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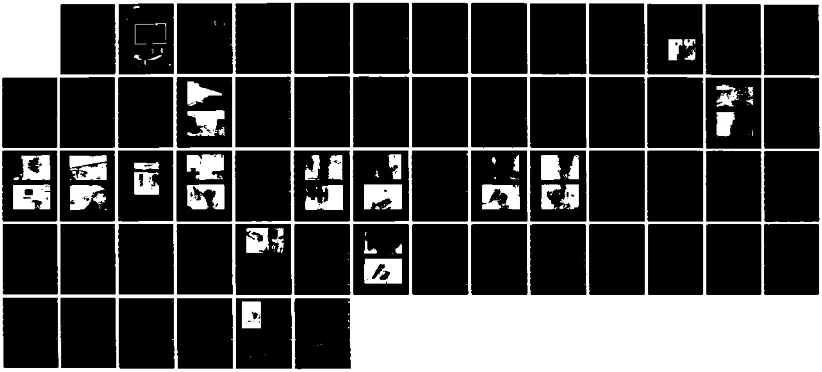

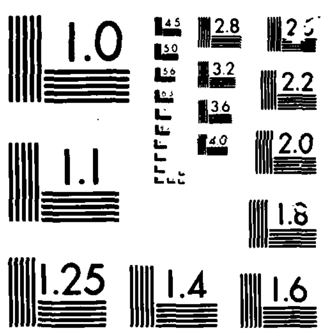

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UNDERWATER FACILITIES INSPECTIONS & ASSESSMENTS

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U.S. NAVAL STATION

KEY WEST, FLORIDA

FPO 1-80(9)

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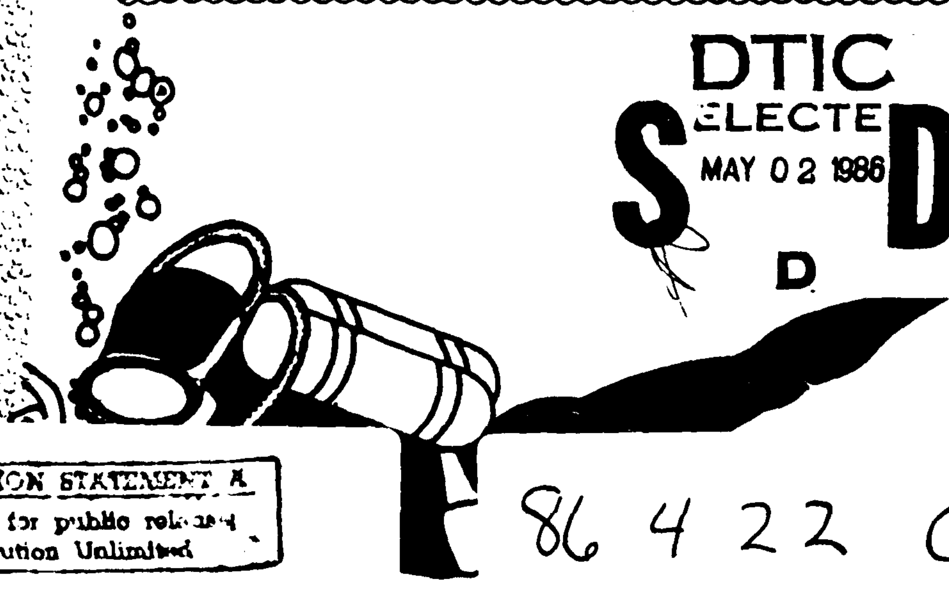

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The underwater inspection was conducted between 20 and 25 January 1980. It included the sheet steel piling that entirely surrounds Pier D-3 as well as part of the adjacent quaywall. It also included the concrete structure of Pier D-1 and two of the three steel H-pile finger piers that jut out to (Con't)

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the south from the offshore end of Pier D-1. A visual and tactile inspection was conducted of all the underwater elements of these piers. In addition underwater photographs were taken of selected parts of the operation and structures, underwater video was utilized, and ultrasonic thickness measurements and underwater potential measurements were made of the steel structures. All significant evidence of underwater deterioration was recorded and the condition of the surface and abovewater structure was noted.

The inspection revealed that, to the extent that could be determined, the underwater sections of sheet piling on Pier D-3 are in excellent condition, however, there was no way of assessing the condition of tie rods securing the internal wales of the sheet pile structure. Abovewater, Pier D-3 showed extensive deterioration of the sheet piling, of the fender system, and of mooring elements along the deck; these were brought to the attention of the NAS representatives.

Pier D-1 was found to be in excellent condition underwater despite its age (68 years). Again the topside fender system and mooring fittings were in a state of disrepair. Finger piers 1 and 3, due to extensive cathodic protection, showed little underwater corrosion or deterioration but, again, the abovewater structures required repair and renovation to restore them to a usable condition.

Depth measurements alongside Piers D-3, D-1, and the finger piers indicated sufficient depth for mooring of those naval vessels for which this inspection was conducted.

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EXECUTIVE SUMMARY

At the request of the Commander, Naval Air Forces, Atlantic (COMNAV-AIRLANT), the Commander, Naval Construction Battalions, U. S. Atlantic Fleet (COMCBLANT) tasked Underwater Construction Team One (UCT ONE) to conduct an underwater inspection of the waterfront facilities at the Trumbo Point Annex of the Naval Air Station (NAS), Key West. The Chesapeake Division, Naval Facilities Engineering Command (CHESNAVFACENGCOM) was in turn requested by UCT ONE to provide engineering assistance in developing an inspection plan and to participate in the inspection.

The underwater inspection was conducted between 20 and 25 January 1980. It included the sheet steel piling that entirely surrounds Pier D-3 as well as part of the adjacent quaywall. It also included the concrete structure of Pier D-1 and two of the three steel H-pile finger piers that jut out to the south from the offshore end of Pier D-1. A visual and tactile inspection was conducted of all of the underwater elements of these piers. In addition underwater photographs were taken of selected parts of the operation and structures, underwater video was utilized, and ultrasonic thickness measurements and underwater potential measurements were made of the steel structures. All significant evidence of underwater deterioration was recorded and the condition of the surface and abovewater structure was noted.

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Pier D-1 was found to be in excellent condition underwater despite its age (68 years). Again the topside fender system and mooring fittings were in a state of disrepair. Finger piers 1 and 3, due to extensive cathodic protection, showed little underwater corrosion or deterioration but, again, the abovewater structures required repair and renovation to restore them to a usable condition.

Depth measurements alongside Piers D-3, D-1, and the finger piers indicated sufficient depth for mooring of those naval vessels for which this inspection was conducted.

PREFACE

BACKGROUND

The Chief of Naval Operations (CNO), in reference (1), assigned to UCT ONE the responsibility for the underwater inspection of waterfront facilities over a two and one-half year period. COMNAVAIRLANT had been tasked to provide an underwater inspection of Piers D-1 and D-3 at the Naval Air Station, Key West, Florida. In accordance with reference (1), COMNAVAIRLANT requested COMCBLANT to arrange for UCT ONE to conduct this inspection in reference (2).

Reference (2) stated that the purpose of the inspection was "to determine costs for any maintenance action required to restore the piers to usable condition in accordance with current standards". It was requested that an accurate, valid survey be made on which could be based high level decisions with regard to ship home porting and facilities retention. Reference (2) also requested that CHESNAVFACENGCOM provide appropriate assistance as applicable under the waterfront facilities underwater inspection program.

Additionally, the Naval Air Station, Key West, was requested to provide, upon completion of the inspection, an itemized cost estimate covering all maintenance required for each pier.

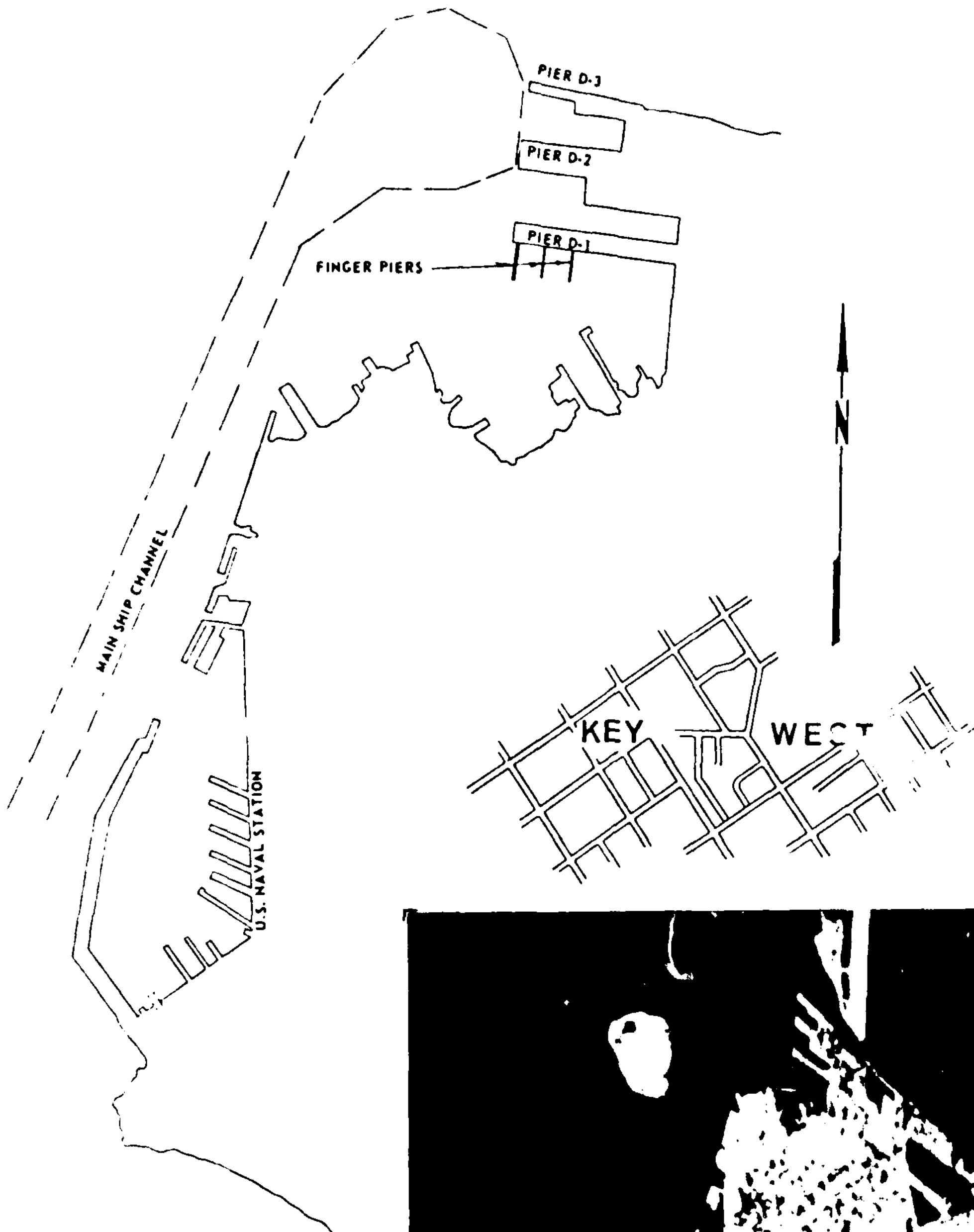
INSPECTION PRIORITIES AND PROCEDURES

Upon receipt of reference (2) on 19 January 1980, CHESNAVFACENGCOM assigned an ocean engineer to accompany the UCT ONE detachment in performing the underwater inspection of Piers D-1 and D-3 at the Naval Air Station, Key West. The engineer and the UCT ONE detachment arrived at the Trumbo Point Annex in the late afternoon of 20 January 1980 and conducted a brief inspection of the diving operations area around Piers D-1 and D-3.

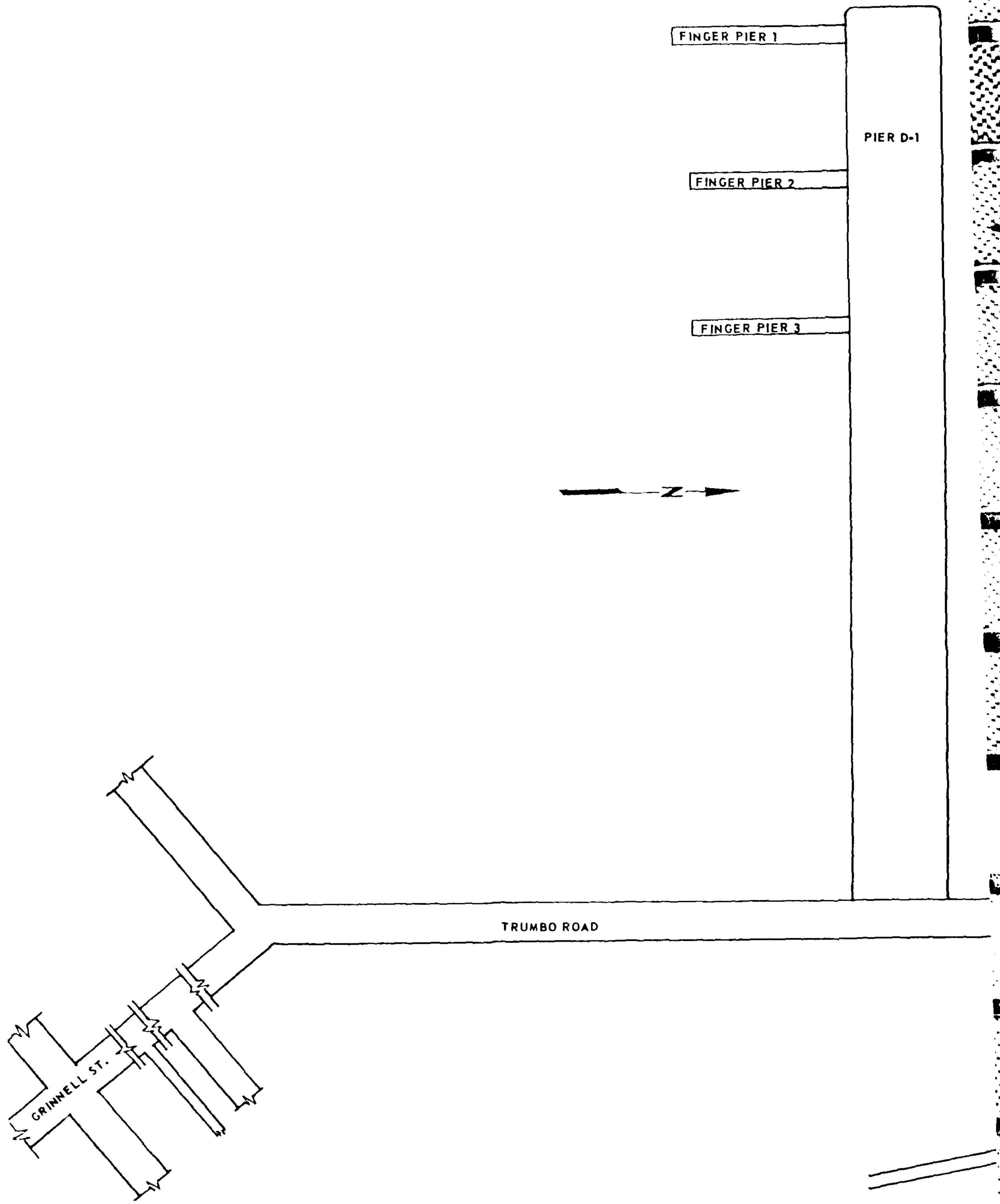
The locations of the U. S. Naval Station and the Trumbo Point Annex with respect to the city of Key West are shown in Figure 1. Details of the pier arrangement at the Trumbo Point Annex are given in Figure 2. After the first examination of the area it was decided to inspect first the underwater structure of Pier D-3 and then to inspect Pier D-1 and its associated finger piers. Initial inspection passes would be visual only with underwater sonic measurements and potential measurements awaiting the arrival of Civil Engineering Laboratory personnel and equipment on 23 January 1980.

