R 731

Technical Report

SEAFLOOR FOUNDATIONS: ANALYSIS OF CASE HISTORIES

June 1971

Sponsored by

NAVAL FACILITIES ENGINEERING COMMAND

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California 93043

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94

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Naval Civil Engineering Laboratory
Port Hueneme, California 93043

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
SEAFLOOR FOUNDATIONS: ANALYSIS OF CASE HISTORIES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Not final; December 1969–June 1970

5. AUTHOR(S) (First name, middle initial, last name)
D. G. Anderson and H. G. Herrmann

6. REPORT DATE
June 1971

7a. TOTAL NO OF PAGES
84

7b. NO OF REFS
111

8a. CONTRACT OR GRANT NO.

b. PROJECT NO. 3.1310-1

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TR-731

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Naval Facilities Engineering Command
Washington, D. C. 20390

13. ABSTRACT

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DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6801

Unclassified
Security Classification

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The characteristics, basic foundation design parameters, and foundation performance of a number of seafloor installations are summarized. These installations include offshore towers, habitats, acoustic arrays, and numerous other objects located in water depths from 20 to 12,000 feet. A number of case histories are analyzed. Some findings indicate behavioral problems not normally considered during foundation design. Several unique foundation configurations are documented which have been devised and utilized by a few to overcome the conditions imposed by the unique seafloor environment. Results of this study reveal that a number of foundation failures and near failures have occurred. Of the approximately 400 installations studied, 4% had experienced performance problems and an additional 3% had experienced failure. The causes, or probable causes, of several failures are examined. The value of foundation performance monitoring, both to the operation of an installation and to the field of seafloor foundation design, and the value and need for continued cooperation in the sharing of such information and experience are discussed.

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Sills Building, 5285 Port Royal Road, Springfield, Va. 22151

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Seafloor foundations						
Ocean-bottom facilities						
Undersea installations						
Offshore towers						
Offshore platforms						
Habitats						
Acoustic arrays						
Deep-sea construction						
Manned underwater stations						
Foundation performance						
Seafloor soils engineering						

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INTRODUCTION

Objective

The objective of this effort was to collect and summarize all available information on the performance of seafloor foundations. This information, along with an analysis, was directed at understanding the parameters which affect performance and establishing guidelines for more effective foundation design.

Scope

This summary of foundation performance is incomplete, because the collection and analysis efforts are to be continued. Often the only available knowledge of performance is that the foundation exists and that it either did or did not apparently function satisfactorily. Efforts are continuing in the collection of more detailed information on installations discussed here and additional information on installations which may have been missed in this initial study.

Background

The Navy is currently utilizing numerous ocean-bottom installations which depend upon the seafloor soils for their support (positive, negative, and lateral). These installations include offshore towers, habitats, and bottom-sitting test structures on the continental shelves. Test structures and a surprisingly large number of acoustic arrays and similar devices located in the deeper oceans constitute the remaining portion of seafloor installations. All of these seafloor structures, or installations, require some form of foundation through which vertical and horizontal forces are transmitted to, and resisted by, the seafloor.

A number of the foundations now in use have experienced difficulties—performance was sufficiently unsatisfactory to impair the mission of the installation. A few foundations have been involved in failures which have required remedial measures.

Numerous other foundations have been overdesigned with what were thought to be large factors of safety to ensure satisfactory performance. This was typically a successful, but usually expensive, approach. All of the systems were designed with what was thought to be an adequate factor of safety. In a few cases, however, because all of the performance parameters were not thoroughly understood, one was neglected. In such cases, when poor performance occurred in that parameter, the overall safety factor of the system became less than one.

As the national interest requires, and as the technology is developed, the Navy is planning more numerous and larger installations for the ocean bottom. With this increased activity on the seafloor, and with the increasing sensitivity of many of these installations (such as manned installations, which require a high degree of confidence in the design, since any unsatisfactory performance may endanger human life), there is a need to (1) improve the capability for designing seafloor foundations which will perform satisfactorily, (2) increase the confidence level in these procedures, and (3) use designs which are economically consistent with safety.

For these reasons, the Navy has undertaken research that will develop design guidelines for seafloor foundations. The overall development of this design capability can be significantly improved by the study of past successes and failures. The results of such a study can be used directly as design guidelines (a strictly empirical approach); or, more appropriately, they can be used to point out past problems (leading to the delineation and understanding of additional design parameters) and to act as test cases against which various proposed design rules may be compared and evaluated.

EVALUATION OF FOUNDATION PERFORMANCE

Satisfactory foundation performance can be defined in several ways. However, satisfactory performance basically is performance that permits the installation to complete its mission as intended.

Specific performance parameters contribute to this overall behavior. These parameters often include the following: (1) stability relative to bearing capacity; (2) stability relative to overturning; (3) stability relative to lateral motion; (4) tolerable differential settlements; (5) tolerable total settlements; and (6) sufficient rigidity (stiffness) to prevent motion. These parameters must consider dynamic (such as earthquake) as well as static (such as submerged weight) situations and soil behavior (such as compression or rupture) as well as other environmental influences (such as undermining, current scouring action, or slope instability).

In addition, for each of these parameters there are different scales of satisfactory performance. For example, manned installations require a high degree of confidence in their stability and, therefore, can tolerate very little motion; whereas, unmanned and relatively insensitive seafloor installations are often capable of tolerating larger settlements without impairment of their mission. In the extreme case, an installation involving numerous identical structures (each of which is unmanned and duplicates to some degree the mission of the others) may be capable of tolerating (for the sake of economy) some failures. In a situation such as this, the scale of performance behavior may be such that fewer than two failures (in the overall installation involving a large number of individual implants) may be considered satisfactory.

The scale of performance may also be influenced by factors such as soil or sediment province, physical environment (such as water depth, current velocity, and biologic activity), and design life of the installation. In spite of the wishes or needs of the owner or operator of an installation, such factors may force a shift of performance scales. For example, performance satisfactory at 6,000 feet may be unacceptable at 60 feet. Such a shift is, in essence, attributable to the state-of-the-art of certain technologies which limit or restrict performance.

To ascertain the scale of performance and the parameters affecting performance, the behavior of the in-situ foundation must be monitored. The monitoring of foundation performance serves six purposes: (1) it initially focuses objective thought on the type of performance which is required, on the level of performance which is satisfactory, and on the parameters which should be considered for satisfactory performance; (2) it keeps the operators informed of the condition of the installation so that remedial steps can be taken if they become necessary; (3) it evaluates the success of the foundation design procedure and the assumptions made therein; (4) it points out behavior parameters which may not have been considered at the time of the design; (5) it begins to give a statistical view of foundation behavior and failure; and (6) it forms a library of past experience or case histories, which can be used in future analyses and comparisons.

Such monitoring of foundations on land has been common throughout the ages. Earliest design techniques were based strictly on observations and experience (the empirical approach). More recently, the need for performance monitoring, as a means of improving foundation design capabilities, has been pointed out in prominent technical literature (Casagrande, 1965; Feld, 1965).

As discussed earlier, a variable and dissimilar number of behavior parameters collectively (and often mutually exclusive) contribute to an installation's degree of satisfactory behavior. The parameters which are most commonly important, and thus worth monitoring, are (in probable decreasing order of importance) the following: (1) total vertical penetration or settlement into the seafloor; (2) differential vertical motions (differential settlement) or rotation; (3) lateral motion (skidding); (4) soil behavior in the vicinity of the installation (such as excess pore pressure and location of soil strain resulting in installation movement); and (5) dislocation of soil mass (such as scour, fill, or mass movement—slope instability) in the vicinity of the installation. Applicable monitoring techniques are in use on land for all of these.

These techniques can, and have been, modified for use on the seafloor for submerged installations. For observing immediate, large-scale movements of an installation shortly after deployment, simply visual (direct or by closed-circuit television) observations by divers, submersible, or some remote observation system [CURV (Cable-Controlled Underwater Research Vehicle), for example] have been successfully employed. Similar visual methods can be employed for monitoring smaller movements (or other behavior phenomena) over longer periods of time if some form of referencing foundation position is added.

Another technique for monitoring smaller movements involves the usage of mechanical and fluid measuring systems such as shown in Figures 1 and 2. The mechanical system references movement to a vertically stable reference rod (isolated from surface movements) while the fluid system relates movement to a constant-elevation fluid interface. NCEL (Naval Civil Engineering Laboratory) divers have monitored the performance of several model foundations which employ mechanical and fluid referencing techniques (Figures 1 and 2) in up to 130 feet of water. The fluid system concept has also been utilized to measure differential vertical movement of a structure. These measurements were made by attaching the reference stand to one end of a structure and locating the sighting tube (Figure 2) at the opposite end. The accuracy of measurements for the mechanical and fluid referencing systems is typically in the order of 0.125 inch.

The periodic monitoring of installations in deeper water could be accomplished by employing the same measuring systems and a small submersible; however, it is typically more economical to use some sort of automated data collection system. The LOBSTER (Long-Term Ocean Bottom Settlement Test for Engineering Research) employs such a method. This device (Figures 3 and 4) uses the same mechanical reference system as shown in Figure 1; however, data are automatically taken (rate is variable from once every 7 seconds to once per hour) from three sensors which measure total settlement (accuracy about 0.02 inch) and footing tilt (differential settlement) in two perpendicular planes (accuracy about 0.5 degree). The LOBSTER is deployable in water depths to 6,000 feet for durations of up to 1 year. All data are stored internally on digital tapes which are recovered at the end of the deployment.

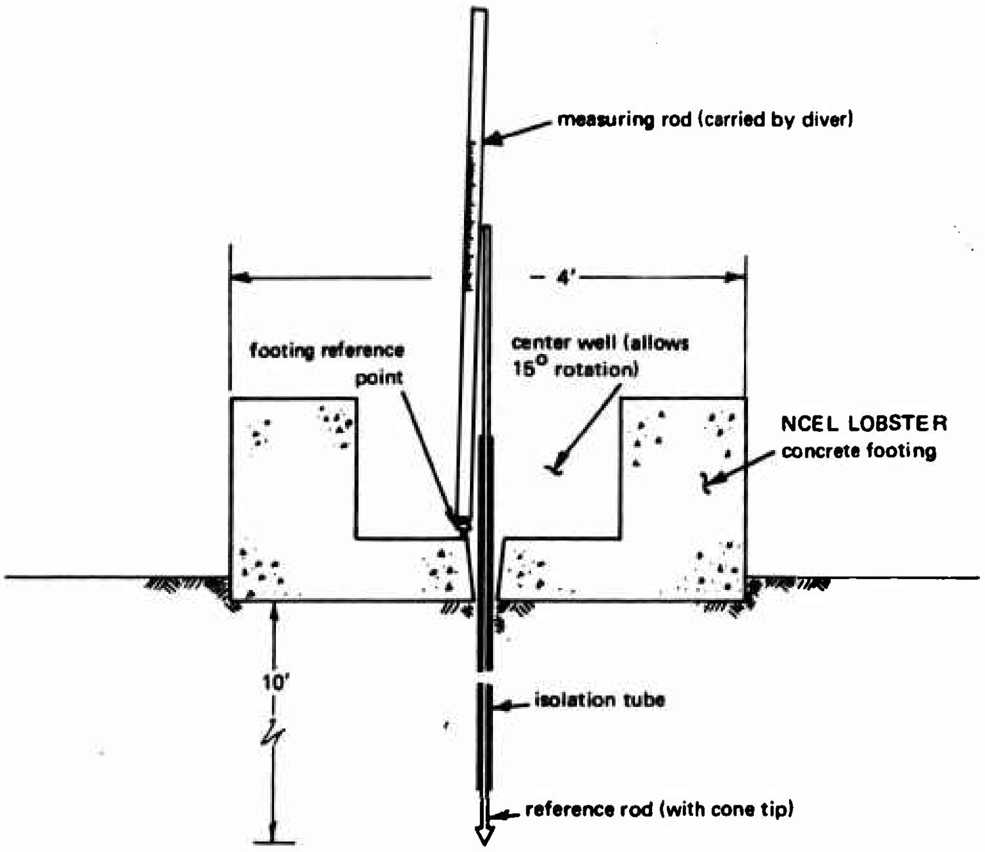

Figure 1. Mechanical reference system (cross-section view).

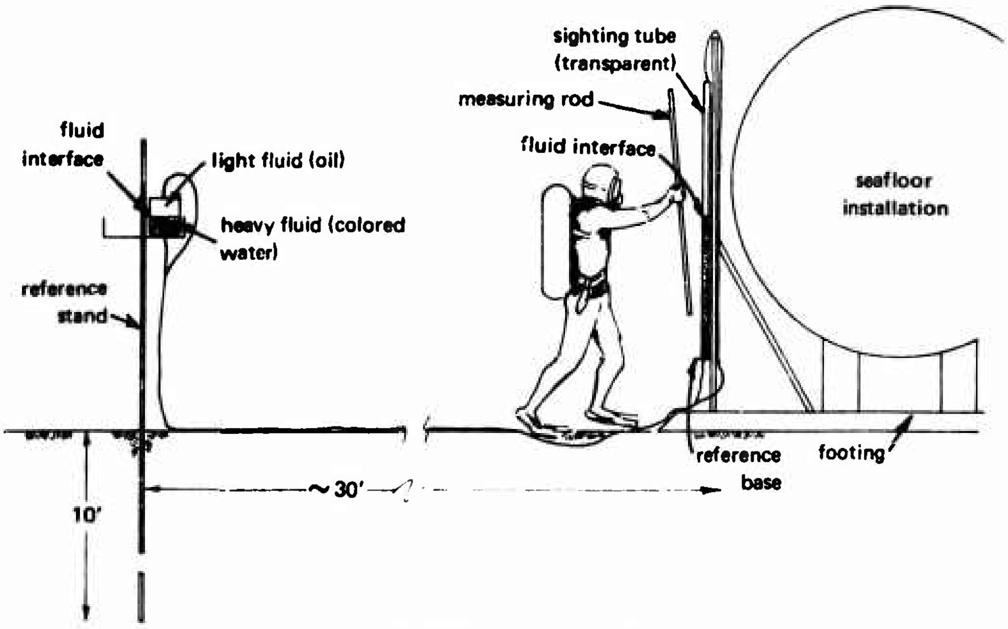

Figure 2. Fluid referencc system.

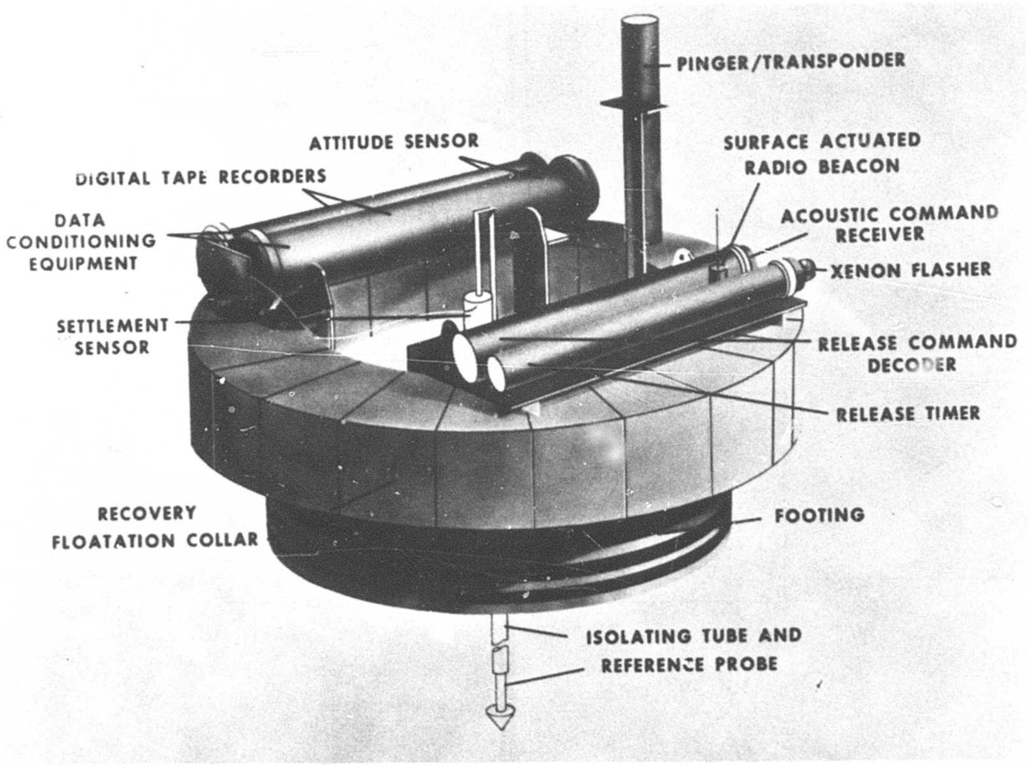

Figure 3. Artist's conception of NCEL automated performance monitoring device, LOBSTER.

Another automated monitoring device is the NCEL Foundation Performance Monitoring System (FPMS) (Figures 5 and 6). The FPMS, which is composed of a Foundation Monitor and an Amplification Module, is designed for general use on a structure of any size, shape, and type (such as mat, spread footings, or piles). The system monitors vertical movement (settlement) by sensing the change in pressure head between the Foundation Monitor and the Amplification Module as the Foundation Monitor settles relative to the Amplification Module. The Amplification Module is physically isolated from the effects of the structure (by a distance of about 30 feet). The Foundation Monitor also records the differential movement of the structure by utilizing two tilt transducers mounted at right angles to each other within the Foundation Monitor. As the structure tilts or rotates, the Foundation Monitor and tilt transducers undergo a similar movement. Precision of vertical settlement readings is better than 0.05 inch, while precision of tilt readings is better than 2 minutes. The Foundation Monitor, which can be deployed in up to 6,000 feet of water, senses the tilt and pressure transducers at various time increments (short during initial phase; longer during latter phase). Once the appropriate transducers are sensed, the Foundation Monitor conditions and stores the digitized data on magnetic tape for later processing.

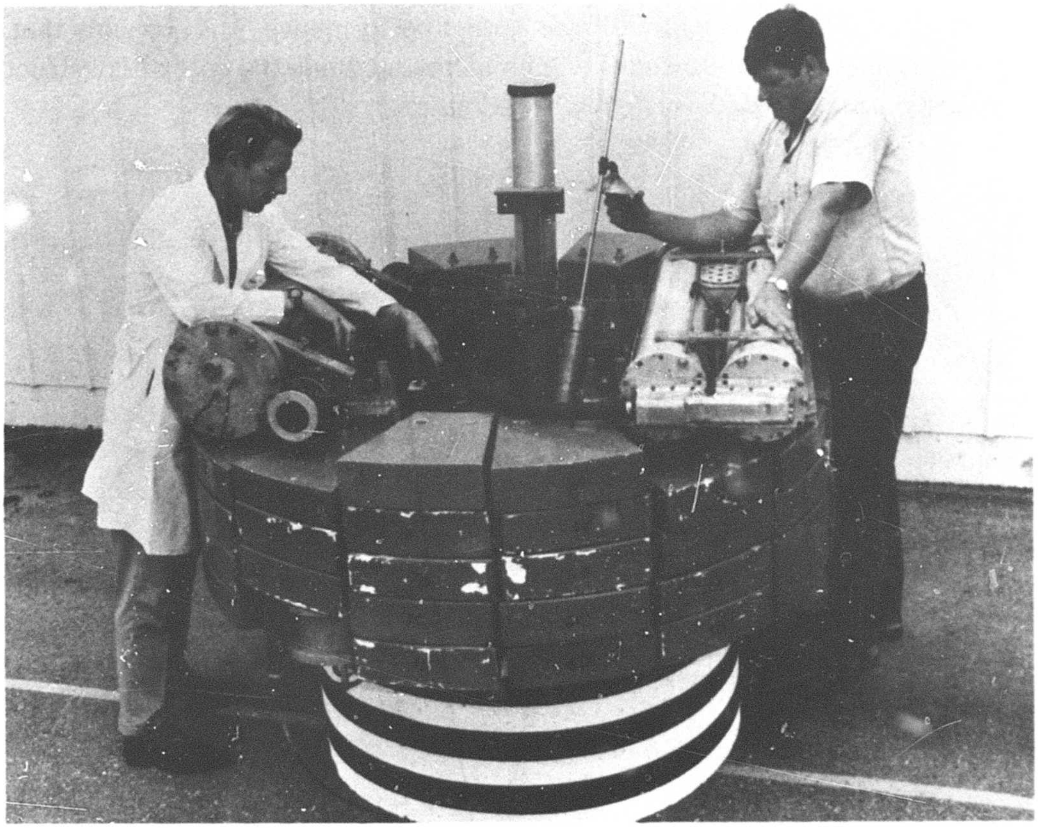

Figure 4. NCEL automated monitoring device, LOBSTER.

The devices mentioned in the previous paragraphs are currently being used to monitor the performance of seafloor structures. These devices, and others not mentioned, succeed in answering some of the questions concerning the scale of foundation performance and the parameters affecting foundation performance and design. However, two points must be emphasized. A need still exists for other, new devices capable of monitoring parameters (such as earthquake response and pore pressure dissipation) presently not being monitored. Some of these devices will have to be sophisticated and expensive; therefore, only foundations which justify a high degree of performance monitoring will be able to afford them. Other devices can be inexpensive and permit low-cost foundation monitoring. The second, and perhaps most important, need is for an increase in the number of foundations being monitored. Whether the monitoring devices are sophisticated (such as LOBSTER) or unsophisticated (such as visual observations), much valuable design data are gained by recording some or all of the in-situ foundation behavior. By establishing a broad program of monitoring performance, it is probable that the reliability of future systems will be increased while the cost of constructing and placing the same system will decrease.

