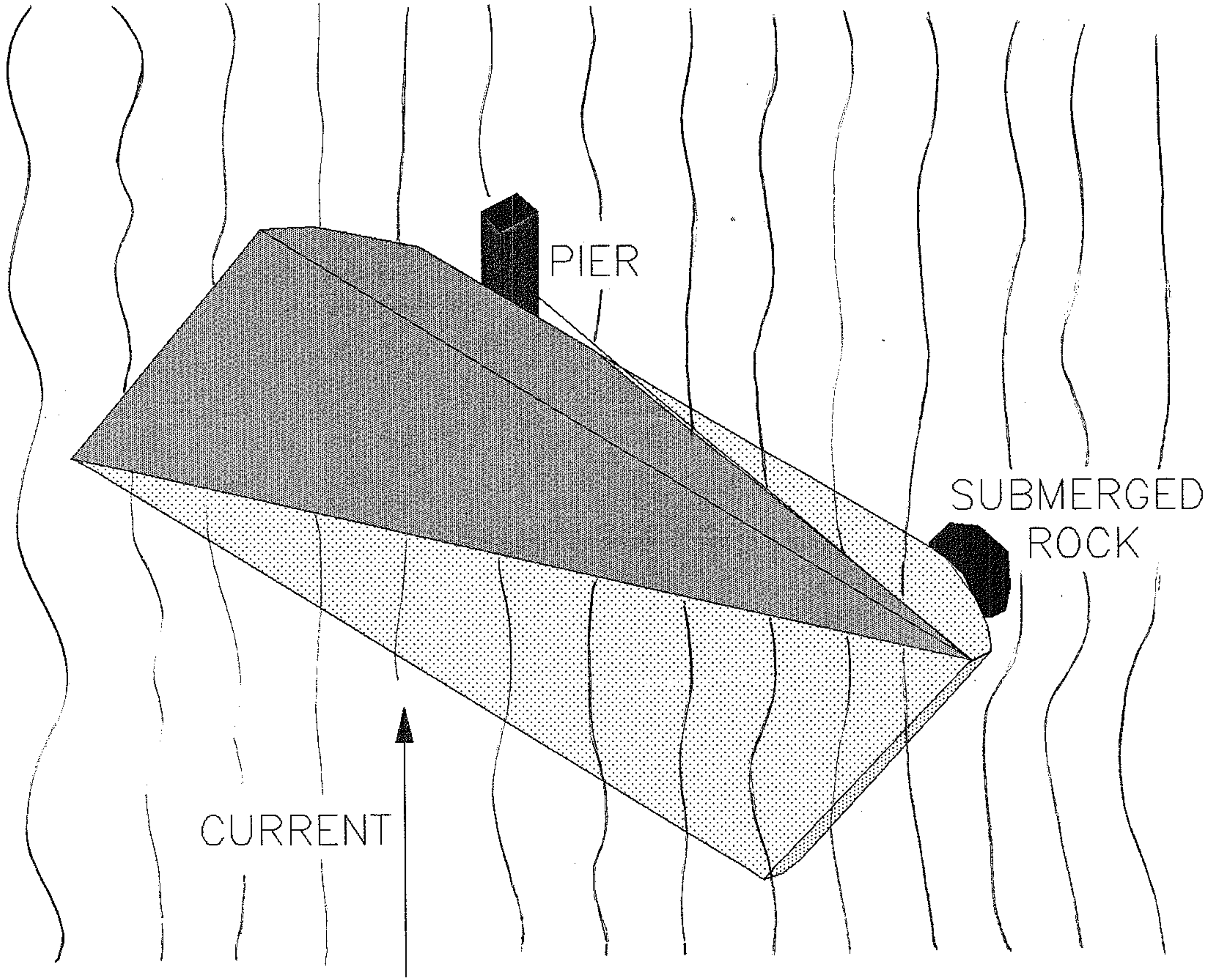


FIGURE B9–5
BARGE GROUNDED, PARTIALLY FLOODED AND SUBMERGED
ISOMETRIC VIEW

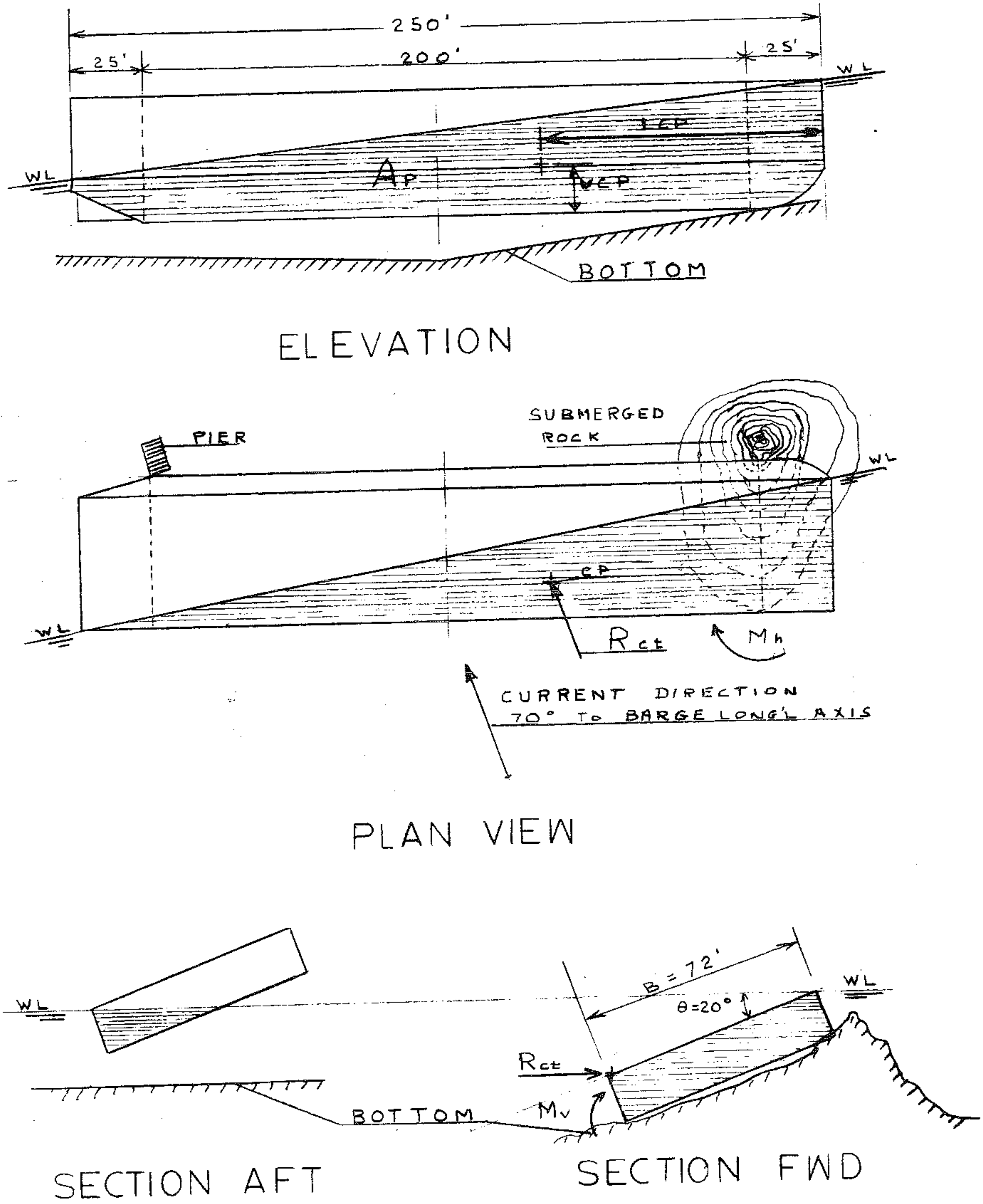


FIGURE B9–6
BARGE GROUNDED, PARTIALLY FLOODED AND SUBMERGED
PLAN AND ELEVATION VIEWS

DETERMINATION OF DRAFTS

The draft of the barge at any given point is equal to the barge depth corrected for the angle of list, less the freeboard at that point. The projected draft is represented as follows in Equation 11 and Figure B9-7.

EQUATION 11

$$\text{PROJECTED DRAFT} = H_p = D \cdot \cos\theta - f$$

WHERE:

D = Barge Depth

θ = Angle of List

f = Freeboard

At any location on the longitudinal axis of the barge, the angle of list may be defined as follows in Equation 12.