MAP OF U. S. NAVAL STATION, KEY WEST
SHOWING INSPECTED PIER AREA

FIGURE 1



AERIAL VIEW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PIER D-1
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FINGER PIER 3
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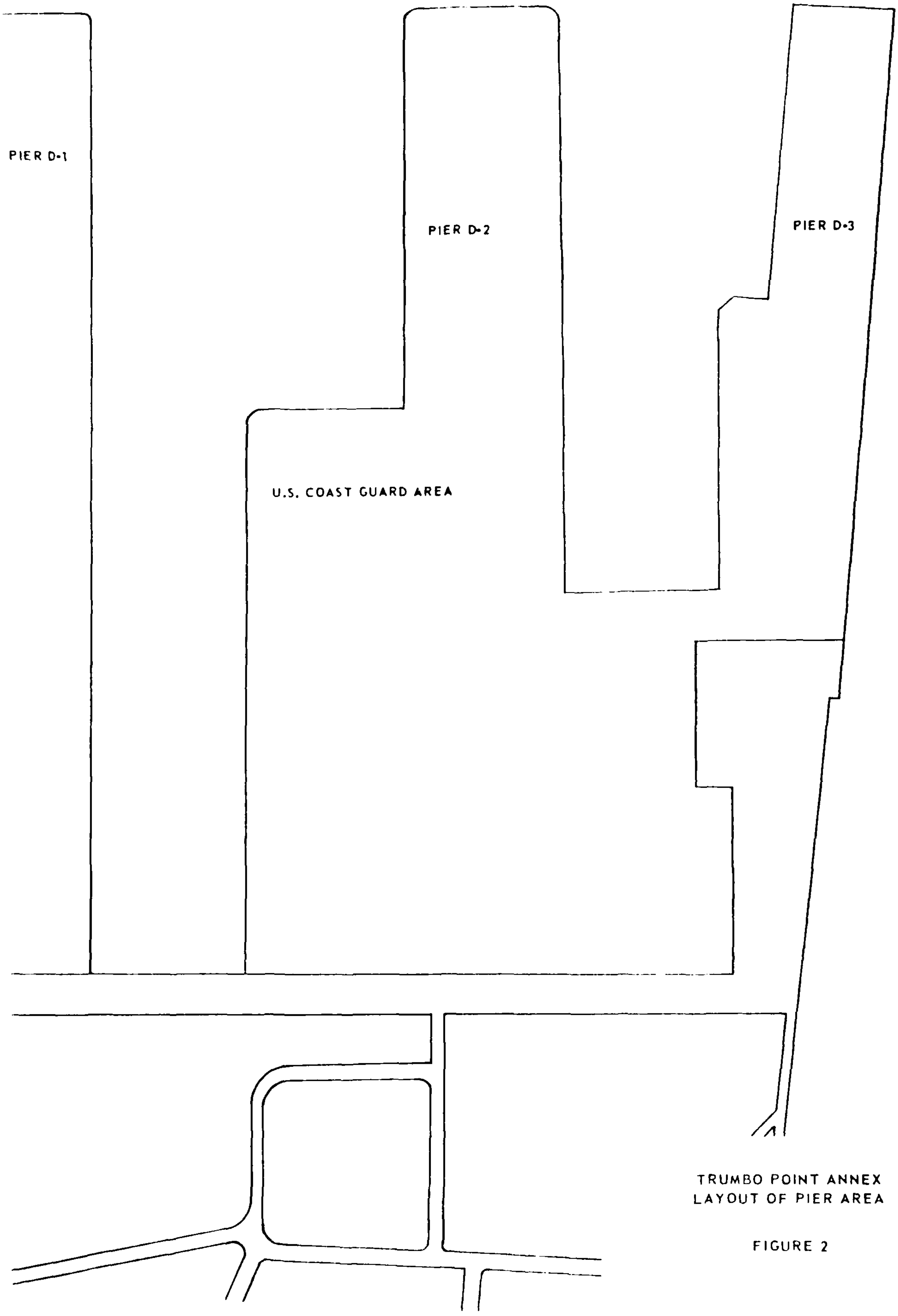
GRINNELL ST.



TRUMBO POINT ANNEX
LAYOUT OF PIER AREA

FIGURE 2

After reviewing available drawings and conferring with on-site personnel, a final inspection plan evolved covering the following areas of concern:

- o Abovewater structure
  - -- subsidence of decks
  - -- condition of wales
  - -- condition of deck fittings
- o Region between waterline and mudline
  - -- buckling of walls
  - -- orientation of sheet piling on pier sides with respect to vertical
  - -- condition of sheet piling where applicable, i.e., interlocking of adjacent piles, holes in piling, and piling thickness
- o Mudline
  - -- depth of bottom
  - -- evidence of rubble exuding from under piling
  - -- relation of piling bottom to mudline

The inspection procedure called for UCT ONE divers to perform all underwater work including visual and tactile inspections, underwater video and photographic work, and utilization of instrumentation transducers and probes. All visual and tactile underwater inspection results were reported to the CHESNAVFACENGCOM representative at predetermined intervals for recording purposes. CEL personnel were to man the instrumentation readout units and to report measured results to the CHESNAVFACENGCOM representative. NAS, Key West personnel were informed verbally of the underwater conditions as the inspection progressed.

FORMAT OF FACILITIES UNDERWATER INSPECTION REPORT

The report begins with a chronological sequence of events related to the activities of the various personnel involved and the inspection tasks that were accomplished. This chronology is followed by a description of Pier D-3, the details of the inspection procedures, inspection results, and conclusions with regard to the pier condition and recommended corrective action. A similar account is then given of the condition of Pier D-1 and its associated finger piers as determined by the inspection.

CHRONOLOGY OF FACILITIES INSPECTION

17 January -- CHESNAVFACENGCOM received a telephone call requesting underwater inspection of Key West facilities from COMNAVAIRLANT including verbal tasking.

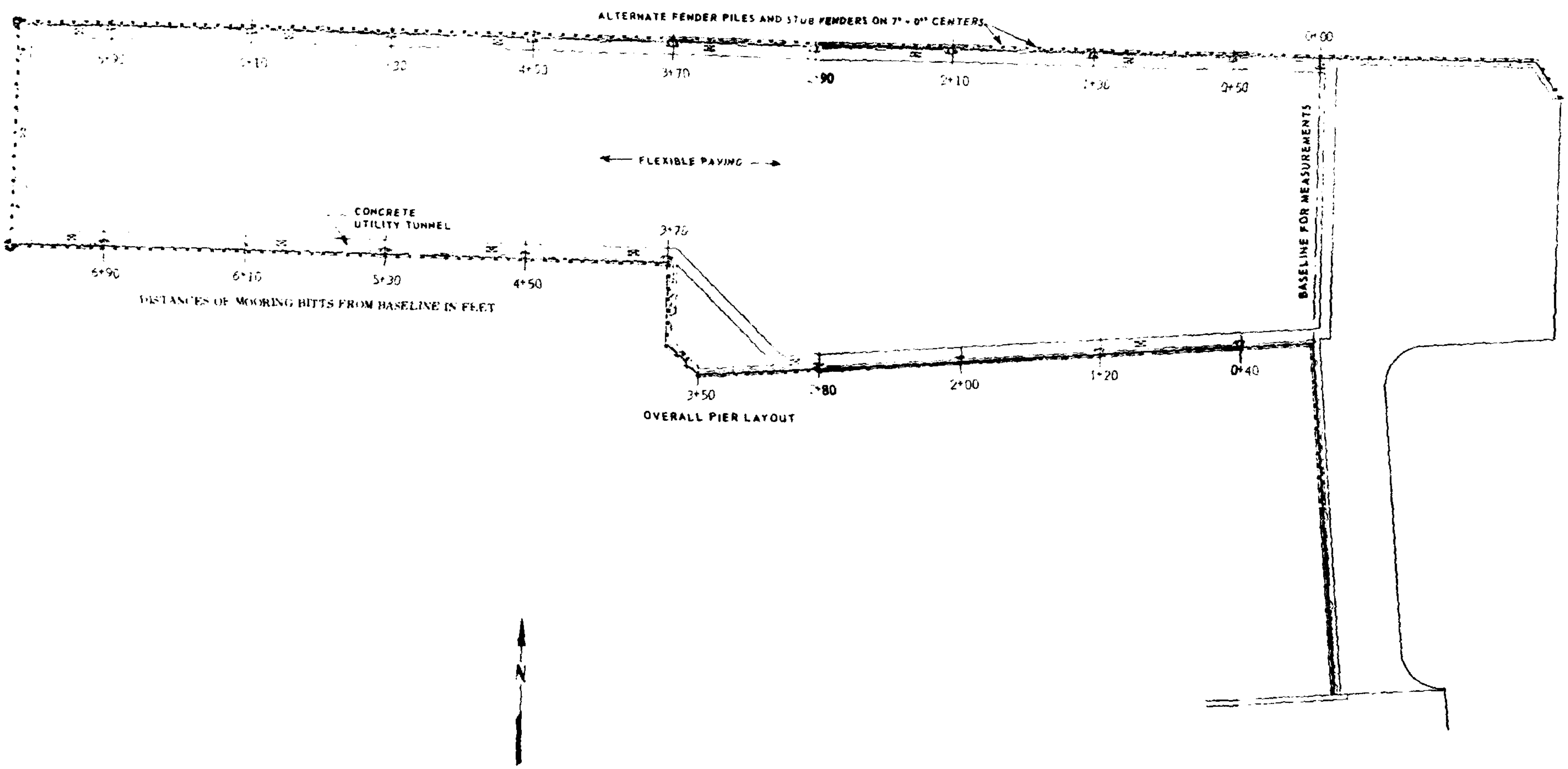
19 January -- CHESNAVFACENGCOM received reference 2. Decision was made to send D. Raecke along with UCT ONE detachment to perform the inspection.

20 January -- Raecke arrived at Key West at 1345 and UCT ONE detachment arrived at 1630. A cursory inspection of the diving operations area around Pier D-3 at Trumbo Point was made.

21 January -- A topside walk-around inspection of Piers D-3 and D-1 was made in the company of R. Young (NAS, Key West) by LCDR G. D. Cullison (OIC, UCT ONE), BUCS/MDV Thompson (UCT ONE), and Raecke. UCT ONE divers set up the diving operations area, charged SCUBA bottles, and made logistics and administrative arrangements. The first dive on the west end bulkhead of Pier D-3 was made between 1500 and 1630 for a visual inspection only.

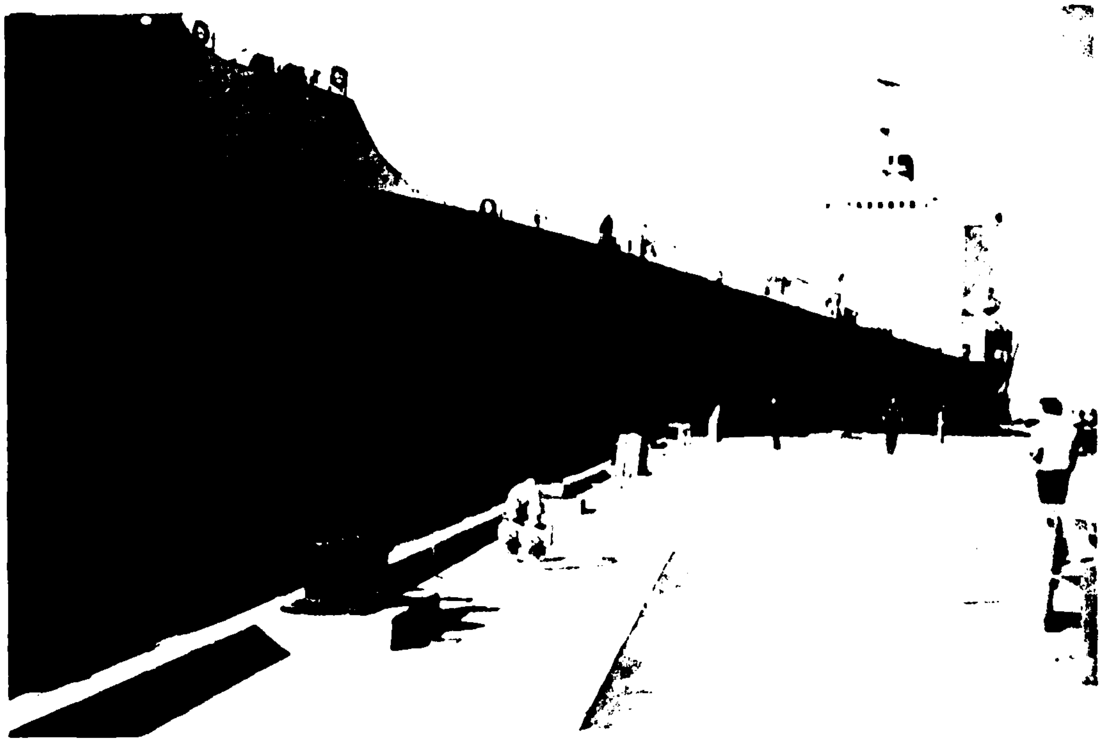
22 January -- The day was spent from 0830 to 1600 conducting a visual inspection of the south side of Pier D-3 using three dive teams. The first dive team worked from the west end easterly along the pier from point 7+42 to point 4+90. The second dive team worked easterly from point 4+90 to point 1+80. The third dive team worked from point 1+80 easterly to point 0+00 and then for 105 feet south along the bulkhead fronting on the U. S. Coast Guard area. These locations can be determined from Figure 3 which shows the baseline for measurement points and the location of mooring bitts along the pier sides. The facility inspection activities were interrupted between 1400 and 1500 due to the berthing of a tanker at Pier D-2. CEL personnel with underwater instrumentation arrived in the evening.

23 January -- Planned inspections with an ultrasonic thickness measuring device, underwater voltmeter, and underwater video were delayed due to scheduled departure of the tanker (*USNS SEALIFT CHINA SEA*) at 0900. The tanker started moving at 0930 and, under the action of a 20 to 25 knot southerly wind, the tanker stern swung and contacted the south side of Pier D-3, Figure 4, and bow contact was made at point 3+50 resulting in damage to the pier, Figure 5, at point 3+50 where the concrete was cracked and broken. Sheet piles



ARRANGEMENT OF PIER D-3

FIGURE 3



TANKER COLLIDING WITH PIER D-3 DURING DE-BERTHING
FROM PIER D-2 WITH THE TUG JEFFERSON ASSISTING

FIGURE 4

DAMAGE TO SHEET PILING AND CONCRETE RESULTING
FROM TANKER CONTACT WITH PIER D-3 AT STA. 3+50

FIGURE 5

were bent slightly but there was no major damage. Additionally, there was some scraping of the pier at point 7+10. By 1100 the tanker had been warped back alongside Pier D-2 but the water in the slip had been stirred up and was too murky for diving. It was therefore decided to move over to Pier D-1 to conduct a visual underwater inspection. Starting at the northeast corner of Pier D-1 and working westerly, the visual inspection of all of the north side, the offshore end, and part of the south side of Pier D-1 was completed. The team then returned to continue operations on Pier D-3 but were driven out of the water by a thunderstorm at 1635.

24 January -- Ultrasonic measurements were started on the south side of Pier D-3 at point 0+05 (southeast corner). This area was mostly in protected water but there was some chop on the surface due to the wind. The divers had difficulty holding the transducer steady because of the chop and surge. Additionally, the transducer was leaking current and the diver holding it received a slight shock when the transducer was out of water. Therefore the ultrasonic tests were called off in order to check out the equipment and to wait for calmer water. The team moved over to complete the visual inspection of the south side of Pier D-1 and then returned to do the visual inspection of the north side of Pier D-3, starting at the west end and working easterly with the assistance of a small current running from west to east.

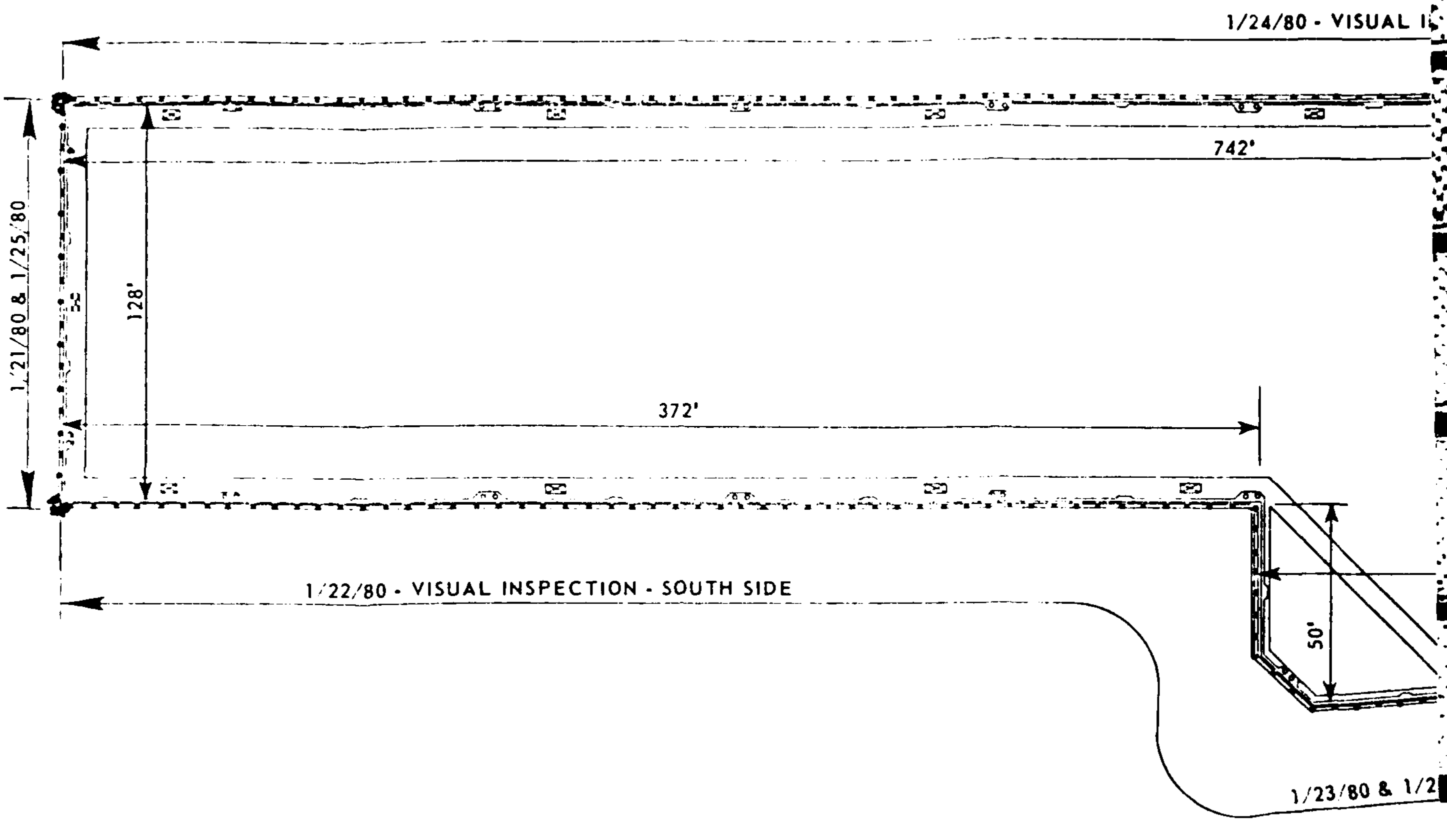
25 January -- Ultrasonic testing, underwater voltmeter measurements, underwater video and still photography work on the south side and west end of Pier D-3 were completed. Then, the underwater voltmeter measurements, video, still photography, and visual inspection of the steel piles supporting the finger piers on Pier D-1 were completed. Finally, video and still photography work on the minor undercutting of the bottom of the concrete along Pier D-1 was completed thus ending the required underwater work.

