LONG-TERM EFFECTS OF DREDGING
OPERATIONS PROGRAM

TECHNICAL REPORT D-86-2

THE DUWAMISH WATERWAY CAPPING DEMONSTRATION PROJECT: ENGINEERING ANALYSIS AND RESULTS OF PHYSICAL MONITORING

by

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Final Report

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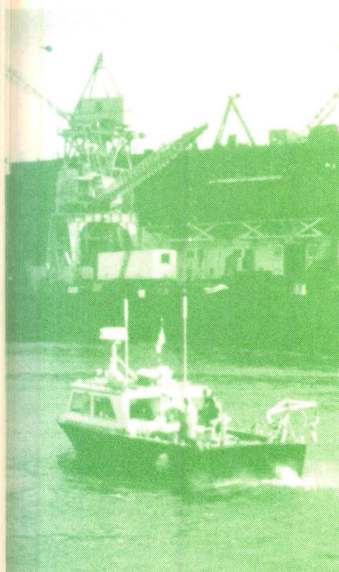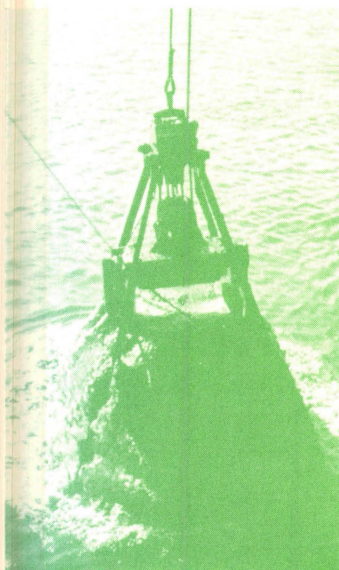of Engineers

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The US Army Engineer District, Seattle, and the US Army Engineer Waterways Experiment Station have cooperated in a project in the Duwamish Waterway that successfully demonstrated the engineering aspects of subaqueous disposal and capping of contaminated dredged material. Approximately 1,100 cu yd of silty, clayey shoal material was removed by clamshell dredge, transported by barge, and bottom dumped through 70 ft of water into an existing depression. The site was

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20. ABSTRACT (Continued).

then capped with successive loads of clean sandy cover. The technique has been termed contained aquatic disposal.

This paper summarizes the initial fieldwork and presents results through the first (6-month) monitoring effort. The engineering effectiveness of the material placement and capping operation is examined using comparisons of replicate bathymetry and side scan sonar. The analysis indicates that the contaminated material exited the barge rapidly and descended to the bottom quickly as a well-defined, cohesive mass. Clean sand was applied successfully as a cap without displacing the softer contaminated material. A volumetric balance of materials is presented together with an error analysis for the calculated volumes based on the precision of the surveys used. Sufficient geotechnical information was also collected to allow for an approximate mass balance calculation. Sources for potential losses of material during the operation are examined. In particular, resuspension of sediment was measured during both the dredging and the disposal operations. A computer-aided method was developed to allow for rapid comparisons of suspended solids levels at different depths in the water column and at various sampling stations.

PREFACE

This paper was prepared and published as part of the Long-Term Effects of Dredging Operations (LEDO) Program, which is sponsored by the Office, Chief of Engineers (OCE), US Army. LEDO Work Unit 31774 addresses the effectiveness of capping as a means of reducing the environmental impact during aquatic disposal of contaminated dredged material.

The analyses and documentation were performed by the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES). The principal investigator for WREG and the author of this paper was Mr. Clifford L. Truitt. This portion of the WES work was performed under the general supervision of Dr. Michael R. Palermo, Chief, WREG, and Dr. Raymond L. Montgomery, Chief, EED. The Chief of EL was Dr. John Harrison. LEDO is managed within EL's Environmental Effects of Dredging Programs, Dr. Robert M. Engler, Manager, and Mr. Robert L. Lazor, LEDO Coordinator. The Technical Monitors were Dr. Robert Pierce and Dr. William Klesch, OCE, and Mr. Charles Hummer, Water Resources Support Center, Fort Belvoir, Va.

The project on which this paper is based was conceived, planned, and initially designed by the US Army Engineer District, Seattle, and the cooperation of Mr. Alex Sumeri is gratefully acknowledged. In addition, the author recognizes the efforts of MAJ Gene L. Raymond, EL, who planned and supervised the initial monitoring fieldwork, Dr. James M. Brannon, EL, who is performing the related portion of the work involving sediment chemistry, Mr. James Clausner, Coastal Engineering Research Center, WES, who conducted the side scan sonar investigation, and Ms. Kathy Smart, WREG, who provided technical assistance. The report was edited by Ms. Jamie W. Leach of the WES Publications and Graphic Arts Division.

Director of WES was COL Allen F. Grum, USA. Technical Director was Dr. Robert W. Whalin.

The paper should be cited as follows:

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons (2,000 pounds, mass)	0.9144	kilograms

THE DUWAMISH WATERWAY CAPPING DEMONSTRATION PROJECT:
ENGINEERING ANALYSIS AND RESULTS OF PHYSICAL MONITORING

PART I: INTRODUCTION

Background

1. Contaminated dredged material placed in open-water disposal sites may be chemically and/or biologically isolated by capping with clean dredged material. Level-bottom capping, or the covering of dredged material mounds with cleaner material to form a larger mound, has been successfully conducted by the US Army Engineer Division, New England (NED), and the US Army Engineer District, New York (NYD). These operations normally involve dredging the material by clamshell equipment, transporting the material to the disposal site in scows or barges, and bottom dumping at a designated point or points marked by buoys.

2. The containment of the disposed material and the capping operation can be more effective if the contaminated dredged material is placed in a natural or constructed depression, thereby providing a more complete confinement. This approach may be termed contained aquatic disposal (CAD). A capping demonstration project using the CAD approach has been conducted in the US Army District, Seattle (NPS), on the Duwamish Waterway. Limitations previously imposed on disposal of maintenance dredged material from the lower reaches of the Duwamish Waterway became apparent with the emergence of a shoal area that reduced the navigable depth to less than 25 ft* (mean lower low water (MLLW)) in the 30-ft authorized channel. Shipping interests in the area were forced to modify drafts and alter schedules causing delays and economic losses. Maintenance work had been restricted by a lack of suitable and economical disposal alternatives for the contaminated sediments found in these reaches of the waterway.

3. The NPS evaluated a number of possibilities for dealing with the shoal including no action, channel relocation, and several dredging/disposal

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

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alternatives (Sumeri 1984). The alternative ultimately selected called for removing the contaminated shoal material with available clamshell equipment and a split hull bottom dumping barge, placing it in an existing subaqueous depression in another part of the waterway, and capping it with clean sandy material from the less contaminated upper reaches of the waterway. It was believed that this approach would provide an environmentally acceptable, cost-effective solution to the immediate problem and at the same time serve as a valuable demonstration project to evaluate the placement techniques and the effectiveness of isolating such sediments through capping.

4. The US Army Engineer Waterways Experiment Station (WES) agreed to assist in the project by conducting an 18-month monitoring and evaluation program addressing the questions of feasibility and effectiveness. This program was planned as an initial field monitoring effort during the construction of the project supplemented with 6- and 18-month follow-up monitoring.

Purpose and Scope

5. The purpose of this report is to summarize the initial field investigation and to present results through the first (6-month) monitoring effort. Dredging and capping operations, sampling and monitoring methods, dredged material and cap configurations, volumetric changes in the capped mound, and measurements of chemical migration through the cap are described.

PART II: DREDGING AND DISPOSAL SITE MONITORING

Disposal Site Conditions

General

6. When NPS decided to pursue capping as the appropriate alternative, work began on identifying and evaluating potential disposal sites. Examination of field survey sounding rolls indicated the presence of a series of depressions in the west waterway of the Duwamish system. It was felt that the use of such a depression for the disposal could assist in confining the bottom surge predicted in earlier studies (e.g., Broughton 1977; Bokuniewicz et al. 1978; Johanson, Bowen, and Henry 1976). The confinement would increase the tendency of the material to mound, making cap placement more effective. It would also reduce resuspension associated with the spread of material across the bottom. Figure 1 presents a general view of the lower Duwamish showing the locations of the shoal and disposal sites and the source of capping material.

7. The depressions are a series of fairly regular, wavelike forms reported to be the result of previous private dredging operations. The depressions are oriented perpendicular to the long axis of the waterway, measure typically 100 ft across, and are from 6 to 10 ft below surrounding elevations. Bathymetry of the depression selected for the disposal site is shown in Figure 2. The contours shown were constructed from soundings provided by the NPS and are referenced to the MLLW datum. The tidal range in the Seattle area is just over 11 ft, so the maximum depth at the disposal site could vary from 64 to 75 ft during a normal tidal cycle. Nominal dimensions of the target site were 100 to 150 ft wide by 300 ft long. The site is approximately 4,000 ft up the waterway from its opening into Elliott Bay. Bulkheads line both sides of the reach and the total width of the waterway in the area is 750 ft. Figure 3 is a general view in the vicinity of the disposal site.

Tides

8. Tides in the region have a basic semidiurnal pattern, although the frequently pronounced inequality in the elevations of the two low waters each day suggests the influence of a diurnal wave, resulting in a somewhat mixed cycle. One effect of this is that tidal currents tend to exhibit only one or two daily peaks of strong, directional flow in an otherwise weak and variable

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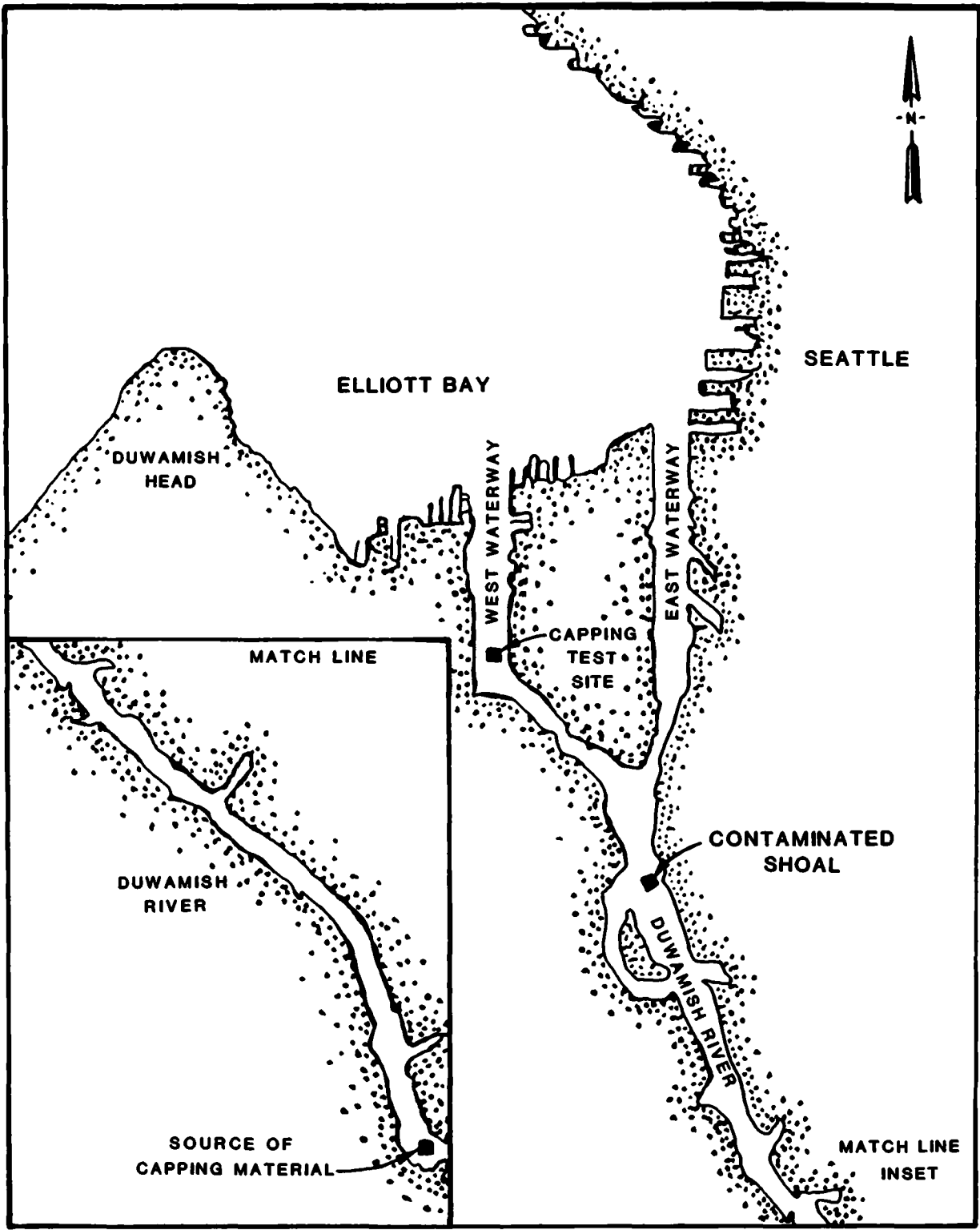
Figure 1. Vicinity map (after Sumeri 1984)