EQUATION 12

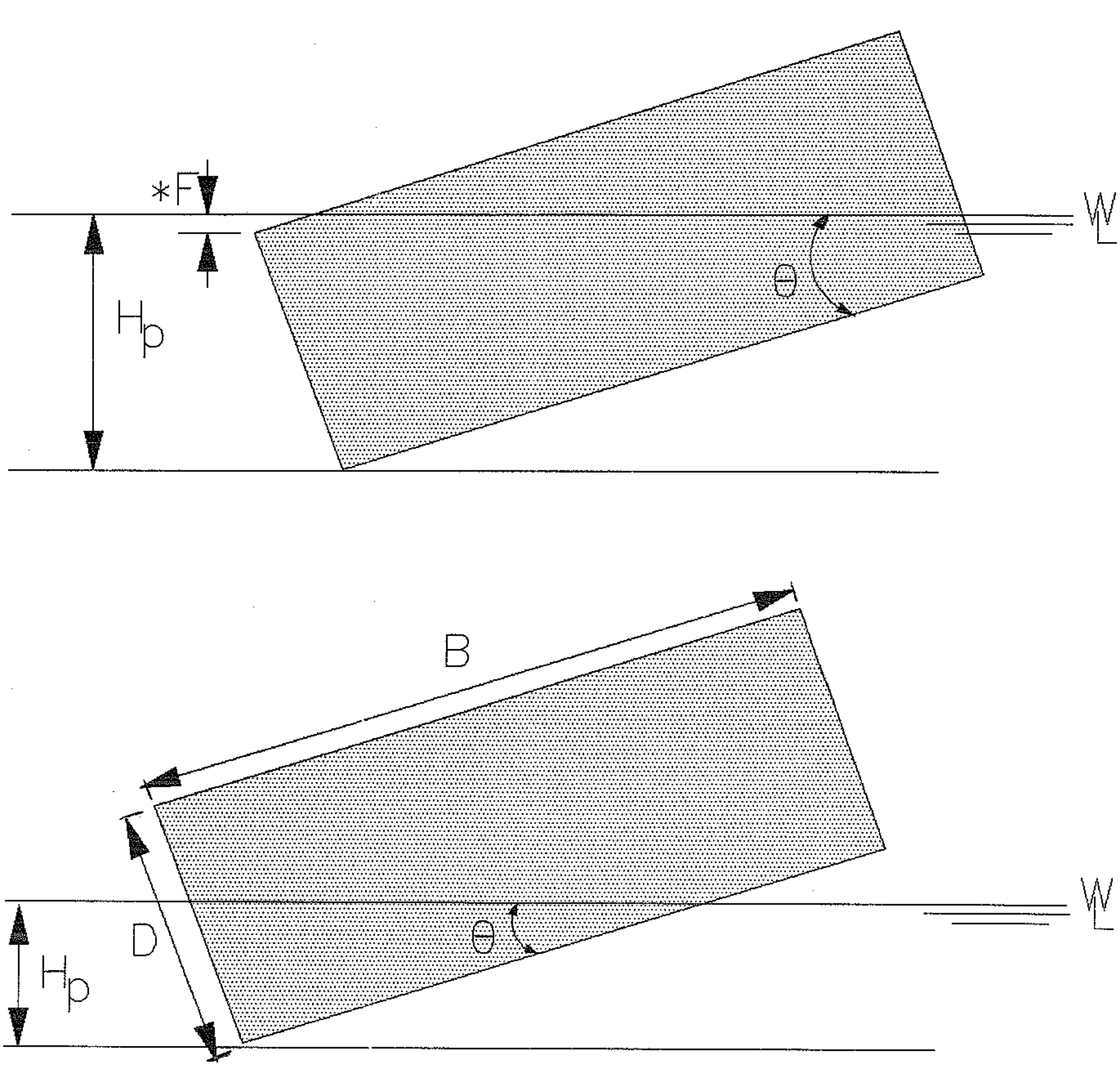
$$\sin\theta = (f_p - f_s)/B$$

WHERE:

f_p = Freeboard Port Side

f_s = Freeboard Starboard Side

B = Beam of Barge



H = Dcos(Θ) - f

* **NOTE: Where deck edge is submerged, submerged depth from deck edge to waterline is considered negative freeboard.**

FIGURE B9-7
BARGE GROUNDED, PARTIALLY FLOODED AND SUBMERGED
PROJECTED DRAFT

At amidships the angle of list is determined as follows.

$$\sin\theta = (12.31 - (-12.31))/72 = 0.340555$$

$$\theta = \arcsin(0.340555) = 20 \text{ degrees}$$

The projected drafts on the low side or starboard side of the barge shall be used in determining the hydrodynamic forces produced by the current. The determination of the projected drafts on the starboard side of the barge are given in Table B-4.

TABLE B-4

Location	Dcos(20)	f	H_p
Forward	15.04	-24.62	39.66
Amidships	15.04	-12.31	27.35
Aft	15.04	0.00	15.04

DETERMINATION OF TOTAL CURRENT RESISTANCE

The total current resistance is defined in Equation 13.