The inspections made around Pier D-3, indicating date and types of inspection, are illustrated in Figure 6.

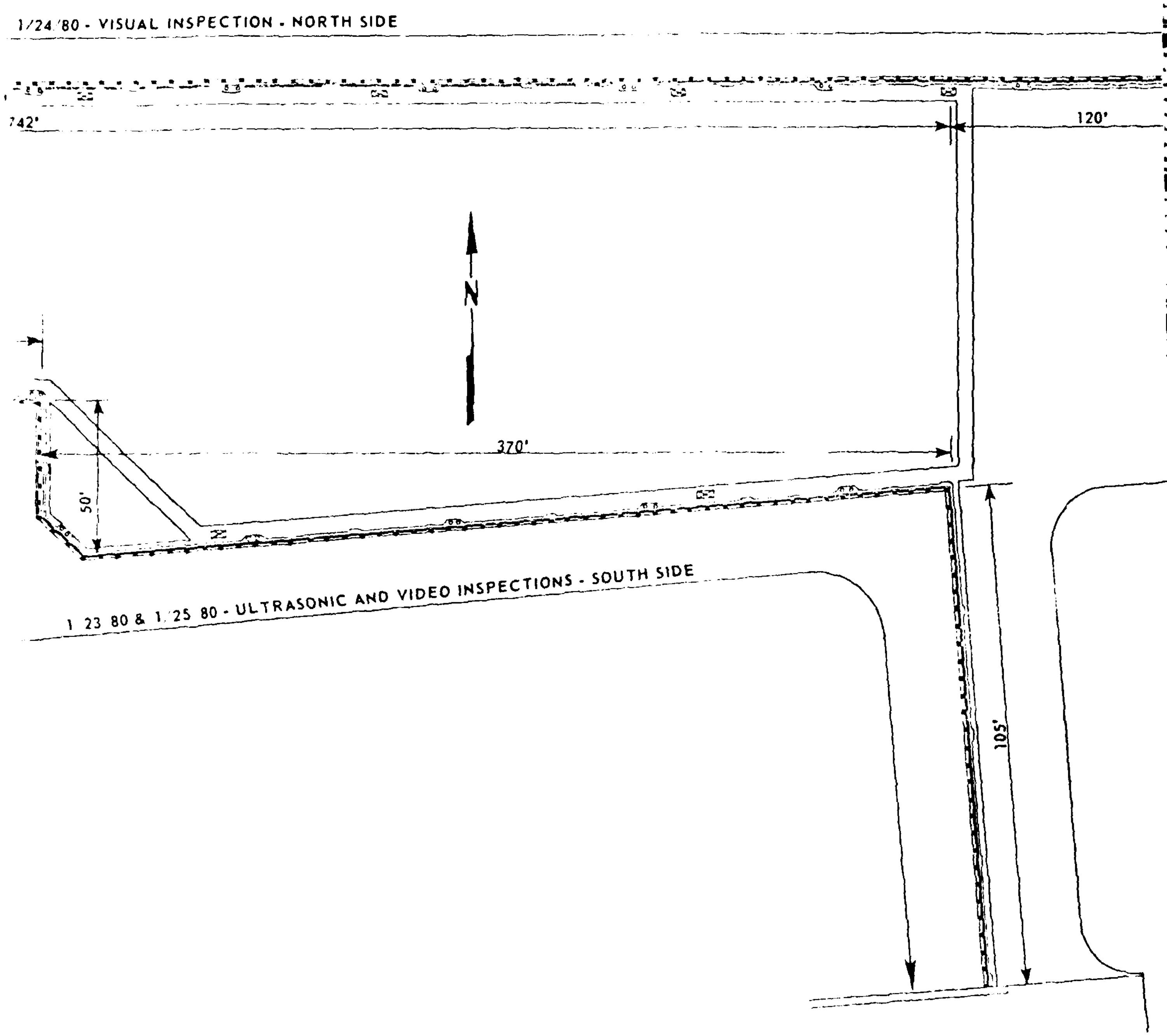
INSPECTION OF PIER D-3

DESCRIPTION

Pier D-3 is constructed basically of a steel sheet pile bulkhead surrounding an area that extends 742 feet west of the quaywall; the outer



1/24/80 - VISUAL I
742'
128'
1/21/80 & 1/25/80
372'
50'
1/22/80 - VISUAL INSPECTION - SOUTH SIDE
1/23/80 & 1/2



PIER D-3 INSPECTION SC

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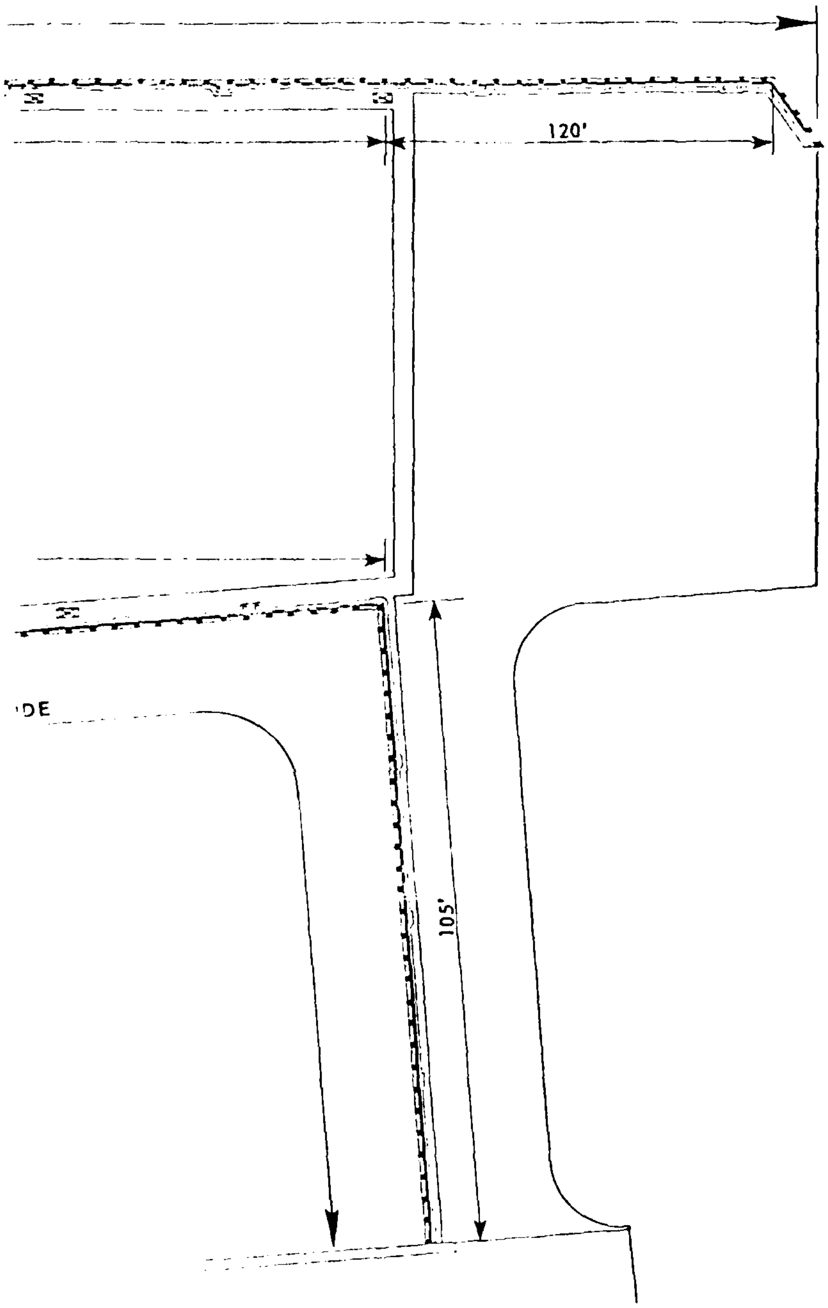


PIER D-3 INSPECTION SCHEDULE

FIGURE 6

372 feet has a width of 128 feet and the inner 370 feet varies in width from 160 feet at the quaywall to 193 feet at the point 370 feet offshore as shown in Figure 6. The sheet piling bulkhead is filled with coral and some debris comprising concrete, asphalt, etc. The pier was originally somewhat smaller but of the same general form of construction. Following extensive hurricane damage the pier was reconstructed (approximately 1951) by surrounding the old damaged sheet piling with new steel sheet piling. The cofferdam space between the sets of sheet piling was filled with debris and the completed pier was paved over.

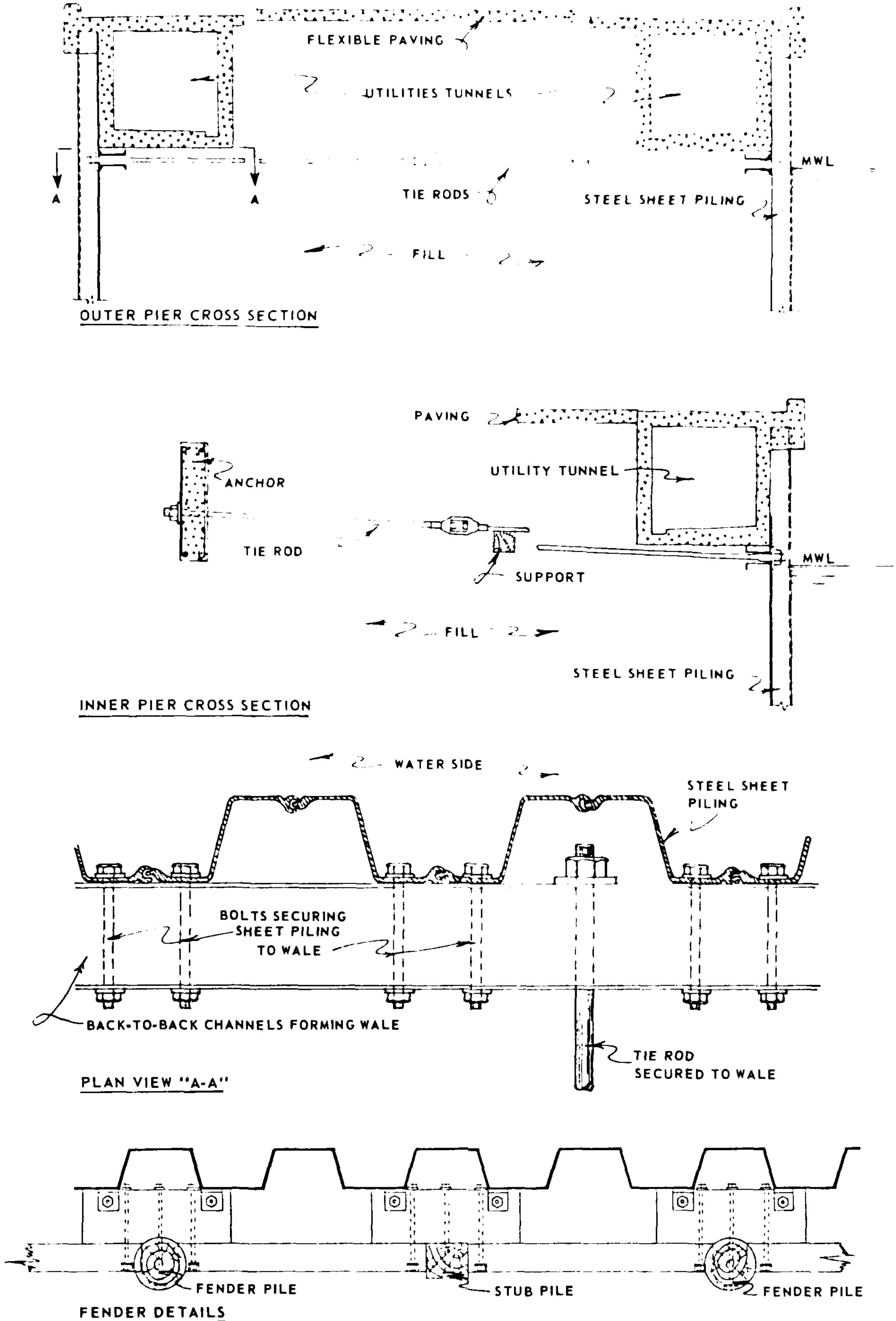
As shown in Figure 7 the north and south lines of sheet piling wales are tied together with threaded rods along the outer 372 feet. These rods are secured by nuts on the interior side of the sheet piling and are tied together by turnbuckles taken up as necessary to maintain the sheet piling on the north and south sides in a parallel orientation. Over the inshore 370 feet the tie rods extend inward from the wales to anchors secured in the rubble fill.

The pier was designed to have 15 inch diameter fender piles spaced 14 feet apart surrounding the sheet piling. These fender piles were tied to the sheet piling and to the concrete deck by means of steel bolts through lower and upper 8" x 10" wooden wales; intermediately spaced between the fender piles were 10" x 12" stub fenders. Detailed design drawings of the total pier structure are available and some of the foregoing details are shown in Figure 7.

Pier D-3 was declared excess several years ago and leased to the city of Key West who in turn subleased the pier to a shrimp packing firm. Currently it is used mostly by the shrimp fishing fleet.

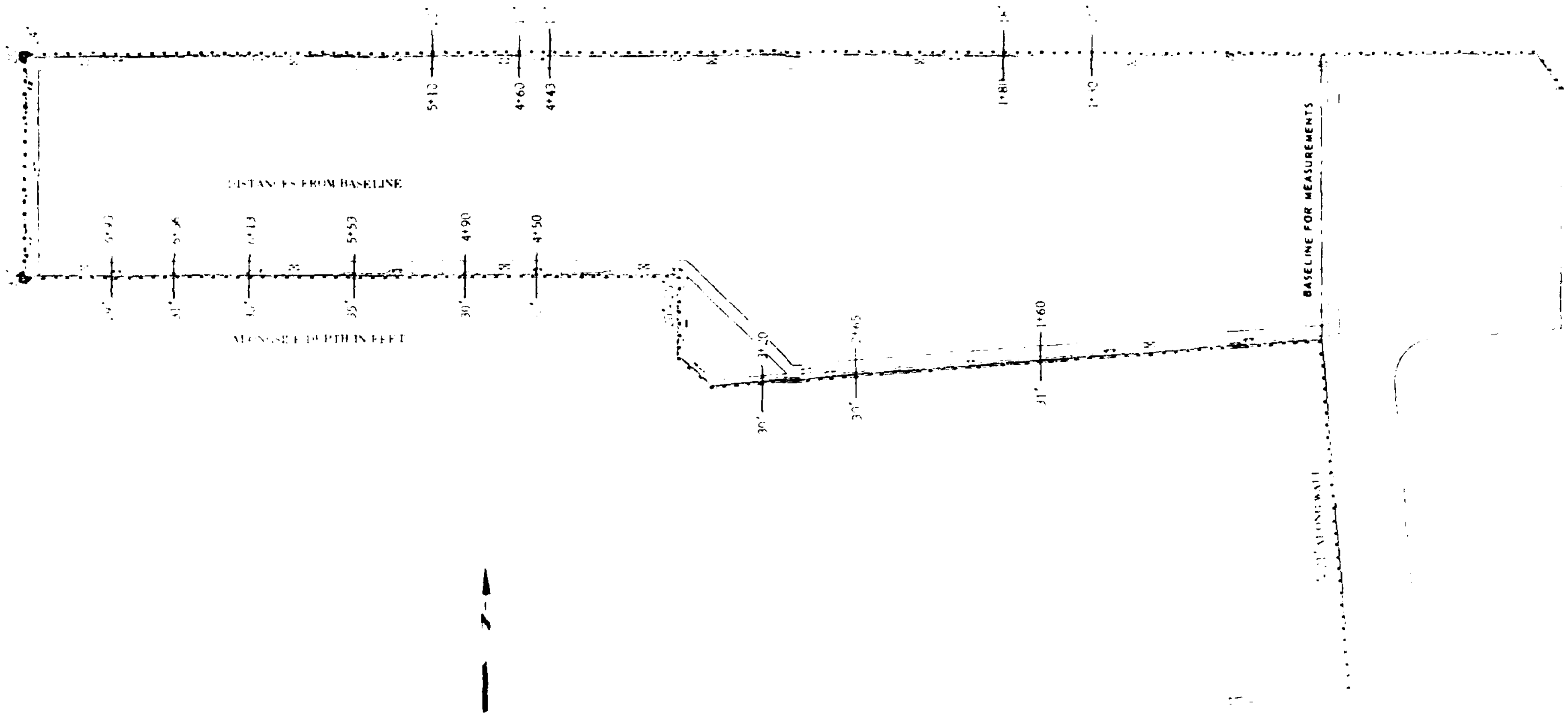
Prior to finally turning the property over to the city of Key West, the Navy reconsidered disposing of the pier and may want to retain and refurbish it for future homeporting of Navy vessels. The inspection reported herein was conducted in order to determine the utility of the pier and to provide a basis upon which the refurbishment cost could be estimated.

Vessels using this pier would primarily be tied up on the south side which is dredged to a depth of more than 30 feet as shown in Figure 8 and was reconfirmed during the current inspection. The bottom is coral covered by a thin layer of sediment. The north side of the pier is dredged to a depth of



PIER D-3 CONSTRUCTION DETAILS

FIGURE 7



DEPTHS ALONGSIDE PIER D-3

FIGURE 8

only 15 feet to 20 feet and is exposed to a tidal current on the order of 4 to 5 knots; the bottom is coral and there is no sediment due to the current action. This side of the pier is probably not usable.