NOTE: CONTOURS ARE DEPTHS IN FEET
BELOW WATER SURFACE AT MLLW
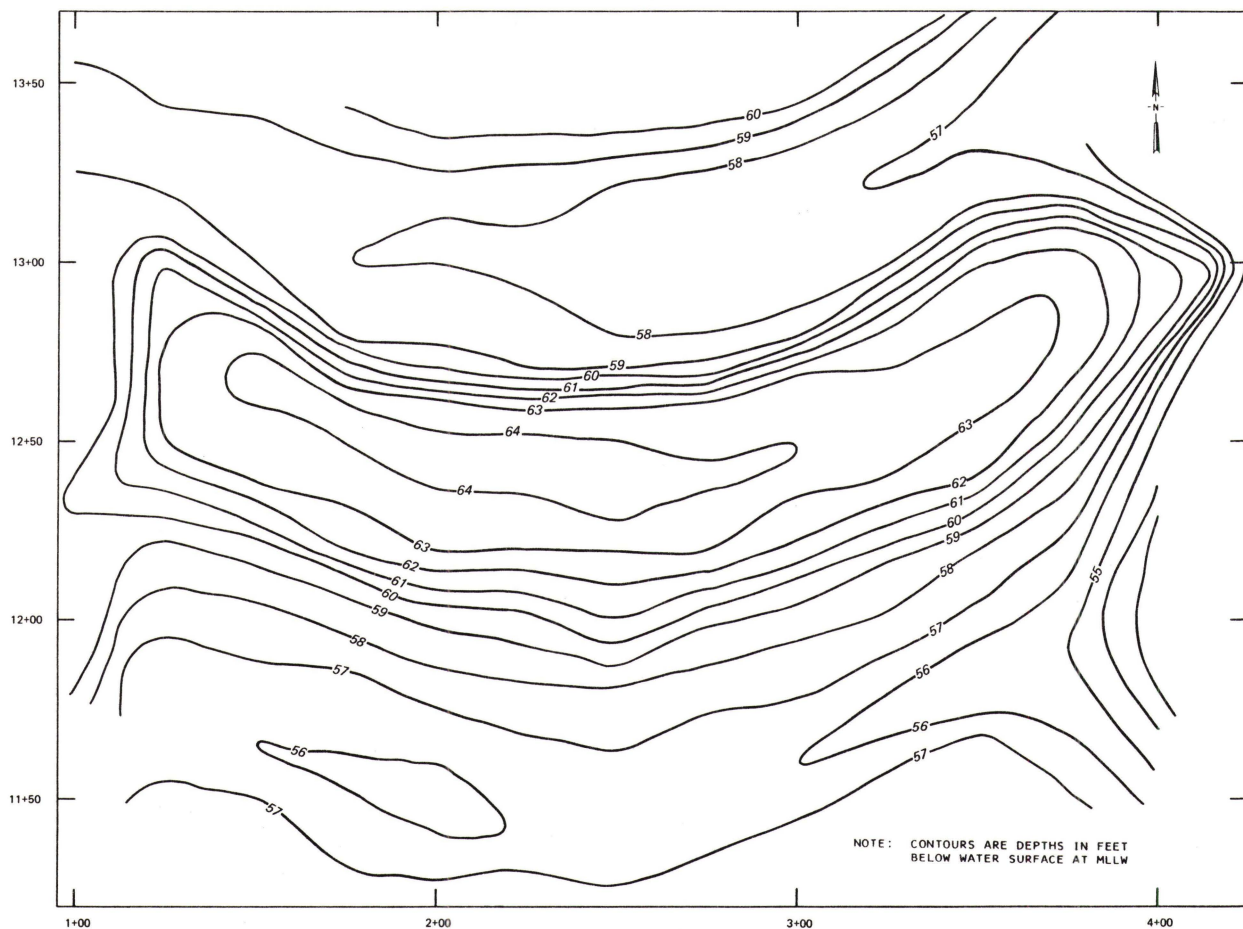
Figure 2. Bathymetry at disposal site
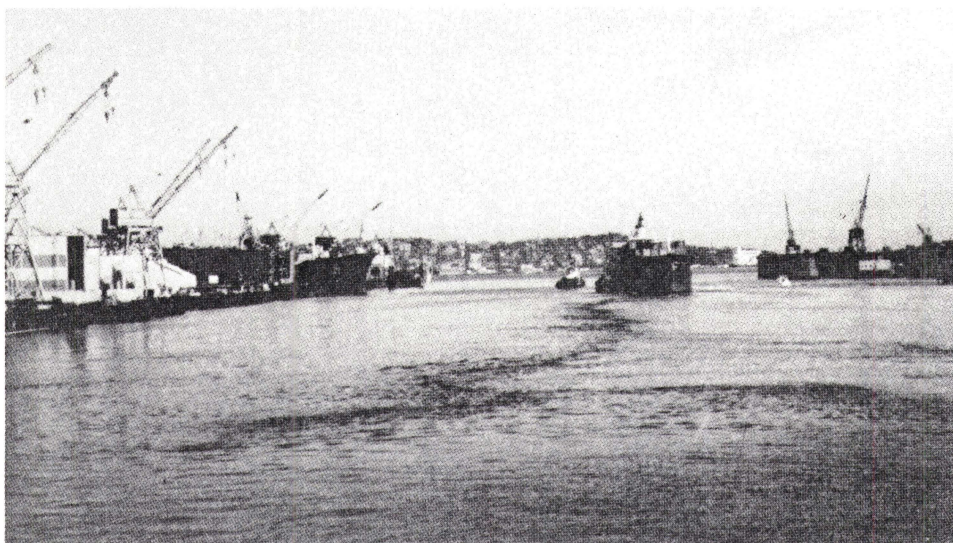
Figure 3. General view at disposal site

velocity field. Freshwater runoff does override the tidal waters, but upstream discharges are regulated. During the initial WES fieldwork two recording current meters were deployed as a vertical pair at a point 200 to 300 ft from the disposal site. In addition, several "spot" measurements were taken with another meter during water sampling operations.

Currents

9. Currents were investigated for two principal reasons. It has been suggested (Bokuniewicz et al. 1978) that strong, unidirectional currents in the mid to upper water column might influence the dredged and/or capping material during its descent from the barge. This influence could range from increasing the degree of resuspension of the material to even deflecting the path of the descending mass. Further, it was recognized that a persistent, strong bottom current, even if cyclic, could provide an erosive mechanism that would affect the long-term stability of the cap. The WES investigation confirmed the District's preliminary conclusion that the current velocities at the site were not so extreme as to prevent the project from proceeding.

10. The highest current velocity measured during the fieldwork was a single value of 1.4 fps just beneath the water surface. Sustained maximum values in the upper third of the water column were more typically 0.4 to 0.8 fps. Sustained maximum values near the bottom were approximately 0.2 fps. The recording current meters showed frequent periods during which current velocities were less than the instrument threshold value of approximately 0.05 fps. Figure 4 presents a current rose representative of site conditions at the actual time of the disposal.

Background water quality

11. Ambient salinity, temperature, and density data are also presented on Figure 4. Bulk samples of the water at both the dredge site and the disposal site were obtained two days prior to the start of dredging for analysis of background chemical constituents and for use in elutriate tests. Results of these chemical analyses are shown in Table 1 as background values.
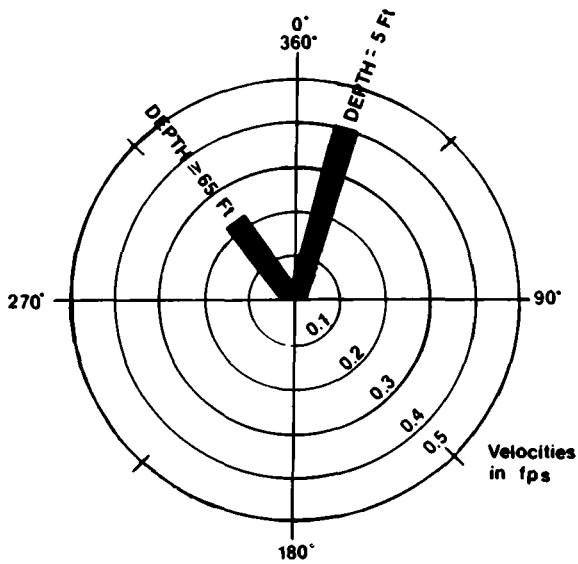
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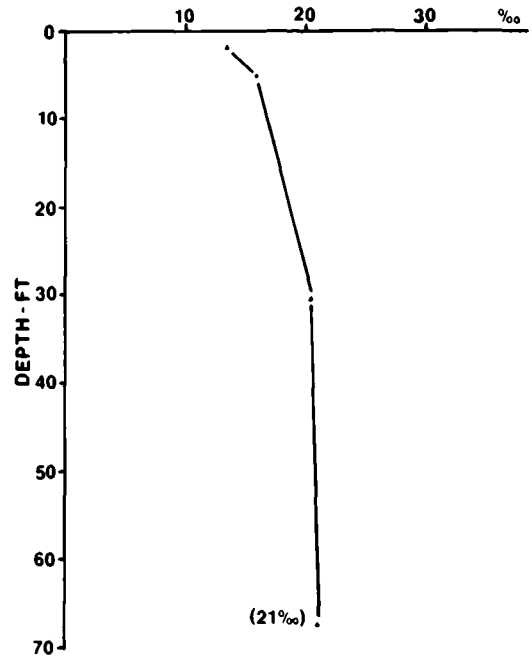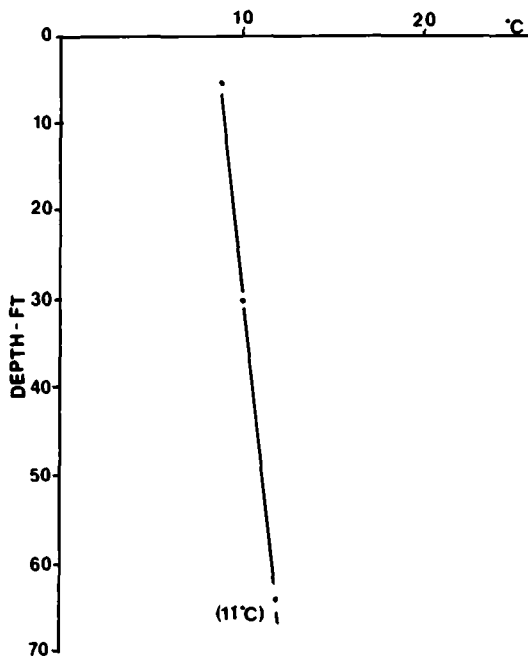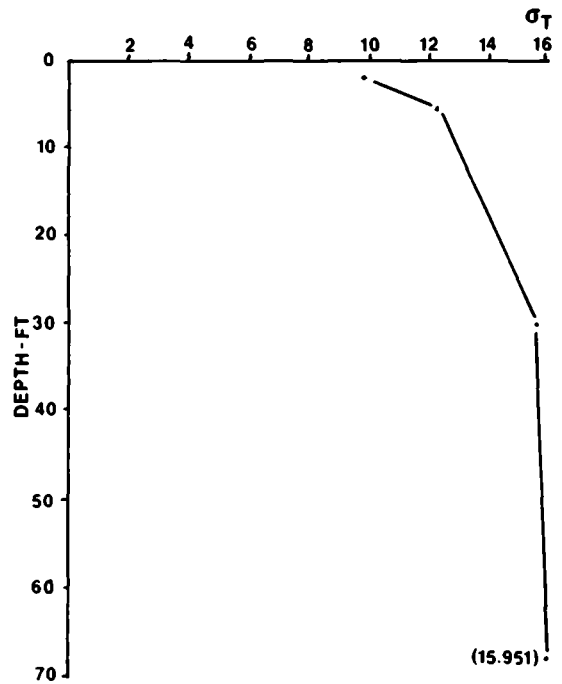
Figure 4. Physical parameters measured at disposal site

Table 1

Chemical Analysis of Background Water Samples

Sample Location	Total Suspended Solids, mg/ℓ*	Copper, mg/ℓ	Lead, mg/ℓ	Zinc, mg/ℓ
Disposal site	5.2	0.015	0.012	0.090
Dredging site	10.7	0.014	0.005	0.480

	Polychlorinated Biphenyls, mg/ℓ						
	1016	1221	1232	1242	1248	1254	1260
(Detection Limits:	0.0005	0.0010	0.0005	0.0005	0.0001	0.0001	0.0001)
Disposal site	ND	ND	ND	ND	ND	ND	ND
Dredging site	ND	ND	ND	ND	ND	ND	ND

* Averages of several samples.

Description of Sediments

Physical

12. Initial sediment sampling was performed by NPS. The contaminated sediment to be dredged from the shoal area consisted of a sandy, clayey silt identified as MH under the Unified Soil Classification System. The physical and engineering properties in the surface layer of the bottom material at the disposal site were very similar to those of the shoal material. The uncontaminated material to be used for capping was a uniformly graded sand (SP). Representative engineering properties of each of these materials prior to dredging are summarized in Tables 2 and 3 based principally on analyses by the NPS laboratory.

Chemical

13. Samples of the sediment to be dredged from the shoal area were also analyzed by the NPS for chemical constituents. The results of this initial analysis are shown in Table 4. Sumeri (1984) states that a subsequent series of tests on similar samples from the shoal also revealed the presence of polychlorinated biphenyls in low concentrations. Volatile solids ranged from 2 to 10 percent.

Table 2

Engineering Properties of Sediments

Material	Unified Soil Class- ification	Liquid Limit	Plastic Limit	Specific Gravity	In-place Density (wet), g/ℓ	Void Ratio	Organic Content %
Contaminated material							
Shoal surface*	MH	53	34	2.60	1,293	4.317	8.2
Cores**							
0.5-1.25 ft	CH	67	32	2.59	1,435	2.642	10.4
2.5-3.5	OH	65	38	2.57	1,483	2.246	7.2
3.0-4.0	OH	70	34	2.62	1,450	2.593	8.9
4.0-5.0 A	ML	44	27	2.68	1,679	1.474	4.4
4.0-5.0 B	MH	66	34	2.62	1,483	2.342	8.7
Disposal site	MH	54	34	2.59	1,316	4.011	7.7
Capping material	SP	-	-	-	1,999	0.717	2.2

* Average of three surface grab samples.
** Two cores, A and B. Reported separately where material differed visually.

Table 3

Grain Size

Material (averages)	Grain Size Indicators, mm		
	D10	D50	D80
Contaminated shoal	0.001	0.012	0.04
Disposal site	0.005	0.020	0.10
Capping material	0.20	0.40	0.60

Table 4

Bulk Sediment Analyses from the Contaminated Shoal to be Dredged

Element	Concentration ppm, dry wt.	Element	Concentration ppb, dry wt.
Beryllium	0.2	Acetone	494
Cadmium	1.4	Methylene chloride	805
Chromium	35	bis (2-ethylhexyl) phthalate	trace
Copper	130	Di-n-octyl phthalate	trace
Lead	190	Aldrin	180
Arsenic	22	Heptachlor	80
Mercury	0.31	4,4'-DDE	30
Nickel	20	4,4'-DDD	80
Selenium	0.4	Alpha endosulfan	30
Silver	1.5	Endrin aldehyde	30
Zinc	240		
PCB - 1242	1.4		
PCB - 1260	3.1		

Dredging and Disposal Operations

14. The planning of the dredging operation represented a balance of objectives. It was, of course, imperative that the shoal be removed to an extent sufficient to satisfy navigation requirements. However, for the purpose of the demonstration, it was desirable to limit the disposal to a single barge load that could be placed in one instantaneous disposal operation. Through the efforts of the District personnel, both objectives were met.