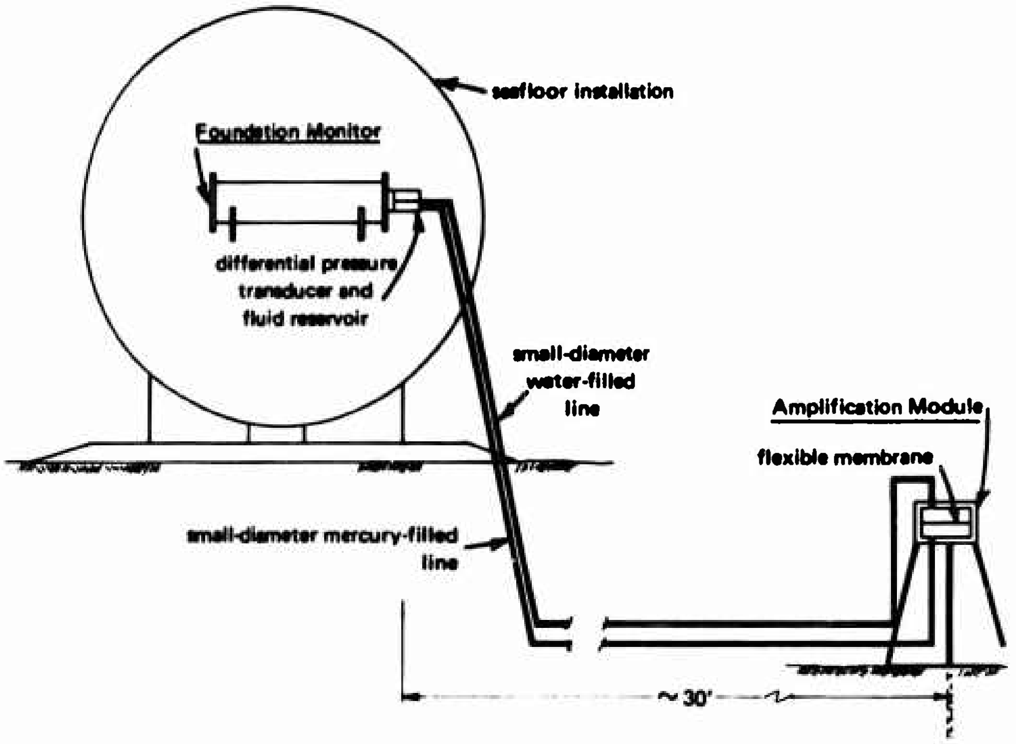

Figure 5. NCEL Foundation Performance Monitoring System (FPMS).

CASE STUDIES

Information has been gathered on the characteristics and performance of approximately 200 foundations which have been used on the seafloor. These case histories have been divided into four categories. The first three categories, Acoustic Arrays, Miscellaneous Structures, and Habitats, include all of the totally submerged structures. The fourth category, Offshore Platforms and Towers, includes the structures which extend to and above the ocean surface. The fourth category also summarizes information on over 300 offshore structures for which specific performance information was unavailable.

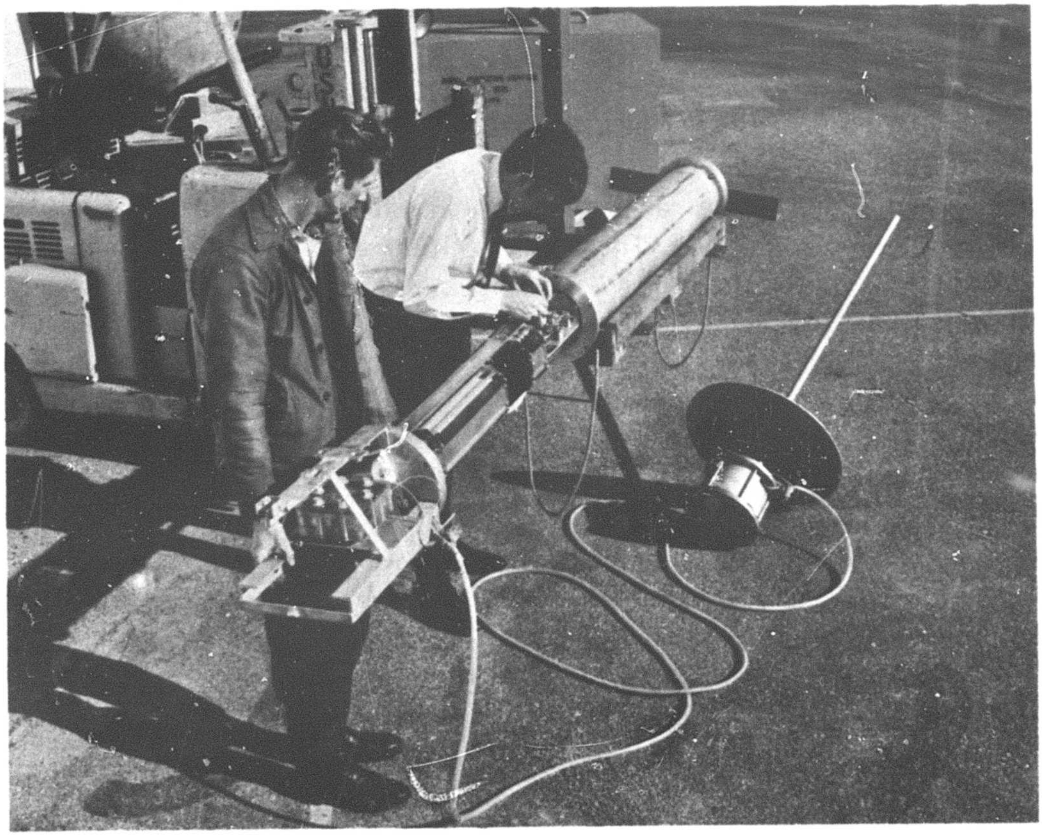

Figure 6. FPMS being readied for deployment.

Acoustic Arrays

A number of underwater ranges, most operating as three-dimensional acoustic tracking systems for training and testing of the Fleet and of various weapons systems, are listed in Table 1. These ranges are located in the northern hemisphere (from Bermuda to Hawaii) and are utilized almost exclusively by the Navy and its contractors.

The ranges are all similar in makeup; consequently, foundation requirements are much the same. The differences in seafloor conditions at the various range sites impose differing restrictions on foundation design. Soil conditions at the sites vary from sand with rock outcroppings to what is described as a silt-ooze.

These underwater ranges utilize a number of hydrophones (varying from 5 to over 200) placed on the seafloor in a specific pattern. The ranges cover areas which vary from several square miles to as large as 200 square miles. The sound created by any object (or of a pinger attached to an object) within the range is received by these hydrophones at slightly different times, depending on the distance from the object to the particular hydrophone. The resulting electrical impulses are usually carried by underwater cable to a submerged termination chamber. In the termination chamber all signals are gathered, and, in some instances, conditioned. From the termination chamber, the data are carried through the surf zone by a smaller number of heavier cables, designed to withstand conditions in this most severe transition zone, to shore-based equipment for final conditioning and analysis.

The underwater termination chambers are usually located in shallow water (60- to 80-foot depths) and are usually larger and heavier than the hydrophone structures which are designed simply to support one or more small hydrophones in a relatively fixed position on the deep-ocean seafloor. The hydrophones are located in water depths from 600 to 12,000 feet. Some individual underwater ranges vary in depth by as much as 9,000 feet. The hydrophone structures, which are usually identical within each range, have heights from 15 to 50 feet, mean lateral dimensions from 4 to 50 feet, and submerged weights from 300 to over 1,000 pounds. Although the basic nature of these structures is such that relatively small loads are involved, their foundations must still minimize settlement, tilt, and lateral movements. The foundation system in combination with the structure also must be designed for easy installation at a rather precise location. Design life for these systems is in the 5- to 20-year category. Some ranges now in existence are as much as 12 years old; most, however, are more recent.

A number of foundation types have been utilized to support hydrophone structures. These include (in general chronological order of development and use) deadweight anchors, simple spread footings, multiple spread footings, and ring footings. Designers of earlier systems liberally employed universal joints and buoyancy elements to overcome the effects of differential foundation settlement. In this configuration, ocean-bottom currents can disrupt the performance of the hydrophones and, at one range, the system was modified to use a series of universal joints which were locked after a short period of time (Green, 1969; Daniels, 1969). The larger portions

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Table 1. Underwater Acoustic Arrays

Name	Operator	Installation Year	Depth (ft)	Location	Structure		Wt (lb) in Water, W, or Air, A	Mean L Dimen
					Type	No.		
AUTEC	Navy (Naval Underwater Weapons Station, Naval Ordnance Station), Newport, R. I.	1967	4,000 to 6,000	Bahamas	hydrophones	55	400 (W)	12-ft-c circle of diam I tubi
BARSTUR	Navy (Pacific Missile Range), Point Mugu, Calif.	1967	2,200 to 5,500	Kauai, Hawaii	hydrophones	37	360 (W)	12-ft-d circle of diam F tubir
			65		junction box	1	≈1,000 (W) and moored with grouted-in stakes	4 x 20
Bermuda Range	Navy (Naval Underwater Sound Laboratory), New London, Conn.	1965 and 1966	3,000 to 12,000	Bermuda	hydrophones	200+		3 x 3
			3,000		DOBACS	1	35,000 (A)	25 ft in
					miscellaneous	10+	varies	varie
Canadian Range	Navy (Naval Torpedo Station), Keyport, Wash.	1965	≈1,350	Straits of Georgia, British Columbia, Canada	hydrophones	6	10,000 (A)	three 3 x
Daybob Bay Range	Navy (Naval Torpedo Station), Keyport, Wash.	1958	650	Hood Canal, Wash.	hydrophones	15	1,000 (W)	4 x 4
SCARF	A. C. Electronics General Motors Corp., Goleta, Calif.	1965	4,200	Santa Cruz Island, Calif.	hydrophones	5	385 (W)	12-ft-di circle of diam P tubing
			60		junction chamber	1	ballasted to compensate for 15,000-lb positive buoyancy	
Sandia Facility	Sandia Corp., Albuquerque, N. M.	1965	2,400	Santa Cruz Island adjacent to SCARF	hydrophones	6	385 (W)	12-ft-di circle of 2 diam P tubing
St. Croix Range	Navy	1964	3,000	St. Croix, Virgin Islands	hydrophones	11		3 x 3 f

Table 1. Underwater Acoustic Arrays

Structure		Wt (lb) in Water, W, or Air, A	Mean Lateral Dimension	Foundation Type	Foundation Bearing Pressure (psf)	Sediment Type	Settlement	Remarks
Type	No.							
hydrophones	55	400 (W)	12-ft-diam circle of 2-in.-diam PVC tubing	ring footing	≈127	silt size carbonate material	no sliding or excessive settlement	Observed from submersible.
ydrophones	37	360 (W)	12-ft-diam circle of 2-in.-diam PVC tubing	ring footing	≈115	thin veneer of sand	unknown	Performing as anticipated.
unction box	1	≈1,000 (W) and moored with grouted-in stakes	4 x 20 ft	spread footing	unknown			
ydrophones	200+		3 x 3 ft	frame	unknown	assumed to be coral material	unknown	Problems with DOBACS.
DOBACS	1	35,000 (A)	25 ft in diam	tubular frame	unknown			
iscellaneous	10+	varies	varies	frames and pads	unknown			
ydrophones	6	10,000 (A)	three 3 x 3 ft	tripod apparatus on three footings	unknown	siliceous ooze	≈1 ft	Tilting has occurred after clamping of hydrophone.
drophones	15	1,000 (W)	4 x 4 ft	concrete blocks	62.5	silty sediment	no settlement noted	
drophones	5	385 (W)	12-ft-diam circle of 2-in.-diam PVC tubing	ring footing	≈123	sand	no evidence of soil failure	Structure attitude corrected by submersible, DOWB.
tion chamber	1	ballasted to compensate for 15,000-lb positive buoyancy		four legs	unknown			
drophones	6	385 (W)	12-ft-diam circle of 2-in.-diam PVC tubing	ring footing	≈123		no problems reported	
rophones	11		3 x 3 ft	concrete blocks and open boxes	unknown	silty sand	no settlement noted	Structure slid down slope.

continued

Table 1. Continued

Name	Operator	Installation Year	Depth (ft)	Location	Structure		Wt (lb) in Wa
					Type	No.	
Other Ranges	University of Miami, Coral Gables, Fla.			Straits of Florida	hydrophones transducer	2 1	low
	Lockheed Ocean Laboratory, San Diego, Calif.	early 1960's		San Clemente Island	hydrophone	1	
	Woods Hole Oceanographic Institute, Woods Hole, Mass.*						
	Columbia University, New York, N. Y.*						
	Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada*						
	Project CAESAR*						

* No data available.

Table 1. Continued

ocation	Structure		Wt (lb) in Water, W, or Air, A	Mean Lateral Dimension	Foundation Type	Foundation Bearing Pressure (psf)	Sediment Type	Settlement	Remarks
	Type	No.							
raits of lorida	hydrophones	2	low weights						
	transducer	1							
Clemente Island	hydrophone	1							

[redacted]

of differential settlement were presumed to occur before the systems were locked. The locking process prevented subsequent movement due to current drag. At another range, a simple spread footing slid down a shallow slope (Linger, 1969). This problem was prevented on later foundations by using footings with cutting edges designed to key the footing into the underlying soil and, thereby, prevent lateral movement.

More recent trends in structural design have been toward the use of simpler configurations. This change was facilitated to a degree by advances in fields related to range design and layout. The change has resulted in the use of lower total weights and larger widths on the footing systems. This more recent and now somewhat standardized design, the ring footing, has experienced no known foundation performance difficulties during use in several diverse soil types.

The following sections summarize the characteristics of several acoustic ranges. Information includes structural aspects (size, weight, configuration) of the system, environmental data (soil parameters, depth of water, currents, terrain) at the site, and performance (settlement, sliding) of the structure with respect to foundation behavior. Data on the systems were generally sketchy; therefore, only an empirical performance investigation can be attempted.

AUTEC Range. The Atlantic Undersea Test and Evaluation Center (AUTEC) was completed in early 1967 (Jackson and Grant, 1967; Busby, 1965 and 1969; Covey, 1967; Austin, 1964). In addition to providing three-dimensional tracking, the range conducts temperature, salinity, and pressure measurements. AUTEC is located about 180 miles southeast of West Palm Beach, Florida, in the Tongue-of-the-Ocean (TOTO)—a sheltered expanse of water parallel to Andros Island in the Bahama Islands. The body of water is approximately 100 nautical miles long by 15 nautical miles wide and has a depth which varies from 3,600 feet in the south to 6,600 feet in the north.

The tracking system is composed of weapons, acoustic, and sonar ranges. The Weapons Range occupies an area 5 miles wide by 35 miles long off the southern end of Andros Island. Three-dimensional tracking is provided by 55 individual hydrophones geometrically arranged into two separate groups at opposite ends of the range. The Acoustic Range is located between the Weapons Range and New Providence Island. Two hydrophones occupy this 5- by 5-mile area. The Sonar Range, scheduled for later completion, will include sonar transponders accurately located on the seafloor.

During 1961 and 1962, approximately 100 sediment cores were taken by the Naval Oceanographic Office (NAVOCEANO). The constituents of the TOTO bottom sediments were predominantly silt size, skeletal and nonskeletal carbonate particles representing both shallow- and deep-water environments (Huddel et al., 1965). Organic carbon content of the sediment ranged from 1% to 2%. The general variations of water content, void ratio, density, and undrained strength with depth in the soil profile all indicated a normally consolidated soil profile. Coarse-grained materials, which formed more than 50% of some of the cores, were attributed to deposition by turbidity currents. Sediment undrained shear strength (vane shear strength) in the northern area ranged from 1 to 3 psi over the length of the cores. In the southern area, strength averaged less than 1 psi. Sediment sensitivity varied from slightly insensitive to slightly quick. Bottom photographs show an almost featureless ooze with a few benthic organisms. In the central northern portion of the channel at a water depth of 6,000 feet, there is a series of cavities and depressions.

The hydrophone structures are designed with the hydrophone attached to the top of a 15-foot-tall conical frame. The 12-foot-diameter base is constructed of 2-inch-diameter polyvinyl chloride (PVC) tubing. Figure 7 shows an almost identical hydrophone structure. Weight of the entire apparatus in water is about 400 pounds.

Visual performance observations were made 6 months and again 3 years after the system was installed. The observations were made from the submersibles *Aluminaut* and *Alvin*. No unusual activities or problems (sliding or excessive settlement) were noticed (Austin, 1964).

BARSTUR. During the spring of 1967, the Navy established a highly instrumented three-dimensional underwater tracking range in Hawaiian waters (Prince, 1968; Okura, 1969). The site is located in the north central Kaulakahi Channel (Kaulakahi Channel separates the Island of Kauai from the Island of Niihau to the west) (Garrison, 1965).

Barking Sands Tactical Underwater Range (BARSTUR), composed of an underwater communications system (UQC) and 37 tracking hydrophones, is located in a 5- by 10-mile area (Figure 8). Water depths within the range vary from 2,200 to 5,500 feet. Each hydrophone is located with respect to a center hydrophone, which, in turn, is referenced (within a 175-foot-diameter circle) to shore facilities. An underwater junction box, located beyond the surf zone in 65 feet of water, forms a terminus for connecting the smaller individual phone cables to a single, multiconductor, heavily armored cable.

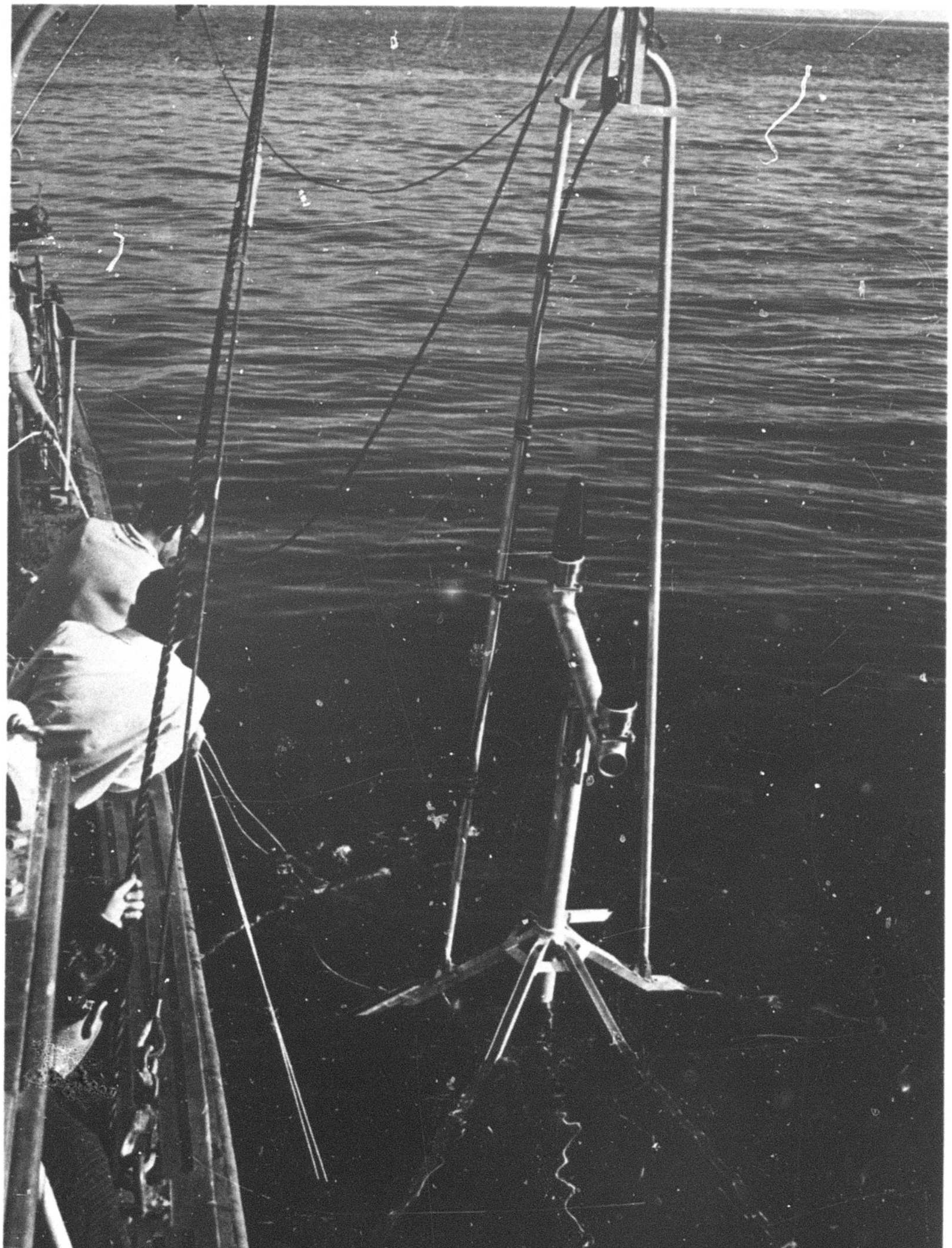

Figure 7. Typical dual hydrophone structure, SCARF range. (From Momsen, 1970. Photo courtesy of AC Electronics.)

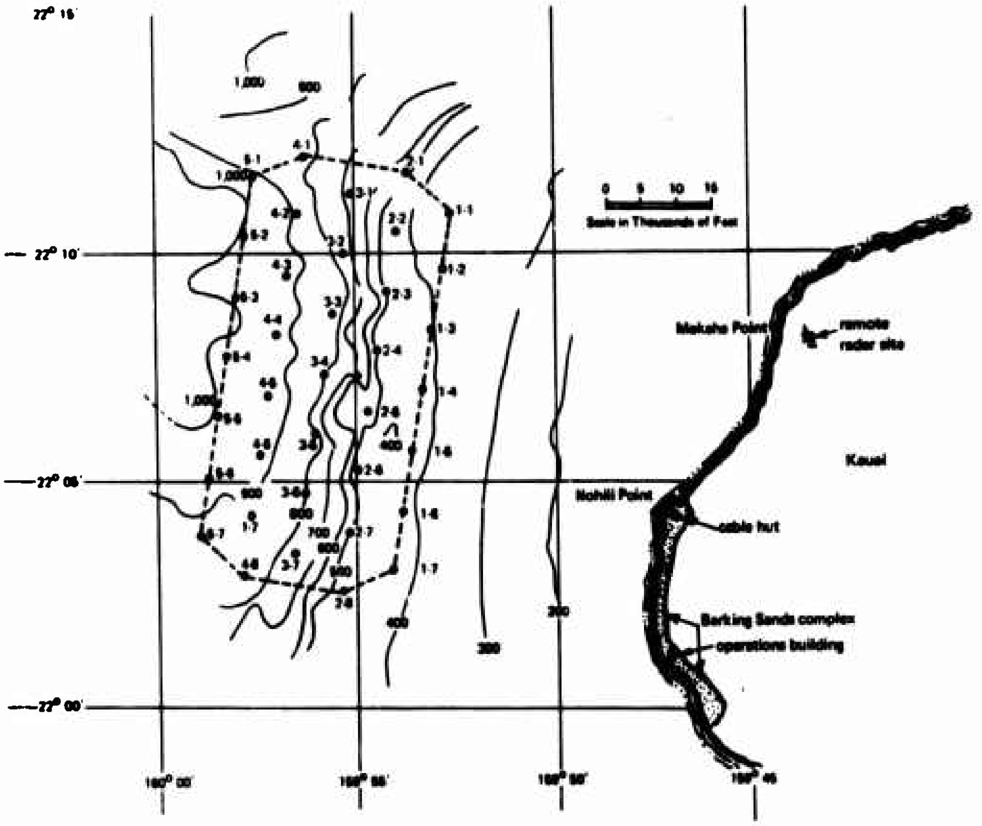

Figure 8. Hydrophone locations for Barking Sands Tactical Underwater Range (BARSTUR). (From NPOLA, 1969.)