INSPECTION METHODS

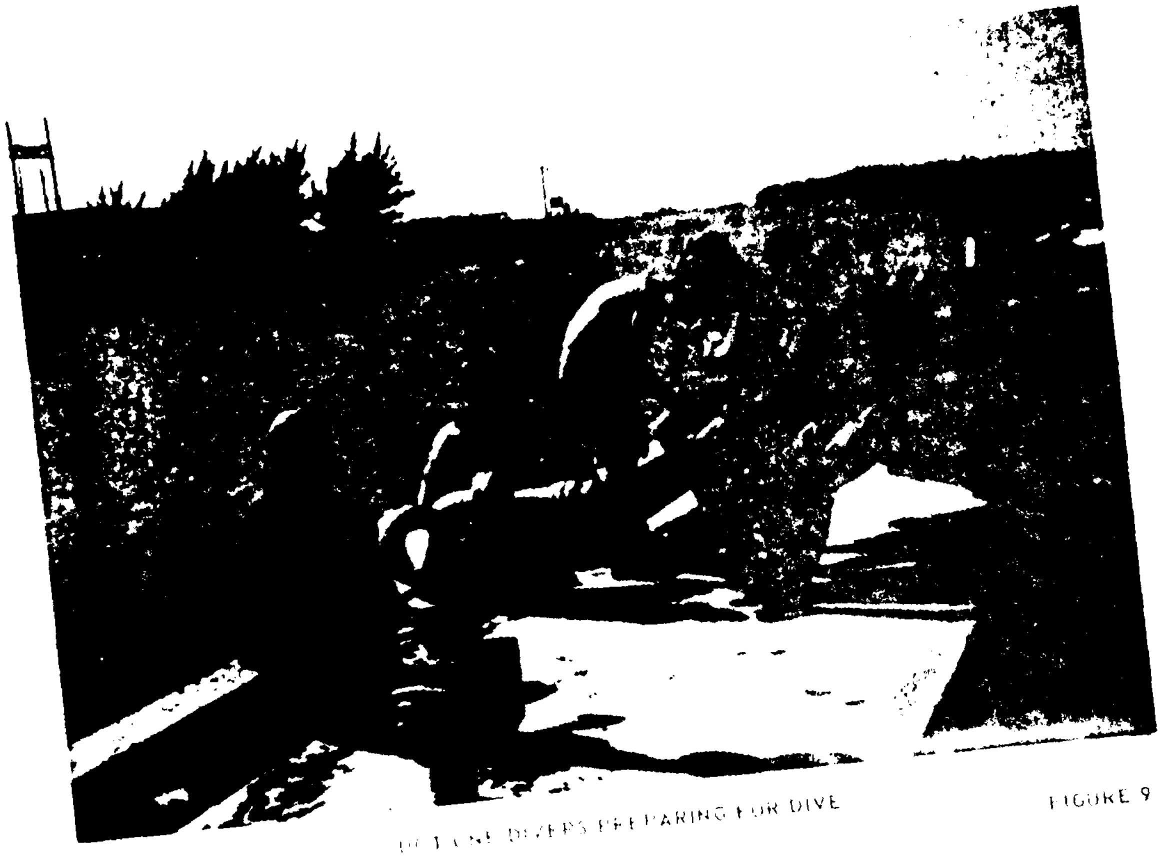
Divers, Figure 9, using open-circuit SCUBA performed a visual and tactile inspection on all sides of Pier D-3. On the west end and on the south side of the pier the visual inspection was conducted by pairs of divers covering 10 foot to 12 foot wide vertical swaths. The divers started at the surface, swam to the bottom, moved over 10 to 12 feet, returned to the surface, and reported their findings. They would then move over 10 to 12 feet along the surface and repeat the cycle.

On the vertical passes, the divers would look at and tap the sheet piling to sound for thin or hollow spots. They also cleaned small areas at random to inspect the bare metal surface. Additionally, they cleaned and investigated blisters in the coral and other marine growth, Figure 10. On the horizontal pass at the bottom the divers inspected the keying of the sheet pile into the sea floor. All diver reports were recorded by the CHESNAVFACENGCOM representative on the pier deck.

The vertical swath method was fairly slow and tedious but gave good coverage of the most important areas. However, this approach took its toll on the divers because the repeated increase and decrease of depth required frequent clearing of the ears and some divers developed "ear-squeeze" symptoms.

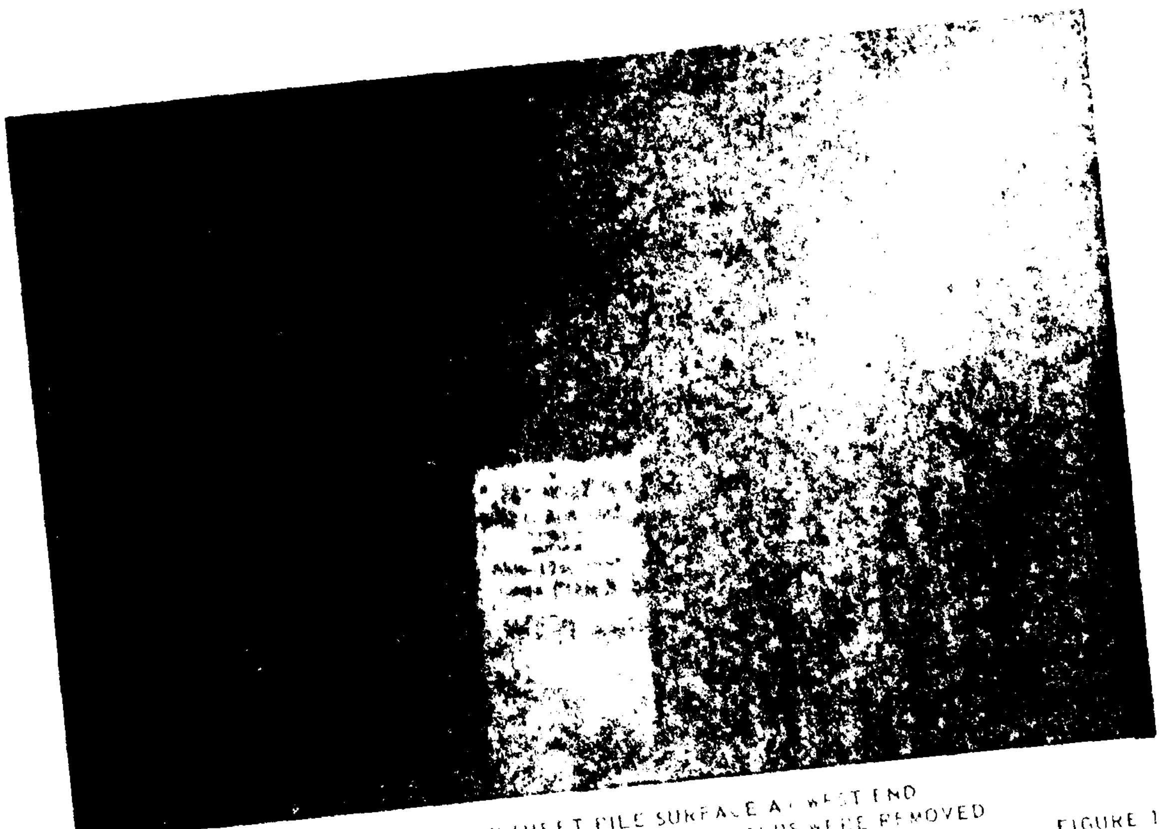
On the north side of Pier D-3 the inspection technique was changed to a horizontal swath approach. Three divers at separate depths, approximately 5 feet, 10 feet, and 15 feet swam laterally along the pier face taking advantage of the current running along the pier. The divers were instructed to surface immediately to report any specific damage and to surface at approximately 10 minute intervals to report depth readings and overall pier condition. No specific damage was found by this visual inspection technique.

Underwater voltmeter readings were taken using an instrument supplied by the Civil Engineering Laboratory. This voltmeter measures potential difference between a silver/silver chloride reference cell and a metal immersed in sea water. The instrument comprises a voltmeter and silver/silver chloride



[illegible] DIVERS PREPARING FOR DIVE

FIGURE 9



UNDERWATER SHEET PILE SURFACE AT WEST END
OF PIER D-[illegible] SHOWING AREAS WHERE BLISTERS WERE REMOVED

FIGURE 10

reference cell housed in a Plexiglas case and attached to a titanium probe. The diver places the probe on the metal, waits a few seconds for the reading to stabilize, then reads and records the potential of the metal.

The ultrasonic thickness measurements were taken with instrumentation supplied and operated by personnel of the Civil Engineering Laboratory, Figures 11 and 12. The equipment for these measurements and for the underwater potential measurements are described in Appendix A. The thickness tester gives a digital display of material thickness and a CRT display that can be used to adjudge the accuracy of the reading.

PIER D-3 ABOVEWATER INSPECTION RESULTS

The topside walk-around inspection revealed that most cleats and bollards on the pier were very heavily pitted by corrosion and all should be replaced if the pier is to be utilized for mooring naval vessels (Figure 13). The fender system is mostly missing or disintegrated and where it still exists it is totally ineffective. The concrete curbing, Figure 14, is cracked and spalled in many locations; although this does not pose any structural problem it should be repaired for cosmetic effect. The utility tunnel access covers are rusted or missing in many locations. Shrimp boat crews have been using the utility tunnels for trash dumping and thorough cleaning-out is needed before they can again serve their basic intended purpose.

At and above the waterline, all sheet piling is in the tidal/splash zone. Virtually all of the coal tar coating is missing, especially on the south side of the pier which has the greatest exposure to prevailing winds and waves (Figure 15). The sheet piling in this zone is generally excessively corroded, Figure 16; in one location, the sheets have corroded completely through and the concrete wall of the utility tunnel is exposed (Figure 17). Corrosion products appear to retain the basic shape of the Z-pile but may have expanded in thickness. The scaling is layered oxidized metal with thicknesses up to 3/4" to 1" in some places.

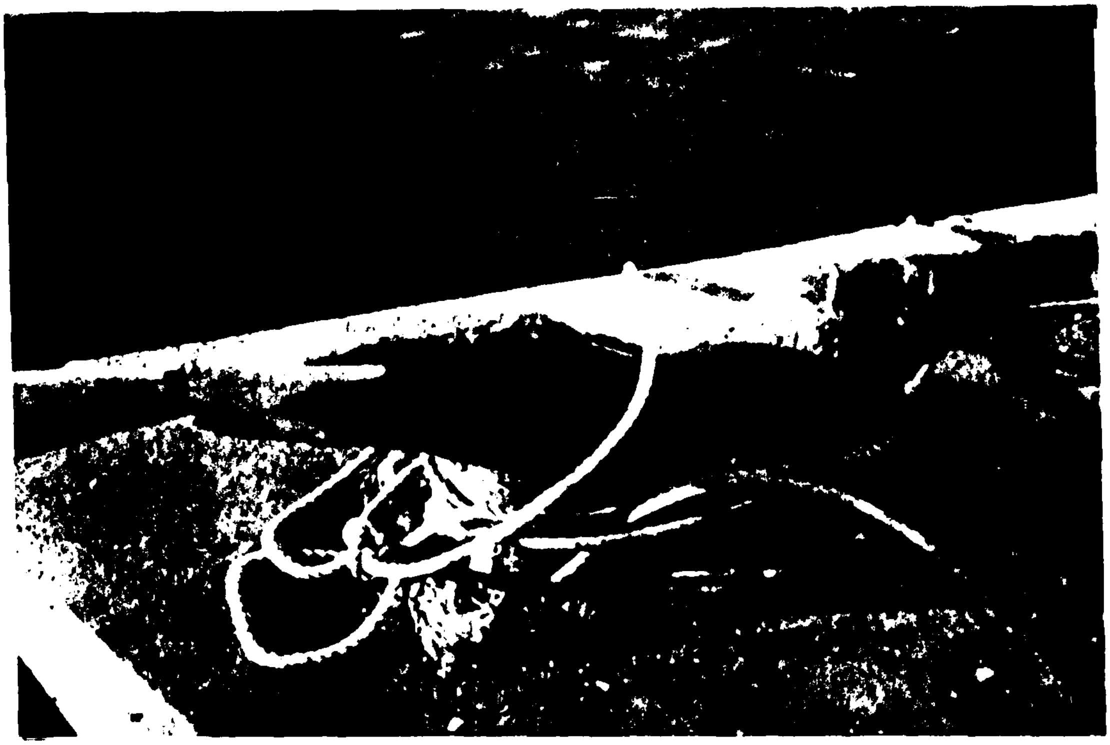
All of the foregoing items were brought to the attention of R. Young of the Naval Air Station and it was strongly recommended that a careful inspection of the sheet piling above the waterline be made.

UNDERWATER ULTRASONIC TRANSDUCER BEING USED
ON CLEARED AREA OF SHEET PILE WEB - PIER D-3

FIGURE 11

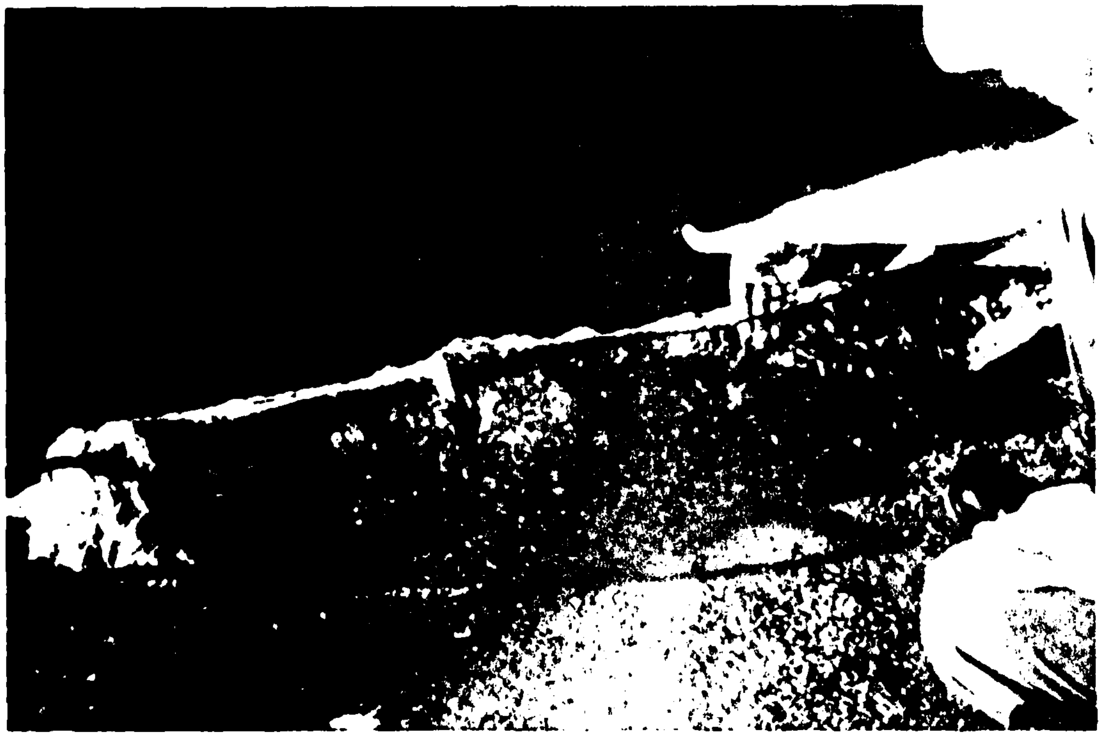
TEST EQUIPMENT READ-OUT UNITS INSTALLED IN
VAN ON DECK OF PIER - TV MONITOR AND ULTRASONIC GEAR

FIGURE 12



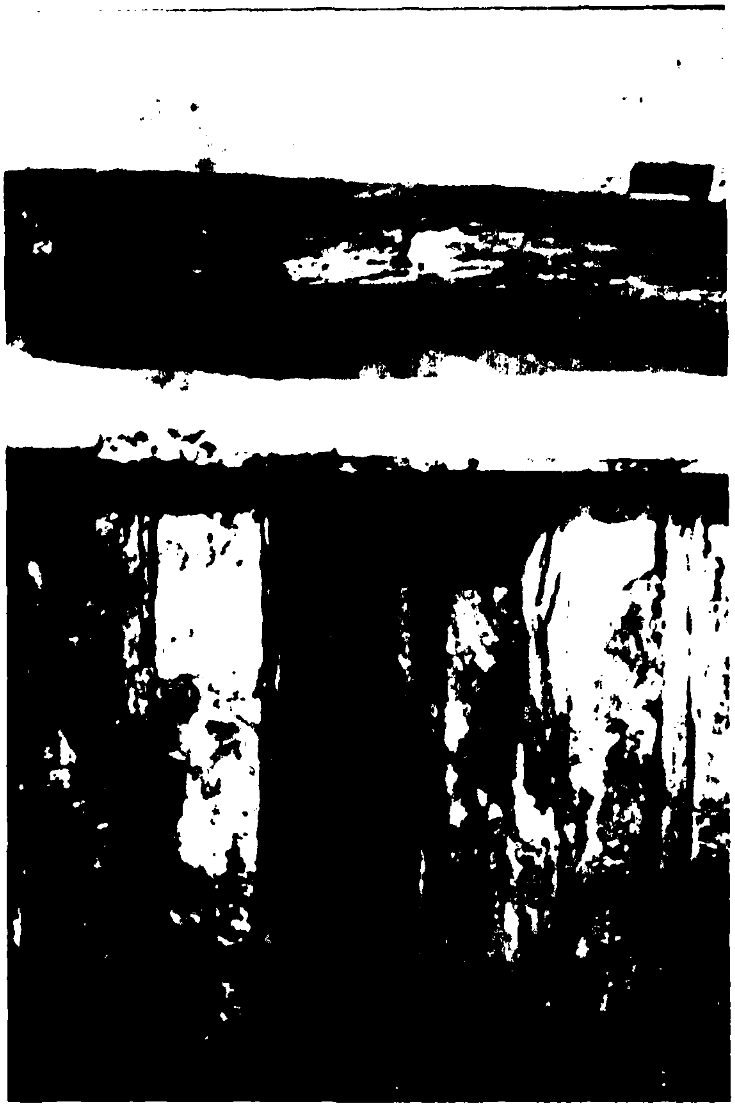
TYPICAL BADLY CORRODED CLEAT ON PIER D-3

FIGURE 13



CONDITION OF CONCRETE CURB ON PIER D-3
SHOWING EXPOSED AND CORRODED REINFORCING BAR

FIGURE 14



CONDITION OF SHEET PILE ABOVE WATERLINE
ON SOUTH SIDE OF PIER D-3

FIGURE 15

PIER D-3 UNDERWATER INSPECTION RESULTS

It was found that the bottom of the sheet piling is keyed into the coral for the full length of the pier on both sides. No fill material is escaping beneath the toe of the sheet pile wall.