15. A conventional clamshell dredge was selected to remove the shoal material. This type of equipment permits sediment to be removed at nearly in situ densities, minimizes entrainment of site water, and allows a greater degree of control in loading the transport barge. The intent was to begin the disposal phase with the contaminated material in a dense, cohesive mass which could be expected to descend into the depression quickly and with minimum dispersion. The transport barge was a split-hull, bottom dumping barge controlled by a separate tug.

16. Dredging took place on 26 March 1984. The conventional operation of the dredge was modified in one respect to help achieve the intent of producing a cohesive mass of material for disposal. Clamshell bucket loads of sediment were carefully placed in the bottom of the barge rather than being allowed to free-fall from above the barge as in a more typical casting cycle. Subsequent estimates based on measurements of barge displacement and material characteristics indicated that approximately 1,100 cu yd of contaminated material was dredged from the shoal area. In a further effort to increase the cohesive strength, the material was allowed to consolidate in the barge overnight before disposal. This also allowed the disposal sequence to be timed at the most favorable point in the tidal cycle. The manner of handling the sediments described is certainly unique to the requirements of this demonstration project and would result in some loss of production and increase in cost if applied in a larger scale project. Note, however, that for any project involving contaminated sediments, overflowing of the barges for economic purposes is likely to be prohibited and a slower, more deliberate placement of material in each barge will probably result as a matter of course.

17. The time selected for disposal was near low tide on the morning of 27 March. This higher of the day's two low tides produced a water surface elevation approximately 6 ft above the datum (MLLW) and resulted in a maximum depth at the disposal site of 70 ft. Currents were expected to be weak and variable for at least 2 to 3 hr. The split-hull barge was initially maneuvered by the tug into an approximate location over the selected depression. This was adjusted to a more precise position using directions from District survey personnel onshore with electronic-optical distance measuring equipment and theodolites. Barge position adjustments continued to be made as necessary during the disposal. Sumeri (1984) describes the positioning equipment and procedures in greater detail.

18. On signal, the barge hull was opened and the mass of contaminated material exited through the open hopper bottom in approximately 19 sec. The descent was traced by surface observers and by side scan sonar. Indications were that the material moved rapidly to the bottom as a well-defined, cohesive mass.

19. Capping operations were not begun until the next day to allow time to accomplish sampling and monitoring tasks following the disposal and to again take advantage of lower tidal current velocities. The capping sand was

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not released as a single mass, but was to be "sprinkled" at a controlled rate over the entire disposal area. It was expected that this method would reduce the chance of displacing the soft shoal material and would provide better overall cap coverage of the site. The sprinkling process was accomplished by slowly opening the barge hull in small angular increments over a period of 45 to 60 min. A few short periods were observed during which the sand bridged in the hopper, but in general the sprinkling process performed as expected. Three barge loads totaling approximately 4,000 cu yd of sand were placed over a period of 3 days. Hydrographic surveys on 25-ft centers were run across the site after each capping operation to verify results and to allow for repositioning of subsequent loads as necessary to ensure complete coverage.

Scope of Sampling and Monitoring

20. Considerable effort and resources were devoted to sampling and monitoring throughout the dredging, disposal, and capping phases. A brief description of the scope of these efforts follows. Greater detail on each task will be presented with the results in subsequent parts of the report.

21. Discrete samples were taken in the water column for subsequent chemical and physical analyses. These samples were taken during all operations at the dredging and disposal sites and at a reference site in the waterway near the disposal area. In each case a number of sampling stations were occupied before, during, and after each phase. Water samples were obtained by several types of equipment, but typically were drawn from near-bottom, mid-depth, and near-surface points at each station. Samples were analyzed for a variety of chemical constituents as well as for total suspended solids. In addition to the discrete samples taken for chemical analysis, nephelometry equipment was employed to continuously monitor turbidity levels. Temperature, salinity, and current measurements were also made from the sampling boats.

22. Side scan sonar was employed in several situations during the project to evaluate its potential as a monitoring tool for such work and to provide verification of other methods. Sonar images were made of the bottom of the shoal area before and after the dredging, of the actual descent of the sediment from the barge to the disposal depression, and of the turbidity plumes during both operations.

23. Samples of sediment at each stage of the project were taken by grab sampler and/or vibracore for physical and chemical testing. Multitiered settlement plates were fabricated and emplaced to measure volumetric changes in the dredged material and cap at the completed disposal site. Divers assisted in all operations and provided visual confirmation of conditions and locations.

24. Throughout the entire project District personnel supported the monitoring with survey and positioning expertise. Bottom profiles were provided on 25-ft centers before and after disposal of the contaminated sediment and after each capping sequence. Positions of water sampling station, settlement plates, and cores were also verified.

PART III: CONFIGURATION OF COMPLETED MOUND AND CAP

Dredged Material Mound

25. The hydrographic surveys supplemented by side scan sonar and subsequent diver observation were used to determine the accuracy of the material placement in the depression. Successive overlays of bottom profiles (adjusted to datum) before and after the disposal and after each capping increment provided a clear time sequence of the disposal site construction. Figure 5 shows two examples of such profiles at different stations within the disposal area. Note that the vertical scale is greatly exaggerated. Side slopes in the original depression ranged from approximately 1V to 5H to as steep as 1V to 3H.

26. The profiles indicate that the dumping phase of the disposal was generally successful in accurately placing the contaminated sediment into the selected depression. The material descended to the bottom as a relatively cohesive mass and struck the targeted portion of the site with little or no deflection by currents. However, some profiles (e.g. Figure 5) show areas in which a volume of sediment has been deposited on the waterway bottom outside the depression. Two explanations seem plausible. Either the force of the impact was such that a portion of the contaminated material surged up the side slope (3-4 ft) and came to rest on the bottom adjacent to the depression; or, the impact displaced a volume of soft, surface sediment originally lining the depression. Analysis of cores subsequently concentrated in this area should establish which process occurred.

27. The profiles were used to produce contour overlays of the original bathymetry showing the thickness of the contaminated material across the site immediately following disposal (Figure 6). As shown, the center of mass of the placed material is clearly within the confines of the disposal depression. The deposited material was just over 3 ft thick at its thickest point. The symmetry of the thickness contours and the steepness of the slopes within the material as indicated in Figure 5 are likely due to the cohesive nature of the descending mass. Even the portion of the load (or bottom sediment) that surged out of the depression appeared to have detached itself as a well-defined mass that came to rest intact rather than flowing in a dispersive, radial pattern.
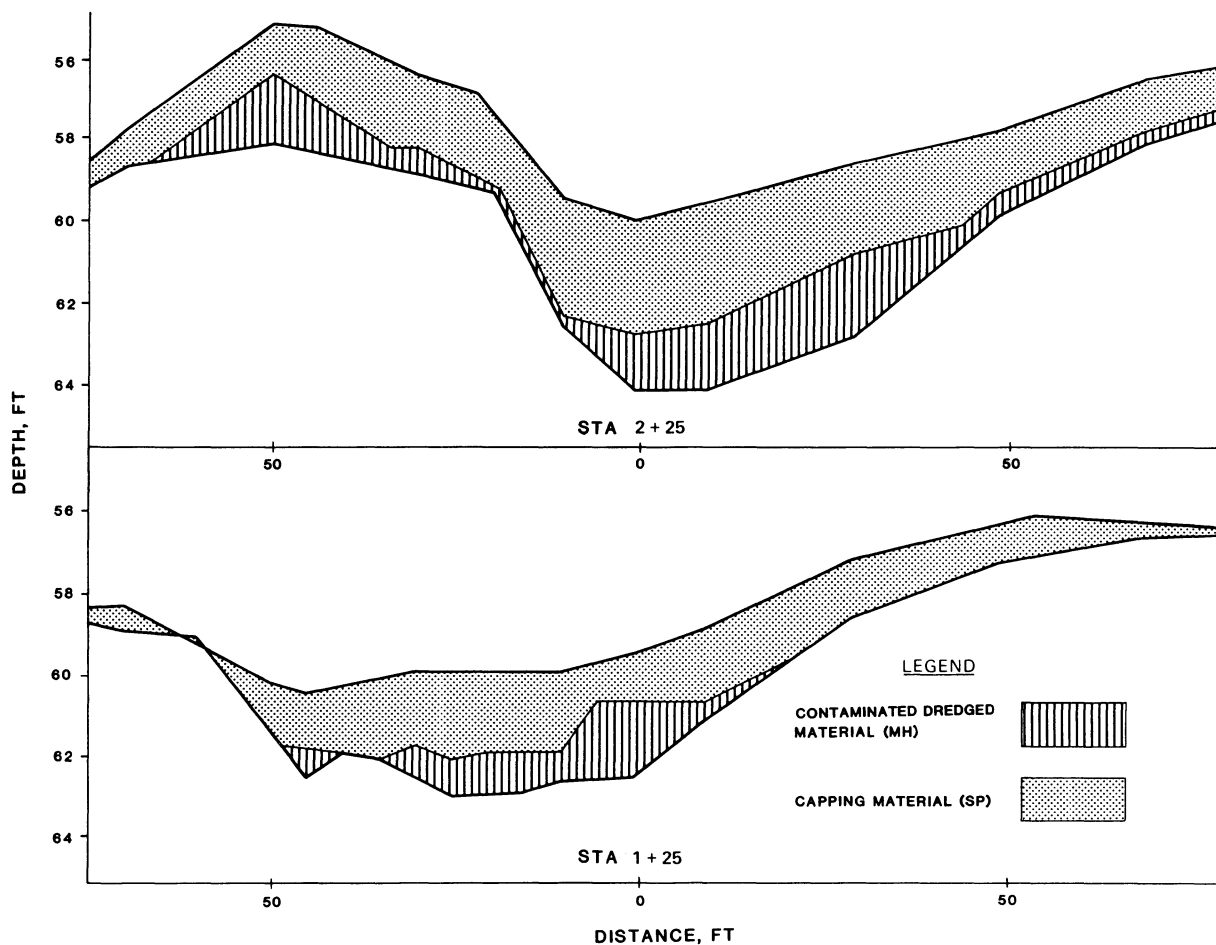
Figure 5. Typical composite profiles through completed disposal mound

28. The dimensions of the hopper in the barge from which the disposal was made were 128 ft long by 40 ft wide (Sumeri 1984). From Figure 6 it can be seen that almost 40 percent of the total volume remained on the bottom in an equivalent size area, never leaving the limits of the barge "footprint" during the exit, descent, and bottom collapse. A volume roughly equivalent to 20 to 25 percent of the original volume appears to be contained in the detached portion of the mound.

Cap Placement

29. Similar procedures were used to sketch thickness contours of the completed cap as shown in Figure 7. The central area represents a cap thickness of at least 3 ft with the majority of the site having a cover of 1 to 2 ft of clean sand. The cap was placed in three successive,
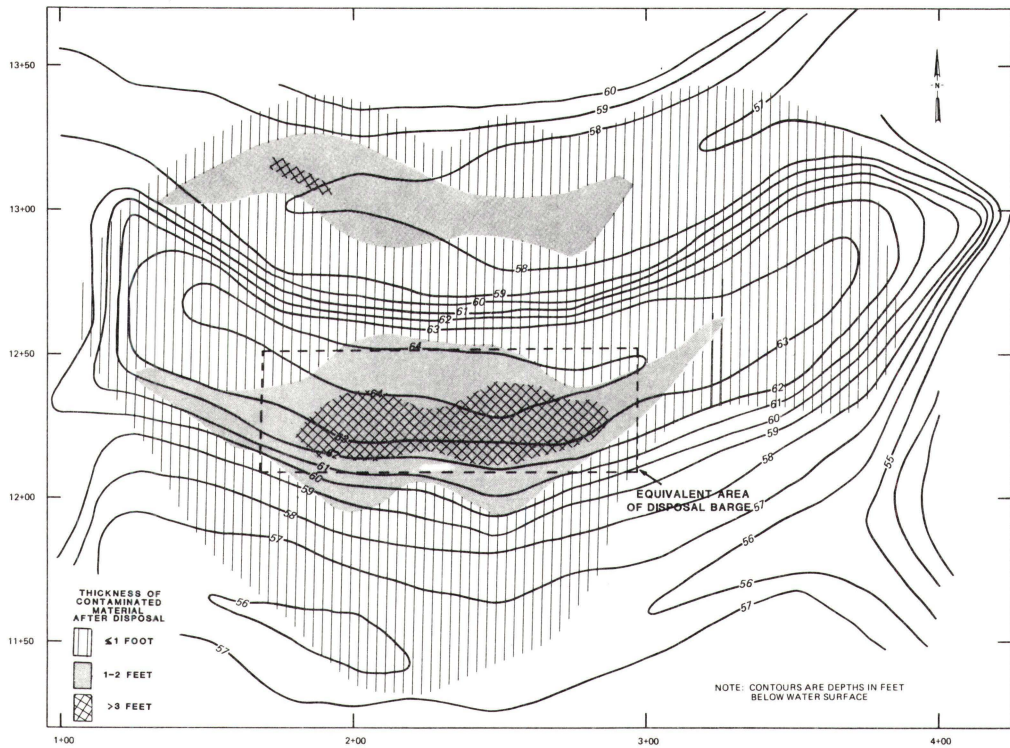
Figure 6. Contours of the thickness of contaminated material
in the disposal mound
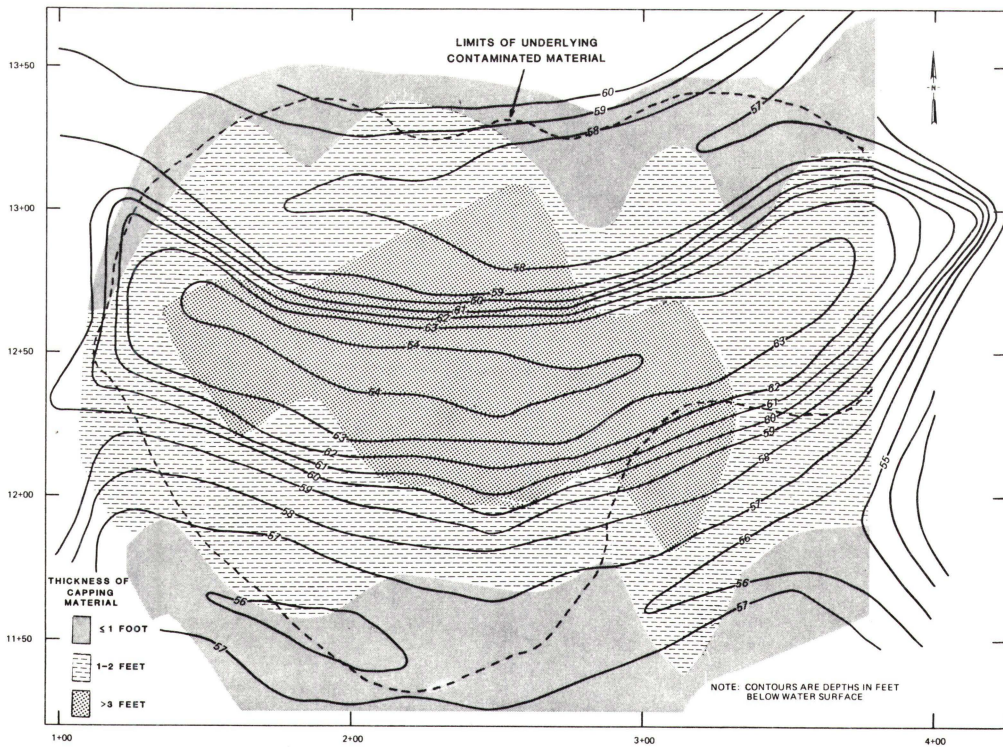
Figure 7. Thickness contours of the completed cap
over the disposal mound

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parallel-positioned, overlapping operations. The pattern effects of the three different disposals can be seen in Figure 7. The desired overlay and uniformity of cap thickness over the entire site are clearly shown. The profiles produced after the contaminated material was placed show the portion of the material that had surged out of the depression and the coverage of this area achieved by the incremental capping technique.