Specific seafloor studies were made by NAVOCEANO and others during 1964 (Belshé, 1967). Records from the seven sediment cores (from water depths of 2,400 to 6,000 feet) and various underwater photographs indicated that a thin veneer of sand covered nearly 70% of the seafloor at the site. Outcrops of basaltic rock accounted for most of the other 30%. About two-thirds of the seafloor at the site had a slope of 5 degrees or less. Nearshore investigations indicated patches of sand distributed in pockets formed in the bedrocks. The greatest thickness of sediment measured in the nearshore region was 18 inches. Maximum relief in the area was 3 feet.

Each hydrophone structure, weighing 360 pounds in water, supports a single hydrophone. These structures are similar to the units used at AUTEC. The detailed configuration is shown in Figure 9.

The 4-foot-wide by 20-foot-long by 1-foot-high junction box rests directly on the seafloor and is secured by five grouted-in stakes.

Weight in Air : **502 lb**
Weight in Water : **360 lb**
Hydrophone Height Above Base: **15 ft**
Diameter of Base Ring : **12 ft**
C. G. Above Base in Air : **32.45 in.**
C. G. Above Base in Water : **30.53 in.**
Yoke Pivot Above Base : **34.0 in.**
Free Fall Velocity : **2.86 ft/sec**

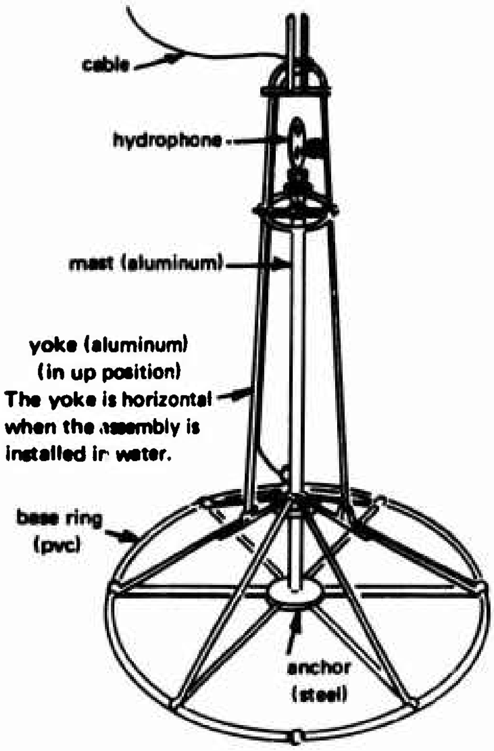

Figure 9. BARSTUR hydrophone assembly. (From NPOLA, 1969.)

BARSTUR has performed satisfactorily to date (Okura, 1969). Difficulties have been experienced with only two hydrophones. One hydrophone has become inoperative and will be replaced. A second hydrophone is experiencing a shadow effect which may possibly be caused by the proximity of a rock outcropping or ledge. Neither difficulty appears attributable to unsatisfactory foundation performance. Tracking is still good in the rest of the range; however, a shift of more than 20 feet would have been required before variations would be noticed. A detailed survey and inspection were planned for the fall of 1969, but have been postponed. Some difficulty has also been experienced with the hydrophone cables at the junction box (Good, 1970). During the winter storms of 1969-1970, several were torn loose from their bottom securing system (deadweight bags) and became entangled about the junction box (Black, Bruce, and Herrmann, 1970). Remedial steps were taken during the summer of 1970.

Bermuda Range. An acoustic range was established in 1961 by the Navy near the Island of Eleuthera in the Bahamas (Moothart, 1969). Water depths at the site vary from 3,000 to 12,000 feet. Although no sediment records are available, nearshore material was assumed to be coral, and offshore sediments were assumed to be even harder. The bermuda system is composed of numerous acoustic arrays supported by a variety of footings.

Difficulties with the Deep Ocean Basin Acoustic Cable Source (DOBACS) have been reported. These problems are apparently not the result of unsatisfactory foundation performance. The DOBACS, which weighs 35,000 pounds in air and is approximately 25 feet in diameter by 50 feet high, was positioned at a water depth of 3,000 feet on a relatively small, steeply sloped (30 degrees) plateau. The plateau is approximately 200 by 400 yards in area. The structure was leveled by a gimbal system after placement.

Canadian Range. The Navy maintains an acoustic range in the Straits of Georgia, northeast of Nanaimo, British Columbia, Canada (Green, 1969; Daniels, 1969). The range, established in 1965, contains six hydrophones located in approximately 1,350 feet of water. Bathymetry in the area is relatively flat, and sediments are predominantly siliceous oozes.

Two configurations have been used for supporting the acoustic instrumentation. The older hydrophones are attached to buoyant spheres and anchored to the bottom. This configuration is flexible, and bottom currents of about 0.1 knot cause undesirable hydrophone movements. The newer and more successful supporting structures consist of a 50-foot tripod apparatus with each corner supported on a 3- by 3-foot concrete footing. The entire apparatus weighs approximately 10,000 pounds in air.

Since sediments in the area were extremely soft, a unique device was designed to minimize attitude change due to differential footing settlement. A universal joint was placed between the hydrophone and the tripod, and a buoyant sphere was attached to the hydrophone. If the base settles differentially into the sediment so that the tripod tilts, the buoyant sphere moves the hydrophone back to a vertical position by rotating the system about the flexible joint. The entire system remains flexible for approximately 2 weeks, after which time the hydrophone's position is fixed rigidly relative to the tripod.

The magnitude of settlement during the first 2 weeks was approximately 1 foot. This value varied according to the buoyant force supplied by the sphere and the properties of the bottom sediments at the specific location. Although some further tilting has been noted subsequent to clamping of the hydrophones, operation of the range has been satisfactory.

Daybob Bay Range. In 1958, the Navy established an acoustic range west of Seattle, Washington, in Daybob Bay (Green, 1969; Daniels, 1969). Fifteen hydrophones were placed in approximately 650 feet of water on a silty sediment. Each hydrophone is attached to a 15-foot length of pipe atop a 4- by 4-foot concrete anchor block. A buoyant sphere and two universal joints maintain vertical position. No unusual performance problems have been noted with the 1,000-pound negatively buoyant configuration.

SCARF. The Santa Cruz Island Acoustic Range Facility (SCARF) is a three-dimensional acoustic tracking range belonging to General Motors Corporation's A.C. Electronics—Defense Research Laboratory (A.C. Electronics, 1968; Chalfant and Buck, 1968; Engstrom, 1969; Momsen, 1970). The hydrophone arrays were implanted in 1965 at an average water depth of 4,200 feet some 6 miles south of Santa Cruz Island (Figure 10).

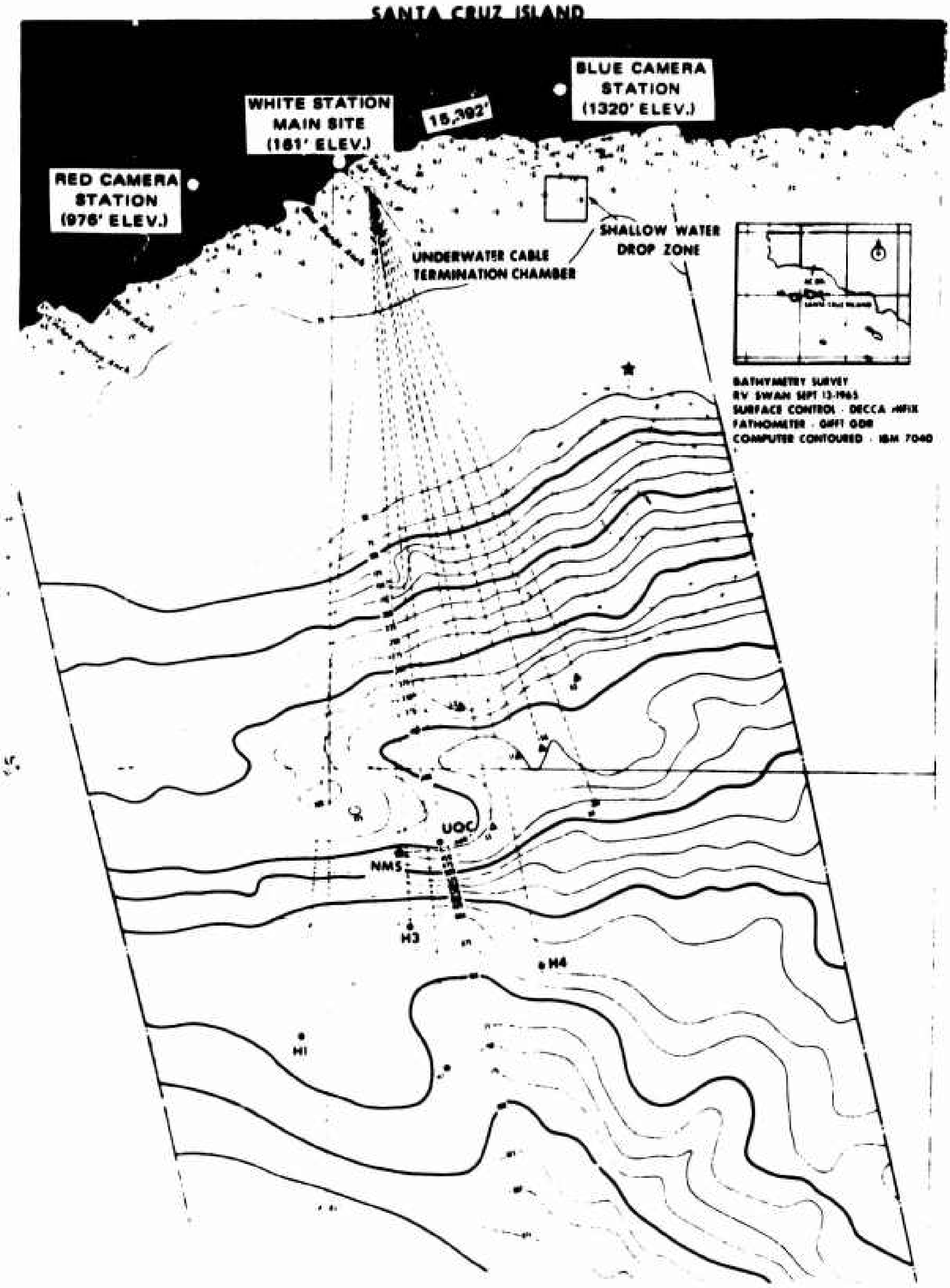

Figure 10. SCARF and Sandia underwater ranges. (From Momsen, 1970. Photo courtesy of AC Electronics.)

The submerged portion of the facility consists of four dual tracking hydrophones, a string of three noise-measurement hydrophones, and a UQC. The tracking and communication hydrophones are supported on 15-foot-tall by 12-foot-diameter aluminum conical frames each weighing 385 pounds in water (Figures 7 and 11, respectively). The noise-measurement string includes three hydrophones attached to a buoyed cable. All sea cables are connected to an underwater termination chamber in approximately 60 feet of water, 1/2 mile offshore. The 6-foot-diameter by 12-foot-tall cylinder is supported on a sandy bottom by four legs. Ballast is used to overcome the 15,000 pounds of positive buoyancy developed by the chamber.

Slight reception problems at one of the four hydrophone structures led to the performance of an inspection of the entire range by the General Motors submersible, DOWB (Deep Ocean Work Boat), in late 1968 and early 1969 (Engstrom, 1969). As a result of this inspection it was discovered that several structures were lying on their sides. This was determined not to have been the result of soil-related problems.

The structures were righted during the summer of 1969 using the DOWB (Figure 12). Output from the tracking hydrophones indicates that the foundations have performed satisfactorily since that time.

It is interesting to note that for all but one of the structures there was no obvious indication of improper orientation of the structures. The range inspection and subsequent remedial actions resulted in an overall improvement of the range effectiveness.

Sandia Facility. In 1965, an acoustic range was installed adjacent to SCARF for the Sandia Corporation by the owner and operators of SCARF (Engstrom, 1969). The six hydrophones are located in approximately 2,400 feet of water (Figure 9). Other physical and mechanical characteristics of the system are similar to those at SCARF. A common underwater cable-termination chamber is used by the two ranges. No foundation problems have been reported.

Saint Croix Range. The Applied Physics Laboratory (APL) at the University of Washington designed and installed for the Navy an underwater tracking range off the west coast of Saint Croix in the Virgin Islands (Garrison, 1963; Rooney, Eppert, Huddel, 1965; Linger, 1969). Four hydrophone structures were emplaced in 1964 at a water depth of approximately 3,000 feet. The range was enlarged to 11 hydrophone structures in 1967.

Sediment investigations were made at the site in 1962 and 1965 by NAVOCEANO and in 1963 by APL. Typical sediment properties as determined by NAVOCEANO were as follows:

Total unit weight	103 to 105 pcf
Specific gravity	2.73 to 2.76
Water content	50% to 80%
Void ratio	1.40 to 1.90
Unconfined compressive strength	1.0 to 4.3 psi

The seafloor topography was relatively smooth with slopes varying from 3 to 20 degrees.

Each hydrophone structure included: (1) an open space-frame, with a major lateral dimension of 30 feet, for supporting the individual hydrophones; (2) a universal joint and buoyant sphere for maintaining the hydrophones on the space-frame in a fixed, stable plane; and (3) a base for anchoring the configuration. The bases for the first structures were concrete cubes with 3-foot sides. The newer hydrophone structures have a 3-foot-square open box base.

Immediately after the first structures were placed, difficulties were noted with one (Linger, 1969). An anchoring base and its attached frame slid down a 10- to 15-degree slope dragging an umbilical cable. A lateral distance of approximately 1,000 feet was traversed. The possibility of sliding was reduced on the seven more recent structures by designing the base with a hollow interior and open bottom so that the perimeter became a cutting edge. During emplacement of these seven, the bases were dropped from approximately 50 feet above the seafloor in order to increase penetration into the sediments. It was intended that any downslope motion would be resisted by the lateral stress mobilized against these "keying edges." No subsequent difficulties with foundation performance have been reported.

Other Acoustic Ranges. The University of Miami installed a transducer and two receivers for measuring environmental fluctuations in the Straits of Florida between Miami and the Island of Bimini (Sykes, 1969; Steinberg, 1969). Bottom sediments were hard, and equipment weights were low. No foundation performance problems have been reported.

The Lockheed Ocean Laboratory, San Diego, installed a hydrophone system off San Clemente Island in the early 1960's (Inderbitzen, 1969). The purpose of the range was to demonstrate the Laboratory's ability to perform oceanographic work. A concrete block base held the hydrophone array in place for 3 months without incident.

Other similar structures have been used by Woods Hole Oceanographic Institute, Columbia University, Bedford Institute of Oceanography, and on Project CAESAR. No foundation problems have been reported; however, in these cases, the only information available is that the structures exist.

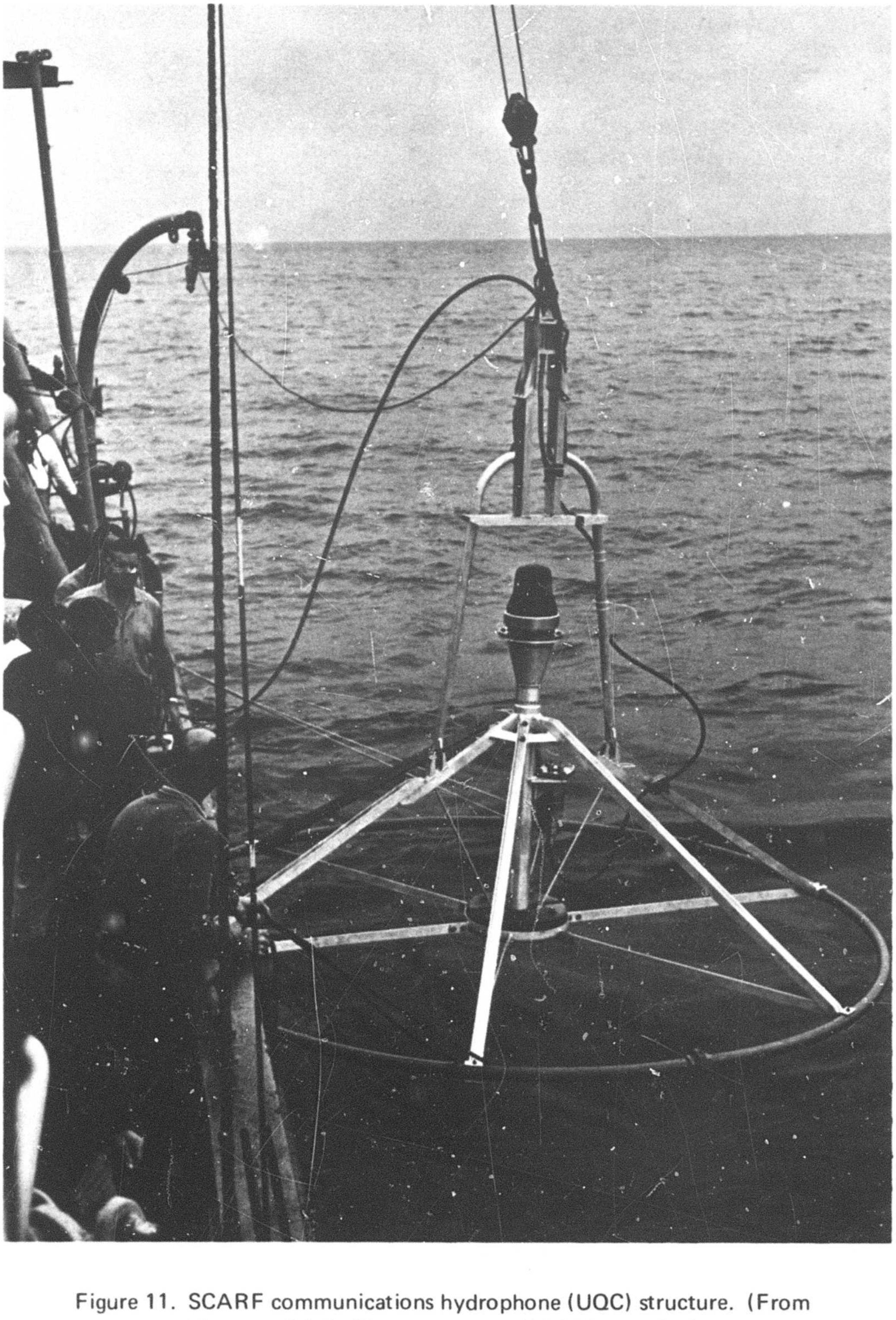

Figure 11. SCARF communications hydrophone (UQC) structure. (From Momsen, 1970. Photo courtesy of AC Electronics.)

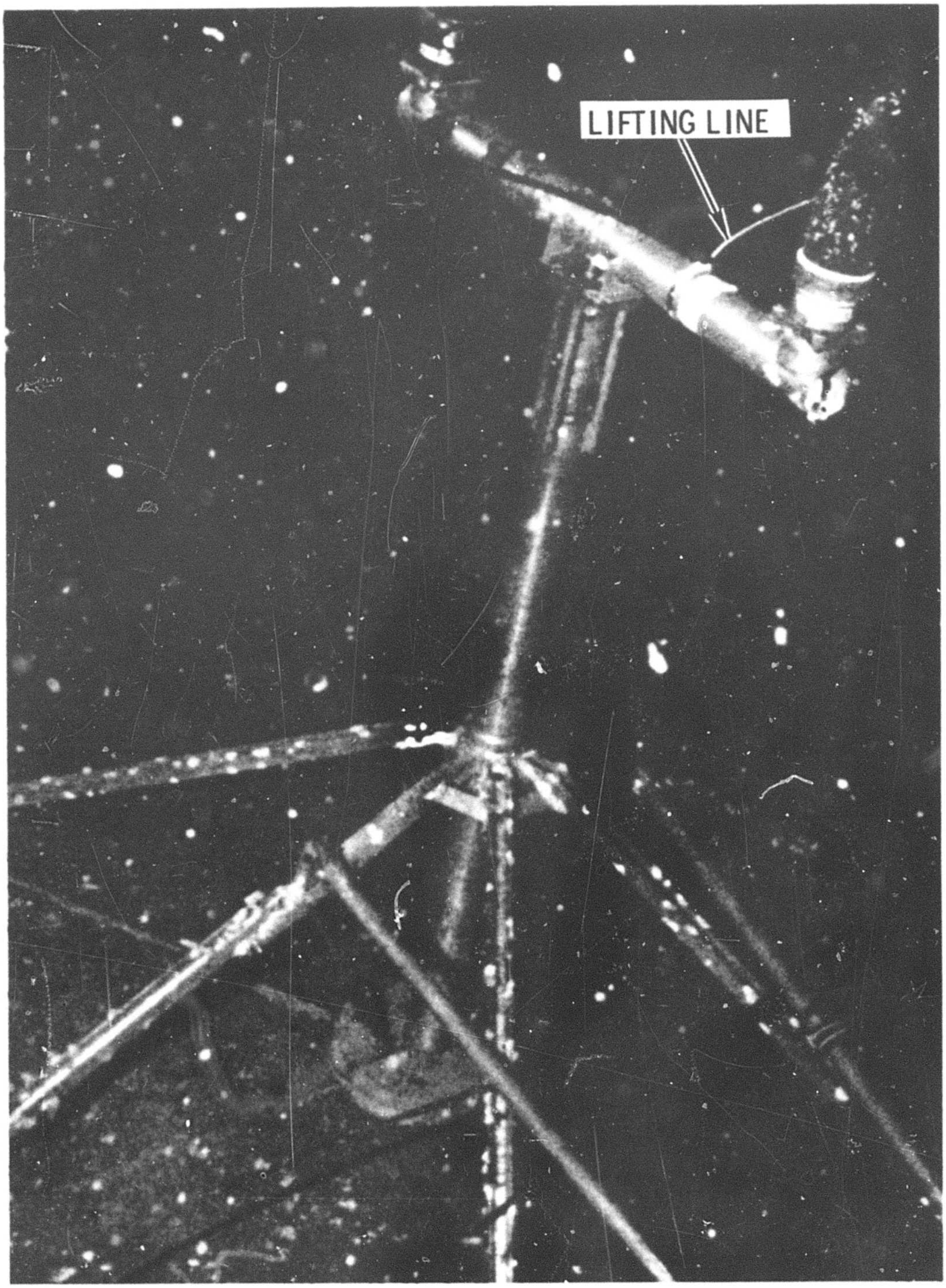

Figure 12. SCARF hydrophone structure during righting by submersible, DOWB. (From Momsen, 1970. Photo courtesy of AC Electronics.)