ACCUMULATED CORROSION PRODUCT FROM SHEET PILE
ABOVE WATERLINE ON SOUTH SIDE OF PIER D-3

FIGURE 16

CONCRETE WALL OF UTILITY TUNNEL EXPOSED BY
CORROSION OF SHEET PILE ABOVE WATERLINE

FIGURE 17

No cracks, rips, tears, or corrosion holes were found below the waterline. Sheet pile joints were all tight, no gaps were found, and no fill was being lost. The pile appeared to be sound and straight. Piles that were tap-tested with a hammer/scraper gave no evidence of thin spots or corrosion cavities. See Figures 18, 19, 20, and 21.

The sheet piling was generally covered by tight marine (coral) growth. The growth thickness varied from approximately 1/4" near the mudline to as much as 3/4" at the waterline. Some fuzzy marine growth, oysters, and other shell fish were also attached to the coral.

The engineering design of the internal wales and tie rods (see Figure 7) is such that no access is provided for the inspection of the tie rod ends. It would be necessary to excavate the fill in order to expose the tie rods for inspection and therefore the inspection team had no knowledge of the condition of the ends of the tie rods. These ends are at or near the tidal zone and could be subject to wet and dry cycles; thus, they could be in poor shape but there is no solid evidence as to whether they are in good or bad condition.

The bolts and plates holding the sheet piling to the internal wales were occasionally missing, but the loss rate does not presently appear to be significant. One bolt and plate was knocked off by a diver with only moderate force while attempting to clean marine growth. Following this incident several other bolt/plate combinations were tested by tapping with moderate to heavy force; however, no additional bolts were dislodged. (Other bolts were probably in poor condition and not all were tested although the majority were observed to be in place. There is no non-destructive test method to determine bolt condition and if failures were located there is no means of replacement other than excavating the fill material inside the sheet piling.)

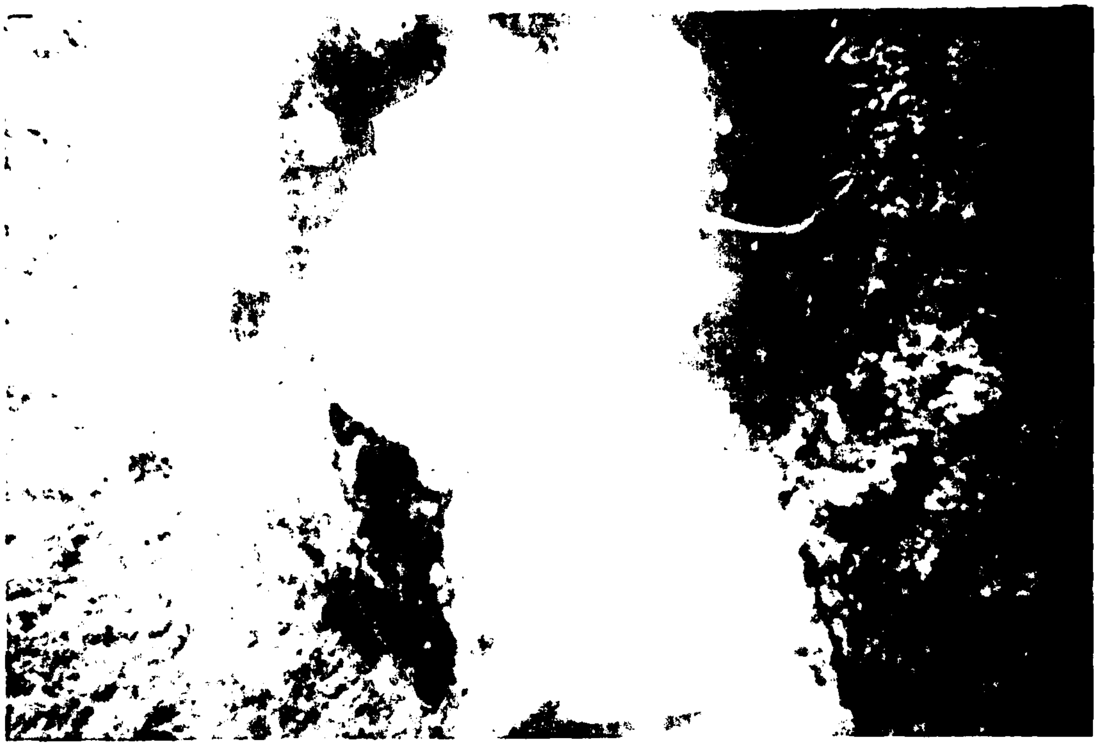
Randomly located, scattered blisters were found on the sheet piling. The blisters were generally orange color from rust bleeding through the coral. These blisters ranged in diameter from 1" to 6" and occasionally larger. These showed as a slight bulge in the coral cover, which, when punctured, would disintegrate into an orange cloud in the water. Several of these blisters gave off a gas bubble when punctured. Under the coral crust, the original coal tar coating was still intact but not firmly attached to the surface. There

CLEANED METAL SURFACE. DARK GRAY AT EDGES OF CLEANED AREA IS ORIGINAL COAL TAR COATING

FIGURE 18

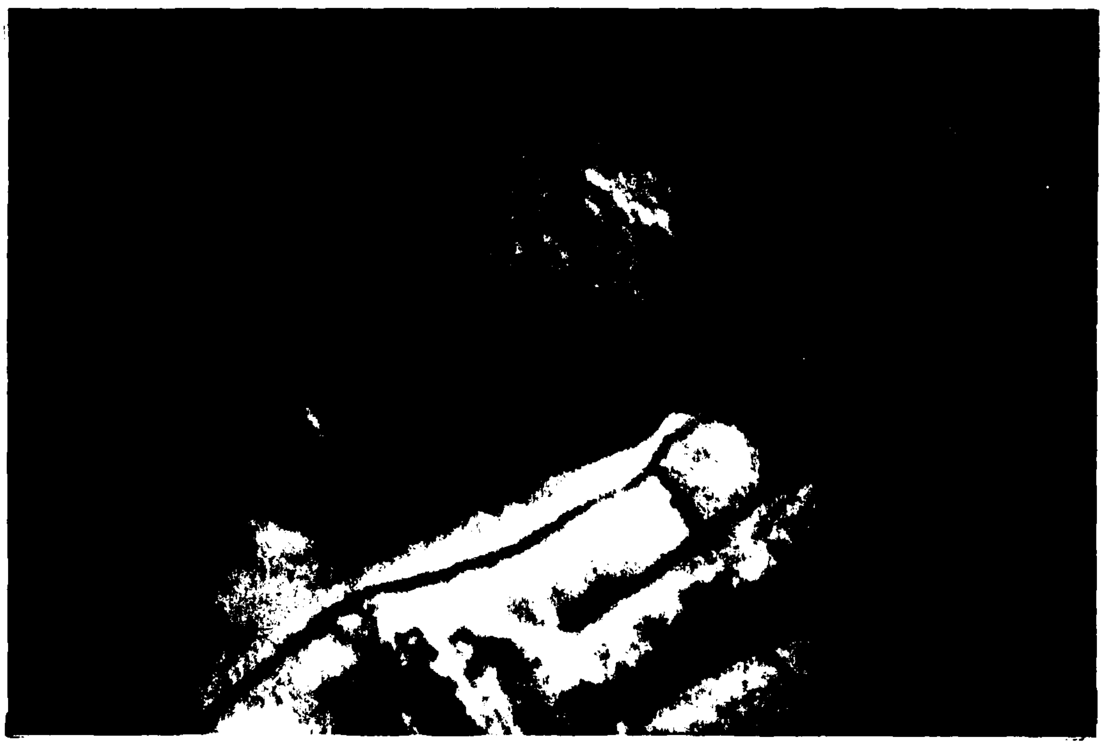
TYPICAL CONDITION OF UNDERWATER SECTIONS OF SHEET PILE. VERTICAL RIDGE IS JOINT BETWEEN SHEETS

FIGURE 19



CLEANED METAL SURFACE. PIER D-3 UNDERWATER

FIGURE 20



CLEANED AREA SHOWING BRIGHT,
SOUND METAL BENEATH CORAL COVERING

FIGURE 21

was a medium gray colored material (corrosion product) under the coal tar with shiny metal beneath the clay material. The metal surface was generally fairly smooth but had some deep pits (1/4" deep and 1/2" to 3/4" in diameter) in various locations on the metal surface. There was no overall patttern as to blister vertical location but the blisters seem to be located on the inner flanges and webs of the sheet pile sections, appearing only infrequently on the outer (seaward) flange.

In areas where there were no blisters and the tight coral growth was scraped off, scraping was very difficult, Figure 22. Under coral the coal tar coating was sound and the metal underneath was shiny and smooth. There was a very thin layer of light gray material between the coal tar and the metal.

Underwater voltmeter readings, Figure 23, were taken to measure corrosion potential. These results range from -0.587 volts at 25 foot depth to -0.597 volts at 8 foot depth with an average for 14 readings of -0.591 volts. The typical corrosion potential for steel is -0.6 to -0.7 volts. Thus, the results indicate that normal corrosion of the sheet pile is occurring and no cathodic protection system is in operation.

Ultrasonic measurements, Figures 24 and 25, were taken at nine locations on the south face and end of the pier at various depths for a total of 18 sets of readings of which about 167 were considered to be good and valid readings. The operator was R. Brackett of the Civil Engineering Laboratory who made the comment that approximately one-third of the readings were very good, approximately one-third of the readings were probably good, and approximately one-third of the readings were no good or unreliable.

The ultrasonic measurements generally support the conclusion that the sheet piling is undergoing fairly uniform normal corrosion. Design drawings give a nominal thickness of the web of three-eights of an inch and of the flange of one-half inch. From the measurements the average web thickness was estimated to be 0.315 inches with a standard deviation of 0.0429 inches. In other words, approximately 60 mils had been lost in the 29 years since the pier was rebuilt or approximately 2 mils per year. From the readings on the flange thickness a comparable loss of thickness was 1.5 to 2.1 mils per year. These results are considered to be normal for steel in sea water.

Although the 1951 drawings indicated that any dredges working around the pier should be limited to a distance of 15 feet horizontally from the

DIVER SCRAPING AWAY CORAL (TOOL LOST IN SHADOW). UNIFORM CORAL COVER AT LEFT

FIGURE 22

UNDERWATER VOLTMETER BEING USED TO MEASURE CORROSION POTENTIAL, PIER D-3

FIGURE 23

ULTRASONIC TESTING. NOTE UNIFORM CORAL COVER TIGHTLY BONDED TO METAL.

FIGURE 24

ULTRASONIC TRANSDUCER IN USE ON PIER D-3

FIGURE 25

sheet pile it was apparent that at some time a dredge had worked considerably closer than this limit. However, there were no problems noted relative to undercutting of the toe of the sheet piles and there was no indicated loss of fill.

CONCLUSIONS AND RECOMMENDATIONS RELATIVE TO PIER D-3

Below the waterline the sheet pile is in good condition. There are no cracks, rips, or open joints. The toe is embedded in the coral and no fill is escaping. At and above the waterline the sheet pile is very corroded, to the point of having disappeared at one location leaving the concrete wall of the utility tunnel exposed.

Bolts and plates attaching the sheet pile to internal wales are occasionally missing but the loss rate is not considered to be of major significance. The tie rod and wale condition is unknown since these structural elements are not susceptible to observation. This is of some concern since these elements are in the tidal zone. The degree of possible corrosion and wet/dry cycling is dependent upon how well the sheet pile isolates the structure from the water. Over the past 29 years it is inevitable that some water has attacked the tie rods and wales.

It is concluded that Pier D-3 can be used for destroyer berthing without major reconstruction, at least for a few years usage.

If the pier is considered for the above use it is recommended that the sheet pile bulkheads be cleaned and coated from about three feet below the mean low water line to the top of the piling to reduce further corrosion. Sand blasting and a hi-build epoxy coating is recommended. Cleaning should be carefully done so as to avoid puncturing through thin spots. Any punctures below the concrete wall of the utility tunnel should be plugged to keep water from the backside of the sheet pile.

Repair of the topside discrepancies noted earlier is under the cognizance of the Naval Air Station, Key West.