30. Figures 4-6 also indicate that even though the combined thickness of contaminated material and capping material approaches 7 ft at some points, the elevation of the completed site is at or below surrounding bottom elevations. Continued mound consolidation will further ensure that the disposal area remains essentially a concave feature with respect to adjacent bottom topography. While this is not considered a requirement for successful CAD design, it is felt to be a desirable condition where possible. Such a condition should reduce the effects of any currents present in the area. A highly depressed cap surface with abrupt side slopes could be counterproductive by inducing turbulence at the discontinuity.

PART IV: VOLUME AND MASS BALANCE

Volumetric Considerations

General

31. Volumes of both the contaminated sediment and the capping material
in place after the disposal operation were calculated using the profiles pro-
vided by the NPS. The cross-sectional areas of each of the materials on the
profiles were computed using an electronic digitizer/planimeter. A number of
trials were averaged to improve accuracy. The total volume of cap and dredged
material was then calculated using the average end area method. The results
indicate that 975 cu yd of contaminated shoal material could be identified on
the profiles together with approximately 3,700 cu yd of capping sand. This
apparent "loss" in volume, from the 1,100 cu yd estimated in the barge led to
a more in-depth investigation of the processes and accuracy of calculating
such balances.

Error considerations

32. The calculation of volumes from average end areas of adjacent cross
sections requires the assumption that variations between profile stations are
essentially linear. In the case of the Duwamish study, this assumption
appears reasonable because profiles were taken on 25-ft intervals and naviga-
tion references onshore were within a few hundred feet. Any errors in the
results should be directly related to accuracy of the depth measurement itself
or possibly to datum corrections. Variations in navigation position, the
assumption of linear changes between tracks, or long-term bias errors are not
likely to have significant effects in this study. This situation is quite
different than much of the previous work on mass (or volume) balances at sub-
aqueous disposal sites. In most open-water site investigations, intervals
between profile replicate tracks are more typically 25 m (82 ft), making the
assumption of linear variations much more questionable. Also, the survey
tracks frequently extend over lengths approaching 800 m (2,624 ft) and are at
sites several miles from navigation reference station. In such cases, a more
usual approach to volumetric calculations is to produce computer-aided plots
of bathymetric contours from the profiles. The volumes are then computed from
area measurement within the plot and from the contour interval.

33. Massey, Morton, and Paquette (1984) describe the details of a volumetric and mass calculation and offer a method for estimating associated random errors. This method recognizes that, in general, random errors can arise from both depth measurements and position inaccuracies along a profile track. Further, all volumetric calculations rely on differences between two sets of profile data, e.g. predisposal and postdisposal, and each survey has independent associated error potential.

34. Appendix A presents a detailed application of this error analysis to the Duwamish data. The results show that typical random errors in the survey process could result in errors in the volume calculation of 90 cu yd or just over 8 percent of the estimated 1,100 cu yd placed. The volume calculated from the averaged profiles of 975 cu yd is outside this range and is therefore statistically distinguishable from the original value. It must be concluded that the contaminated material underwent a volumetric reduction during the transport/placement processes.

35. It is worth noting that if any one of the error source estimates of ±10 cm described in Appendix A had been applied as a uniform bias over the entire site, the resulting error would have been over 900 cu yd or 90 percent. This points out the effect of the type of analysis used and the need for great care in the calibration of instrumentation and in the adjustment of replicate profiles to an accurate common datum. This analysis also reinforces the potential pitfalls of accepting volumetric balances directly as mass balances. A volumetric reduction does not directly imply that the entire amount of material was actually lost from the area.

Mass Balance Considerations

Void ratio

36. A number of assumptions must be accepted in order to balance material on a volumetric basis rather than a mass basis. Perhaps the fundamental consideration is that any changes in the void ratio of the material throughout the dredging, transporting, placing, and capping operations are taken into account. Void ratio is defined as the total volume of void or pore space in a sample divided by the volume of the solids. If the time for the dredging operation is short enough so that any volatile solids present are assumed to not be lost, then the volume of the solid fraction can be taken as a constant.

Any changes in volume (other than true losses) must then be related to changes in the volume of the voids in the material. However, these changes in void space reflected by changes in the void ratio are usually not measured directly, but are calculated from measured changes in water content of the material. All calculations of void ratio are directly dependent on the accuracy of measuring water content changes and the degree to which the samples represent the condition of the material.

37. Studies have shown that clamshell dredging tends to produce less change in the in situ condition of the dredged material than other types of dredging. However, there is still a slight addition of water to the load as it is lifted through the water column. Some displacement, i.e. removal of excess water, then takes place as additional buckets of material are stacked in the barge. When the barge load of dredged material subsequently descends through the water column during the placement operation, additional water may be entrained in the mass. Finally, initial consolidation of the mound by self-weight and by the placement of the capping layer causes a loss of water. (Of course, consolidation continues for a considerable period of time and further affects the water content and apparent volume of material.) In summary, even during the relatively short time frame of the actual capping operation, at least four opportunities exist for changes in the water content and void ratio of the material that could cause errors in using a volumetric approach to tracking the fate of the dredged material.

38. Table 2 showed that the contaminated shoal material had an in situ void ratio ranging from 1.5 to 4.3. Specific gravity averaged 2.60. Moisture contents (weight of water ÷ weight of solids) were also measured and ranged from around 60 to 170 percent. Bulk density (wet) averaged 1,425 g/ℓ. The ranges of void ratio and moisture content appear very wide. However, they reflect the expected increase of sediment density with depth into the bottom. It is difficult to establish a meaningful, representative single value since dredging takes place through each depth/layer to different degrees.

39. Samples of the same material were taken directly from the disposal barge the day after dredging was completed and subsequently analyzed at WES. The average bulk density (wet) of the material in the barge was 1,464 g/ℓ compared with the average density in the shoal of 1,425 g/ℓ. Since no solids were gained, the apparent increase in density must have been due to a decrease in void ratio and a reduction in the moisture content from consolidation and

drainage in the barge. In fact, the moisture content of material in the barge prior to disposal was measured to be 99 percent. The void ratio was then calculated to be 2.6, confirming the reduction indicated. It should be noted that some free water was observed on the surface of the material in the barge. This was evidently water added by the bucket during dredging and the small actual amount freed during the change in void ratio. It appears that any water added by the bucket dredging process did not readily find its way into the pore space of this soil and is an addition only in the sense of bulk volume. At the time of disposal the material was in a similar or slightly denser state with greater internal strength than it was in situ. Figures 8 and 9 show the dredge placing material in the barge and the surface of the material in the barge after loading had been completed.

Initial mass

40. Obviously, a mass balance must begin with the calculation or estimation of some initial mass of material. Tavolaro (1983) provides one of the few attempts at a mass balance calculation using data collected from several projects in New York Harbor. In that study he approached the calculation of the initial mass as follows. Cores of shoal material were obtained prior to dredging and tested for in situ bulk (wet) density and water content. These density values were converted to dry specific weight using relationships proposed in previous work. The initial dry mass of material in situ was simply this dry unit weight multiplied by the volume it occupied. However, to obtain the volume, he compared bathymetric surveys of the sites before and after dredging.

41. This method of calculating the initial mass is dependent on the accuracy of the volume determination and the survey. With the exception of the water depth, conditions and equipment used at the Duwamish dredging site were very similar to those at the Duwamish disposal site. It is therefore reasonable to assume that the error analysis earlier in this report for volumetric considerations at the disposal site would apply to calculation of the excavation volume at the dredging site. This analysis indicated an error range on the order of 8 percent. If the above approach were applied to the Duwamish data, the resulting initial calculated mass would be accurate to not better than ±8 percent.

42. If, on the other hand, the balance begins with the mass as measured in the barge after dredging, the mass of the solids which were suspended
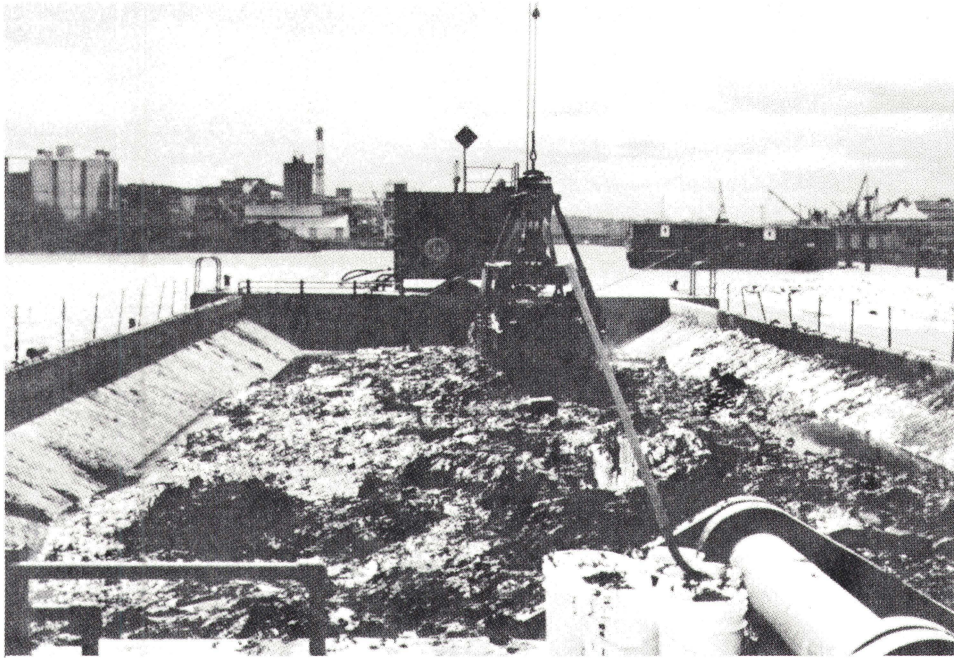
Figure 8. Clamshell loading barge during dredging operation

Figure 9. Contaminated material in barge prior to disposal

during dredging and transported out of the area will not be counted in the balance. (Those solids which are suspended but drop back to the bottom at the site are not considered "lost.") However, in the New York Harbor work the mass of solids which was indeed lost between the in situ condition and the loaded barge was reported as 2 to 3 percent of the total mass of material (Tavolaro 1983). This level of loss could not be identified with confidence using the standard bathymetric surveying techniques. Keeping in mind that the primary objective of the WES involvement in the Duwamish project was to evaluate capping and that the placement/capping phase follows from the condition of the material in the barge, the mass balance was started at that point as well.

43. Bokuniewicz et al. (1978) presented a method for determining the bulk density of materials in a hopper. The formulation uses differences in the vessel's draft for various loadings and the total hopper volume and has been applied with success by Tavolaro and others. The resulting bulk density is then converted to dry density and multiplied by the hopper volume to produce a value for dry mass present. However, care must be used in its application in that the assumption is made that the container, i.e. the hopper, is loaded to the same internal level in preparing the capacity plan for the barge as when loaded with dredged material. This is accomplished in a practical sense by placing material until the hopper is "full" (and usually deliberately overflowing). In the Duwamish project the barge was not filled to its level capacity and overflowing was not allowed. The bulk density cannot be calculated directly from the equation as given by Bokuniewicz.

44. The mass of material in the barge can still be estimated by bypassing the question of bulk density and calculating the weight of material present directly from the drafts of the barge. Careful measurements of the barge drafts at each of the four corners were made with the barge empty and with the partial load of contaminated material. From a Properties of Form table provided by the contractor for the specific barge used, the weight of the material in the hopper can be calculated from the displacement. This is, in effect, the basis for the equation proposed by Bokuniewicz, but without the hopper volume term simply yields the weight directly rather than density. The wet weight of the material in the hopper was found to be approximately 1,366 tons. The dry weight can be calculated as follows using an average moisture content in the material:

$$W_D = \frac{W_w}{(1 + w)} \qquad (1)$$

where

W_D = dry weight of material

W_w = wet weight of material

w = moisture content

The results using the measured moisture content of 99 percent indicate that approximately 686 tons of solids (dry weight) were present in the barge at the beginning of the disposal operation.

Losses at disposal site

45. The time between dredging and placement of this material was so short that potential losses due to oxidation of organics present were not included in the balance. Therefore, the primary sources of material loss were resuspension during descent and flow on impact. As described earlier, the WES monitoring effort included extensive sampling to determine the load of suspended solids in the water column. Samples were taken along three radials extending from the barge at the point of disposal. Stations were occupied at varying distances from the barge along the radials. The closest station was located approximately 50 ft from the center of the barge and the farthest station was just over 800 ft from the site. At each station discrete samples of water were taken at several depths in the water column as rapidly as the sampler could be cycled through the depths. This provided a reasonably continuous time series during the first 30 to 40 min after disposal. The sample time intervals were increased thereafter to 5 min, then to 10 min, and finally to 20 min for approximately 3 hr after disposal. Samples were returned to an analytical laboratory and tested for total suspended solids (in addition to other parameters).