Miscellaneous Submerged Structures

A great number of structures other than acoustic arrays and habitats have been placed on the seafloor (Table 2). Many of the structures included in this category are scientific or experimental devices and packages. Some of the structures are installed semipermanently, while others are deployed many times but only for short durations. The foundation types include both pile and footing configurations.

NCEL DOTIPOS System. The NCEL DOTIPOS (Deep Ocean Test-In-Place and Observation System) is a tethered, bottom-sitting platform (Figure 13) with observation systems, control mechanisms, power source, and data telemetry (Kretschmer, 1969; Padilla, 1969 and 1970).

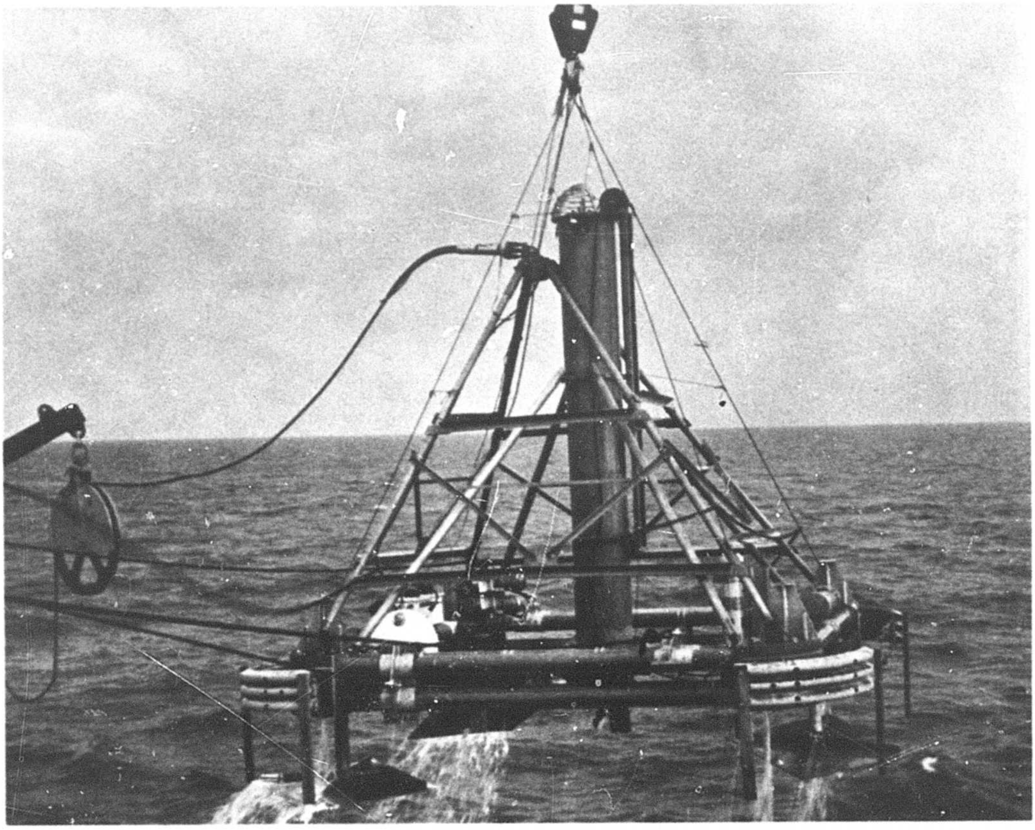

Figure 13. NCEL DOTIPOS.

DOTIPOS has a pyramidal frame with an 18-foot-square base and an overall height of approximately 16 feet. The platform is supported by three 4-foot-square pads. The total submerged weight varies from 1,900 to 4,000 pounds, depending upon the type of accessories attached. At maximum submerged weight, the bearing pads apply a stress of 85 psf. Short-term settlements from 0.5 to 1.5 inches have been observed in soft cohesive sediments. No foundation performance difficulties have been experienced during more than 30 deployments on the seafloor in water depths to 5,600 feet.

ESSA Bottom-Sitting Observation Stand. The Seattle, Washington, Division of the Environmental Science Services Administration (ESSA) used an observation stand equipped with a camera and current meter array to observe ocean-bottom currents in the Tasman Sea (Ryan, 1969). The device, which weighs 200 to 300 pounds in water, is pyramidal with a 12- by 12-foot base fabricated from 1-inch-diameter pipe. Water depths at test locations varied from 2,600 to 15,000 feet. Sediments were predominantly calcareous oozes. Although bottom penetration and settlement varied from site to site, no foundation performance difficulties were experienced. Performance data are being assembled by ESSA for future publication.

ESSA Plate Load Device. Two series of plate bearing tests were performed by Harrison and Richardson on sandy marine sediments in the shallow waters of lower Chesapeake Bay (Figure 14) (Harrison and Richardson, 1967; Harrison, 1969). The behavior of the sediments was compared to the theoretical behavior as predicted by the Terzaghi and Taylor equations for terrestrial soil.

A load frame (Figure 15), which weighed 82,000 pounds in air and was estimated to weigh 48,000 pounds in water, supplied the reaction for each of the in-situ load tests. The frame had a bearing area of approximately 48 square feet (giving an applied stress of 1,000 psf). A 20,000-pound calibrated hydraulic jack on the frame was used to apply loads to the 12-, 19-, and 24-inch-diameter plates.

Before tests were performed, soil at the site was evaluated for grain size, void ratio, density, and wet unit weight. A series of triaxial tests, conducted in the laboratory, established the sediment's angle of internal friction.

When the load frame was slowly placed on the seafloor, the frame settled 1-1/2 to 3 inches into the sediment at Site A and 1 inch at Site B. Once SCUBA divers had instrumented the frame, the plate bearing tests were performed. Values of ultimate in-situ bearing capacity as determined by this procedure were found to be generally higher (by factors of 2 to 3) than predicted by theory. The amount of settlement under a given stress increased as the plate diameter increased, as predicted by existing terrestrial theory.

NCEL LOBSTER. The NCEL LOBSTER (Long-Term Ocean Bottom Settlement Test for Engineering Research) was designed to measure the in-situ long-term compression of soft sediment under typical foundation loads.

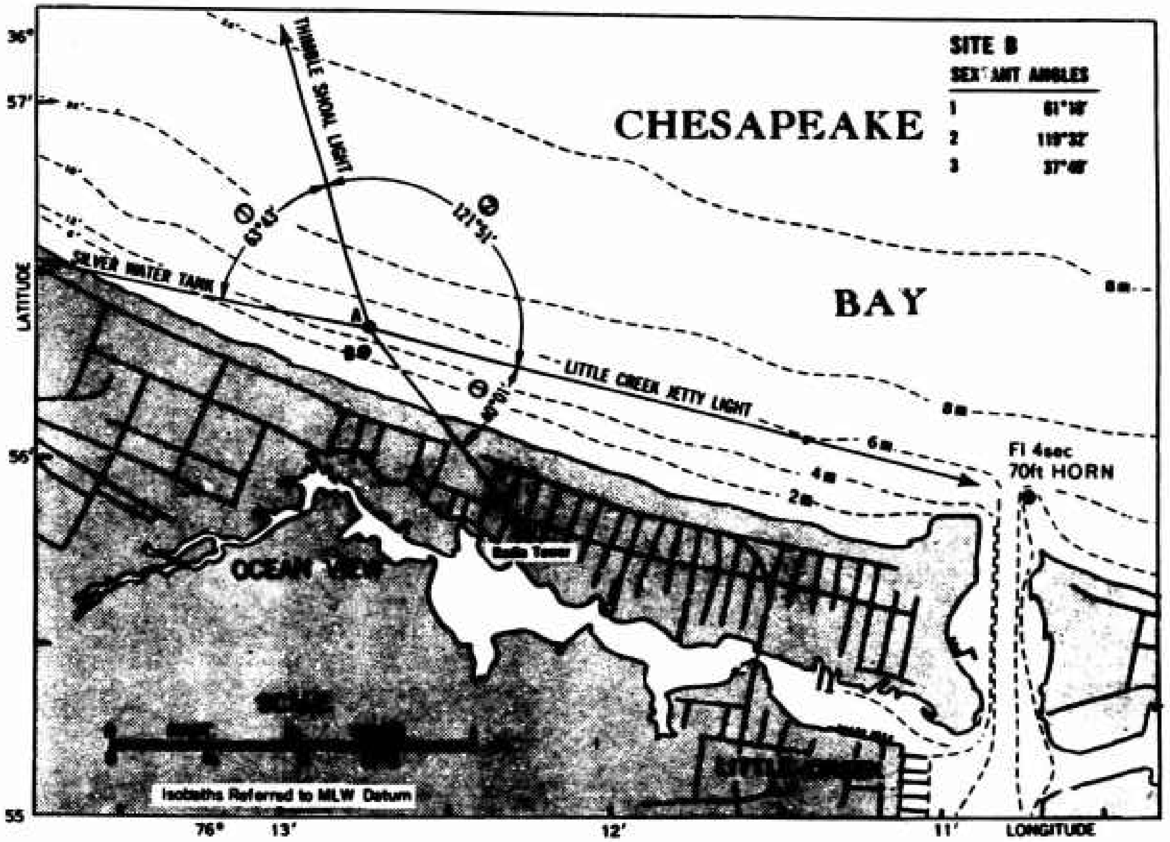

Figure 14. Location of ESSA plate bearing test sites. (From Harrison and Richardson, 1967. ©University of Illinois Press. Used by permission.)

Table 2. Miscellaneous Submerged Structures

Name	Operator	Initial Installation Year	No. of Structures or Deployments	Depth (ft)	Location	Wt (lb) in Water, W, or Air, A	Latera Dimensi (ft)
NCEL DOTIPOS (Deep Ocean Test-In-Place and Observation System)	NCEL (Naval Civil Engineering Laboratory)	1967	≈30	0 to 5,600	off Southern California coast	1,900 to 4,000 (W)	18 x 1
ESSA Bottom-Sitting Observation Stand	ESSA (Environmental Science Services Administration), Seattle, Wash.	≈1966	numerous	2,600 to 15,000	Tasman Sea	200 to 300 (W)	12 x 1
ESSA Plate Load Device	ESSA, Norfolk, Va.	1966	2	20	Chesapeake Bay	82,000 (A) 48,000 (W)	5 x 3
NCEL LOBSTER (Long-Term Ocean Bottom Settlement Test for Engineering Research)	NCEL	1967	9	4 to 1,200	off Southern California coast	1,300 (W)	6-ft di
NCEL Plate Bearing Device	NCEL	1965	≈100	120 to 6,000	off Southern California coast	3,000 to 6,000 (W)	fits ins 12-ft-d circl
NASL Deep-Sea Exposure Array	NASL (Naval Applied Science Laboratory)	1967	2	4,500	Tongue-of-the-Ocean, Bahamas	650 (A)	10 x
NCEL STU (Submersible Test Unit)	NCEL	1963	8	120 to 6,780	off Southern California coast	≈5,000 (A)	≈10 x
NRL's STU	NRL (Naval Research Laboratory)	1962	3	5,800	Bahamas	200 to 300 (A)	6 x
		1961	1	300	near Fort Lauderdale, Fla.	200 to 300 (A)	3 x
		1961	1	500	near Fort Lauderdale, Fla.	1,000 (A)	5 x 2 (
NUSL Transponder Block	NUSL (Naval Underwater Sound Laboratory)		1	60	Long Island Sound, New London, Conn.	≈730 (W)	3 x

A

Miscellaneous Submerged Structures

Wt (lb) in Water, W, or Air, A	Lateral Dimension (ft)	Foundation Type	Foundation Bearing Pressure (psf)	Sediment Type	Settlement	Remarks
1,900 to 4,000 (W)	18 x 18	three 4-ft-square spread footings	40 to 85	soft cohesive sediments	0.5 to 1.5 in.	In-situ vane shear strength and cone penetration available.
200 to 300 (W)	12 x 12	12 x 12-ft base of 1-in.-diam pipe	50 to 75	predominantly calcareous ooze	varies	No difficulties encountered.
82,000 (A) 48,000 (W)	5 x 32	two 5 x 5-ft spread footings	1,000	sandy marine sediments	1 to 3 in.	In-situ load-versus-deflection curves available.
1,300 (W)	6-ft diam	circular spread footing	100	soft cohesive sediments	1 to 8 in.	In-situ settlement-versus-time records available.
3,000 to 6,000 (W)	fits inside 12-ft-diam circle	three 2 x 5-ft strip footings	100 to 200	cohesionless and cohesive	0 to 3 in.	In-situ load-versus-deflection curves available.
650 (A)	10 x 10	10 x 10-ft base of 1-1/2-in. angle	less than 130	silts	no excessive settlement	Shear strengths available.
≈5,000 (A)	≈10 x 10	two strip footings	110	sands and silty clays to clayey silts	0 to 8 in.	Settlement estimates based upon mudline markings.
200 to 300 (A)	6 x 6	6 x 6-ft base of 1-in. pipe	less than 150	silt size calcareous sands	thought to be less than 1 ft	Settlement estimates based upon mudline markings.
200 to 300 (A)	3 x 4	spread footing	less than 25	calcareous sand	no sinking noted	
1,000 (A)	5 x 2 (diam)	deactivated mine	less than 100	calcareous ooze	no settlement noted	Observed with television.
≈730 (W)	3 x 3	spread footing	81	predominantly sands	base was partially covered with sand	Observed with divers.

continued

Table 2. Continued

Name	Operator	Initial Installation Year	No. of Structures or Deployments	Depth (ft)	Location	Wt (lb) in Water, W, or Air, A
NUC Pop-Up Test Site	NUC (Naval Undersea Research and Development Center), Pasadena, Calif.	1958	1	115	Wilson Cove, San Clemente Island, Calif.	up to 400,000 (W)
		1960	1	170	Wilson Cove, San Clemente Island, Calif.	up to 700,000 (W)
			2	165	Wilson Cove, San Clemente Island, Calif.	unknown
			21	170	Wilson Cove, San Clemente Island, Calif.	unknown
St. Andrews Bay Model Studies	ESSA, Miami Beach, Fla.	1961	3	17	St. Andrews Bay, Fla.	2,100 each (W)
Miscellaneous	Petroleum Companies		≈20	varies	varies	varies
University of Miami's Reflector and Cameras	Institute of Marine Science, University of Miami, Coral Gables, Fla.	1964	1	85	near Miami, Fla.	
			numerous	50 to 100		
FORAC Stations	APL (Applied Physics Laboratory), University of Washington, Seattle, Wash.		varies	100 to 2,600	varies	
Pipe Sections	University of Rhode Island, Kingston, R. I.	≈1968				

Table 2. Continued

	Location	Wt (lb) in Water, W, or Air, A	Lateral Dimension (ft)	Foundation Type	Foundation Bearing Pressure (psf)	Sediment Type	Settlement	Remarks
	Wilson Cove, San Clemente Island, Calif.	up to 400,000 (W)	30-ft diam	30-ft-diam mat foundation	850	loose coarse sand atop dense sand over bedrock	no problems noted	
	Wilson Cove, San Clemente Island, Calif.	up to 700,000 (W)	20 x 20	four 14-in.-diam piles embedded 65 ft		loose coarse sand atop dense sand over bedrock	no problems noted	Differential movement of 1/8-in. would have been detected.
	Wilson Cove, San Clemente Island, Calif.	unknown	24-in diam	24-in.-diam piles embedded 36 ft		loose coarse sand atop dense sand over bedrock	no problems noted	Resist a maximum of 410,000 ft-lb.
	Wilson Cove, San Clemente Island, Calif.	unknown	24-in. diam	24-in.-diam piles embedded 36 ft		loose coarse sand atop dense sand over bedrock	lateral deflection = 1/2 in. at 50,000-lb load	Ran lateral-load-versus-deflection test.
	St. Andrews Bay, Fla.	2,100 each (W)	2 x 7 3 x 3 4-ft diam	strip footing spread footing spread footing	164 246 166	silty clay to silty sand	6 to 37 in.	Predicted depth of penetration from bearing capacity equation.
	varies	varies	varies	usually mat foundation	unknown	varies	unknown	
	near Miami, Fla.			three 12-in.-diam pipe piles driven 20 ft	unknown	calcareous sand	no settlement noted	
)				spread footings		dense granular material	no settlements noted	
00	varies			unknown	unknown	unknown	unknown	
					unknown	bay sediments		

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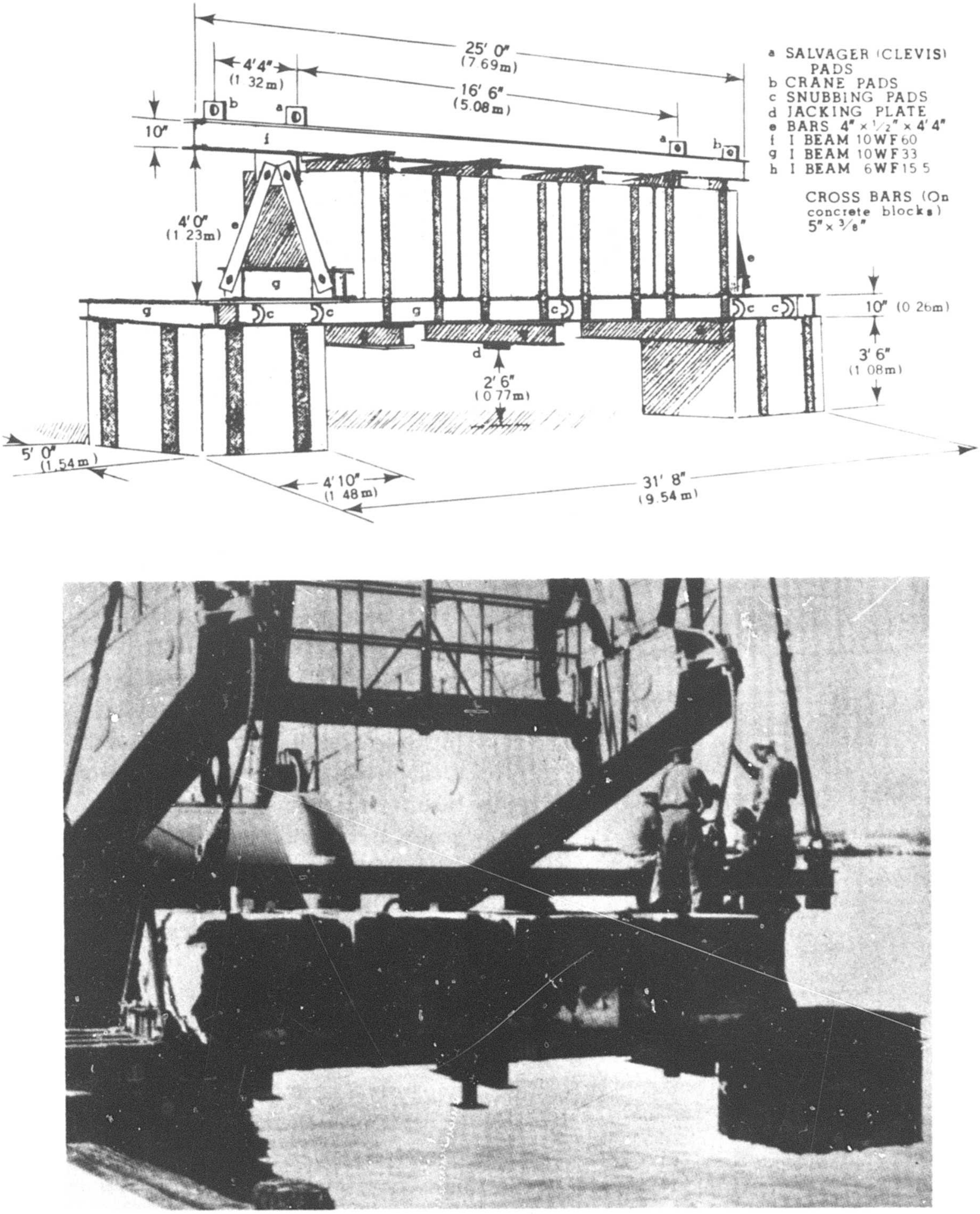


Figure 15. Load frame for ESSA plate bearing tests. Top: drawing and specifications. Bottom: photograph of frame being transferred (by crane) from wharf to suspension cables of U.S.S. *Salvager*.

(From Harrison and Richardson, 1967. ©University of Illinois Press. Used by permission.)