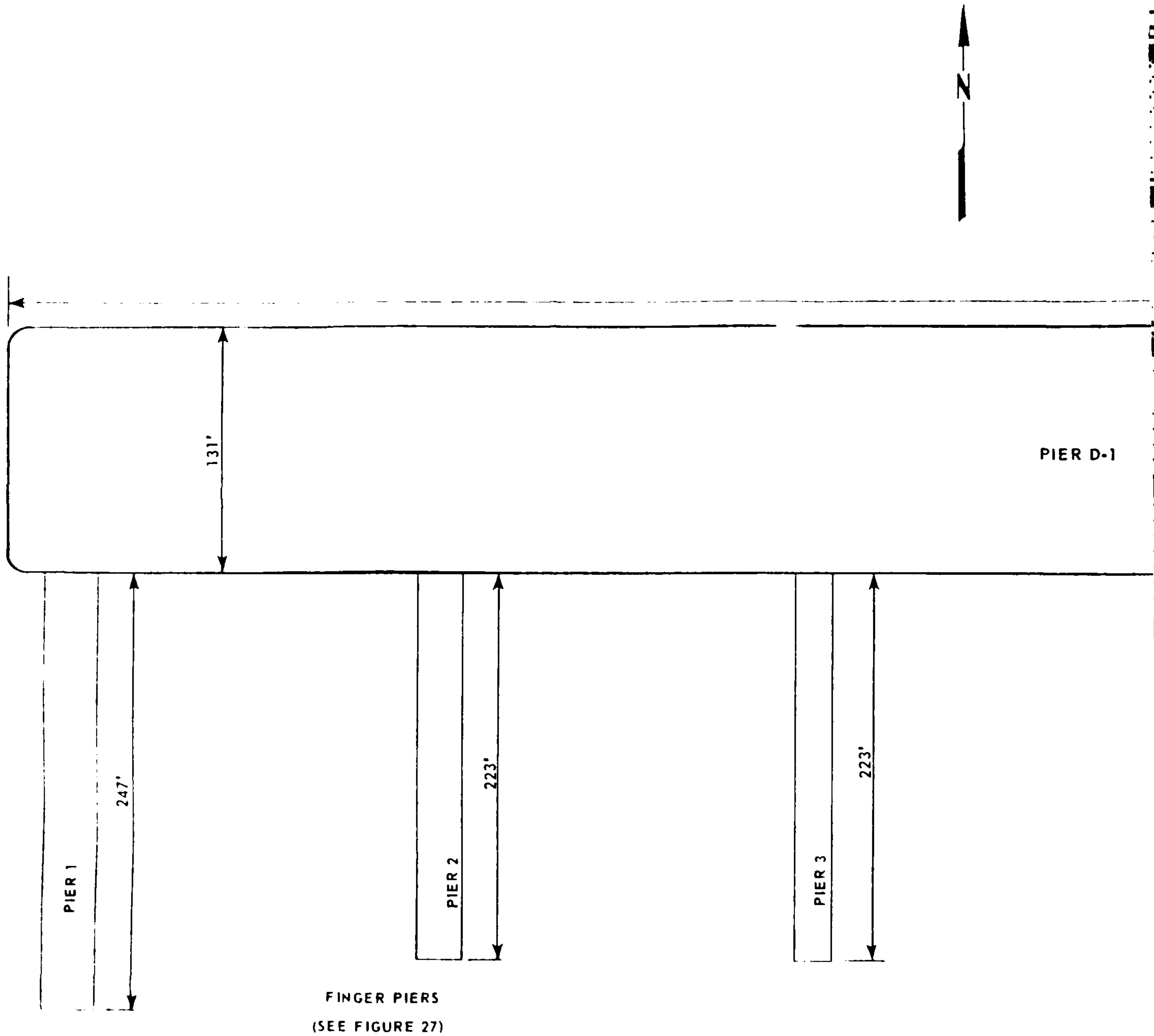
INSPECTION OF PIER D-1 AND FINGER PIERS

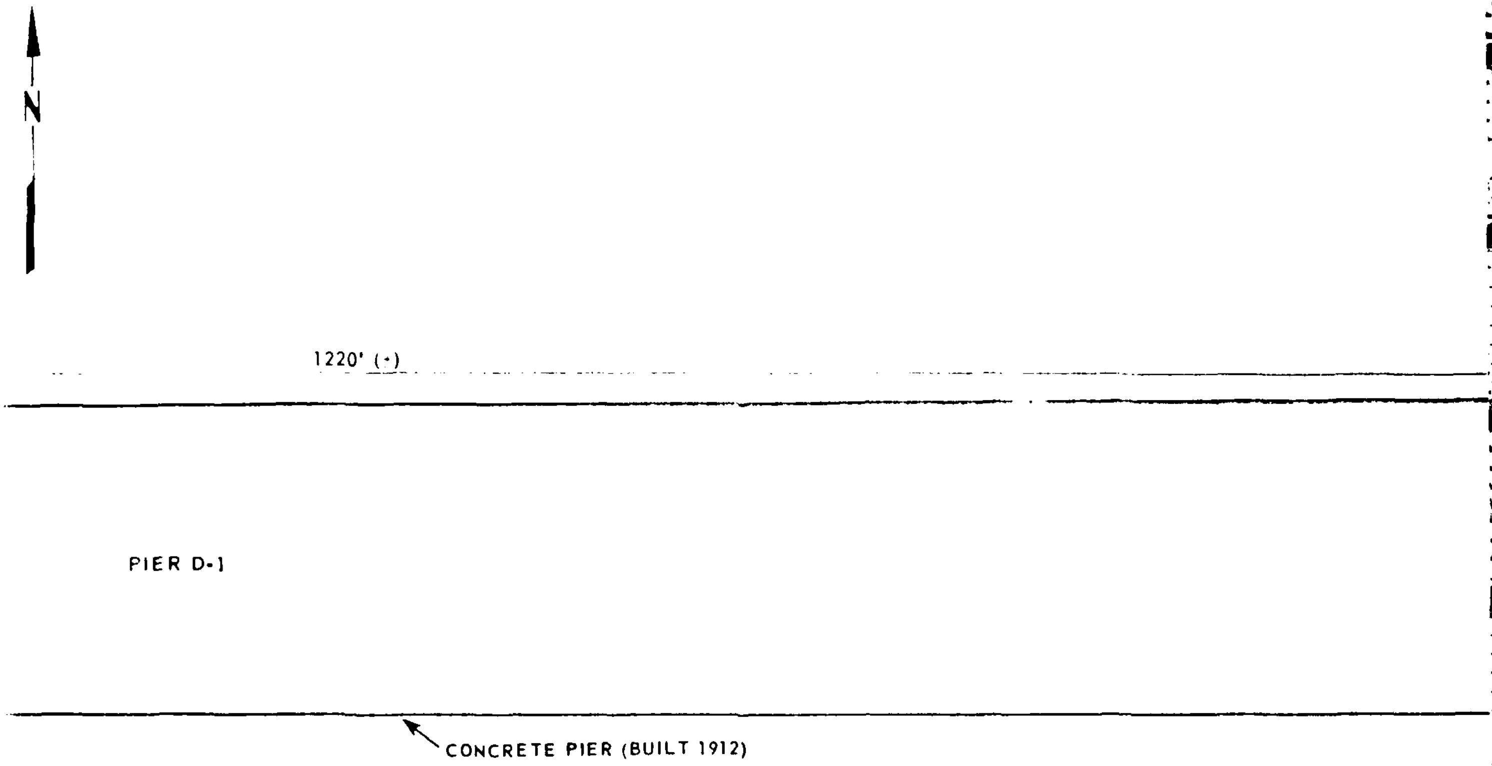
DESCRIPTION

Pier D-1 comprises monolithic poured concrete walls surrounding compacted coral fill with a paved-over deck. It was constructed in approximately 1912 by the Flagler Steamship Line. The general design is known and a few drawings are available but complete details of the original construction are lacking. The pier has been in use by the Key West detachment of the Naval Air Development Center (NADC) of Warminster, Pa. and therefore is not involved in the "excess property" situation that applies to Pier D-3. As shown in Figure 26, there are three finger piers extending out to the north from the western extremity of Pier D-1; these piers are numbered 1, 2, and 3 working from the outer pier toward the shoreline. The two of these finger piers involved in the inspection are the finger piers 1 and 3 of which a typical plan view is given in Figure 27; the typical cross section also given in Figure 27 shows the bent detail. The caps are 18 WF114 steel H-beams; additionally both the bearing piles and brace piles are 10 BP 57 H-pile construction. Stringers and sway braces are also fitted. I-beams running longitudinally atop the bents support the concrete paving of the deck. Wooden stub fenders are supported out from the bents and from the bearing piles by wooden wales. Both the north and south sides of Pier D-1 are dredged to 20 feet with the north side dropping off to 30 feet within 2 to 3 feet of the pier. Since the north side of Pier D-1 may be utilized for PHM craft, it is important that any obstacles on the bottom or shallow spots be located.

INSPECTION METHODS

Divers using open circuit SCUBA performed both a visual and tactile inspection of all sides of Pier D-1. In order to avoid the diver "ear-squeeze" problem, the concrete structure of Pier D-1 was inspected using the horizontal swath technique. This was the same technique employed on the north side of Pier D-3 using the same number of divers at approximately the same depths. The inspection of the main structure of Pier D-1 was exclusively a visual and tactile inspection of the outer concrete walls.


N
131'
PIER D-1
247'
PIER 1
223'
PIER 2
223'
PIER 3
FINGER PIERS
(SEE FIGURE 27)



ARRANGEMEN
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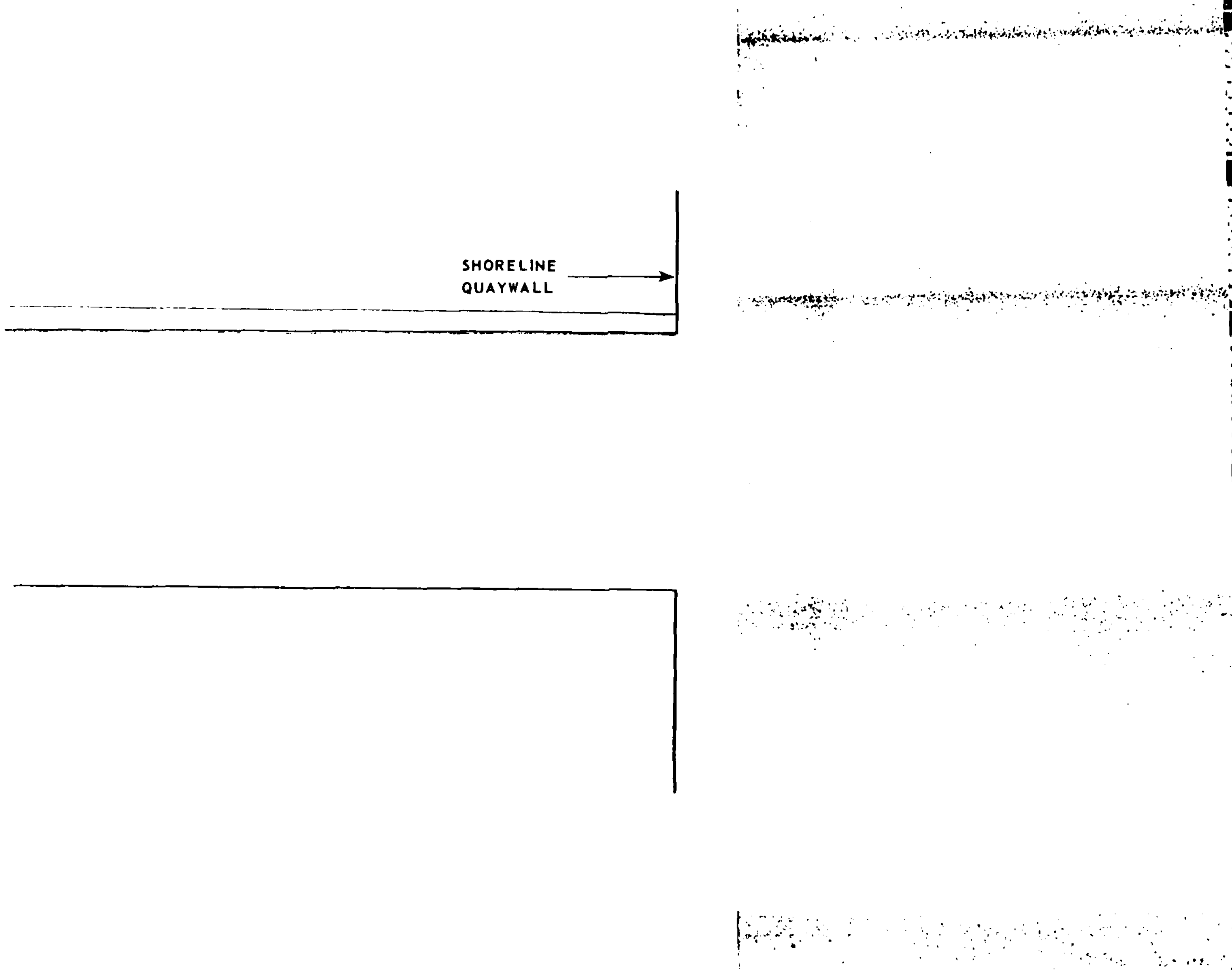
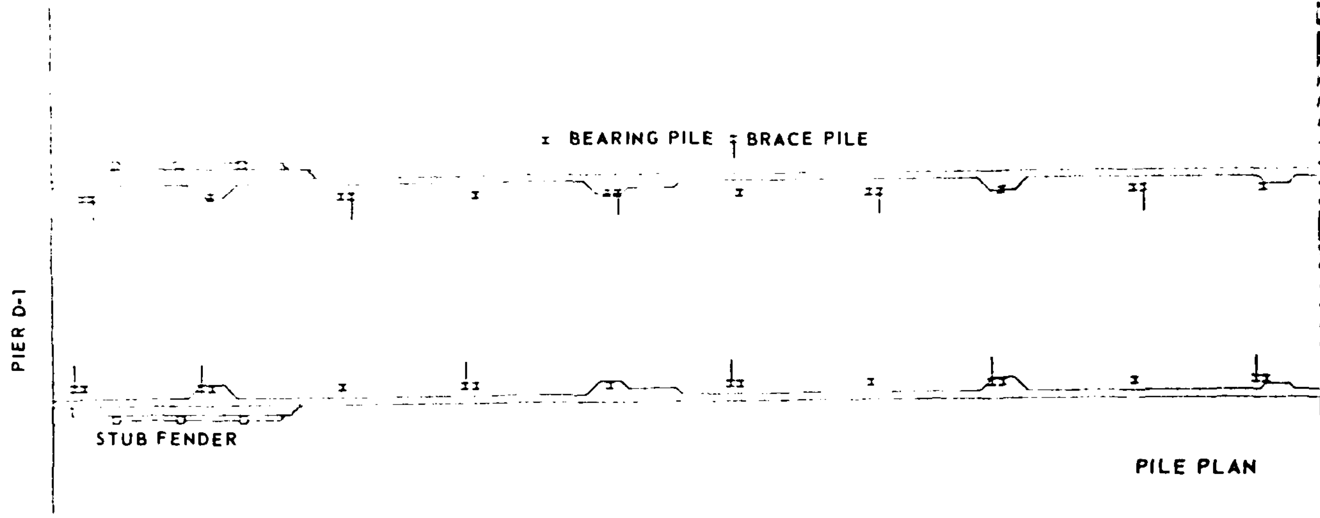
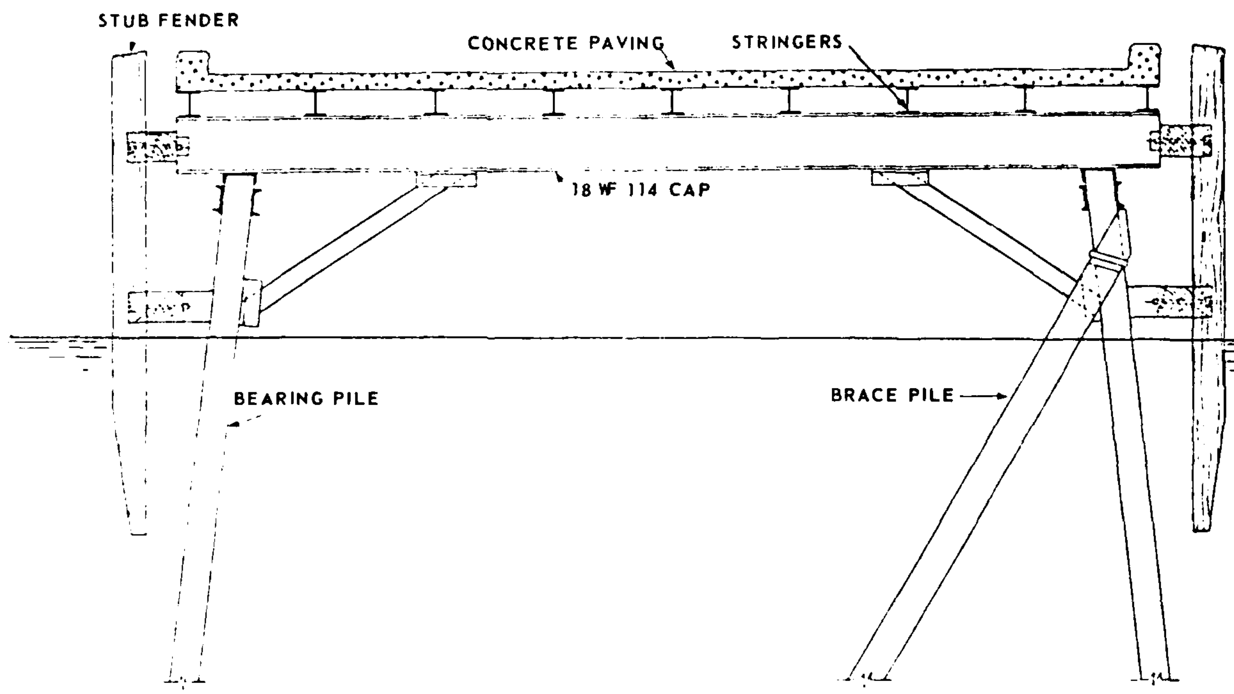


ARRANGEMENT OF PIER D-1
AND FINGER PIERS

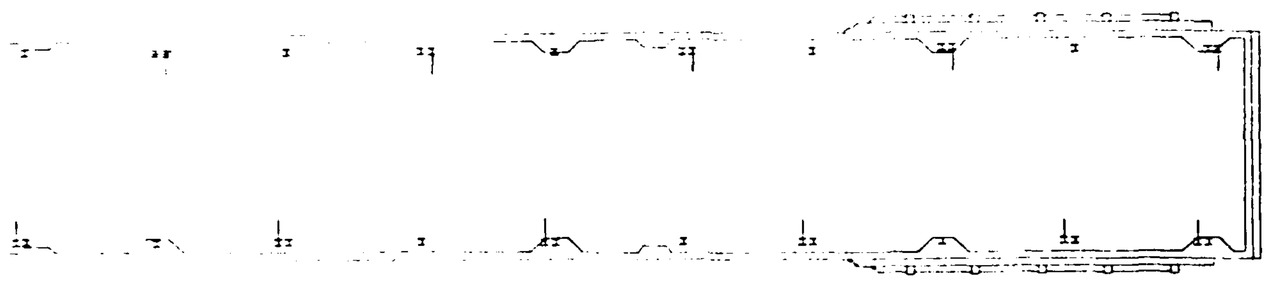
FIGURE 26



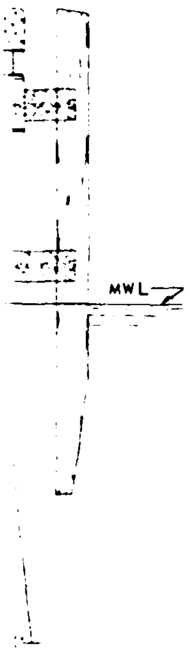
PILE PLAN



FINGER PIER BENT DETAIL



AN



FINGER PIER PLAN AND DETAILS

FIGURE 27

All three of the finger piers jutting out from the south side of Pier D-1 were inspected abovewater,with the inspection including several steel H-piles, caps, and stringers. A visual and tactile underwater inspection of piers 1 and 3 was made and, in addition, underwater voltmeter readings were taken on the H-piles and sacrificial anodes on the finger piers. The underwater inspection involved underwater photography and video documentation.

PIER D-1 FINGER PIERS ABOVEWATER INSPECTION RESULTS

Above the waterline (in the splash zone), the H-piles showed some corrosion damage and no coating was evident. The stringers, on the other hand, are in poor condition. They are quite corroded especially on the outboard ends which receive the most exposure to wave action. Some flanges are very thin and some holes exist in the webs to the extent that a dive knife can be pushed through the holes in the webs, Figure 28. This information was conveyed to R. Young of the Naval Air Station with the suggestion that these piers be inspected from a small boat to determine and document their condition.

PIER D-1 UNDERWATER INSPECTION RESULTS - MAIN PIER

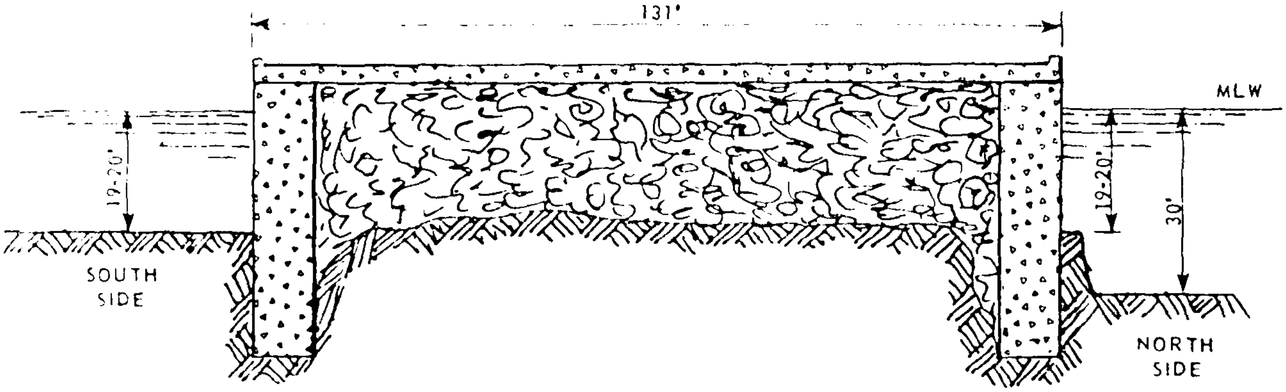
During some previous dredge operation the dredge apparently worked very close to the concrete wall of Pier D-1; the wall is undercut in a few places. The undercutting is minor, however, and there appears to be no major damage to the pier. A typical dredging profile along the length of Pier D-1 is shown in Figure 29.