46. One method which attempts to quantify the mass of sediment lost due to resuspension takes a single average value for the suspended solids concentration throughout an area and multiplies it by the volume of the water in the area or basin. This approach essentially ignores (or considers only in the averaging process) any variations in the concentration with time or depth. Results are at best a very rough estimate. Hayes, McLellan, and Truitt (1985) have suggested a method of analyzing suspended solids data that may provide a

first level of refinement to such calculations. In this approach the values
of suspended solids concentration measured from discrete samples taken at
varying depths are assigned or averaged over only an increment of depth at
which they were taken. This replaces a single depth-averaged value with a
series of concentrations associated with a number of "slices" through the
water column. Further, as shown in Figure 10, the depth scale itself is nor-
malized by the total water depth at the station in order to present the values
as an incremental percentage of depth. This allows comparison of relative
concentrations at stations with different water depths.
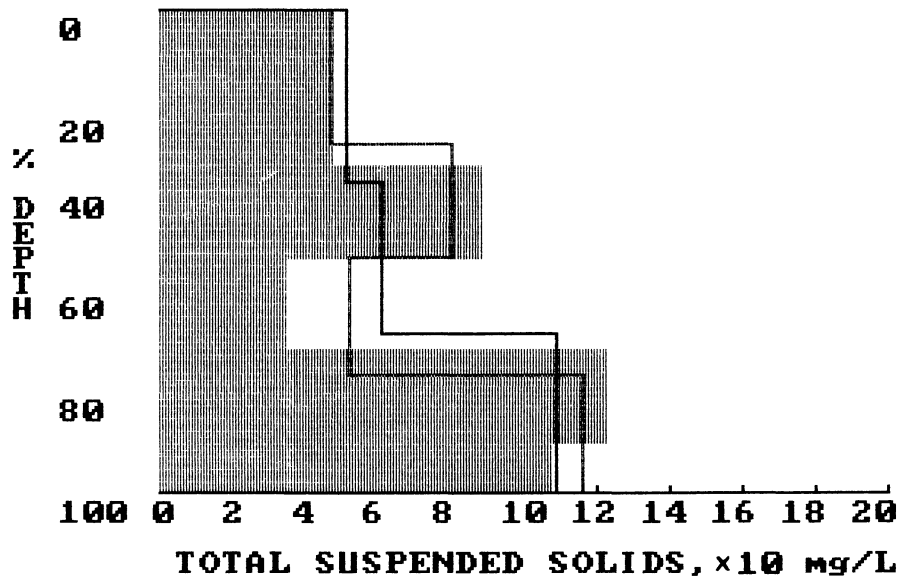
Figure 10. Typical representation of total suspended solids
from single sampling event

47. In contrast to the dredging operation itself, the actual disposal
was a short-term event. The variation of solids concentration with time
during that period is an important factor. Figure 11 is a plot of total sus-
pended solids versus time after disposal at a representative station approxi-
mately 400 ft downcurrent from the disposal site. The three different curves
represent samples taken near surface, mid water column, and near bottom.
Background levels of solids at the time were measured as typically 5 mg/ℓ or
less and the values shown in the figure have not been adjusted. The rela-
tively rapid passage of a very distinct solids plume can clearly be seen.

48. For this study the following approach was used. A cylindrical
control volume in the water column is assumed at the point of disposal, the
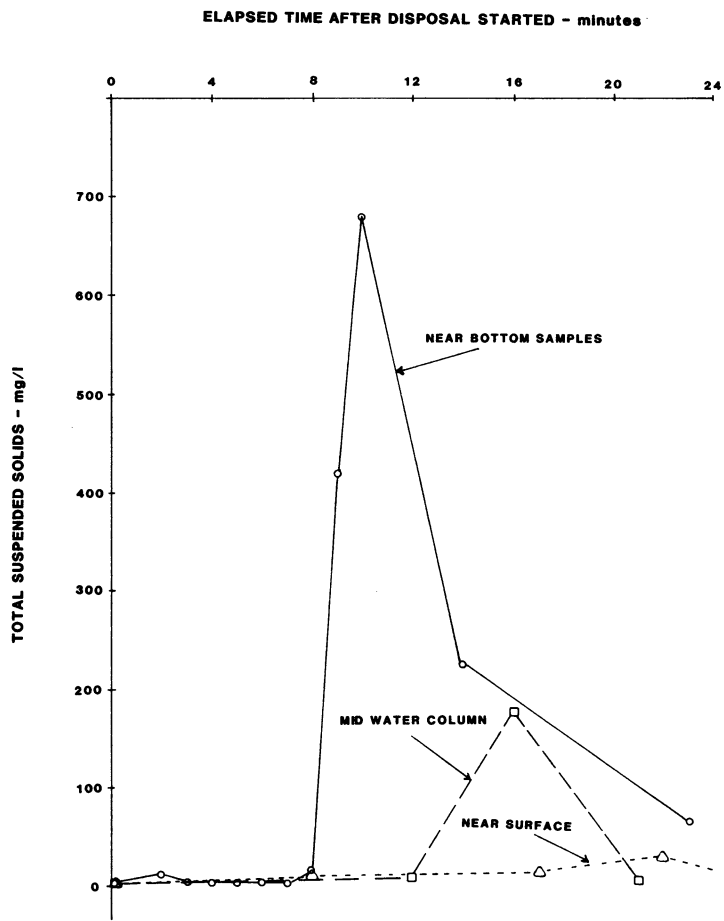
Figure 11. Time series of total suspended solids at typical
station following disposal

radius of which is nominally the dimension of the disposal depression itself.
This volume is taken as the source of solids leaving the site by both resus-
pension during descent and flow after collapse. The flux of suspended solids
passing through an appropriate portion of the surface area of this cylinder is
then the loss of mass from the site. It is recognized that particles will
settle out of suspension continuously as they progress radially from the dis-
posal point. However, the distribution of concentration with time or radial
distance is not necessary for mass balance. The mass that reaches the bottom
within the limits of the cylinder is not lost from the site. That mass which
passes through the surface area is lost from the site regardless of where it
ultimately comes to rest. This approach also requires a near-field viewpoint
of the transport process. The assumption is that advective transport domi-
nates over diffusive processes at least to the limits of the control volume.
Data from a station approximately 50 ft upcurrent from the disposal point

30

indicate that the concentration of solids in the mid and upper water column did not increase above typical background levels. A peaked distribution similar to that shown in Figure 11 was observed at the near-bottom sample series. This supports the assumption that advective processes, e.g. currents and momentum driven flow, were the principal sources of transport within the limits of the disposal site itself.

49. Using this approach, the mass of material lost from the site during the disposal can be estimated as follows. A weighted, time-averaged value for the solids concentration during the passage of the plume is computed for each of the three sample depths at the representative stations. An effective transport rate at the station can be estimated from calculating the velocity of the solids plume using the time of arrival at the station. Again, this velocity is computed separately for each of three depth increments and the resulting transport rate is the velocity multiplied by the depth increment and by a unit width or arc length along the control cylinder. The incremental loss of mass is then simply the transport rates multiplied by the corresponding time-averaged concentrations. This value still represents only the mass lost per unit arc length and an appropriate length must be selected to calculate the total mass leaving the site. The length selected is certainly somewhat subjective, but should at least consider factors such as the distance to the solid bulkheads paralleling the site and the width of the flow projected in the direction of the currents.

50. The result of the application of the above method indicated that losses during the disposal operation were on the order of 50 to 100 tons of solids. This is on the order of 7 to 15 percent of the total mass calculated in the barge prior to placement. Note that using a nominal wet unit weight of 90 pcf, 50 tons of solids is actually only 41 cu yd of material or less than 4 percent of the original volume. The losses could not be distinguished within the 8-percent error limits of the volume calculation.

Final mass

51. Paralleling the above discussion of the initial mass, the calculation of the final mass in the mound is also dependent on a volume computation. The volume identified in the mound was 975 cu yd within an accuracy of 8 percent. Vibracore samples were taken in the mound immediately after capping and the sediment was tested for the same parameters as the shoal and barge samples. The moisture content in the mound material was found to average

86 percent and the bulk (wet) density averaged 1,509 g/ℓ. After adjusting for the moisture content and multiplying by the 975-cu-yd volume, the calculated dry mass in place in the mound was estimated to be 666 tons.

Balance

52. A simplified mass balance can be stated using the above results. The balance is simplified in the sense that the initial mass was taken as the in-barge condition so that losses at the dredge are not included, nor are any potential losses due to volatilization of solids. The balance is then,

$$\begin{pmatrix} \text{Dry Mass} \\ \text{in Barge} \end{pmatrix} - \begin{pmatrix} \text{Dry Weight of} \\ \text{Solids Lost} \\ \text{During Disposal} \end{pmatrix} = \begin{pmatrix} \text{Dry Mass in} \\ \text{Disposal Mound} \end{pmatrix} \quad (2)$$

and, substituting values from above including error limits,

$$\left(686 \text{ tons} \right) \quad - \quad \left(50 \text{ to } 100 \text{ tons} \right) \quad \overset{?}{=} \quad \left(666 \pm 53 \text{ tons} \right)$$

or,

$$\left(636 \text{ to } 586 \text{ tons} \overset{?}{=} 719 \text{ to } 613 \text{ tons} \right)$$

Clearly the ranges overlap and the mass does balance within the accuracy of the measuring processes.

53. Sources for the differences in the terms could include nonrepresentative material samples (especially effects of the vibracore), variations in geotechnical testing procedures, or underestimation of any of the several error sources identified in the survey/volume computation. In general, most of these considerations would serve only to widen the error limits. The two readily identifiable factors that would actually change the calculated masses are densification of the samples by the vibracore, and any uniform bias in the survey, e.g. datum adjustments, tides, etc, that would incorrectly estimate the volume in place. Problems with both factors are possible and even likely. However, the equipment, techniques, and expertise used in both procedures represent the accepted practice in the field and the resulting balance with an uncertainty in the range of 8 to 10 percent may be the best available at this time and for this level of monitoring effort.

Mound Consolidation

54. In order to evaluate the long-term stability of the constructed disposal mound it is necessary to distinguish changes in elevation (and volume) resulting from erosion and transport of material from the site and from consolidation of the mound itself. Consolidation can occur in the cap material, the contaminated dredged material, and in the underlying bottom sediments. This portion of the WES study was directed toward careful evaluation of consolidation from each of these sources and the development of information that will lead to a better understanding of the consolidation process in subaqueous dredged material deposits.

55. Settlement plates were placed at the site prior to disposal operations to facilitate monitoring of consolidation in the materials over time. These plates were of tiered design so that changes in each of the materials could be evaluated independently. A telescoping arrangement permitted placement of the lower plates on the foundation soil prior to disposal, the second tier on the surface of the dredged material, and the third tier of plates on the surface of the cap (Figures 12 and 13). Plates were installed by divers and initial readings of exposed riser lengths were noted. The lowest level of plates was anchored to the bottom using helical earth anchors. In spite of this anchoring arrangement, the impact of the dredged material on the bottom after disposal was so violent that several of the plates were overturned and lost. The presence of 1 to 2.5 ft of very soft organic silts (ML, MH) overlying more sandy foundation materials is believed to be a major factor in the instability of the settlement plates. Readings of the remaining usable tiers were made after each phase of the disposal, after approximately 1 week, and after 6 months. Analysis of the data is continuing, but readings indicate that the original 24- to 36-in. thickness of deposited dredged material has consolidated to 21 to 33 in. in the 6-month interval. The consolidation progressed rapidly with approximately 75 percent of the total settlement to date occurring in the first week after placement. Little change has been noted in the thickness of the sand cap.
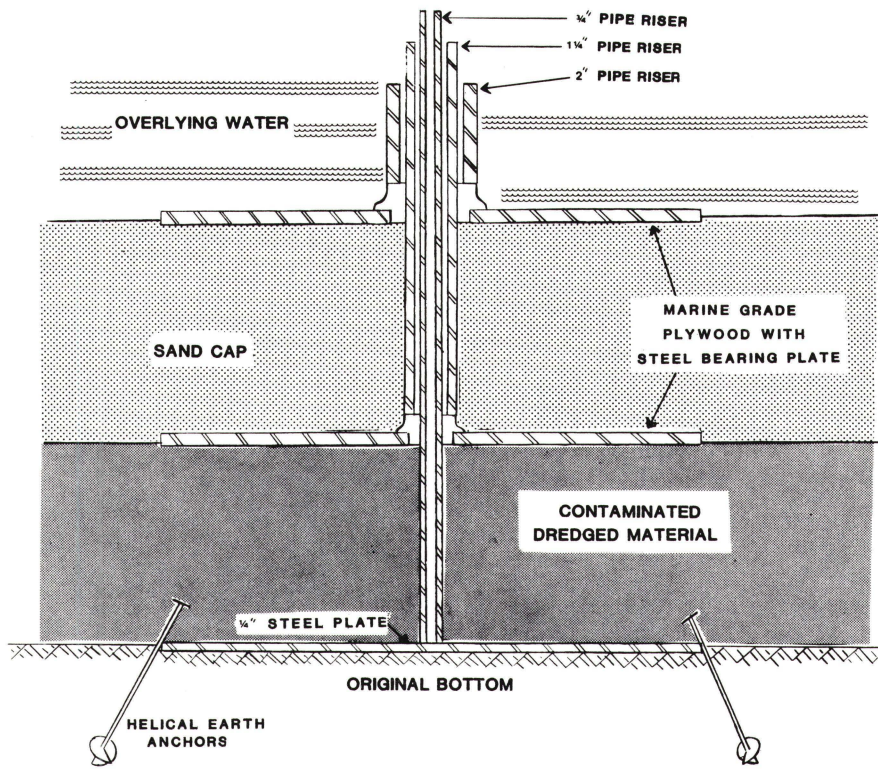
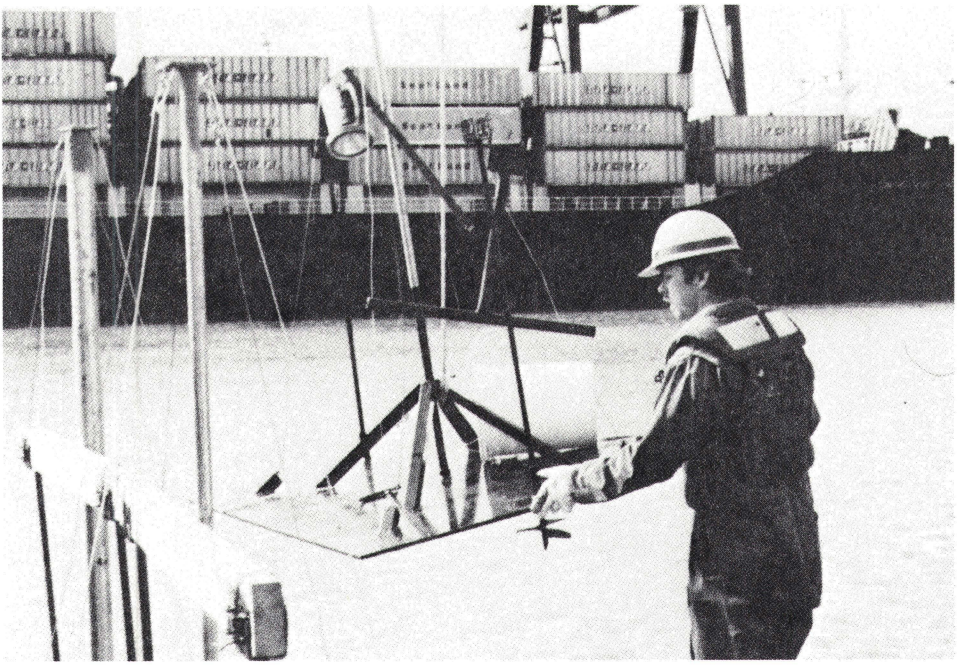Figure 12. Schematic of tiered settlement plates

Figure 13. View of settlement plates prior to placement

PART V: SIDE SCAN SONAR MONITORING

General

56. The WES Coastal Engineering Research Center provided side scan sonar (SSS) monitoring of the dredged material disposal in the Duwamish Waterway in Seattle in March and April 1984. The following sections from Clausner (1984) describe the SSS phase of the Duwamish field project.