Concrete blocks, 48 inches in diameter, which apply 100 psf to the sediment surface, are employed as the standard footings during the LOBSTER tests. Settlement is measured relative to a stationary reference rod extending 10 feet into the sediment. The reference rod is protected from intermediate settlement by a 9-foot-long outer casing or isolating tube. In one test (Figure 16) multiple reference rods were utilized to monitor soil compressions at various depths. Movement is recorded by either SCUBA divers (Figures 1 and 2) or an automated electronics package (Figure 3). Nine long-term tests (duration of observation up to 2 years) have been performed at sites near Port Hueneme, California, in water depths varying from 4 to 1,200 feet. The soils in all cases were soft cohesive materials with grain sizes predominantly in the silt and clay ranges. The sediments' vane shear strengths at a depth of 12 inches varied from 0.2 to 0.5 psi.

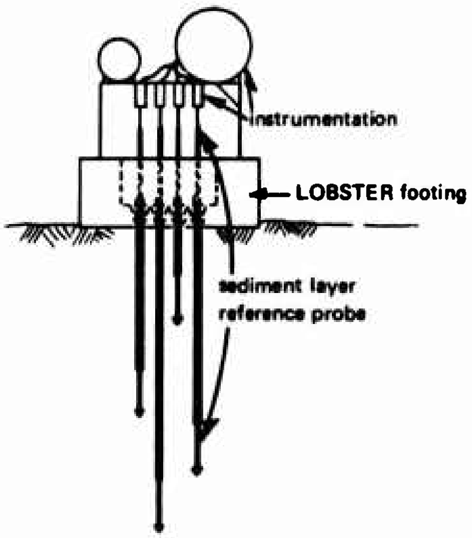


Figure 16. Early, shallow-water LOBSTER structure and reference systems for investigation of long-term foundation behavior on the seafloor.

In general, the settlement data generated by these deployments (Figure 17, typical example) have confirmed analytical predictions based upon the magnitude of primary consolidation measured during laboratory consolidation tests. Settlement predicted in this manner typically varied from 1 to 3 inches. However, the in-situ results also indicated a surprisingly large amount of continuing long-term settlement, apparently caused by secondary compression (about 4 inches in one case). Results of the in-situ deployments also indicated that undermining of the foundation by burrowing animals and hydraulic scour can cause large settlement and, in some instances, render the foundation useless. These two effects have caused up to 7 and 8 inches of foundation settlement at one particular site. In the latter case, 7 inches of settlement caused by scour was accompanied by a tilting of about 20 degrees. This tilting is equivalent to a differential settlement of about 18 inches. A more typical value of differential settlement, resulting from primary and secondary compression only, was 1 inch.

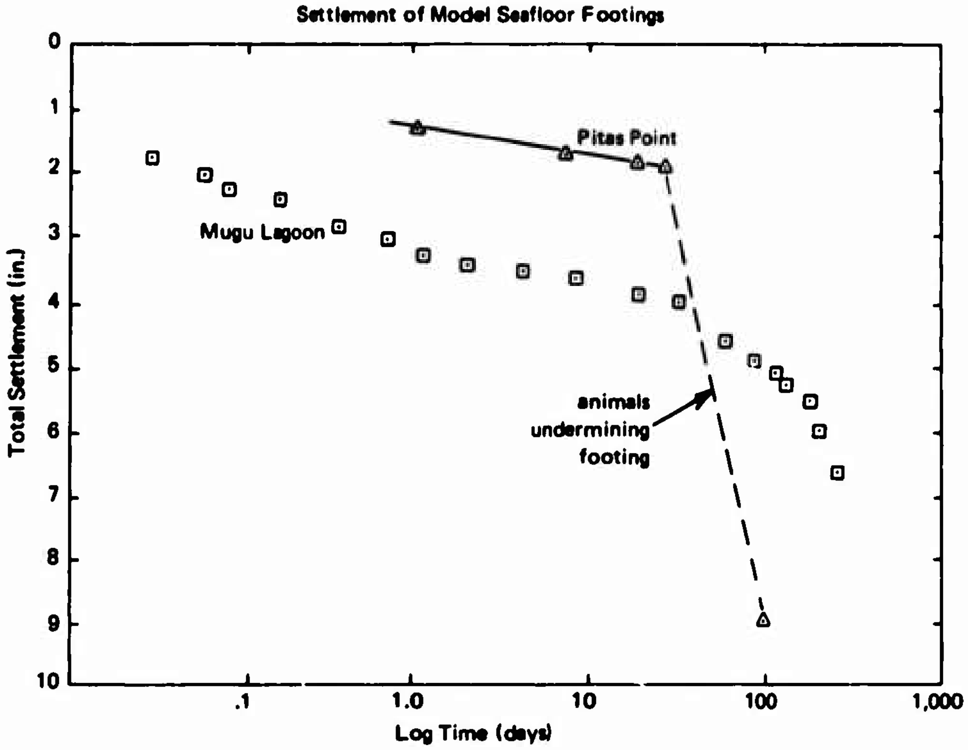


Figure 17. Typical settlement data from LOBSTER tests.

NCEL Plate Bearing Device. The NCEL plate bearing device (Figure 18) was developed in 1965 to determine the short-term in-situ bearing pressure and settlement response of marine sediments (Kretschmer, 1967). The tripod frame is approximately 7 feet tall and has overall lateral dimensions which allow it to fit within a 12-foot-diameter circle. Three articulated support pads (each approximately 2 feet by 5 feet) connected to the legs of the framework transfer the weight of the device to the seafloor. Total pad bearing pressure when fully loaded is approximately 200 psf.

Circular and square bearing plates, ranging in diameter from 6 to 18 inches, transfer loads of 0 to 5,500 pounds to the sediment during a controlled penetration-rate test. About 100 tests have been performed in water depths from 120 to 6,000 feet, at a number of sites off the Southern California coast. No difficulties have been experienced with the foundation system for the device Results of the individual in-situ plate tests are discussed in detail by Kretschmer (1967), Kretschmer and Lee (1970), and Taylor (1970).

NASL Deep-Sea Exposure Arrays. The Naval Applied Science Laboratory (NASL) placed two specimen racks in the TOTO as part of a material evaluation program (Macander, 1969). The racks, which were installed in early 1967, were 13 feet tall and had a 10-foot-square base. The bearing surface area was approximately 15 square feet; the total weight of the structures in air was 650 pounds. The tests were conducted in 4,500 feet of water. Sediments at the site were predominantly silts with shear strengths of 1 to 3 psi. One unit was removed in 1968, and the other will be removed later. No excessive settlement was noted on the recovered rack.

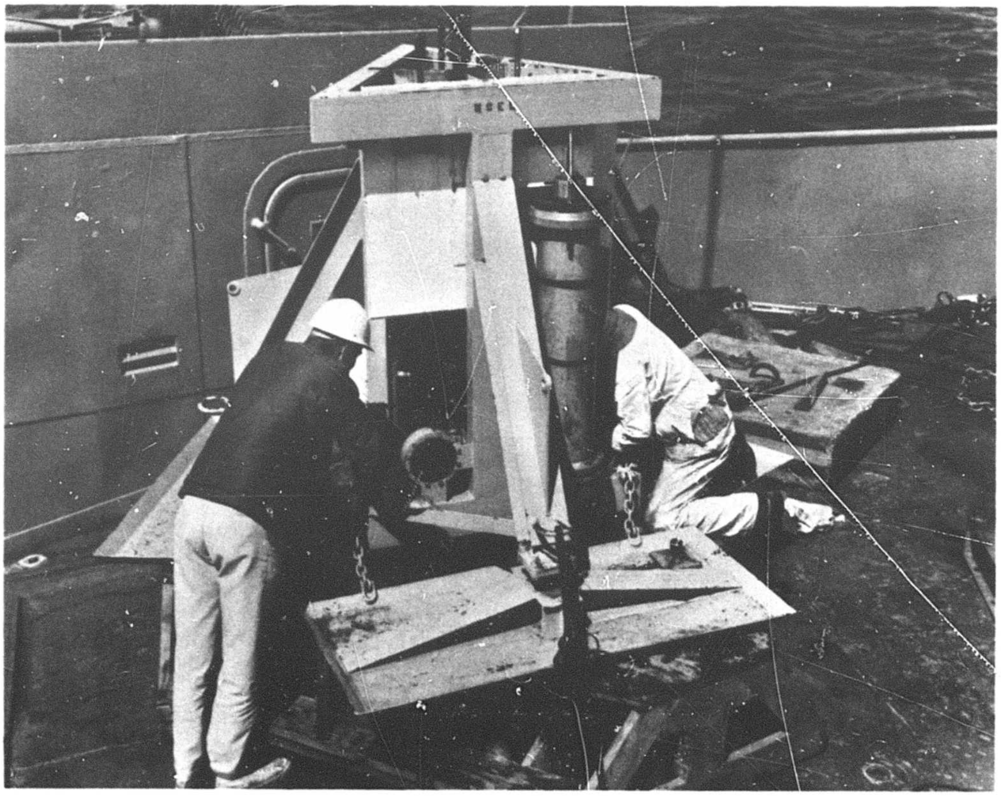


Figure 18. NCEL plate bearing device.

NCEL Submersible Test Unit. Seven Submersible Test Units (STUs) (Figure 19), which expose material specimens to the seafloor environment at and just above the sediment line, have been placed by NCEL in water depths of 2,370 to 6,780 feet (Jones, 1965; Hironaka, 1966; Reinhart, 1969). An eighth STU was placed in 120 feet of water. The test units have remained on the bottom for intervals of 4 to 24 months.

In most cases, the STUs were supported by two strip footings. The footings applied approximately 110 psf to the sediments. Sediments generally varied between silty clays and clayey silts. The soil at the shallow-water location was predominantly sand size.

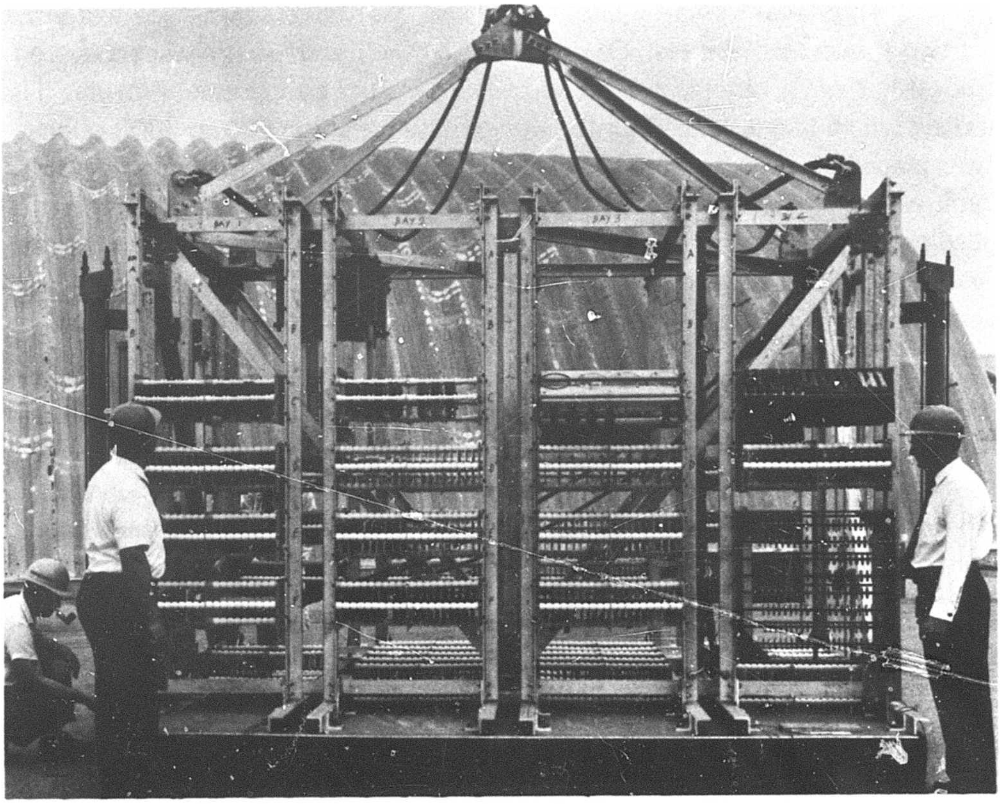


Figure 19. NCEL STU.

Estimates of total settlement were determined from mudline markings on test specimens. Total penetration values varied between negligible and 8 inches. No distinctions could be made between dynamic, immediate, and long-term settlement processes.

Naval Research Laboratory STUs. In 1961, a cooperative program of deep-sea test panel exposures was initiated in TOTO by the Naval Oceanographic Office, the Naval Research Laboratory, and the Naval Underwater Ordnance Station (De Palma, 1962 and 1969; Hersey, 1969). Three test units were placed in 5,800 feet of water about 3 miles off Andros Island, in the Bahamas. The 200- to 300-pound pyramidal arrays, supported on a silt-size calcareous ooze, were constructed of 1-inch-diameter pipe with a 6-foot-square base. Of the three units placed in the spring of 1962, one was recovered 3 months later, another 34 months later, and the last has yet to be recovered. Settlement for the two recovered arrays was thought to be less than 1 foot, since test plates located above that elevation showed no effects from burial in the sediment.

The Naval Research Laboratory also has placed submerged test units at two shallow-water sites. During 1961, a cagelike structure was recovered monthly from a water depth of 300 feet near Fort Lauderdale, Florida. The array, which had a 3- by 4-foot concrete base weighing 200 to 300 pounds, was placed on a calcareous sand bottom. No sinking was ever noted. Another unit was deployed near Fort Lauderdale in 500 feet of water for 12 months. Sediments at the site were calcareous oozes. The unit, which used a deactivated mine for a base, weighed approximately 1,000 pounds. No settlement was noted when observed with television camera just prior to recovery.

NUSL Transponder Block. A small transponder block was placed in the Long Island Sound near New London, Connecticut, by the Naval Underwater Sound Laboratory (NUSL). The water depth at the site was approximately 60 feet, while sediments in the area were predominantly sand. Divers observed that the 3- by 3- by 1-foot concrete block base and the acoustic relay cables have been partially covered with sand (Moothart, 1969).

NUC Pop-Up Test Site. Two foundation types have been used by the Naval Undersea Research and Development Center (NUC), Pasadena (formerly Naval Ordnance Test Station), for pop-up tests conducted off the northwest tip of San Clemente Island (Gardner et al., 1969; Sutton, 1969; Ridlon, 1969). The first foundation was installed in 1958 to test *Polaris*-type missiles. The foundation, which was in 115 feet of water, employed a 30-foot-diameter by 9-foot-high concrete-filled steel caisson. This caisson was embedded 7 feet into the soil. The soil profile consisted of 8 feet of loose coarse sand atop a 6-foot layer of dense sand. A fractured andesite with pockets of gravel lay beneath the sand. This foundation supported a 400,000-pound launcher; additional dynamic compression loadings as large as 140,000 pounds resulted during individual tests. No foundation problems were reported.

In 1960, a more complex launch system (Figure 20) was installed in 170 feet of water at a nearby site. The soil profile was essentially the same. This system had a static weight of over 700,000 pounds and resisted dynamic compression loads of up to 220,000 pounds during individual tests. The test structure was supported on four 14-inch-diameter by 65-foot-long drilled-in, grout-filled, pipe piles. Over 200 simulated launchings have been performed. Although no foundation monitoring was provided, it is known that the threshold sensitivity of other electronic equipment mounted on the structure (differential movement of less than 1/8 inch) was not exceeded.

Two camera mounting piles, which extend to the ocean surface, have also been installed at the Pop-Up Test Site. These 24-inch-diameter piles were drilled in 36 feet and filled with grout. The piles were designed primarily to resist a maximum overturning moment of 410,000 ft-lb caused by wind and wave forces. The two structures have exhibited no serious foundations problems.

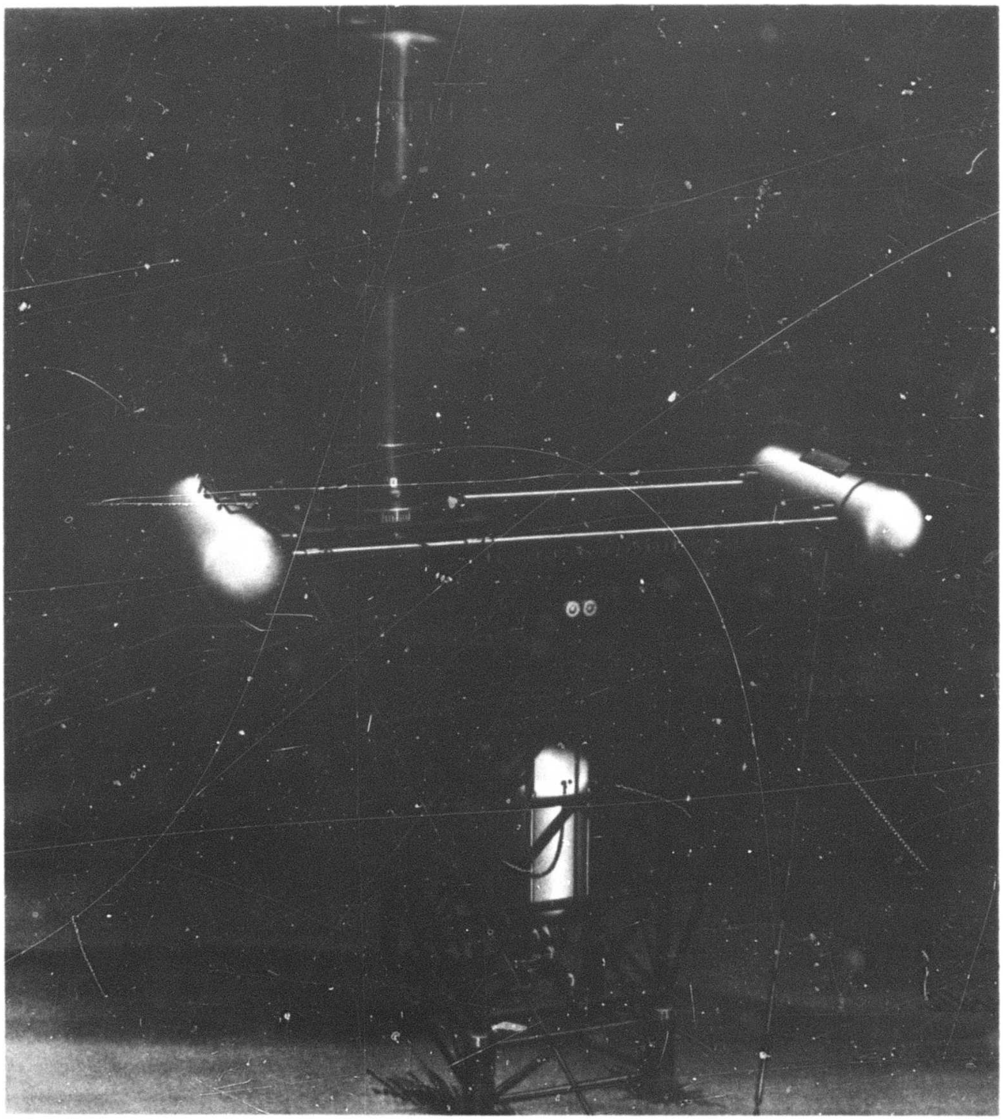


Figure 20. NUC's Pop-Up Launcher II. (From Gardner et al., 1969.)

Twenty-one mooring piles were also installed in the seafloor surrounding the pop-up launchers. These 24-inch-diameter by 36-foot-long, drilled-in, grout-filled, pipe piles are similar to those used for the camera support. One of the mooring piles was tested in 1964 to evaluate its lateral load capability. Figures 21 and 22 show the in-situ test setup. A lateral load of 50,000 pounds caused a maximum deflection of 1/2 inch and maximum angle of deflection of 25 minutes.

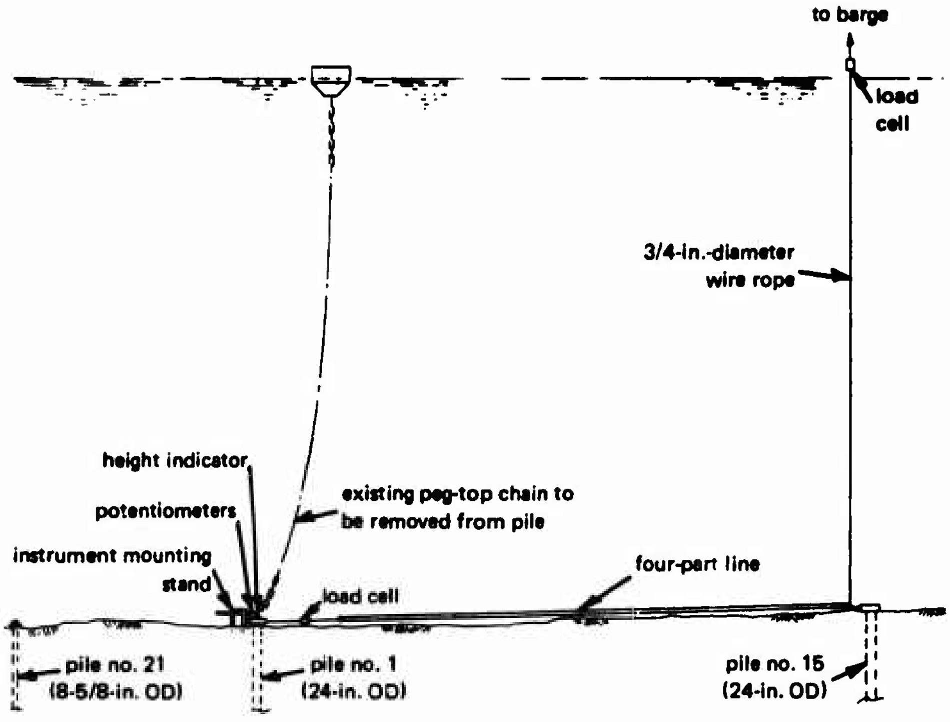


Figure 21. Pop-Up Site pile load test. (After Sutton, 1969.)

St. Andrews Bay Model Studies. In 1961, Keller (1964 and 1969) placed three concrete blocks on the shallow seafloor (water depth averaged 17 feet) to study the bearing capacity of spread footing foundations. Two test sites in St. Andrews Bay, Florida, were used during the investigation.