The concrete wall, covered with coral and marine growth, is in very good condition. There are no signs of spalling or other age effects such as corrosion or deterioration. No reinforcing materials are exposed. There is some evidence of mechanical damage, probably from collisions of ships using the pier.

There are occasional vertical cracks in the pier wall which are wider at the top and thin down to the point of disappearing at the bottom. This is considered to be normal settlement-type cracking. There are some minor gouges in the wall that appear to have been caused by the cutter-head of a dredge. The general conclusion, with respect to the primary concrete Pier D-1, is that

CORRODED CONDITION OF DECK, STRINGERS ON
PIER D-1 FINGER PIERS. NOTE KNIFE BLADE THROUGH BEAM WEB.

FIGURE 28



CROSS SECTION OF PIER D-1 SHOWING DEPTHS

FIGURE 29

the pier is in good condition. There is apparently no problem with regard to obstructions or shallow points along the pier for the mooring of PHM craft.

PIER D-1 UNDERWATER INSPECTION RESULTS - FINGER PIERS

The finger piers had been identified as lowest priority for inspection and therefore were done at the end of the inspection period resulting in only a cursory look at the piers. There were no signs of any major deterioration or corrosion in the underwater portion of the H-piles. No hourglassing or thinning of flanges was noted. Neither were there signs of any major impact damage nor bent or buckled piles evident. Some marine growth was present, Figure 30.

The finger piers were protected by a cathodic protection system comprising two zinc anodes, 9" x 9" x 10.5" in each bay, one at approximately 3 foot depth and one at approximately 14 foot depth below the surface. The underwater voltmeter, Figure 31, was used to measure the effectiveness of the cathodic protection system.

Twelve piles were tested in two of the three piers out of a total of 80 total piles in these two piers. There were 32 readings of potential ranging from -0.973 to -0.986 volts with an average of -0.979 volts and a standard deviation of 0.0036 volts. These results indicate full cathodic protection of the underwater steel sections of these piles; in fact, the results indicate over protection and therefore excessive use of the zinc anodes. Thus, the finger piers are in excellent condition below the water surface.

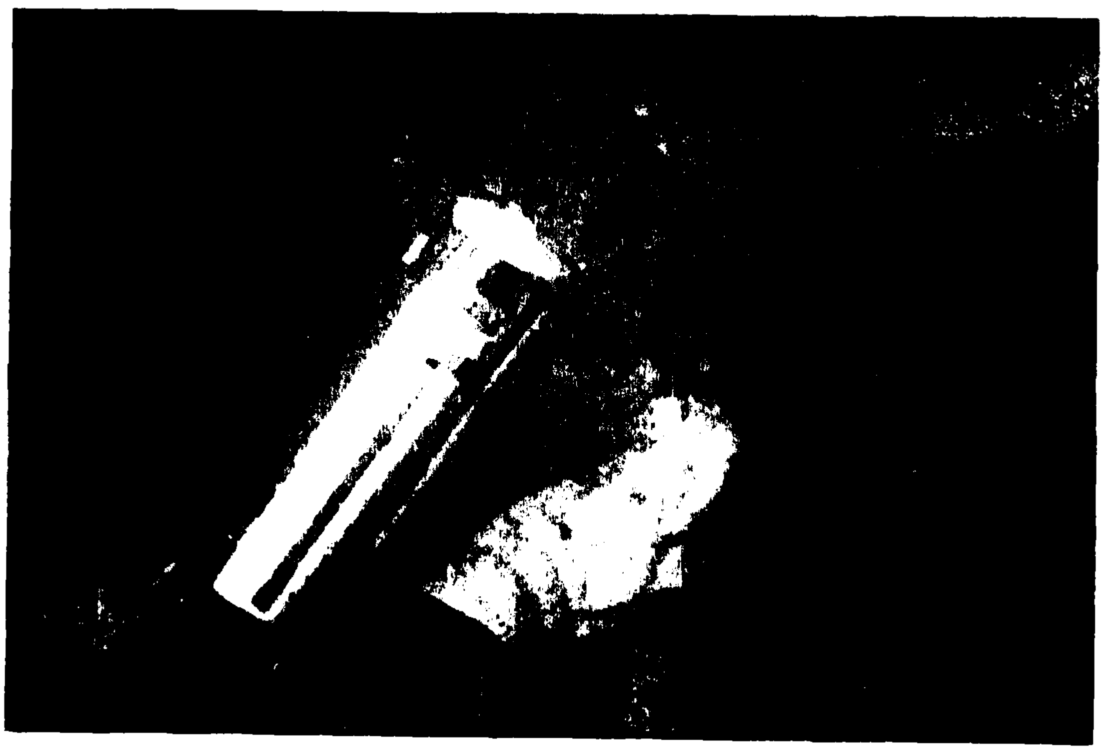
CONCLUSIONS AND RECOMMENDATIONS RELATIVE TO PIER D-1

The main concrete structure of Pier D-1 is in excellent condition with only minor vertical cracks in the pier wall and occasional undercutting due to dredging. No repairs are required on the underwater portion of the pier in order to make it acceptable for the berthing of vessels on either the north or south sides that require a 20 foot depth.

The underwater condition of the finger piers is excellent and they are more than adequately protected by anodes currently in place. There is abovewater deterioration which should be arrested if the piers are to be utilized. It is recommended that the H-piles, stringers, and caps be cleaned and coated from about three feet below the mean water line to the deck in order to reduce further corrosion. Sandblasting and a hi-build epoxy coating is recommended.

MARINE GROWTH ON H-PILE
UNDER PIER D-1 FINGER PIER

FIGURE 30



UNDERWATER VOLTMETER BEING USED
ON PIER D-1 FINGER PIER

FIGURE 31

REFERENCES

(1) CNO LTR SER 44/391983 of 29 Mar 79

(2) COMNAVAIRLANT MSG 181428Z JAN 80

APPENDIX A

INSTRUMENTATION EMPLOYED IN THE KEY WEST - TRUMBO POINT UNDERWATER FACILITIES INSPECTION AND ASSESSMENT

USE OF UNDERWATER VOLTMETER

PRINCIPLE OF OPERATION

This instrument measures the potential difference between the titanium probe, or as we shall see the structure contacted by the titanium probe, and the silver/silver chloride reference electrode near the base of the probe in tthe probe holder. The silver/silver chloride electrode has a known potential in seawater. Therefore, if the potential difference between the silver/silver chloride electrode and another piece of metal is known then we know the potential of the metal. When the titanium probe is not touching a metal structure the voltmeter indicates the potential of the titanium. However, when the probe makes contact with any metal structure, the potential of the titanium probe changes quickly (less than 1 second) to the potential of the metal structure. This property of the titanium probe is known as polarization. While all metals polarize to some extent titanium polarizes almost completely. This is why titanium was selected for use as the probe in this instrument.

OPERATION TECHNIQUES

Apart from the normal operating procedures (turn meter on, etc.) it is important for the operator to be able to distinguish between true and false readings in the use of this instrument. This can readily be accomplished by noting the changes in meter readings when the probe is brought into contact with the portion of the structure to be measured. It should be noted that when the probe is not in contact that the potential indicated on the meter usually drifts between - .200 and - .400 and never really settles down to a constant reading. When good contact is made with a metal structure the reading will quickly change to a nearly stable reading (say - .648) then change slowly in one direction for one or two seconds (say - .649 then - .651). The reading will then stay constant, except perhaps with the last number changing back and forth (say - .651 to - .650 to - .651 etc.). This behavior indicates that a true reading of the metal structure potential is being obtained. If good contact between the structure and the probe is not maintained, false or erroneous potential readings will be obtained. This lack of good contact can be detected by noting the stability of the potential readings indicated on the voltmeter. If the indicated potential drifts more than .010 volts over a short period, particularly if it shifts rapidly between a high and low value then good contact between the probe and structure is probably not being maintained. In order to make good contact with some structures, particularly if they are painted or covered with fouling or corrosion products, the probe can be used as a type of scraper actually removing the interfering material in a small area. The titanium probe is strong and tough and will survive moderate abuse. If the probe tip is dulled or broken it can be resharpened using a file or sharpening stone.

TYPICAL USES AND TYPES OF READINGS OBTAINED

Galvanic Corrosion. When two or more metals are electrically connected and immersed in seawater a type of battery is formed and the electric current produced results in some components of the system corroding at an accelerated rate. This type of corrosion is dependent on the potential difference between various metals in seawater as shown in Table 1. However, when galvanic corrosion is occuring there is little potential difference between the various components. The potential of the combination is somewhat between the uncoupled potential of the materials involved. Therefore, if a significant potential difference (more than 0.050 volts) is found between different materials on the same structure, then galvanic corrosion is probably *not* occuring. However, if there is less difference in potential between known dissimilar metals than is predicted from the values in Table 1, then galvanic corrosion is probably occuring.

Cathodic Protection. When a structure is being protected by either galvanic anodes (e.g., zinc) or impressed current the underwater voltmeter can be used to evaluate the extent of protection. For steel structures a potential of -0.800 volts is usually considered to indicate complete protection. Potentials above -0.800 volts (such as -0.700 volts) indicate underprotection and potentials under -0.800 volts indicate overprotection (such as -0.900 volts).

A survey of any cathodically protected structures to determine the potential at various areas can be used to evaluate the extent of protection achieved. Then the cathodic protection system can be modified as required to maximize the protection of the structure.

Table 1   Typical Corrosion Potentials

Material	Potential Range
Magnesium	-1.6V
Zinc	-1.0V
Aluminum Alloys	-0.75 to -1.0
Steel	-0.6 to -0.7
Brass	-0.3 to -0.04
Bronze	-0.25 to -0.35
Stainless Steel (400 series)	-0.25 to -0.30
70-30 Copper Nickel	-0.20 to -0.35
Stainless Steel (304)	-0.05 to -0.10
Monel	-0.05 to -0.10
Stainless Steel (316)	-0.00 to -0.10
Inconel 625	-0.05 to -0.05

Low-frequency Ultrasonic Testing

J. P. JOHNSTON, Sonic Instruments, Inc.

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Instrument Society of America, 1977

Although ultrasonics has been used in nondestructive testing for almost 30 years, almost all the work has been in metals testing. For those who are involved with nonmetallic materials, such as glass and ceramics, the author presents a brief survey of low-frequency ultrasonic techniques.

ULTRASONIC TESTING METHODS fall into one of two categories: pulse-echo and resonance techniques. For nonmetallic materials, the vast majority of testing methods are pulse-echo types.

Basic pulse-echo testing equipment consists of pulser, transmitter, receiver and display modules. The pulser generates electrical impulses of short duration, typically less than one μs for a half-cycle pulse, and with a peak voltage between 100 and 1,000 V. These pulses are repeated at regular intervals, usually from 500 to 10,000 per second.

A transmitter uses a piezoelectric transducer to convert the pulses into acoustic waves and transmit the waves into the material being tested. The acoustic waves are returned as echoes to a receiving transducer which, in turn, sends the impulses to a receiver circuit. The receiver usually consists of a broad band amplifier and some form of display.

A typical display is a CRT, in which the horizontal sweep is triggered by the initial signal from the pulse circuit and the vertical sweep is the rf or rectified video of the echoed signals. Amplitude and time delay are the two most important characteristics of the echoed signals, and these variables are the basis for flaw testing and thickness gaging, respectively.

Orienting transducers

Figure 1 illustrates the most common technique in ultrasonic testing: a single transducer, placed on the surface of the material under test, is used for both transmitting and receiving. If the transducer is placed parallel to the surface, then the acoustic signal will reflect correctly from the back wall of the material only if the two surfaces are parallel.

If the material surfaces are not parallel, then two transducers must be used. The transmitting and receiving transducers must be oriented so that the echoed signal from a nonparallel back wall or from a flaw can be picked up by the receiver, Figure 2A.

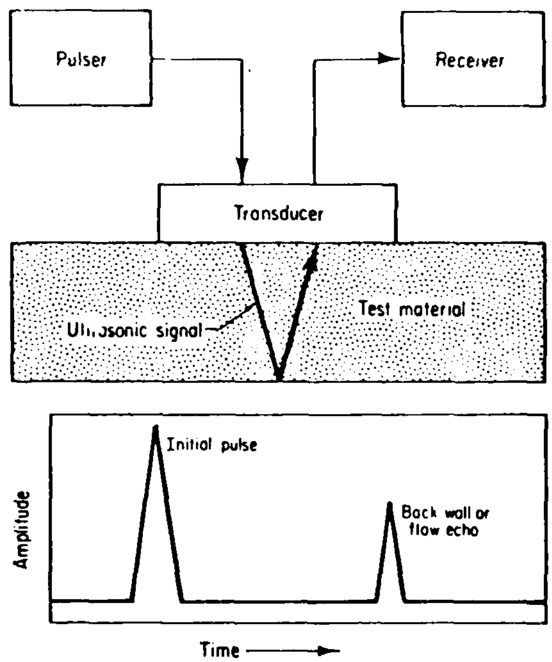


Figure 1. The simplest and most common method of ultrasonic testing requires only one transducer and parallel front and back surfaces on the material under test. Both the initial pulse and its echo are displayed on a CRT or oscilloscope for analysis.

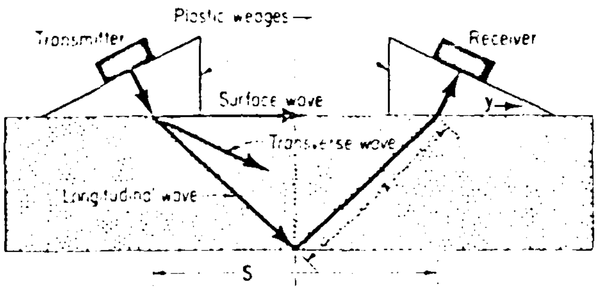
High Temperature Testing

Ultrasonic testing techniques were used in a series of experiments to determine characteristics of both glass and ceramic materials at high temperatures. A variety of transducer configurations were attemped, including single and dual transducer installations.

Because of high sound attenuation and the porous, granular nature of ceramics, a low-frequency electronic pulser rated at 90 kHz to 9 MHz was used. To achieve good penetration, tests were conducted with two transducers: a 160 kHz, 2-1/2-in. dia PZT undamped crystal, and a 320 kHz, 2-in. dia PZT unit. Both transducers had face plates made from temperature-resistant polyimide plastic to withstand high surface temperatures, and were acoustically coupled to the material surface with silicon grease.

Using a single transducer for both transmitting and receiving the acoustic signal proved to be successful only when the material being tested was very dense—such as isostatically pressed alumina or dense zircon and glass—and when the front and back surfaces were parallel.

A dual-transducer method was attempted, with both transducers positioned on the top surface. This technique yielded suitable results for moder-



The best configuration for high-temperature testing proved to be dual transducers mounted on heat-resistant plastic wedges. The angle of 30-35 deg permitted propagation of all three wave types.

In some instances, flaw geometry is so varied that it is very difficult to determine where the receiving transducer should be located for optimum return amplitude. This problem can be overcome by placing the receiver transducer *behind* the flaw, Figure 2B. With this configuration, the flaw will be detected because of signal loss rather than echo analysis.

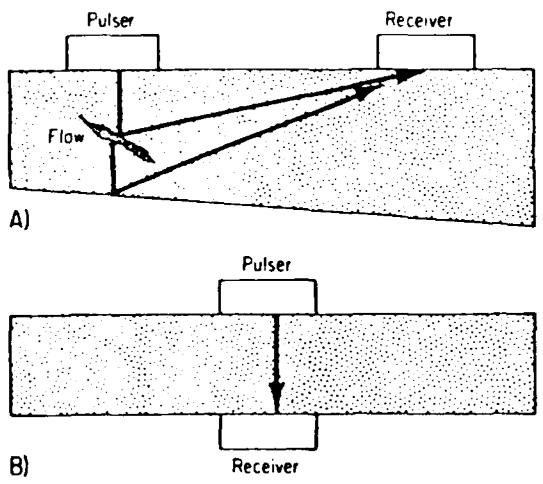


Figure 2. If two transducers are used, the receiver can be placed so that it correctly picks up an echo from a flaw or nonparallel back wall (A), or the receiver can be placed on the back wall (B) for through-transmit testing.

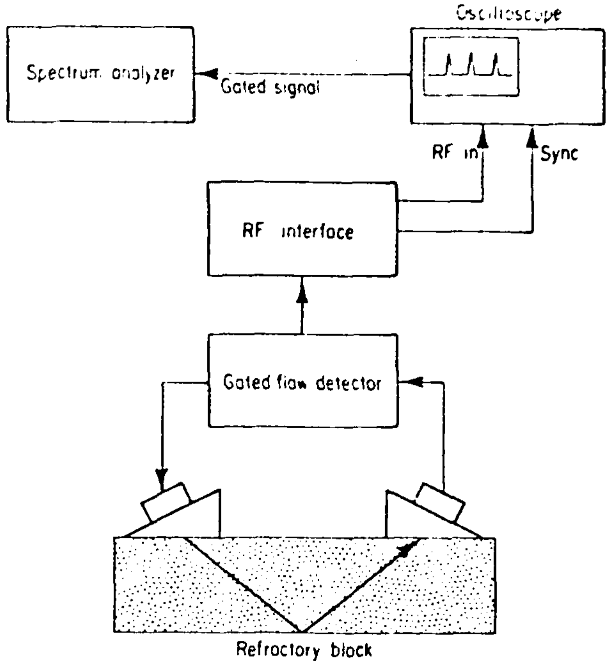
In some cases, it may be desirable to transmit the acoustic energy into the material at an angle. This technique requires the use of an intermediate material, or wedge, Figure 3, that transmits the sound freely into the material under test. The wedge must be carefully designed so that energy reflected from the wedge boundary dissipates in the wedge material and does not return to the transducer. This problem is especially apparent at low frequencies, where the attenuation of most wedge materials is small. However, proper wedge design can usually result in low internal noise even at the low frequencies required to penetrate porous ceramics.