57. The primary mission in the monitoring operation was to use SSS to measure the time for the initial mass of disposal material to reach the bottom, a value needed for verification of a mathematical model. This was accomplished successfully. A secondary objective was to determine the extent of the sand cap. This second objective was only partially successful primarily due to environmental constraints. Also, SSS inspection of the actual dredging operation was accomplished and proved to be successful in locating the sediment plume in the water column. Appendix B (Clausner 1984) provides a summary of the background and principles of SSS operation for those readers not familiar with the equipment.

Operations

Initial observations

58. On 24 March 1984, the SSS and other water sampling equipment were loaded aboard the WALTON, a 31-ft work boat. The SSS "fish" was deployed from a wheel and pipe clamped to the stern of the boat. This method of deploying the "fish" worked well throughout the operation.

59. The depression into which the dredged material would be dropped was approximately 150 ft wide, 300 ft long, and 6 to 6.5 ft deep, with the long axis of the hole positioned perpendicularly to the axis of the Duwamish Waterway. Bottom surface sediments are uniformly soft silts, and the water depth at the site was 55 to 65 ft deep.

60. The narrow waterway (approximately 750 ft wide) with its vertical sides, heavy traffic, and industrial operations made producing good SSS images of the area very difficult. In addition, a large container ship was continuously tied up to the western bank, reducing the effective width of the

waterway another 100 ft. Also, the area is heavily trafficked, with tugs pushing barges through regularly.

61. The 100-kHz "fish" was used first. The hole was easily located, showing up as a depression in the bottom trace. However, the soft material, gentle slopes, and high level of background noise made topographical features of the hole impossible to distinguish on the record. Reference rods (2-in. outside diameter steel pipes), plates, and subsurface buoys, placed by divers in the depression prior to the SSS survey, were slightly visible on the 100-kHz record. Runs parallel to the long axis of the hole were very difficult. By the time the "fish" stabilized after making the turn, the boat was already over the hole. As the "fish" was reaching the end of the hole, the boat had to turn to avoid the dock or the moored ship. Also, the changes in speed caused by the turn caused the "fish" to move up and down, making evaluating the bottom elevation changes impossible.

62. A significant problem was experienced because of self-made and outside noise. This was particularly evident when operating the SSS and the subbottom profiler simultaneously. It became very difficult to tune the side scan, and the quality of the subbottom record was reduced. The probable cause is the narrow channel with its vertical sides. Instead of disappearing into the distance, as is the usual case, the sound energy remains trapped, causing interference and tuning problems. In addition, there were times when just tuning the SSS was very difficult. Noise produced by the shipyards and factories may have been the reason. The interference pattern on the side scan record made determining textural differences on the bottom impossible.

63. Residual air left in the water from the wake of the WALTON or other boats distorted the records. After several passes, it became necessary to stop and wait 10 to 15 min while the water acoustically cleared.

Reference sand disposal

64. One day before the actual disposal of the contaminated sediments, a practice or reference sand disposal was made. One purpose of the practice disposal was to allow all those participating in the monitoring operation an opportunity to become familiar with the procedures and equipment to be used in the actual disposal. This practice disposal was most important for the SSS portion of the monitoring effort since it had never been used in this kind of operation before.

65. For the practice disposal, the SSS was suspended horizontally on

premeasured ropes 36 ft below the surface. The 500-kHz "fish" was used. It was set on the 50-m range, and paper speed was 50 lines/cm. The WALTON was tied to a tug positioned parallel to the barge at its midpoint (Figure 14). The addition of the 20-ft beam of the tug caused the SSS "fish" to be 45 ft from the centerline of the barge.

Figure 14. SSS positioning during dredged material disposal

66. When the drop started, the sand plume in the water column was such a strong reflector that the sound signal saturated the record, making the determination of the time for the material to reach the bottom impossible. After that time, the SSS record showed that the sand did not drop at a steady rate but instead came out in a series of concentrated masses. Six individual masses could be seen, starting at 2, 6.5, 15, 21, 26, and 36 min, respectively. There is a good possibility that the individual masses seen on the record may be due to the drifting of the barge which was eliminated on

subsequent disposals. Motion by the barge would cause the SSS "fish" to move. Movement of the sonar beam in and out of the sand plume would cause the appearance of a sand mass each time the beam swung back into the plume.

67. Post sand disposal inspection with the 100-kHz "fish" and subbottom profiler set on a 50-m range, towed at a depth of 40 ft, did not reveal any noticeable changes in the bottom topography.

Dredging operation inspection

68. After the reference disposal, the 500-kHz SSS "fish" was used to monitor the dredging operation. This operation was very successful. The Seattle District contract dredge, its spud, the barge, and the dredged area are all clearly visible on the SSS record (Figure 15). Also, most importantly, the dredge plume was visible on the record. The plume can be seen clearly in the water column for a distance equal to approximately half the length of the dredge. Analysis of the water samples taken for total suspended solids confirmed the location of the solids plume at this point. However, further examination of the records shows a dark area to the right (east and north) of the dredge and extending at least 200 ft past the back of the dredge. This dark area was originally postulated to be the water column plume moving downstream, a concentrated sediment layer near the bottom, a tuning anomaly, or a change in bottom material or slope. Subsequent review of the suspended solids data does not support the presence of the plume at that location. The channel slope does occur, however, in the same general area.

Contaminated material disposal

69. On the morning of 27 March 1984, SSS was used to time the fall of the contaminated dredged sediments. The same configuration of the split-hull barge, tug, and WALTON was used as for the reference disposal. Here, the "fish" was at a depth of 54 ft (10 ft off the bottom). Based on the reference disposal experience, SSS gain controls were tuned down so only strong reflectors would produce an image. This was done by towing the "fish" next to the docks prior to the drop and adjusting the gain controls to produce an image from the piles but not from the bottom.

70. Fortunately, these settings proved to be correct, and the disposal was clearly visible on the record (Figure 16). According to the barge operators, the material did not completely exit the barge until 20 sec after the start of the disposal. This corresponds exactly with the SSS record (Figure 16). The material exited the barge at just/ over 20 sec and hit the bottom
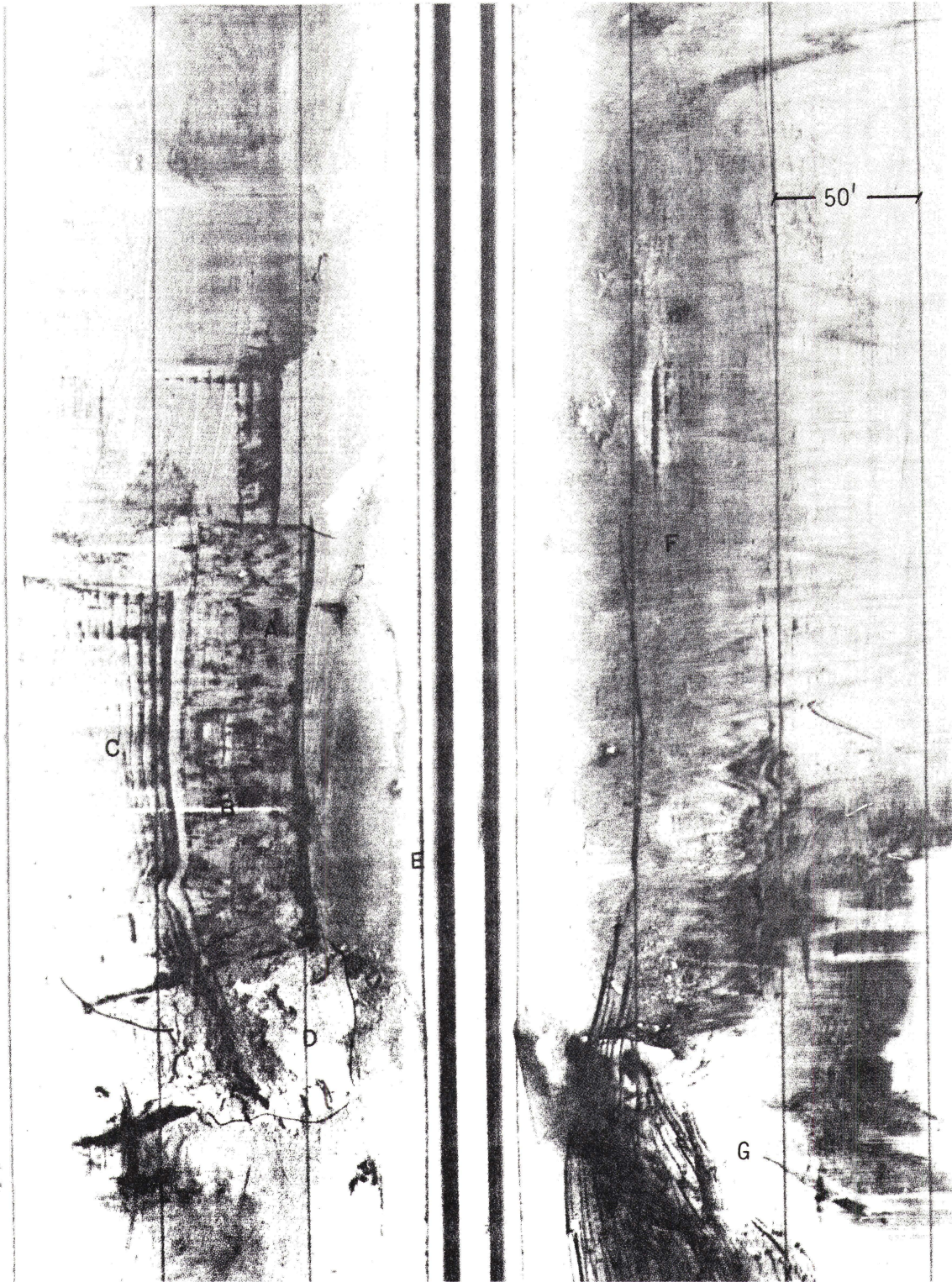
Figure 15. SSS image of contaminated sediment dredging.
A = dredge, B = dredge's spud, C = barge, D = dredged area,
E = dredge plume, F = dark area, and G = log boom

39

SIGNAL DISAPPEARS →

BOTTOM IMPACT →

15 SEC
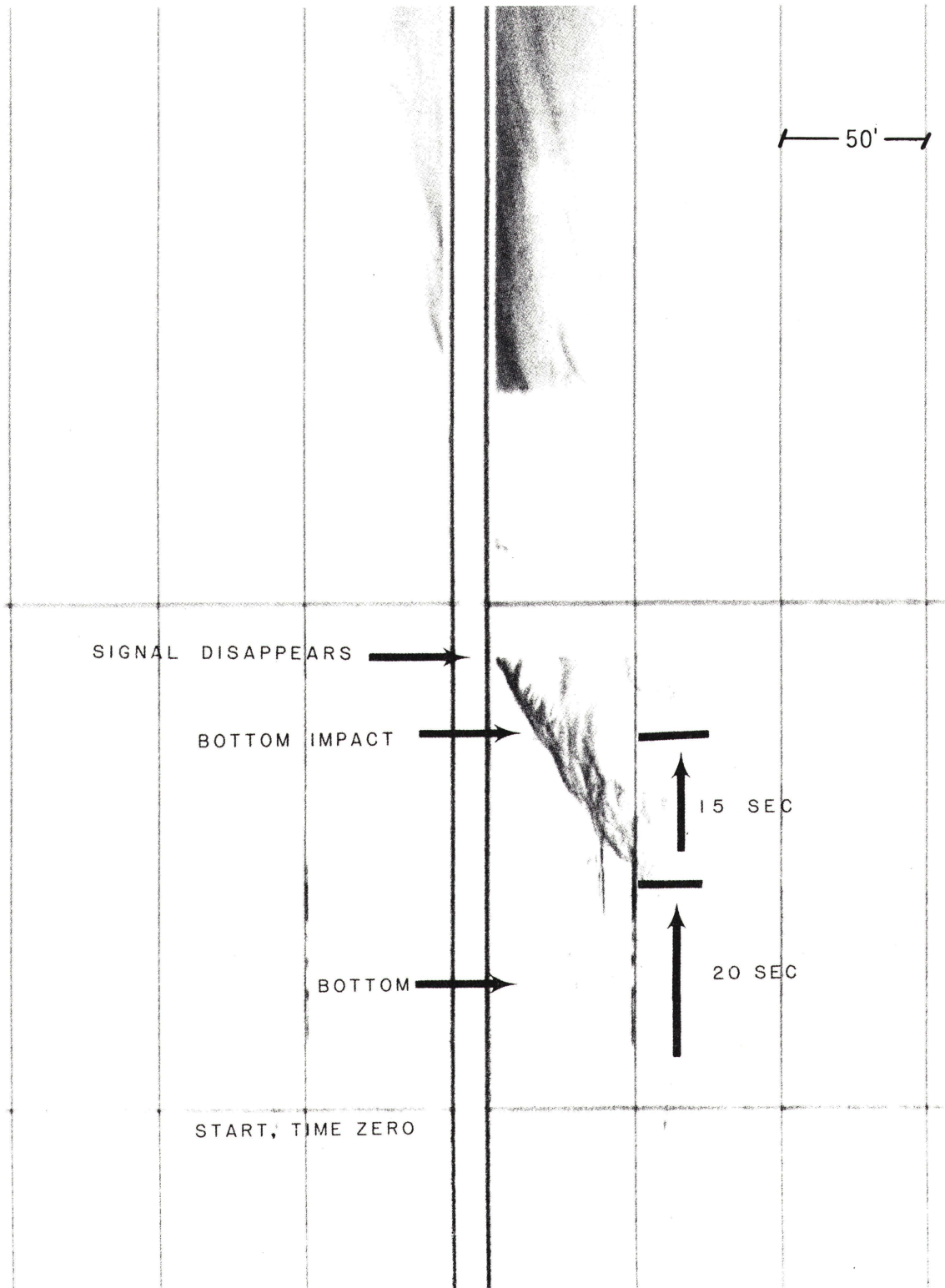
BOTTOM →

20 SEC

START, TIME ZERO

50'