The concrete blocks were rectangular, square, and circular in plan (Figure 23). Each weighed approximately 2,100 pounds in water. Applied pressures ranged from 164 to 246 psf. The soil at each site was sampled and evaluated. It varied from a silty clay to a silty sand classification and, in all cases, would be considered a weak and compressible cohesive soil. Results of the laboratory study were then used to estimate the bearing capacity at various levels of object penetration.

Laboratory data indicated that the undisturbed strength of the soil could not support the blocks at the soil surface; thus, a bearing capacity failure was expected. The extent of block penetration was predicted by determining the depth at which the bearing capacity, based upon undisturbed soil strength, had increased enough (assuming soil strength increased with depth) to support the block. However, the blocks penetrated beyond the estimated depths. Subsequent analysis of the data has shown that use of remolded strength values in the bearing capacity equation predicts fairly closely the observed depth of penetration. The strains imposed on the soil mass as a result of the initial bearing capacity failure possibly caused remolding and the reduction in soil strength.

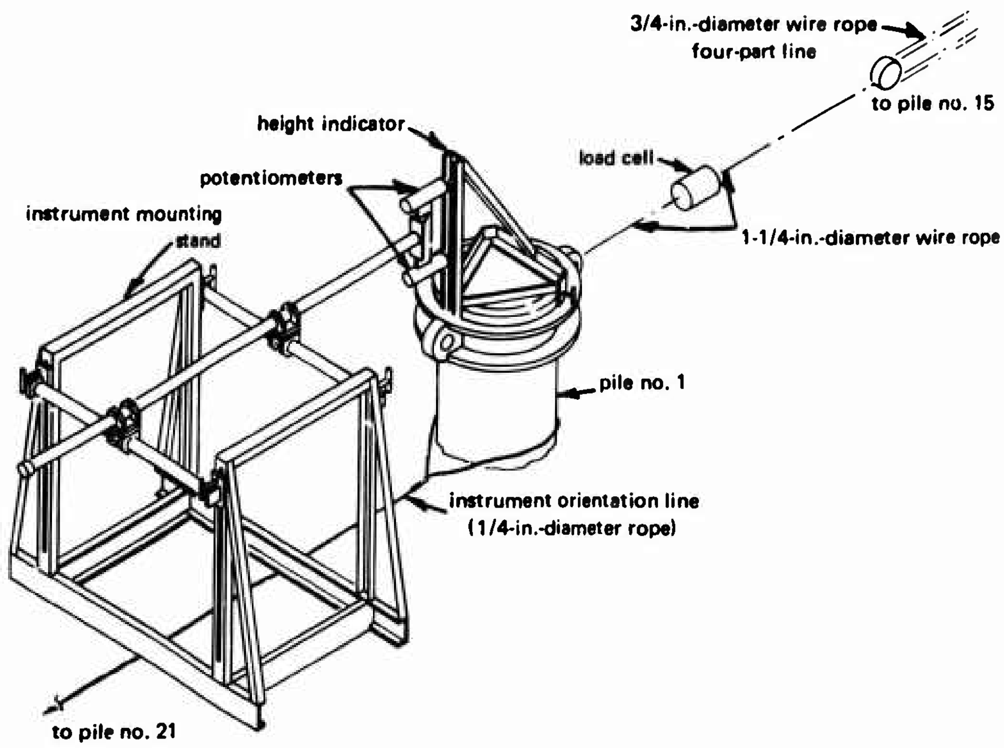
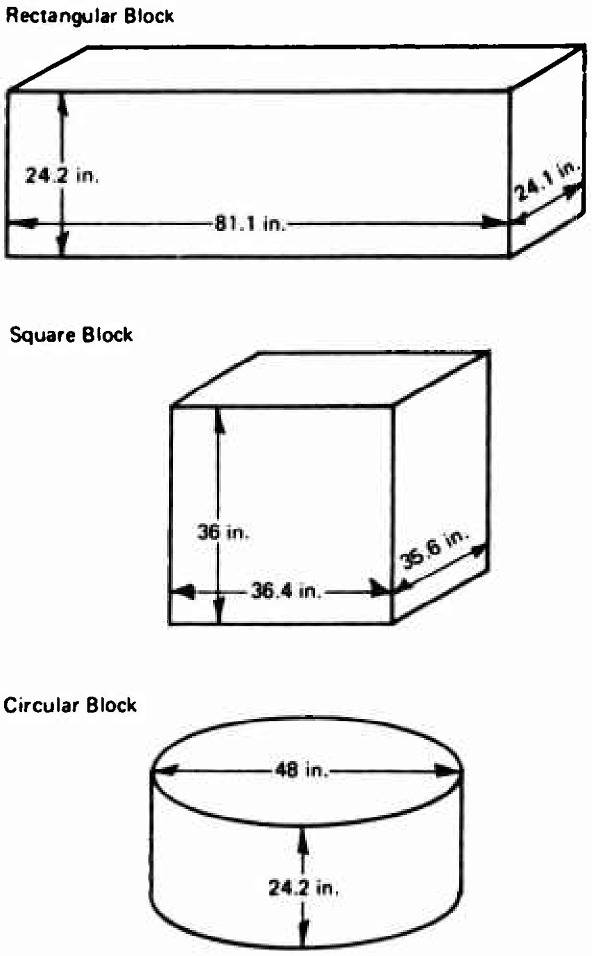


Figure 22. Pop-Up Site mooring pile load test setup. (After Sutton, 1969.)

Submerged Petroleum Production Facility. The petroleum companies maintain a few totally submerged structures. At least 20 production facilities (flow-line manifolds, separators, heat treaters, oil storage tankage, gas compressors, etc.) are currently in use on the seafloor. Most of these facilities utilize mat foundation systems. Mat foundations were generally selected because of the extremely weak soil conditions and because this type of foundation provides good resistance to scour effects. No foundation performance difficulties have been reported.

University of Miami Reflector and Cameras. The Institute of Marine Science at the University of Miami has been using a reflector and various pad-mounted cameras on the seafloor periodically for the past 5 years (Kronengold, 1969). The reflector is 24 feet in diameter and is supported by three 12-inch-diameter pipe piles driven to refusal (approximately 20 feet). The water depth at the site is 85 feet; sediments are calcareous sand. No settlement has been noted. The cameras, supported on flat pads, were placed in 50 to 100 feet of water. Sediments at the site were a dense granular material. No settlements were observed.



Weight in air: 3,974 lb
Weight in water: 2,219 lb
Bearing pressure in water: 1.14 psi

Weight in air: 3,9 0 lb
Weight in water: 2,214 lb
Bearing pressure in water: 1.71 psi

Weight in air: 3,700 lb
Weight in water: 2,076 lb
Bearing pressure in water: 1.15 psi

Figure 23. Dimensions and weights of concrete blocks used in St. Andrew's Bay model studies. (After Keller, 1964.)

Other Structures. The Applied Physics Laboratory (APL), a division of the University of Washington, maintains FORAC stations at various localities (Linger, 1969). The devices, placed in 100 to 2,600 feet of water, consist of tripods with transducers. No indication of unsatisfactory performance has been reported.

The University of Rhode Island has observed the settlement of simulated pipe sections on bay sediments. Results are to be compared to predicted values (Nacci, 1969).

Habitats

A number of manned habitats (Table 3) have been deployed on the seafloor. General observations of their performance are available. Other habitats are in the design or fabrication stages. In these cases, the details of the selected foundation systems are useful as case histories, since the systems display the thinking of the designer relative to his past experience and knowledge of foundation performance.

Habitats represent a somewhat specialized set of case histories for several reasons. To date, the deepest deployment of a habitat for which any information is available has been 328 feet. Site selection for such deployments is usually heavily influenced by the requirement for good diver visibility. This requirement typically results in selection of sandy sites. In addition, consideration of the consequences of any sort of foundation failure (in terms of possible loss of human life) usually leads to an extremely conservative approach to site selection and foundation design. The following sections summarize some of the pertinent characteristics of various habitats.

Conshelf One. During September of 1962, an 8-foot-diameter by 17-foot-long steel cylinder was anchored horizontally in the Mediterranean near Marseilles, France (Cousteau, 1963). Conshelf One (Continental Shelf Station One) became Captain Jacques Yves Cousteau's first in a series of manned underwater habitats. The station, which housed a crew of two men for a week at a water depth of 33 feet, experienced no foundation problems.

Conshelf Two. Cousteau placed his second underwater manned station, Conshelf Two (Figure 24), in June of 1963 (Cousteau, 1964). Conshelf Two was located in the Red Sea approximately 5 miles northeast of Port Sudan. The main structure, Starfish House, sheltered five men for a month at a depth of 36 feet. Five telescopic legs with 4- by 4-foot bearing plates supported Starfish House on a coral sand ledge. Lead ballast of 200,000 pounds was added to the habitat to provide negative buoyancy. During Conshelf Two, Deep Cabin, a 20-foot-long rocket-shaped underwater chamber, housed a two-man crew for a week at a depth of 80 feet. Although three telescopic legs with bearing plates were intended for support, extremely steep rocky terrain precluded their use. Instead, the Deep Cabin was anchored on the steep slope. A third structure, the diving saucer hangar, allowed Cousteau's diving saucer to operate from a dry base 36 feet below the water surface.

The round hangar was supported by three 3- by 3-foot bearing plates on telescopic legs. Negative buoyancy was established by 120,000 pounds of lead. Except for the required revision of the foundation system for the Deep Cabin, no foundation difficulties were reported.

Conshelf Three. A third station, Conshelf Three, was placed near Villefranche, France, in October 1965 (Cousteau, 1966). The 18-foot-diameter steel sphere was occupied at a water depth of 328 feet by a six-man crew for 3 weeks. The sphere weighed 280,000 pounds and rested on a 48- by 28-foot chassis that held 154,000 pounds of ballast, ballast tanks, and reservoirs of helium, oxygen, and compressed air (Figure 25). The entire assembly was supported by four legs with sediment bearing plates. Crew members obtained undisturbed sediment cores by forcing water cans into the bottom sediments. At the project's completion, minor difficulties were encountered in breaking the feet free from the bottom. Several anxious minutes were required before breakout occurred.

Sealab I. On July 18, 1964, the Office of Naval Research, in conjunction with other Navy activities, placed a manned undersea habitat next to Argus Island, approximately 27 miles south of Bermuda (O'Neal et al., 1965; Groves, 1965). Sealab I (Figure 26) was lowered by the Argus Island crane from the water surface 193 feet to the very dense coral sand bottom. The bottom, which was leveled prior to the deployment, exhibited a minimum amount of loose, soft material. The 9-foot-diameter by 40-foot-long station was fabricated by the Naval Ship Research and Development Laboratory (NSRDL) (formerly Mine Defense Laboratory) at Panama City, Florida, from two mine sweeper floats. The Sealab's 3,000 pounds of negative buoyancy were supported by two 3- by 40-foot rectangular bins which doubled as ballast tanks (Figure 26). The habitat housed a crew of four men for 11 days. No foundation problems were recorded.

Sealab II. Sealab II was the Navy's second major step in a continuing man—undersea research program. Three 10-man teams occupied Sealab II for approximately 15 days each (Pauli and Clapper, 1967). Habitation occurred between August and October of 1965, 3,000 feet off Scripps Pier at La Jolla, California, in 205 feet of water (Fehl, 1969; Tolbert, 1969).

The habitat was essentially a nonpropelled submarine built to withstand an internal working pressure of 125 psi. The hull was constructed of 1-inch-thick mild steel, 12 feet in diameter and 57-1/2 feet long. When on the bottom, Sealab II was 26,000 pounds negatively buoyant. The bearing surfaces, two 3- by 18-foot pads extending fore and aft, were designed to provide a maximum bearing stress of 300 psf.

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Table 3. Habitats

Name	Operator	Year	No. of Structures	Depth (ft)	Location	Wt (lb) in Water, W, or Air, A	Foundation Type
Conshelf One	Jacques Cousteau	1962	1	33	Mediterranean near Marseilles, France		anchored
Conshelf Two	Jacques Cousteau	1963	3	36 80 36	Red Sea Red Sea Red Sea		five bearing pads anchored three bearing pads
Conshelf Three	Jacques Cousteau	1965	1	328	near Villefranche, France		four bearing pads
Sealab I	ONR (Office of Naval Research)	1964	1	193	Argus Island, near Bermuda	3,000 (W)	strip footings
Sealab II	ONR	1965	1	205	off Scripps pier at La Jolla, Calif.	26,000 (W)	bearing pads
Hydrolab	Florida Atlantic University	1967 1969	1 1	50 50	near Palm Beach, Fla. near Riviera Beach, Fla.	37,200 (W) 37,200 (W)	mat footing concrete mat footing concrete
Makai Habitat II (Aegir)	Oceanic Enterprises, Inc.	1969	1	200	Makapuu Oceanic Center, Hawaii	80,000 (W)	strip footings
Tektite I	Navy, Department of Interior, NASA, and General Electric Co.	1969	1	58	Lameshur Bay, St. Johns, Virgin Islands	20,000 (W)	mat footing
Chernomer I	Russia	1969	1	33	Golubaya Bay, Black Sea	125,000 (A)	hydraulic base supports
Chernomer II	Russia		1	115		144,000 (A)	four legs
	Deutsche, Babcock, and Wilcox (Germany)	1968	1	33	East Sea		four bearing pads
EDALHAB	University of New Hampshire		1	26	Alton Bay, N. H.		two anchors, 6,000 lb each
	German	1969	1	75	off Helgoland in North Sea		two strip footings
Sprut	Russia	1967-70	several	30 to 40	Black Sea		anchored

Table 3. Habitats

n	Wt (lb) in Water, W, or Air, A	Foundation Type	Foundation Size (H)	Foundation Bearing Pressure (psf)	Sediment Type	Settlement	Remarks
n near rance		anchored		unknown			No foundation problems.
		five bearing pads	4 x 4	unknown	coral sand		No foundation problems.
		anchored			rocky		Terrain too rough for planned footing foundation.
		three bearing pads	3 x 3	unknown			No foundation problems.
nche,		four bearing pads	≈5 x 5	unknown			Encountered minor breakout problem.
nd, nda	3,000 (W)	strip footings	two 3 x 40	12.5	dense coral sand		No foundation problems.
ier at lif.	26,000 (W)	bearing pads	two 3 x 18	300	very fine silty sand	0 to 15.8 in. of differential settlement	Extensive soils investigation performed.
ach,	37,200 (W)	mat footing concrete	20.66 x 18	100	coarse calcareous sand	no movement detected	Scour and fill.
each,	37,200 (W)	mat footing concrete	20.66 x 18	100	dense sand	differential movement	Movement attributed to extensive scour and fill.
anic aii	80,000 (W)	strip footings	two 9 x 70	>63			No foundation problems.
y, ds	20,000 (W)	mat footing	15 x 37	36	coral sand		No foundation problems.
y,	125,000 (A)	hydraulic base supports		unknown			Used large surface buoy for support. Gale lifted and moved habitat.
	144,000 (A)	four legs		unknown			
		four bearing pads	5-ft diam	unknown			
H.		two anchors, 6,000 lb each		unknown			
d		two strip footings	2 x 30	unknown			Has adjustable legs to compensate for uneven bottom.
		anchored		unknown			Buoyant tent.

continued

Table 3. Continued

Name	Operator	Year	No. of Structures	Depth (ft)	Location	Wt (lb) in Water, W, or Air, A	F
Sea Igloo	E. A. Link	1964	1	33	Caribbean		
Sublimnos		1969	1	30	Great Lakes		
Atlantis	University of Miami and Chrysler Corp.	planned	0	up to 1,000	continental shelf	64,000 (W)	spr
MUS	NCEL	planned	0	up to 6,000		≈12,000 (W)	four
	Santa Barbara City College	planned	0	30 to 40			
Sealab III	ONR	planned	1	610	Wilson Cove, San Clemente Island, Calif.	≈26,000 (W)	n v S
Seause		planned	0	120	Cobb Seamount, Pacific (near state of Washington)	appears similar to Makai Habitat	si Mak
Tektite II	same as Tektite I	1970	1	50	Virgin Islands	similar to Tektite I	si T
	same as Tektite I	1970	1	100	Virgin Islands		

Table 3. Continued

Location	Wt (lb) in Water, W, or Air, A	Foundation Type	Foundation Size (H)	Foundation Bearing Pressure (psf)	Sediment Type	Settlement	Remarks
Caribbean		anchored		unknown			Buoyant tent.
Great Lakes		four pads	four 2 x 2	unknown	cohesive soils		No foundation problems.
continental shelf	64,000 (W)	spread footing	two 17 x 33	57	soils with bearing capacity > 72 psf		
	≈12,000 (W)	four bearing pads	12-ft diam	≈26	soils with bearing capacity > 144 psf		
Wilson Cove, San Clemente Island, Calif.	≈26,000 (W)	modified version of Sealab II	similar to Sealab II	≈300	dense, well-graded sand		
Cobb Seamount, acific (near state of Washington)	appears similar to Makai Habitat	similar to Makai Habitat	similar to Makai Habitat	≈63			
Virgin Islands Virgin Islands	similar to Tektite I	similar to Tektite I	similar to Tektite I	≈36	similar to Tektite I		

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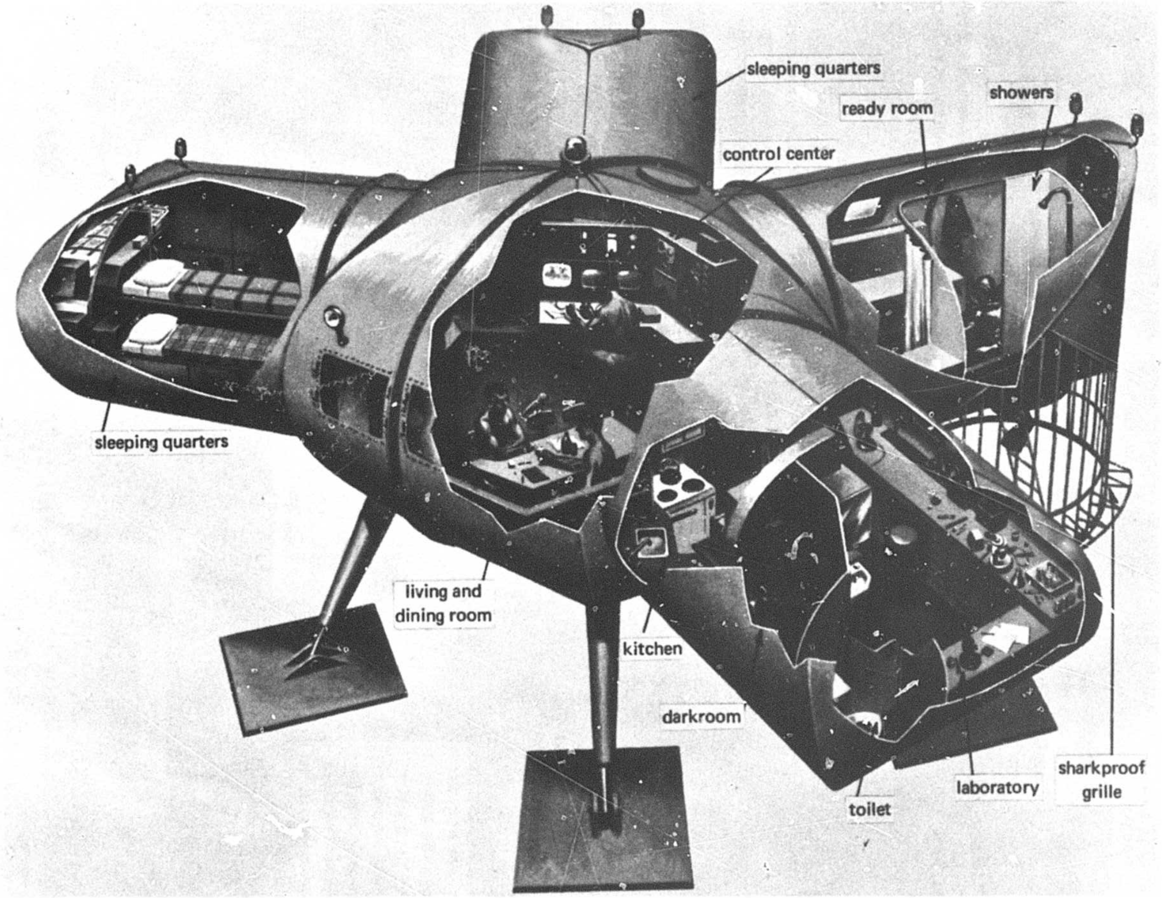


Figure 24. Conshelf Two habitat—Starfish House. (From Cousteau, 1964. Painting by Davis Meltzer. ©National Geographic Society. Used by permission.)