EQUATION 13

$$R_{ct} = C_d \quad K \quad \rho/2 \quad L \cdot H_p \cdot v_c^2$$

Since H_p and K vary along the length of the barge, the equation is redefined as follows:

EQUATION 13A

$$R_{ct} = C_d \cdot \rho/2 \cdot A_p \cdot v_c^2$$

WHERE:

A_p = Projected Pressure Area Perpendicular to Current

A_p = $\int_0^L$ of $(K \cdot H_p \cdot L)$

C_d = Current Drag Coefficient

C_d = 0.528 When Angle of Attack is 70 Degrees

V_c = 10.00

v_c = 16.9 ft/sec

K = Shallow Water Correction Coefficient

L = 250

sm = Simpson Multiplier

$f(A_p)$ = $H_p \cdot K \cdot sm$

ρ = 1.938

Simpson's Method of integration is used for determining Ap as given in Table B-5. A_p is shown in Figure B9-6.

TABLE B-5

Location	H_p	d	d/H_p	K	sm	$f(A_p)$
Forward	39.66	39.65	1.00	7.00	1.00	277.59
Amidships	27.35	30.00	1.10	6.00	4.00	656.29
Aft	15.04	25.00	1.66	3.35	1.00	50.37
Total						984.25

$$A_p = f(A_p) \cdot L/2 \cdot 1/3 = 41010 \text{ ft}^2$$

$$R_{ct} = C_d \quad \rho/2 \cdot A_p \cdot v_c^2 = 5992677 \text{ lbs}$$

DETERMINATION OF HYDRODYNAMIC MOMENTS

The vertical or transverse hydrodynamic moment produced by the current is defined as follows in Equation 14.

EQUATION 14

$$M_v = R_{ct} \cdot vcp$$

WHERE:

vcp = Vertical Center of Pressure Above Starboard Bilge Forward

The longitudinal hydrodynamic moment produced by the current is defined as follows in Equation 15.

EQUATION 15

$$M_h = R_{ct} \cdot lcp$$

WHERE:

lcp = Longitudinal Center of Pressure From Bow

Vcp and lcp are determined following the principles of naval architecture as shown in Table B-6.

TABLE B-6

Location	H_p	f(A)	vcp	vcp · f(A)	lcp	lcp · f(A)
Forward	39.66	277.59	19.83	5503.88	0.00	0.00
Amidships	27.35	656.29	13.67	8973.13	125.00	82035.67
Aft	15.04	50.37	7.52	378.65	250.00	12592.00
Total		984.24	15.09	14855.66	96.14	94627.67

$$vcp = \Sigma vcp \cdot f(A) / \Sigma f(A) = 15.09 \text{ ft}$$
$$lcp = \Sigma lcp \cdot f(A) / \Sigma f(A) = 96.14 \text{ ft}$$

$$M_v = R_{ct} \cdot vcp = 5992677 \cdot 15.09 = 90429495 \text{ ft-lbs}$$
$$M_h = R_{ct} \cdot lcp = 5992677 \cdot 96.14 = 576135966 \text{ ft-lbs}$$

DETERMINATION OF HORIZONTAL REACTIONS

Horizontal reactions in the pier and rock are defined as follows in Equations 16 & 17.

EQUATION 16

$$R1 + R2 = R_{ct}$$

EQUATION 17

$$M_h = (R1 \cdot L1) + (R2 \cdot L2)$$

WHERE:

R1 = Horizontal Reaction Against Pier

R2 = Horizontal Reaction Against Rock

L1 = Distance of R1 From Bow = 225 ft

L2 = Distance of R2 From Bow = 25 ft

Solving for two equations with two unknowns

$$R1 = 5992677 - R2$$

$$225 \cdot (5992677-R2) + 25 \cdot R2 = 576135966$$

$$R2 = 3861082 \text{ lbs}$$

$$R1 = 2131595 \text{ lbs}$$

B10. BIBLIOGRAPHY

1. Applied Hydro And Aeromechanics, L. Prandtl and O.G. Tietjens, Dover 1957

2. Coefficients for International Towing Tank Conference, 1957, Model-Ship Correlation Line, Hadler Report No. 1185, Apr. 1958, David Taylor Model Basin, Department of the Navy

3. Principles of Naval Architecture, The Society of Naval Architects and Marine Engineers, Edited By Comstock, 1967

4. Design Considerations and Resistance of Large Towed Seagoing Barges, The Society of Naval Architects and Marine Engineers, Technical and Research Bulletin 1-29, May 1969

5. A Reanalysis of the Original Test Data for the Taylor Standard Series, Navy Department, The David W. Taylor Model Basin, Report 806, March 1954

6. Resistance Data Sheet #99, Model No. MU-361-A, Society of Naval Architects and Marine Engineers (SNAME)

7. Research Investigation For The Improvement of Ship Mooring Methods, Appendix V, The British Ship Research Association, Report NS 179, 1967

ADDITIONAL READING

Hydrodynamics in Ship Design, Vol. I, II, III., Edited By Saunders, 1957, The Society of Naval Architects and Marine Engineers