Figure 16. SSS image of contaminated sediment disposal

15 sec later. Twenty-one seconds after the material left the barge, the image disappeared for 24 sec. It is possible that this disappearance was due to the mud wave covering the "fish." After the image returned at 65 sec from the start, there appeared to be a substantial amount of material in the water column on both sides of the "fish." At 2 min 2 sec after the start, the amount of sediment in the water column was greatly reduced but did not disappear. This could be the result of a change in orientation of the SSS "fish" due to barge maneuvering. However, the image was not smeared as it usually is during maneuvering. This water column sediment reduction lasted for 50 additional seconds. After that point, the sediment content of the water column increased to about its former level and remained there until approximately 10 min after the start. Past 10 min, maneuvering of the barge made good observations of the sediment level determination impossible up to the time the recorder was turned off at 15 min from the start of the disposal.

Inspection of the first sand cap disposal

71. The estimates of the extent of the sand cap in this section and in the following section are somewhat subjective. Textural differences between the native bottom clay sediments, the contaminated clay sediments, and the sand cap were not particularly evident on the SSS record. The tuning problems discussed previously also made precise interpretation difficult. Finally, positioning was inaccurate. Not all the range marks were visible, and distances off the channel and hole center lines had to be visually estimated.

72. Using the 500-kHz "fish," an SSS inspection of the first sand cover was made on 29 March 1984. After several passes, both parallel and perpendicular to the channel, a fair estimate of the shape and extent of the sand cover could be made. The shape was basically rectangular (Figure 17) with slight indentations on the perpendicular axis. It appeared that the cover extended 65 ft north and 90 ft south of the cross channel center line and 70 ft on either side of the channel center line. However, the dark event line on the figure representing the center line of the hole is displaced by an estimated 10 to 20 ft to the north. It appears to be on the top of the edge of the depression instead of in the center. After the event line is moved back to the center of the hole, the revised estimate for the sand cover dimensions is 75 ft north and 75 ft south of the center line. These dimensions correspond well to the contours produced from the hydrographic surveys shown in Figure 6.
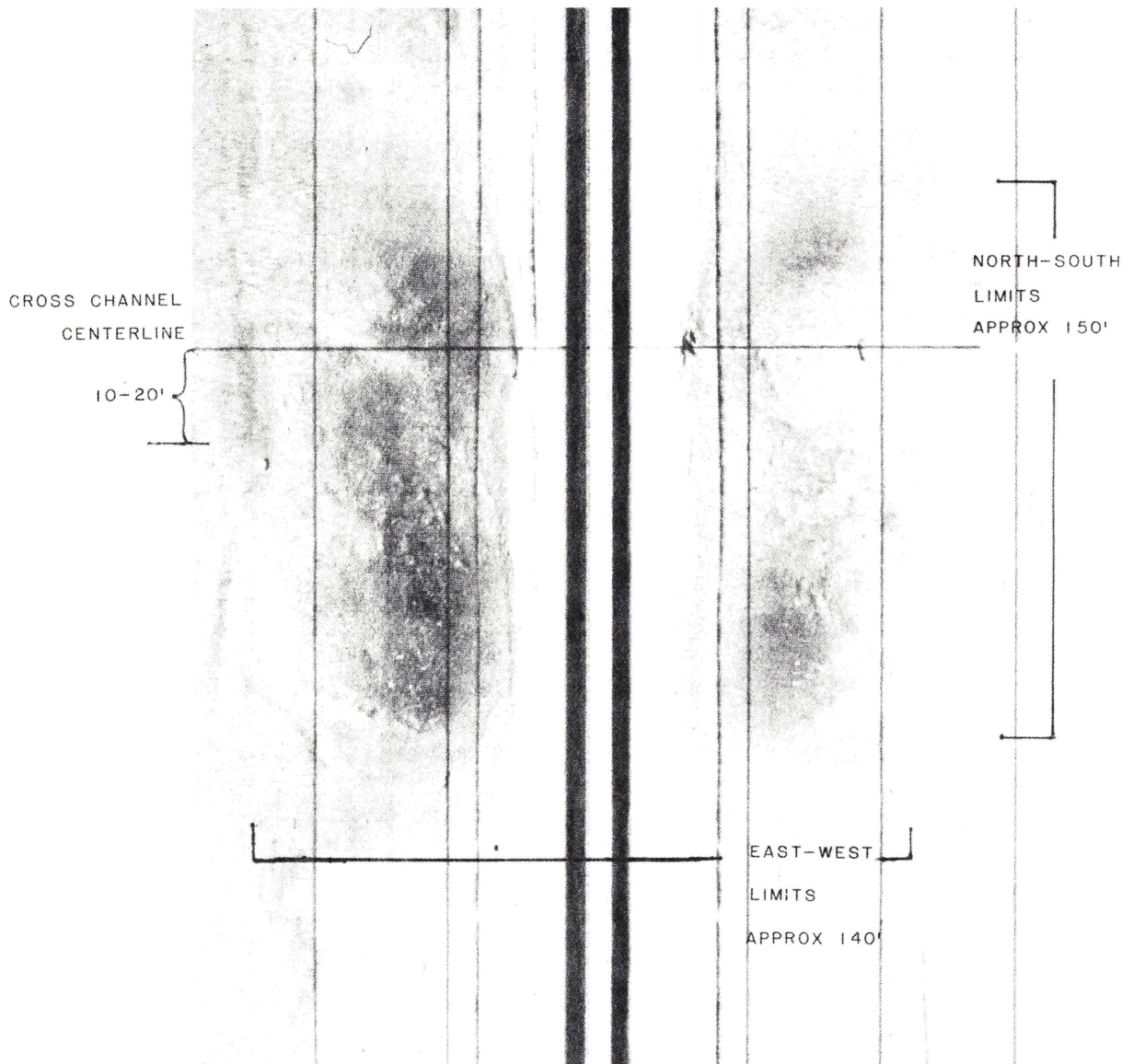
41

CROSS CHANNEL
CENTERLINE

10-20'

NORTH-SOUTH
LIMITS
APPROX 150'

EAST-WEST
LIMITS
APPROX 140'

Figure 17. SSS image of the first sand cap

Inspection of the completed sand cap

73. On 2 April 1984, the 500-kHz "fish" was used to inspect the com-
pleted sand cap. A total of ten passes was made over the drop site. An
attempt was also made to determine the thickness of the sand cap using the
subbottom profiler. The sound pollution created by using the SSS and subbot-
tom profiler simultaneously seriously degraded the topographic features and
sediment texture differences on the record while producing a poor estimate of
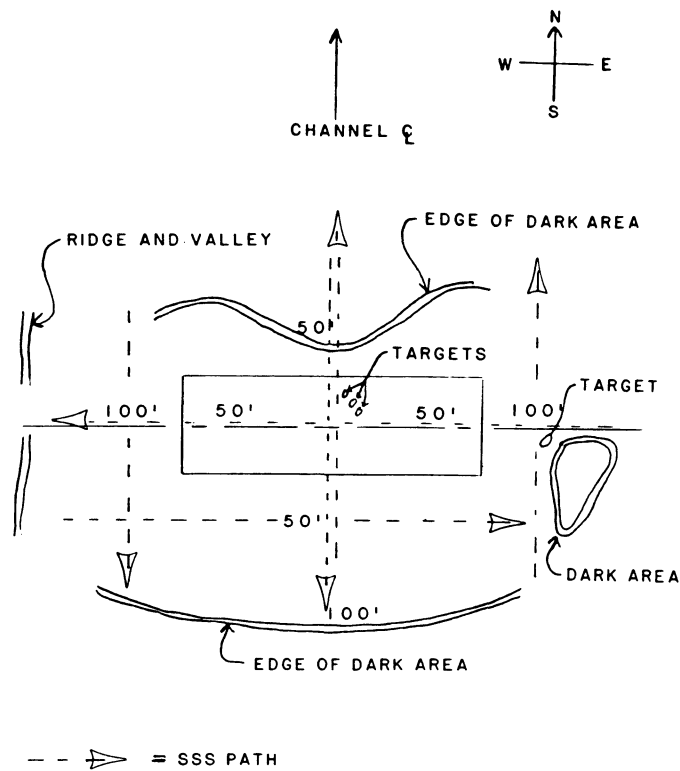the cap thickness.

Figure 18. Completed sand cap coverage

74. Although the quality of the records was too low for good reproduction, it was possible to make an estimate of the extent of the sand cap. In Figure 18, the outline of the depression is shown along with the tracks of the six best SSS passes. On the figure are four features which show the estimated boundaries of the sand cap. A north-south running ridge and a valley are seen at the western edge of the channel. Dark areas, presumed to be areas covered by sand, are seen to the north, south, and east. Several targets are also illustrated. They aided in determining location of the features. The northern boundary is 35 to 65 ft north of the long axis of the depression, and the southern boundary is approximately 100 ft south of the axis. The eastern and western boundaries are 140 and 150 ft, respectively, from the center line of the channel. It appears that the original depression was completely covered by the sand cap.

75. As mentioned earlier, the subbottom profiler was used to make an estimate of the cap thickness. The quality of these data is not good, but a rough estimate of the thickness using these data would be about 6 ft, compared with a thickness of 3 to 4 ft estimated in Part II from comparison of the replicate survey profiles.

43

Summary

76. SSS was used successfully to monitor a dredged material disposal operation in Seattle. Timing of the fall of the dredged material was completely successful once the proper methodology was determined. Monitoring of the dredging operation provided an unexpected bonus when it was discovered that the sediment plume in the water could be detected. The more conventional use of SSS to determine the limits of the sand cap cover was successful, although record quality was limited by channel dimensions and configuration and noise pollution. Finally, the subbottom profiler was marginally successful at determining the sand cap thickness.

77. The ability of SSS to determine cap coverage or disposal sediment coverage is a function of grain-size difference between the two sediments. The greater the difference, the more easily the boundary between the native and the disposed sediments can be seen. The limiting factor in determining boundary location is positioning. Even in a small area with many landmarks and ranges like the Duwamish Waterway, visual estimation of location is difficult. To accurately locate features on an SSS record, a positioning system, e.g., a miniranger, is necessary.

78. Determination of disposed material thickness or cap thickness is possible with a subbottom profiler. For accurate results, a fairly sophisticated unit is needed. However, in most instances, a standard hydrographic survey depth sounder is still the best tool for determining sediment thickness from replicate surveys. Only in areas without proper elevation reference marks and tide data would a subbottom profiler be better for determining sediment thickness.

PART VI: CHEMICAL STUDIES

79. The portion of the work addressing the effectiveness of the cap in
isolating the chemical constituents in the shoal material from the water col-
umn will not be completed until longer term sampling has been accomplished and
the results analyzed. The following brief summary of preliminary results has
been provided by Dr. James M. Brannon of WES who is performing this work.

80. Sediment samples were analyzed for total concentrations of poly-
chlorinated biphenyls (PCBs), copper (Cu), lead (Pb), and zinc (Zn) in core
samples from the Duwamish capping sites. This testing was conducted to deter-
mine if these contaminants, which were present in the dredged material but
absent or present in trace quantities in the caps, were migrating upward in
the cap material. Samples were taken within 2 weeks following capping opera-
tions and then 6 months after capping. An additional set of samples will be
taken 18 months after cap placement.

81. Samples were taken for chemical analysis from vibracores taken at
the Duwamish capping site and at an adjacent reference site (cap material
only). After the core had been opened with an electrical circular saw and any
plastic shavings on the sediment carefully removed, the sediment/cap interface
was identified. The interface was usually strikingly evident because of the
textural differences between the cap (sand) and the dredged material (mainly
silt). Ten samples were taken in the cap and seven samples were taken in the
dredged material at consecutive 4-cm intervals on either side of the dredged
material/cap interface. An additional sediment sample was also taken in each
core at various depths below the cap/dredged material interface to chemically
characterize unusual sediment layers.

82. Results of chemical analysis of initial core samples indicated that
the dredged and cap materials formed a sharp, relatively unmixed interface.
This is illustrated in Figure 19, which presents Pb and Arochlor 1242 PCB con-
centrations in a core at the Duwamish capping site. Both Pb and PCBs were
initially either absent or present in low concentrations in the cap materials.
Below the cap/dredged material interface, however, high concentrations of Pb
and PCB relative to those in the cap material were noted.