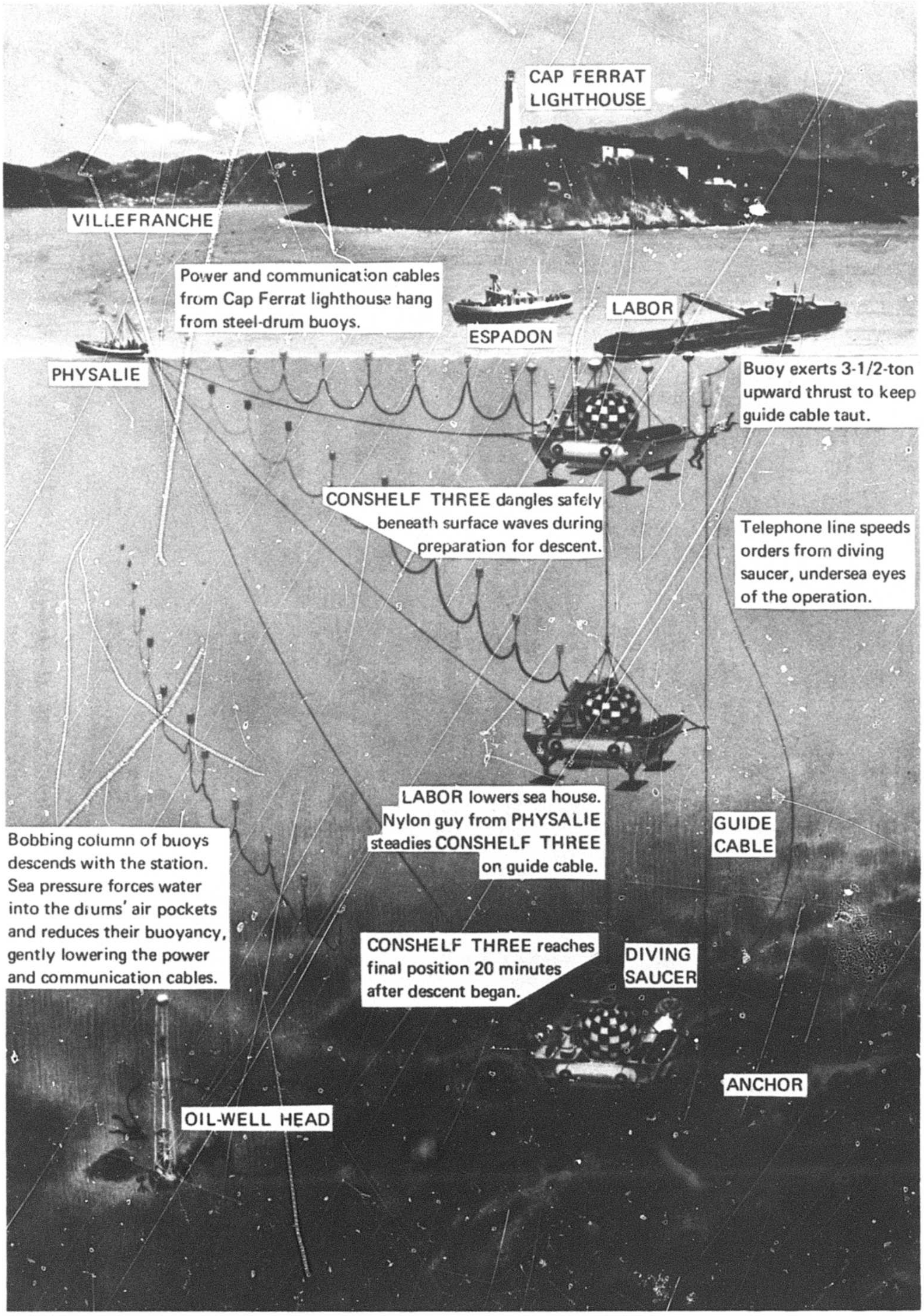


Figure 25. Conshelf Three. (From Cousteau, 1966. Painting by Davis Meltzer. ©National Geographic Society. Used by permission.)

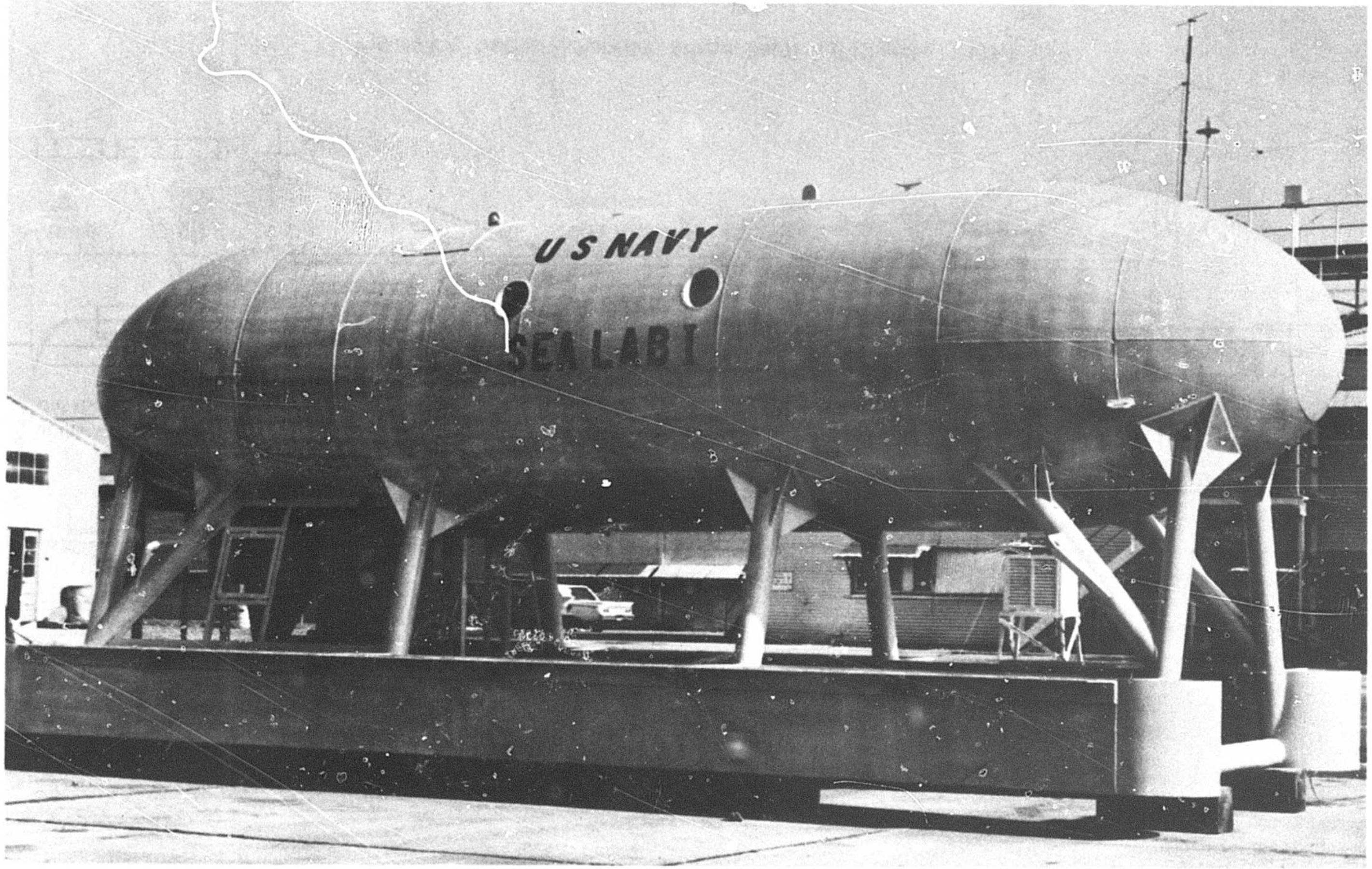


Figure 26. Sealab I habitat. (From O'Neal et al., 1965.)

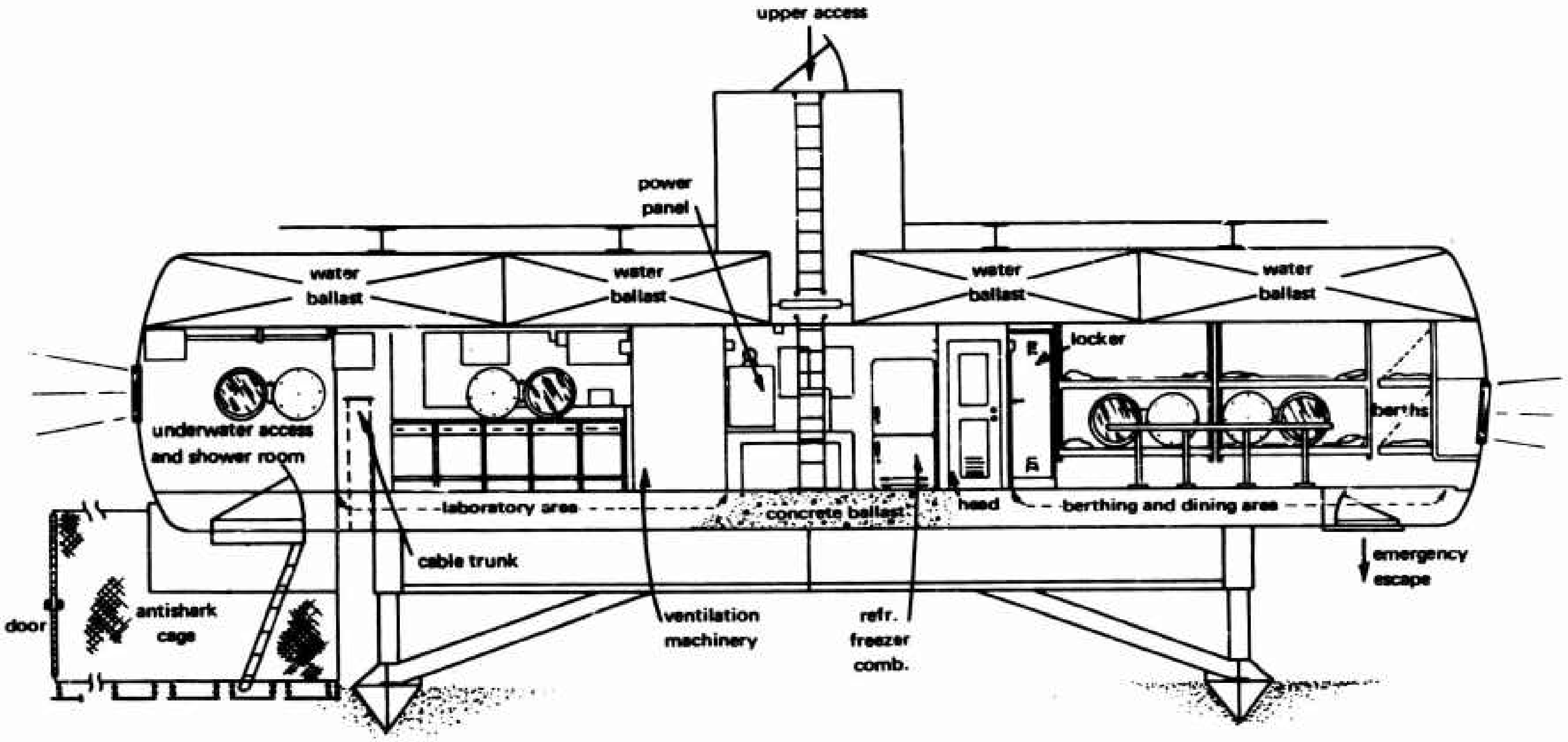


Figure 27. Sealab II habitat. (From Pauli and Clapper, 1967.)

Corner spades, 15 inches in depth, increased resistance to lateral movements (Figure 27). Sediment in the vicinity of Sealab II was a dark-gray, micaceous, very fine silty sand with few marine animals and a trace of clay. Analysis of surface cores indicated that the material contained 81% sand, 19% silt and clay. Median diameter of the material was approximately 0.004 inch. Laboratory tests of sediment engineering properties gave the following results: angle of internal friction, 22 degrees; vane shear strength, 1.4 psi; buoyant unit weight, 52 pcf. In-situ tests of the seafloor indicated a minimum soil bearing capacity of 1,300 psf. A safety factor of three was used to minimize settlement. The seafloor at the site sloped to the southeast at approximately 8 degrees. Typical microrelief was of the order of 4 inches. When Sealab II was positioned, instrumentation showed a 10-degree trim by the stern and a list to the port of 3 degrees. The habitat was then lifted about 10 feet from the bottom, rotated, and replaced. A check indicated a port list of 6.54 degrees and a bow-up pitch of 5.96 degrees; these angles did not change appreciably during the three weeks of occupancy. Since Sealab II was sitting at a lesser slope than the terrain, differential settlement was assumed to have occurred. Measurements on the footings indicated the following settlements: starboard aft, 9 inches; starboard forward, 15.8 inches; port aft, 9.2 inches; port forward, negligible. Later measurements found little additional settlement; therefore, settlement apparently occurred on impact or almost immediately thereafter.

Hydrolab. During October of 1967, Florida Atlantic University placed an underwater research laboratory in approximately 50 feet of water, 3,100 feet offshore of Palm Beach, Florida (Stephan, 1969; Perry Oceanographics, 1970). The 12-foot-diameter by 20-foot-long habitat, which was designed and fabricated by Perry Oceanographics, was supported on a prestressed concrete foundation, 18 feet by 20 feet 8 inches (Figures 28 and 29). Bearing pressure exerted on the coarse calcareous sand bottom was approximately 60 psf. Hydrolab remained in position for 11 months. During this period, no movement was detected. Scour and fill were noticeable but not large enough to cause undermining of the Hydrolab foundation.

This habitat was modified to operate as a one-atmosphere, lock-in/lock-out facility, and it was placed on the seafloor in 50 feet of water off Riviera Beach, Florida, during July 1969. The soil in the area was a dense sand. The same concrete base, with floodable ballast chambers, was used. In this instance. four 4-foot-diameter metal "cookie-cutter"-type keys extended 1 foot below the concrete base.

During October 1969, four men spent 2 days living in the Hydrolab during Project Powercel (Ocean Industry, Jan. 1970, p. 23). At the beginning of this project, no scour problems were noted; however, by the end of the

2 days, undermining of the concrete slab along a major portion of one side and a corner was obvious (Hallanger, 1970). The resulting pit was estimated to be 3 feet deep and to extend 3 to 5 feet under the foundation slab. Only a small portion of this pit extended beyond the slab. Bottom currents estimated at 3/4 knot were prevalent during the 2-day project. This strong bottom current obviously contributed to the undermining. Marine animals inhabiting the area may also have contributed to the pit's existence and extent. An additional external effect may have resulted when a support ship was moored to one corner of the slab. Dynamic action of the mooring line might have caused an up–down movement of the habitat, resulting in a pumping action in the sediment. However, this movement was not noted by inhabitants. A slight increase in the inclination of the Hydrolab was observed by at least one of the aquanauts during the habitation. The inclination apparently had no adverse effect on the overall experiment.

Makai Habitat II (Aegir). Aegir is a submersible habitat designed to support six men on missions for 14 days in water depths to 580 feet (Fahlman, 1968). The 400,000-pound, three-section habitat is made up of two 9-1/2-foot-diameter by 17-foot-long cylinders which connect axially to a central 10-foot-diameter sphere. This structure is mounted athwart two large floodable pontoons. The pontoons are 9 feet in diameter by 70 feet in length and rest directly on the seafloor during use.

The structure is designed to be towed on the surface to the site, where ballast tanks are flooded. Two anchored lines are used as lowering guides. A third and fourth anchor block are suspended beneath the habitat complex and supply the additional weight required to make the complex negatively buoyant. Once these blocks are on the bottom, the complex becomes positively buoyant and must be winched down to the bottom. Additional ballast tanks, which are flooded after the complex is on the bottom, give a total negative buoyancy of 80,000 pounds. The system was designed to include four hydraulically operated legs for leveling on slopes up to 10 degrees.

Aegir underwent its first sea trial during November of 1969 when five men spent 2 days on the seafloor in 200 feet of water (Ocean Industry, Feb. 1970). Since no large difficulties were encountered during the overall test, it is assumed that the foundation performed adequately.

Tektite I Program. The Tektite I habitat was placed on the ocean floor at Lameshur Bay, St. Johns, Virgin Islands, as a joint effort involving the Navy, Department of Interior, NASA (National Aeronautics and Space Administration), and General Electric Company (Pauli, 1969; General Electric, 1969; Stevenson, 1969; and Pauli and Cole, 1970). A four-man crew occupied the habitat for 60 days beginning in February of 1969.

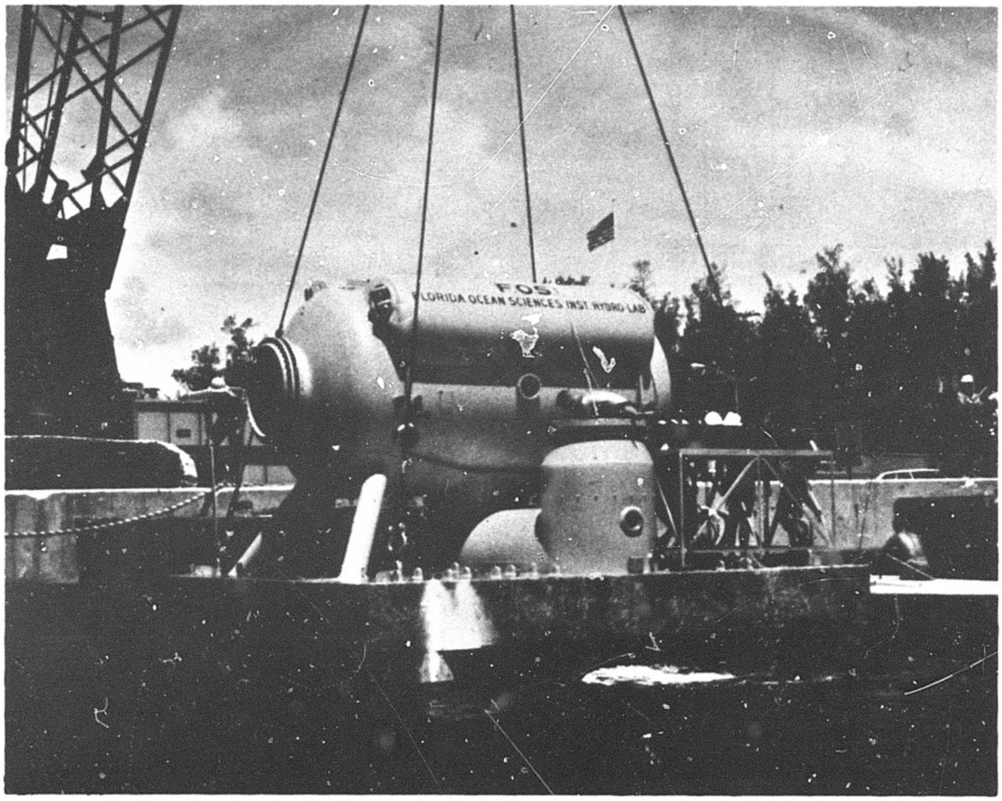


Figure 28. Hydrolab Habitat. (From Perry Oceanographics, 1970. ©Perry Oceanographics, Inc. Used by permission.)

The habitat was positioned in 53 feet of water on a 10-foot layer of coral sand. Bedrock underlies the sand. The sand surface at the habitat site was leveled using a bolted steel frame with a diver-manipulated traveling screed. This technique established a flat bearing surface within 2 degrees of horizontal.

The undersea habitat structure consisted of two pressure hulls connected by a pressurized crossover tunnel and attached to a rigid base. Each pressure hull, a vertical cylinder with domed head, was 12-1/2 feet in diameter and 18 feet long (Figure 30). A reinforced rectangular box with approximate dimensions of 15 by 37 by 6 feet formed the rigid base.

After jetting embedment anchors in at the site, the 5,000-pound positively buoyant habitat structure was to be jacked down to these anchors. However, this plan was abandoned in favor of a deadweight anchor technique, primarily because no reliable embedment anchor performance data could be obtained. Four 2,500-pound steel clumps were used as anchors. Once the habitat structure was on the seafloor, ballast tanks were flooded, and additional weights were added. The total resultant load, 20,000 pounds of negative buoyancy, was applied to the seafloor over the 555-square-foot bearing surface. No foundation problems were experienced.

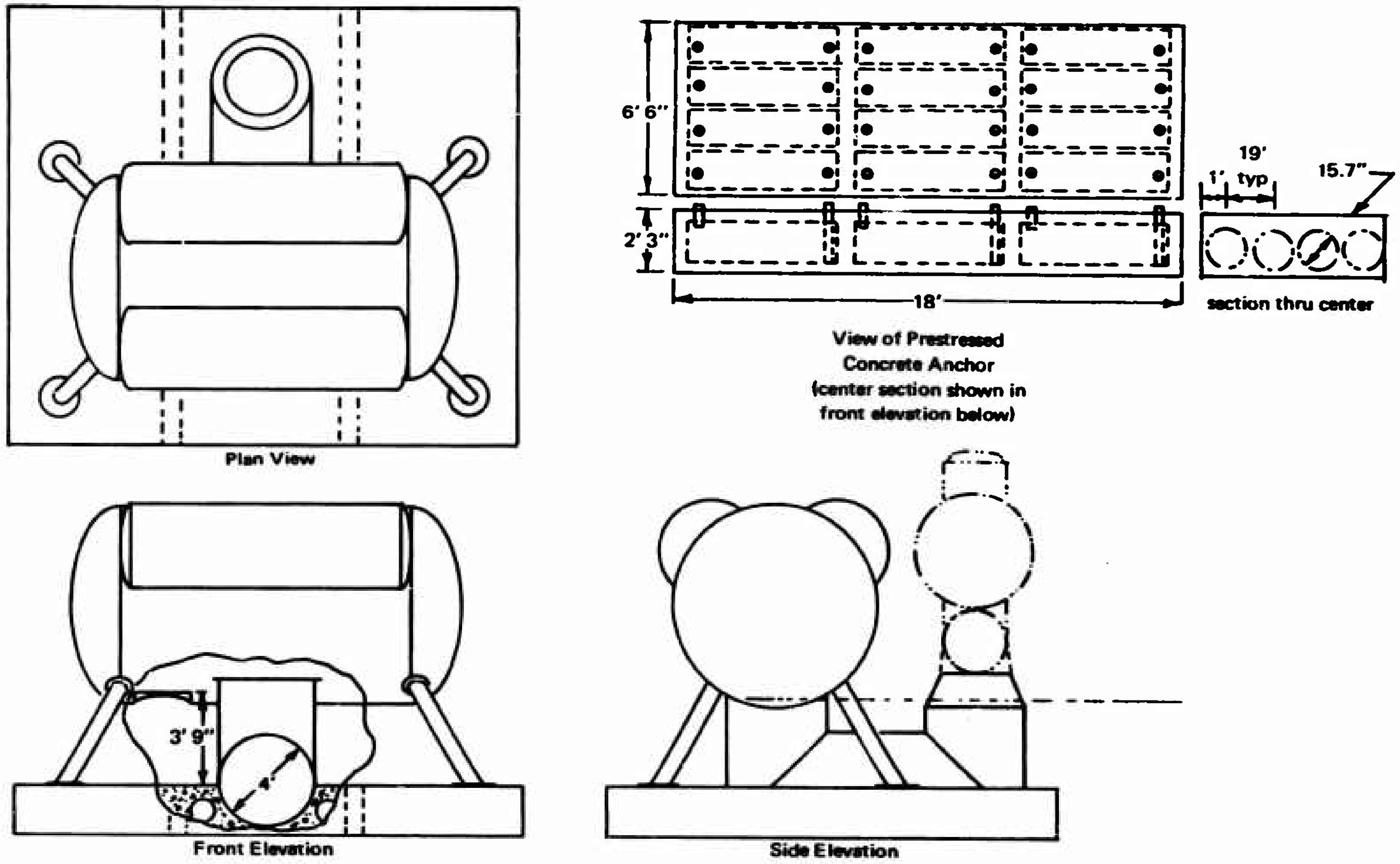


Figure 29. Hydrolab Layout. (From Perry Oceanographics, 1970. ©Perry Oceanographics, Inc. Used by permission.)