As in any other wave phenomenon, when energy encounters a boundary at an angle, Snell's law determines the angle of refraction. Unlike light waves, however, ultrasonic waves undergo a mode conversion at the boundary when the angle of incidence is sufficiently large. When initially transmitted, the ultrasonic wave is longitudinal; when the angle is large enough, a second wave type occurs, in which particle motion is at right angles to the direction of propagation. This phenomenon is ately porous materials such as slip-cast clays and silica. It was also found that the back surface did not need to be parallel with the front surface. Although the sound path through the material was angled somewhat, longitudinal vibration modes could be used and precise velocity measurements were possible.

The most successful method for velocity determination was achieved by mounting the transducers on plastic wedges (left) made from the same material as the face plates. The angle of 30-35 deg was sufficient to propagate transverse waves, but the frequency had to be lowered somewhat because the transverse waves were easily attenuated in the material and the shear path was longer than the longitudinal path.

It was also possible to propagate surface waves directly between the transmitting and receiving transducers with this configuration. With the three velocities—longitudinal, transverse and surface—it was relatively easy to calculate various material parameters such as Poisson's ratio and elastic moduli.

Other tests carried out with the acoustic equipment (right) included determining acoustic velocities in isostatically pressed zircon and performing spectral analyses on various materials.



Electronic hardware for the test configuration consisted of a low-frequency pulser with a 600 V output, low-frequency transducers, rf gate/alarm, oscilliscope and a spectrum analyzer.

called a *transverse* or *shear wave*, and it has a velocity of approximately half that of the longitudinal wave.

The exact angle at which the transverse wave appears is governed by the velocity ratio between the wedge material and the material under test. If the angle of entry increases beyond this point, a *Rayleigh* or *surface wave* appears. This wave does not penetrate further than one wavelength into the material, and its velocity is usually 80 percent of the transverse wave. Another wave occurs when the acoustic wavelength is approximately equal to the thickness of the material. This is called the *plate* or *Lamb wave*, and it can be thought of as a surface wave that is in resonance with the thickness of the material under test. Plate wave velocity will vary, depending on what fraction of a wavelength constitutes material thickness.

Focusing on flaws

Another ultrasonic testing technique involves immersing the material to be tested in water. With this method, the transducers need not be in direct contact with the material because the ultrasound signal can travel through a water path of a few inches to several feet before entering the material. Immersion testing offers three advantages over direct contact testing:

1. Ultrasonic coupling into the material often is improved.
2. Transducer angles can be altered without the use of a wedge.
3. The ultrasonic beam can be focused.

A focused beam concentrates the ultrasonic energy on a very small flaw area, thus increasing intensity of the return echo from that flaw. In the case of a typical 1/2-in. diameter unfocused beam, a flaw of 1/8-in. diameter would intercept only 1/16 of the total beam energy; with a focused beam, the flaw would intercept the entire signal, increasing sensitivity by a factor of 16. This sensitivity increase is at the expense of the scanning rate, however, because each ultrasonic scan covers only 1/8 in. rather than 1/2 in.

Focusing is accomplished with a lens made from material (usually plastic) that has a sound velocity greater than water. A spherical concave lens converges the ultrasound signal to a spot, and a cylindrical concave lens converges the signal to a straight line. Improvements in scanning rates can be achieved with a line-focused lens, in which a 1/2-in. dia beam can be made into a rectangular one, 1/2-in. wide by 1/32-in. long. In this example, sensitivity is increased somewhat and the scan rate of 1/2 in. is maintained.

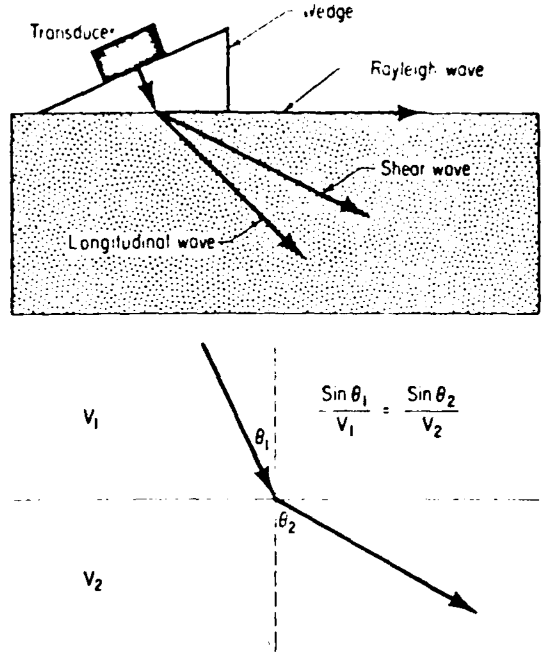


Figure 3. Transmitters (and receivers) can be mounted on a wedge, so that the acoustic signal enters the material at an angle. The angle of refraction θ is dependent upon the acoustic velocities V of the materials. When the angle of entry becomes large, a variety of waves can be generated, including shear, surface and Rayleigh waves.

Effective reflection

Regardless of the test method chosen, transducer frequency is of great importance. Since an ultrasonic signal will not reflect effectively from a flaw that is smaller than one wavelength, transducer frequency directly determines flaw resolution. For example, a 2.25 MHz signal has a wavelength of approximately 1/10-in. in steel; at this frequency, therefore, flaws smaller than 1/10 in. will be difficult to detect.

A large number of small flaws can be detected, however, by sound scattering in a through-transmit test. This scattering effect often is used to determine material grain structure. If testing is carried out along perpendicular axes, it may reveal an anisotropic condition in the grain if the throughput of ultrasonic energy is greater along one axis than the other.

Because ultrasonic signal penetration depth is inversely proportional to frequency, the testing frequency may have to be quite low to penetrate attenuative materials such as ceramics. Typical frequencies required to penetrate 12 in. of porous ceramics are between 100 and 500 kHz. At these frequencies, the flaw size that can be resolved effectively is rather large, and other methods may be required to supplement data from direct flaw reflection.

Enhancing low-frequency data

One method for handling data from a low-frequency transducer is spectral analysis of the reflected or through-transmitted signal. The frequency spectrum of the transducer is compared with the frequency spectrum of the signal after it passes through the test material, Figure 4. In higher frequency portions of the spectrum, the degree of attenuation is proportional to the number and size of flaws, or even to the size of the material's grain structure. Comparing the frequency domain signature of known material to that of tested material may reveal small discrete flaws or evidence of large grain structures.

Spectral analysis naturally would be enhanced by transducers with very wide bandwidths. In practice, however, the bandwidth at very low frequencies is limited by constraints in the transducer's internal design. A piezoelectric crystal essentially is a mechanically resonant system with a quality factor *Q* of at least 10 and a correspondingly narrow bandwidth. The most practical method for decreasing Q, and thus increasing the bandwidth, is to mechanically constrain or damp the crystal's tendency to "ring" at its resonant frequency.

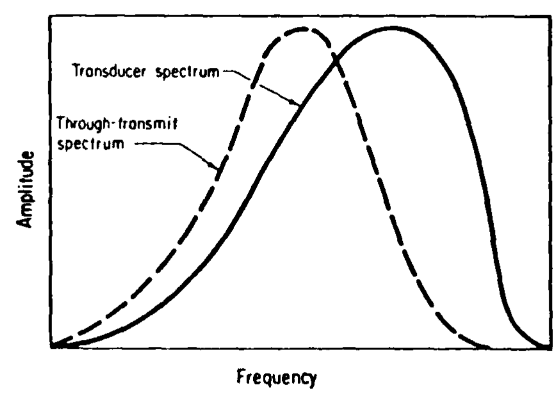


Figure 4. Analyzing the spectral signatures of the acoustic signal by comparing the spectrum before and after it passes through the material under test is one method for determining flaws when using low-frequency transducers.

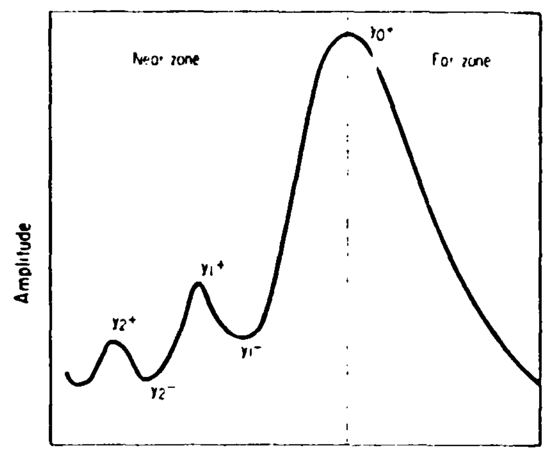


Figure 5. When a disc-shaped transmitter is used, the signal can be partially cancelled or reinforced at certain points by waves arriving out of or in phase from the outer edges of the disc. This can cause minimums and maximums, as shown by the Y values. This phenomenon occurs only for a certain distance, and the region in which it occurs is called the near zone.

When a circular transducer is used to generate the ultrasonic signal, certain beam pheomena occur due to destructive and constructive interference from beam constituents. At various points along the central axis of the beam, for example, signal intensity can be increased by waves arriving in phase from different parts of the radiating disc. The beam area where sound intensity exhibits maximums or minimums is known as the *near zone* or *Fresnel zone*, Figure 5. Beyond the near zone, beam intensity decreases monotonically and exponentially; this area is called the *far zone*.

Because of minimums and maximums in the near zone, flaws of different depths will yield reflections of different amplitudes, even if the flaws are the same size. To account for this, modern ultrasonic equipment often includes a time-varied gain on the receiver that compensates for irregular sensitivity in the near zone.

Ceramic crystals

The choice of piezoelectric material is important when selecting a transducer. Materials available

A damping material must be quite dense, and therefore sound transmissive, in order to affect Q significantly. At the low frequencies required for ceramics, the damping material might produce stronger echoes than the material under test; therefore, damping materials normally are not used for transducers of less than 500 kHz frequency. In higher frequency transducers, damping materials have been formulated that reduce the transducer Q to as low as one, while providing an attenuation of up to 100 dB/in.

As transducer frequency increases, the beam divergence for a given diameter will decrease. Consequently, the transducer diameter must be sized so as to allow the ultrasonic beam to propagate through the test material with a minimum amount of beam divergence. For example, a 10 MHz transducer of 1/2-in. dia will have a beam divergence of aboug 5 deg, while a 2.5 MHz transducer must be of 1-in. dia to have the same divergence. For low-frequency testing below 500 kHz, practical transducer diameters are 2 in. and larger.

If small flaws must be detected, beam diameter cannot become arbitrarily large because the beam fraction reflected by the flaw will approach the sum total of grain structure noise reflected by the rest of the beam.

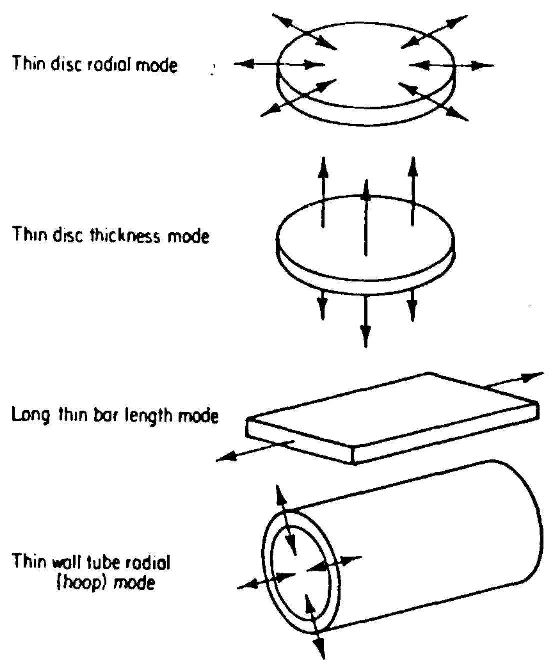


Figure 6. Piezoelectric transducers are available in a variety of configurations and frequencies. The transducers can transmit or receive acoustic signals in radial or longitudinal modes, depending on which surfaces are electroded and the direction of polarization.

include naturally occurring crystals—quartz, lithium sulfate and tourmaline—and polycrystalline ceramics such as PZT, barium titanate and lead metaniobate. The great advantage of natural crystals is the absence of spurious vibration modes, but natural crystals also have several disadvantages. Quartz and tourmaline have very low sensitivities, and lithium sulfate is both water-soluble and fragile. For these reasons, most ultrasonic testing is performed with ceramic crystals.

Of the ceramic crystals, lead metaniobate exhibits the lowest level of spurious wave propagation and PZT has the highest overall sensitivity. Any of the piezoelectric crystals can be mechanically damped to produce a broad band frequency response, and mechanical resonance can be reinforced with an electrical tuning network to produce a narrow band transducer of high sensitivity at the resonant frequency.

Most commercial transducers orient the crystal's axis to yield longitudinal waves; however, transducers that propagate transverse waves also are available, Figure 6.

The diameter of practical transducers at a given frequency is limited by the capacitance increase at larger sizes; for example, a 10 MHz crystal seldom is larger than 3/4 in. To meet scan requirements, transducers can be assembled in a multichannel array, with separate pulse circuits for each element. Another multichannel technique is the *phased array*, in which the pulse to each element is delayed electronically to accomplish beam steering and/or beam focusing. Phased arrays have been successful in achieving good flaw resolution through a wide range of material thicknesses.

Calculating Material Parameters from Ultrasonic Measurements

Young's modulus $E = \frac{V_l^2 D f(P)}{g}$

Shear modulus $U = \frac{V_t^2 D}{g}$

Poisson ratio $P = \frac{1-2(V_t/V_l)^2}{1-2(V_t/V_l)^2}$

Bulk modulus $K = \frac{E}{3(1-2P)}$

Bergmann approximation $\frac{V_s}{V_t} = \frac{0.87 + 1.12P}{1+P}$

f = frequency
V_l = longitudinal velocity
V_t = transverse velocity
V_s = surface velocity
D = density
g = acceleration of gravity

Other applications

In addition to flaw detection, ultrasonic measurements can easily determine a material's thickness and acoustic velocity. In a sample of known thickness, acoustic velocity can be calculated from the time required for a signal to pass through the material. Acoustic velocity information can be used to determine many important structural parameters of materials, such as the elastic modulus and Poisson ratio (see Box.) Especially useful are velocity ratios of the longitudinal, transverse and surface waves. Also, structural anisotropy can be determined by measuring the acoustic velocity along perpendicular axes.

If the acoustic velocity of a material is known, sample thickness can be calculated from the transit time of an ultrasonic signal. Thickness measurements, however, are limited by transducer frequency. Higher frequencies permit thinner specimens to be measured, since the smallest thickness that can be measured at a given frequency usually corresponds to one wave length of sound in that material.

High-temperature testing often reveals changes in acoustic velocity that relate to the strength of materials at elevated temperatures. Since typical transducers usually cannot be operated over 100 °C, a delay line or standoff material is placed between the transducer and the test material. These standoffs often are constructed of temperature-resistant plastics that can withstand continuous temperatures up to 400 °C. If higher temperatures are encountered, metallic or quartz standoffs and water cooling can be used.

Many physical properties of materials can be quickly and accurately determined with nondestructive ultrasonic testing techniques. Many feel that the capabilities of ultrasonic methods for flaw detection have only just begun to be explored. The development and design of such methods certainly will receive a higher priority in the next few years as increased quality control becomes more emphasized. Although ultrasonic technology is well developed in other industries, its application to glass and ceramic materials is still in its infancy.

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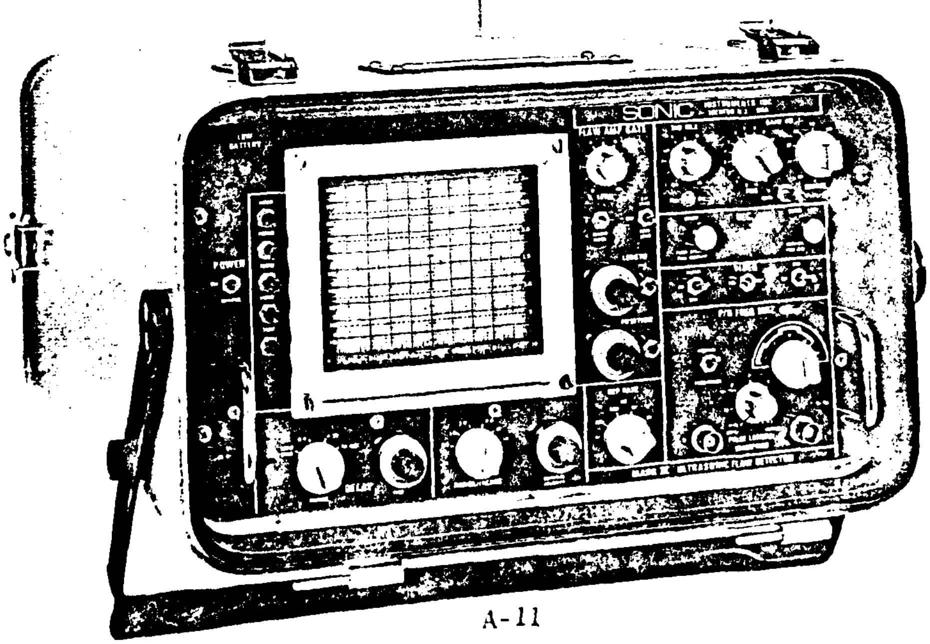

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