83. Water samples (four) were also taken 1 m above the sediment at the
capping demonstration site. For comparison purposes, water samples were also
taken either upstream or downstream of the demonstration site at each
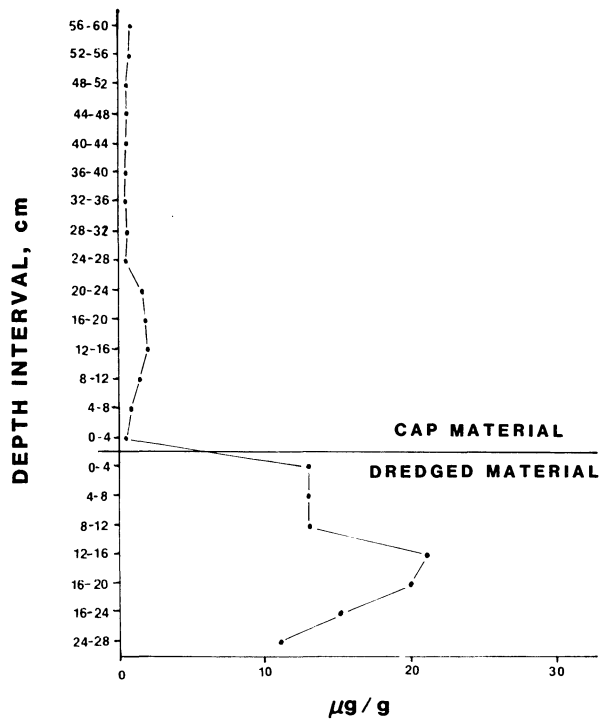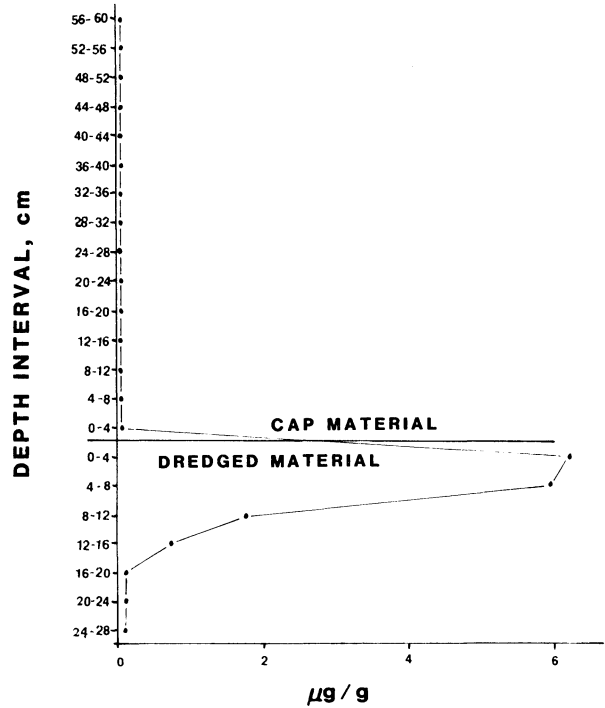
Figure 19. Chemical profile through the cap

sampling; selection of the upstream or downstream sampling location depended on the direction of tidal flux at the time of sampling. These water samples allowed evaluation of any measurable impacts on water quality due to contaminants from the dredged material moving through the cap. Analysis of these data continues and the final results of the chemical studies will be reported in a subsequent document.

PART VII: SUMMARY

84. The Seattle District and the Waterways Experiment Station have
cooperated in a project in the Duwamish Waterway that successfully demon-
strated the engineering aspects of subaqueous disposal and capping of con-
taminated dredged material. Approximately 1,100 cu yd of silty, clayey shoal
material was removed by clamshell dredge, transported by barge, and bottom
dumped through 70 ft of water into an existing depression. The site was then
capped with successive loads of a clean sandy cover. All operational features
of the demonstration were completed successfully. This report has analyzed
the results of the initial field operations and the first (6-month) monitoring
effort.

85. The results of bathymetric surveys were reported showing that the
material formed an identifiable mass at the disposal site. The physical
impact of the descending material on the bottom was violent, but subsequent
surges were confined to the immediate vicinity. Approximately 40 percent of
the original volume could be identified in a bottom area equivalent in size to
the "footprint" of the discharging barge's hopper. Maximum thickness of the
mound of shoal material was measured to be 3 ft. The cap covered the disposal
site completely with a thickness ranging up to 3 ft. The ratio of the volume
of capping material required to the volume of contaminated material was
approximately 4 to 1.

86. Discussions of both volumetric and mass balances have been pre-
sented. A volume of material in the depression equal to that measured ini-
tially in the barge could be clearly identified on the surveys. An error
analysis is described suggesting that the accuracy of the volumetric computa-
tion is within approximately 8 percent. Suspended solids concentrations were
measured in the water column at both the dredging and disposal sites. Losses
during disposal were estimated to be on the order of 7 to 15 percent of the
initial dry mass. A subsequent mass balance was presented. Differences in
computed values were in the range of only 8 to 10 percent. Possible sources
of error in the balance were examined.

87. Side scan sonar was used in several ways during the dredging and
disposal and an analysis of its utility for such work was presented. A small
solids plume associated with the dredging could be see through the sonar
equipment and the descent of the material through the water column at the

disposal site was also monitored. The primary problem noted was the high level of acoustic background "pollution" in the busy waterway which may make the application of side scan sonar at such sites more difficult and time-consuming.

88. Brief scopes have been included summarizing the fieldwork and intent of associated monitoring of mound consolidation and chemical effectiveness of the capping procedure. These studies are continuing and additional sampling and testing will be completed at approximately 18 months following the original disposal.

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APPENDIX A: ERROR ANALYSIS OF BATHYMETRY

1. The error analysis by Massey, Morton, and Paquette (1984)* is based
on weighted averages of depth readings and track errors across a grid square
or cell of arbitrary size. The standard deviation of the calculated value of
the volume is given by:

$$\sigma_v = A \sqrt{2} \; \sigma \qquad\qquad (A1)$$

where
$$\sigma = \frac{\sigma_c}{\sqrt{M}} \; ; \quad \sigma_c = \frac{s_r}{\sqrt{N}}$$

and

σ_v = standard deviation in volume calculated

A = area of total survey

σ_c = standard deviation of the depth error in any given cell

M = number of grid cells in the entire survey

σ_r = standard deviation of all measurements of depth in a cell

N = number of individual depth measurements in a given cell

2. The error analysis can be extended to the Duwamish data by making
the following assumptions. An arbitrary grid system can be constructed over
the disposal site with the grid size equal to the width of one track interval
or 25 ft. This grid size would result in a 13 by 10 array totaling 130 cells.
The shallower water depths, closer proximity of navigation references, and
more sheltered hydrodynamic environment all suggest that the lower values in
the ranges given for each source of error are reasonable for the Duwamish
data. Fathometer error would then be estimated as ±10 cm. The cross-track
position error would produce errors in the depth measurement of no more than
±10 cm, and short-term fluctuations in the water surface elevation during the
actual survey (waves, tide, boat draft, etc.) could produce errors of ±10 cm
also. The root-mean-square for these three source errors would also be ±10 cm
and is then the value of σ_r in Equation A1. Using approximately 1.8 as a
typical value for N for a 25-ft square cell gives:

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* See References at the end of the main text.

$$\sigma_c = \frac{\sigma_r}{\sqrt{N}} = \frac{10}{\sqrt{1.8}} = 7.45 \text{ cm}$$

then
$$\sigma = \frac{\sigma_c}{\sqrt{M}} = \frac{7.45}{\sqrt{130}} = 0.65 \text{ cm}$$

and
$$\sigma_v = A\sqrt{2}\,\sigma = A\sqrt{2}\ (0.65) = \text{approximately 90 cu yd}$$

APPENDIX B: BACKGROUND AND PRINCIPLES OF SIDE SCAN SONAR OPERATION

How a Side Scan Sonar Works

1. Side scan sonar (SSS) is an outgrowth of the echo sounding depth
finders developed during World War II. It has been used to map the sea bottom
and to search for submerged objects since the 1960s.

2. In SSS systems acoustic energy is projected laterally from a pair of
transducers mounted in a towed cylindrical body ("fish"). The horizontal beam
of energy is from 1-1/2° to 2.0° wide. Vertically the beam covers approxi-
mately 40°, and it is usually aimed 10° below the horizontal.

3. Electrical energy applied to the piezoelectric transducers in the
"fish" causes them to vibrate, creating pressure waves which travel out
through the water. The energy is reflected and backscattered from the seabed
or structure and is finally picked up by the transducers and recorded on
continuous chart paper. The continuous paper image of the bottom or structure
produced by the recorder is referred to as a record or sonograph. Transducers
typically vibrate at frequencies from 50 to 500 kHz. The most commonly used
frequencies are 100 and 500 kHz. The 100-kHz frequency provides greater
range, up to 1,500 ft on either side, and is most often used for sea bottom
mapping and locating objects. A frequency of 500 kHz gives a shorter range,
up to 300 ft on either side, but provides greater detail. A Klein 500-kHz
unit was used in the Seattle operation.

How to Interpret a Sonograph

4. Before discussing the results of any SSS survey, a brief explanation
of how to interpret a sonograph is in order. SSS records are remotely similar
to low-level oblique aerial photographs. However, they can best be interpreted
by thinking of the SSS beam as showing what a flashlight would illuminate in a
darkened room.

5. Skilled interpretation of sonographs is as much an art as it is a
science. While the following discussion gives the basic knowledge needed to
read the record, the only way to become proficient is through experience.

6. The following discussion applies to Figure B1. The dark parallel
lines (A) running down the center of the sonograph are the starting points of
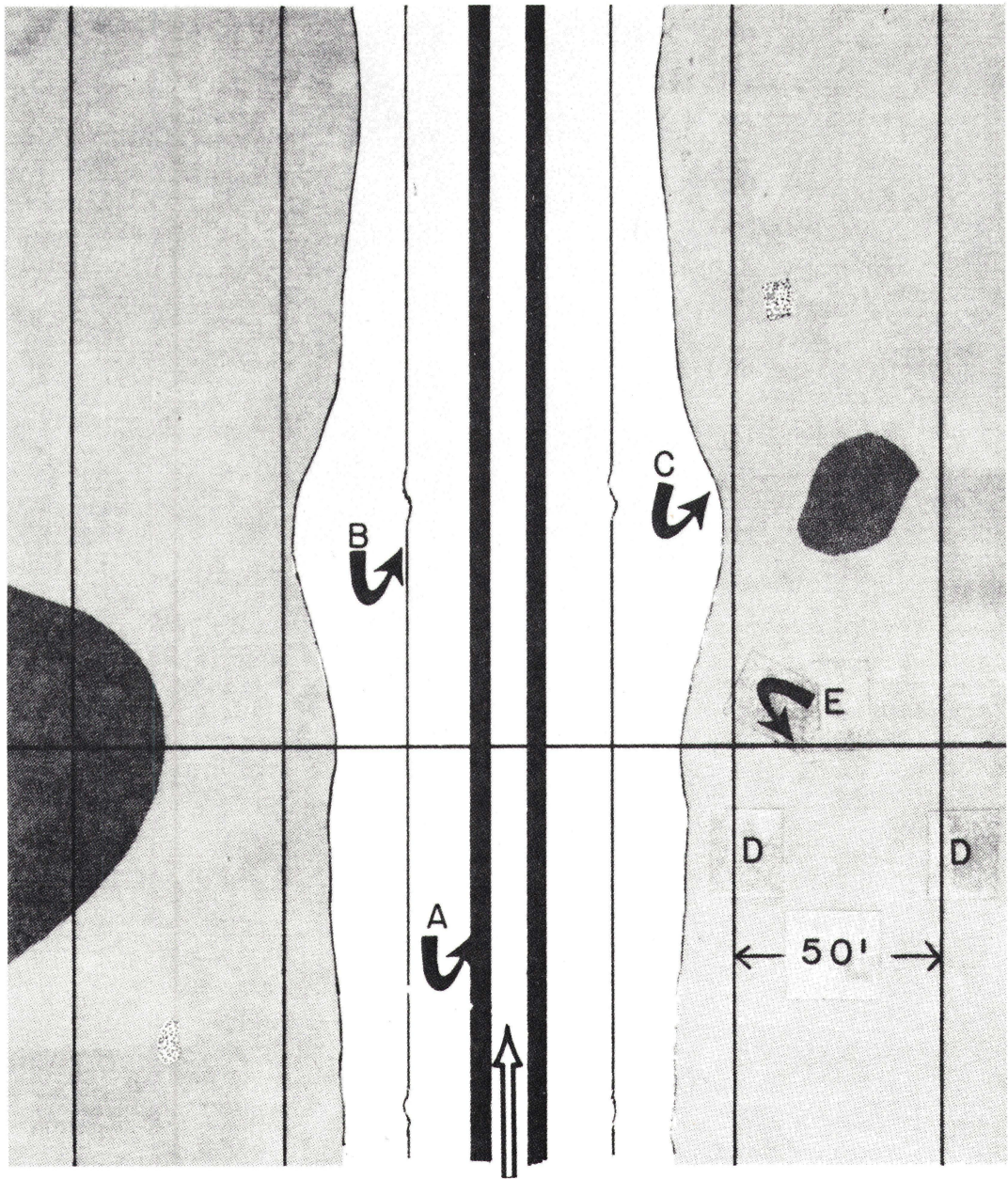
DIRECTION OF FISH MOVEMENT

Figure B1. Example SSS record

the pulses from the left and right channels. Line B is surface return, and
line C is the initial bottom return. Total depth can be calculated by adding
the distance (B and C). The regularly spaced parallel slant range lines (D)
are produced by the recorder to allow distance perpendicular to the line of
travel to be determined. The spacing in the figures in this report is 50 ft.
As the range (25 to 100 m per channel on 500-kHz SSS) changes, so does the

spacing of lines. To highlight a particular instant in time or object on the record, an event mark (E) can be placed on the record.

7. The images produced, i.e., the varying shades made on the recording paper, are functions of the intensity of the returning acoustic signal. The stronger the returning signal the darker the image. A number of factors affect the strength of the returning signal. Reflectivity of the target is one. Steel has a higher reflectivity than stone or concrete, which has a higher reflectivity than wood. The coarser the sediment, the higher the reflectivity. Consequently, gravel produces a darker shade than sand, which produces a darker shade than silt or clay.

8. The slope also affects the strength of the returning signal. As the slope becomes more perpendicular to the incoming sound wave, the strength of the reflected signal increases. Projections, such as armor stones sitting on the bottom, will produce a dark image on the near side of the record, but they will also produce a shadow on the far side of the record. The acoustic shadow, where no signal is reflected, shows up as a white area on the sonograph. Also, the height of an object above the bottom can be determined from the record if the length of the shadow and the height of the "fish" above the bottom are known.

9. A subbottom profiler was used in Seattle also. It operates in the same manner as SSS but uses a lower frequency acoustic pulse (3.5 kHz) that penetrates the sediments on the bottom. The subbottom profiler is pointed straight down and produces an image that shows the bottom and sediment layers below the bottom.