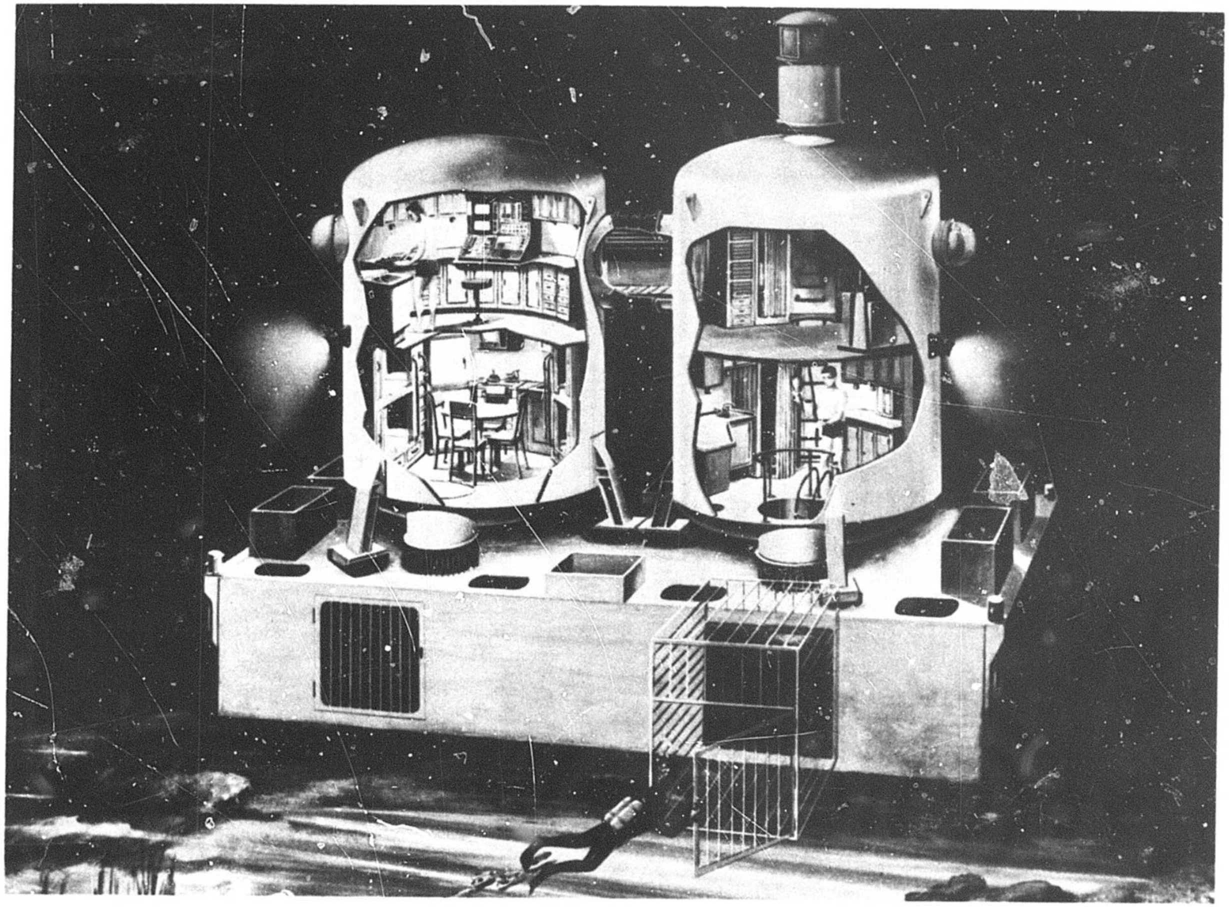


Figure 30. Tektite habitat. (From General Electric, 1970. ©G. E. Re-entry and Environmental Systems Division, Ocean Systems Programs, Philadelphia, Pa. Used by permission.)

Other Deployed Habitats. Although a number of additional habitats have been used on the seafloor, little information exists on their performance.

During the spring and summer of 1969, Chernomer I, a Russian habitat, was placed in 33 feet of water at Golubaya Bay in the Black Sea (Hydrospace, 1969). The 125,000-pound habitat utilized a large surface buoy for support. During a gale, the habitat was reported, in one instance, to have been lifted 3 feet off the seafloor—presumably by the surface support buoy. The habitat then dropped, and "bounced on hydraulic base supports." As a result of this treatment, the habitat assumed a cant of 40 degrees.

Chernomer II was designed for use in water depths to 115 feet (Hydrospace, 1969). This habitat, which was to be nearly independent of surface support, is 10 feet in diameter by 25 feet long, weighs 144,000 pounds, and is supported on four legs.

The German company of Deutsche, Babcock, and Wilcox deployed a habitat in 33 feet of water in the East Sea during the fall of 1968 and the summer of 1969 (Ocean Industry, Jan. 1970, p. 12). The habitat was manned for 14 days and remained on the seafloor for 2-1/2 months. From photographs, the habitat appears to be supported on four footings. The footings are about 5 feet in diameter, and each is rigidly attached to a stiff leg.

Students and faculty at the University of New Hampshire fabricated and deployed the 8-foot-diameter by 12-foot-long habitat, EDALHAB (Engineering Design and Analysis Laboratory Habitat), in Alton Bay, New Hampshire (University of New Hampshire, 1967; Undersea Technology, 1970). EDALHAB supported four men for 48 hours at a depth of 26 feet. The EDALHAB structure is slightly buoyant. The foundation consisted of two 6,000-pound anchors.

A second German habitat was deployed in 75 feet of water off Helgoland in the North Sea during the summer of 1969 (Hydrospace, 1969). Three teams of aquanauts spent a total of 22 days in the habitat. The habitat, which was left in place on the seafloor for use during the summer of 1970, is 8 feet in diameter, 30 feet long, and has a design depth capability of 330 feet. A large surface support buoy, moored by three anchors, provides required breathing gases and power. The foundation for the habitat consists of two strip footings, each approximately 2 feet wide by 30 feet long. The habitat is supported on footings by four adjustable legs designed to compensate for uneven seafloor topography.

On several occasions during the past 3 years, the Russians have used a hemispherical fabric tent with a wooden floor as a habitat (Hydrospace, 1969). These habitats, called Sprut, have been used in the Black Sea to support two men for 2 days at water depths of 30 to 40 feet. The fabric tents are buoyant and are anchored to the seafloor. In at least one instance, Sprut was secured to two submerged rocks.

Link demonstrated a similar rubber-walled habitat, Sea Igloo, in 1964. The rubber habitat supported a man for 24 hours in 33 feet of water (Link, 1964).

An underwater diver rest station, named Sublimnos, has been used at 30-foot water depths in the Great Lakes (Somers, 1970). The 8-foot-diameter by 8-foot-long vertical cylinder is ballasted for negative buoyancy. The foundation consists of four pads, each about 2 feet square. This structure has been successfully located on cohesive soils.

Other Planned Habitats. Atlantis was a joint planned program between the University of Miami and Chrysler Corporation (University of Miami, 1968; Chrysler Corporation, 1968; Breckenridge, 1969). The two organizations intended to emplace a 1-atmosphere manned laboratory on the continental shelf (to 1,000-foot water depths). The tentative habitat consisted of a horizontal cylinder, 12 feet in diameter by 80 feet long, applying a negative buoyancy of 64,000 pounds to the seafloor through two 17-foot by 33-foot spread footings (Figure 31). Static bearing pressures would equal 57 psf. The overall design was based on the following criteria:

1. maximum bottom currents of 5 knots
2. soil bearing capacity of 72 psf
3. a maximum slope of 5 degrees

Each spread footing is connected to the superstructure by a hydraulic leveling system.

Preliminary designs for a similar manned underwater station (MUS) were developed by NCEL and several contractors (General Dynamics, 1968). The selected concept consisted of two vertical cylinders; one containing a nuclear power generator and the other housing six men. The habitat would be capable of 30-day missions in water depths to 6,000 feet (Figures 32 and 33). The structure was designed to be slightly buoyant until the addition of a 12,000-pound anchor clump. This clump would be placed on the seafloor and the station winched down to it. Upon approaching the seafloor, four boom-mounted footing pads would swing out and stabilize the station in a vertical position on slopes as steep as 15 degrees and in currents as large as 1 knot. The design was such that negligible loads would be applied to the seafloor soil by the 12-foot-diameter bearing pads. Design criteria assumed a soil bearing capacity of 144 psf. In the most critical situation, a current-induced overturning moment would be resisted by a single boom-mounted footing pad. In this situation, a vertical force of 12,000 pounds (108 psf) and a horizontal force of 12,600 pounds would be transmitted by the pad to the seafloor. The circular pads were to be made of a permeable screen to reduce the breakout forces. The pads were also to have a circumferential ring to protect against scour and presumably to act as a key to resist the horizontal forces.

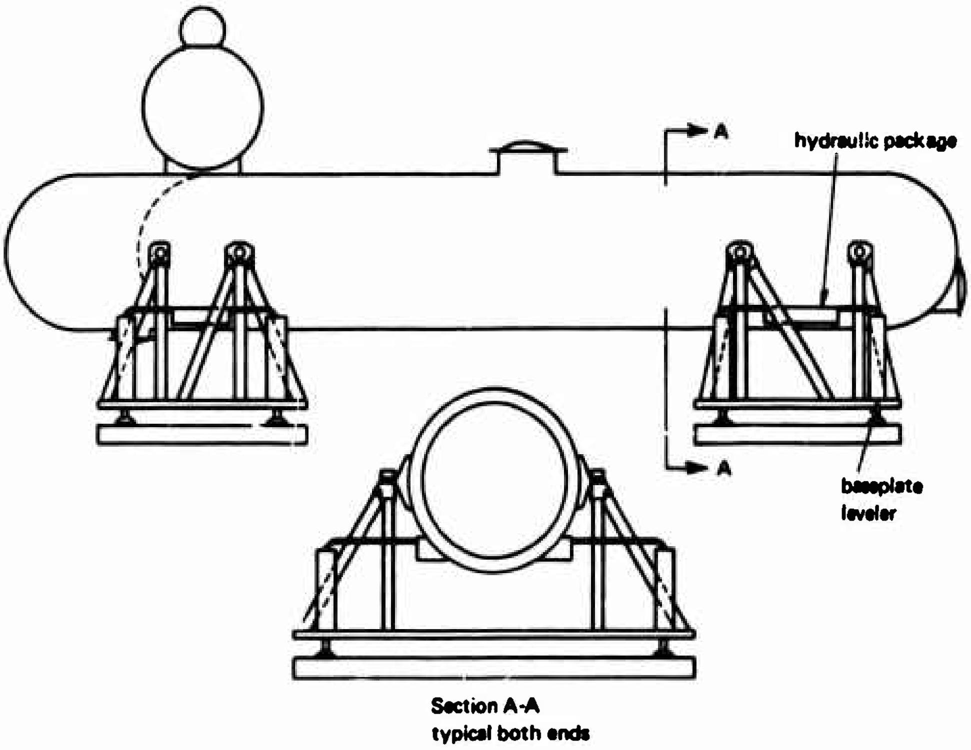


Figure 31. Project Atlantis manned station. (From Chrysler Corporation, 1968. ©University of Miami and Chrysler Corporation. Used by permission.)

Santa Barbara City College is fabricating an ambient pressure structure for temporarily sheltering several men (Hallanger, 1970). The structure, which will be deployed in 30 to 40 feet of water, will include a tower that extends above the air–sea interface.

Three other habitats have been fabricated and will be utilized in the near future. Sealab III, the first of these habitats, is basically a modified version of the habitat used in Sealab II (Eager, 1968; Dowling, 1969; Hallanger, 1970; Huh, 1969; Stiles, 1969). It was designed to be deployed in 610 feet of water near Wilson Cove on San Clemente Island, California. The seafloor at the site was investigated extensively by NAVOCEANO and was found to be basically a dense, well-graded sand with occasional larger rocks. Average slope at the site was 3 degrees.

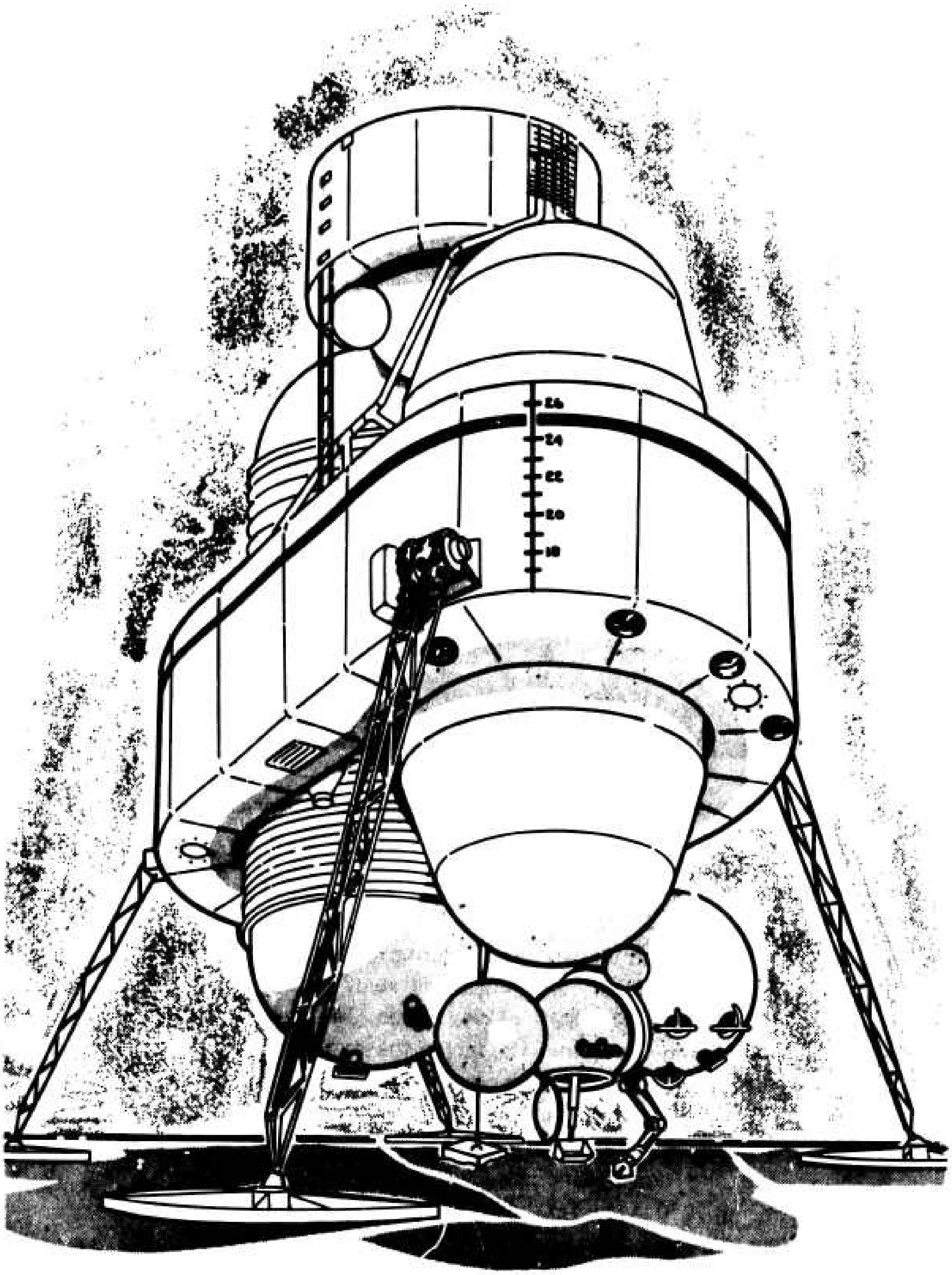


Figure 32. Artist's conception of NCEL Manned Underwater Station.

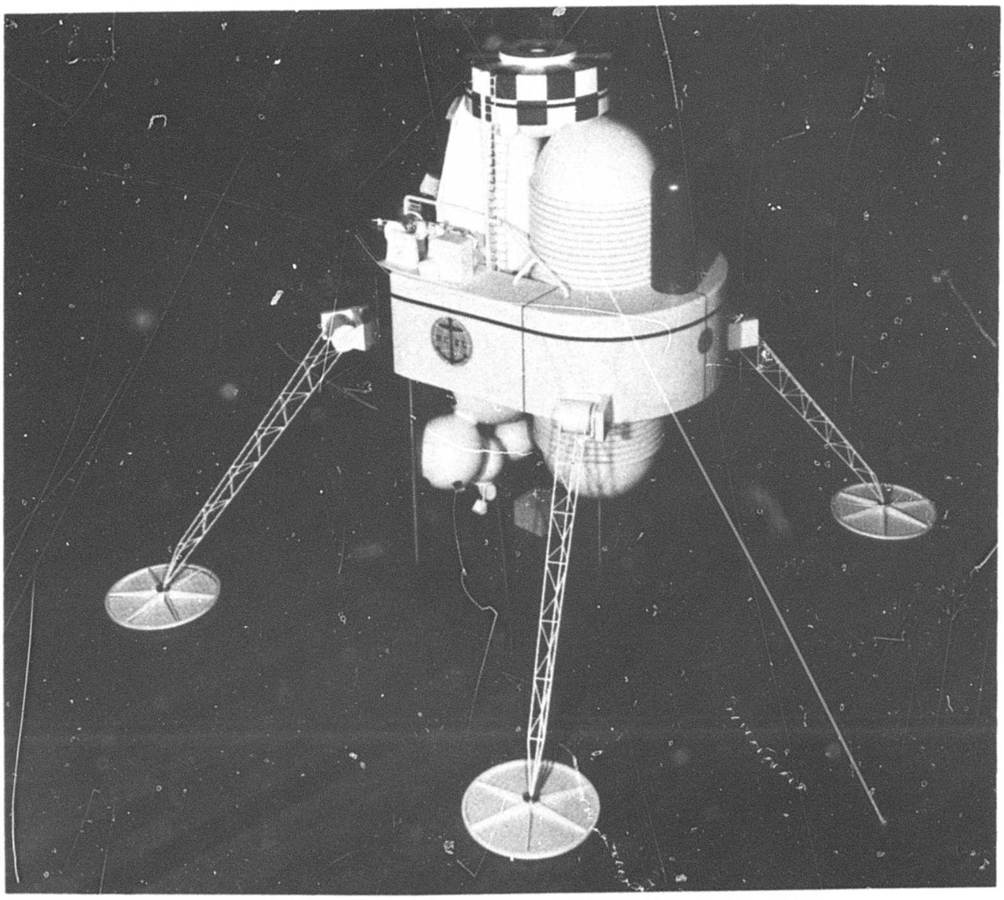


Figure 33. Model of NCEL Manned Underwater Station.

The second habitat will be used during Project Seause (Battelle et al., 1968; Breckenridge, 1969). This project will study in detail Cobb Seamount, in the Pacific Ocean off the state of Washington. The rock summit of the seamount, which reaches to within 120 feet of the sea surface, has been studied indirectly with various types of instrumentation and directly by SCUBA divers. A habitat has been designed for use at the site. This habitat appears to be similar to the Makai Habitat II (Aegir).

The third habitat, a modified version of Tektite I, was used during the summer of 1970 in the Tektite II program (Ocean Industry, 1969). The same site in the Virgin Islands was utilized for a period of approximately 7 months. A new, two-man habitat, located at a 100-foot water depth, was also employed during a portion of the program.

Offshore Towers and Platforms

Offshore towers and platforms differ from totally submerged structures in three major ways:

1. They are currently used only in the shallow portion of the continental shelf.
2. They extend through the air–water interface and are thus subjected to large wave forces.
3. They are often large and massive because of the magnitude of environmental factors encountered.

Several hundred offshore platforms are in existence (Howe, 1967). These structures are located in water depths of up to 370 feet, have total weights in excess of 3,500,000 pounds, and use pile or caisson foundations almost exclusively as their permanent foundation systems (Figure 34).

Platforms in shallower waters are often constructed on site, beginning with pile driving and continuing upward. For the larger offshore platform, the underwater substructure, which doubles as a guide for the pile driving, is usually prefabricated, towed to the site, and positioned on the bottom. The substructure typically utilizes a spread footing or shallow caisson configuration for temporary support while the piles are being driven and grouted. These platforms are founded on soils ranging from sand to soft clayey silt. As much as 300 feet of pile penetration and as many as sixteen 56-inch-diameter piles may be required to resist the loads of larger platforms.

In addition to these relatively permanent structures, there are about 100 drill rigs of the jack-up variety (Howe, 1969a). These rigs use large caissons, pads, or mats as their foundation system. The structures are movable and have been used in water depths to 300 feet. Total weights of the jack-up rigs range from 1,000,000 to 10,000,000 pounds. Maximum lateral dimensions may exceed 240 feet. Foundation pads or mats range from 20 to 120 feet in major lateral dimension (Figure 35).

Specific information is available on a limited number of offshore platforms and towers (Table 4). Most information is considered proprietary and is, therefore, available only in generalized form. Generalizations concerning performance of petroleum structures (information collected from a number of sources) are summarized in the following paragraphs along with available specific performance information.

Argus Island. Argus Island was constructed in the summer of 1960 as a Navy research platform (McDermott, 1960). This structure, which is similar to oil well drilling platforms, supports a two-story, 85- by 85- by

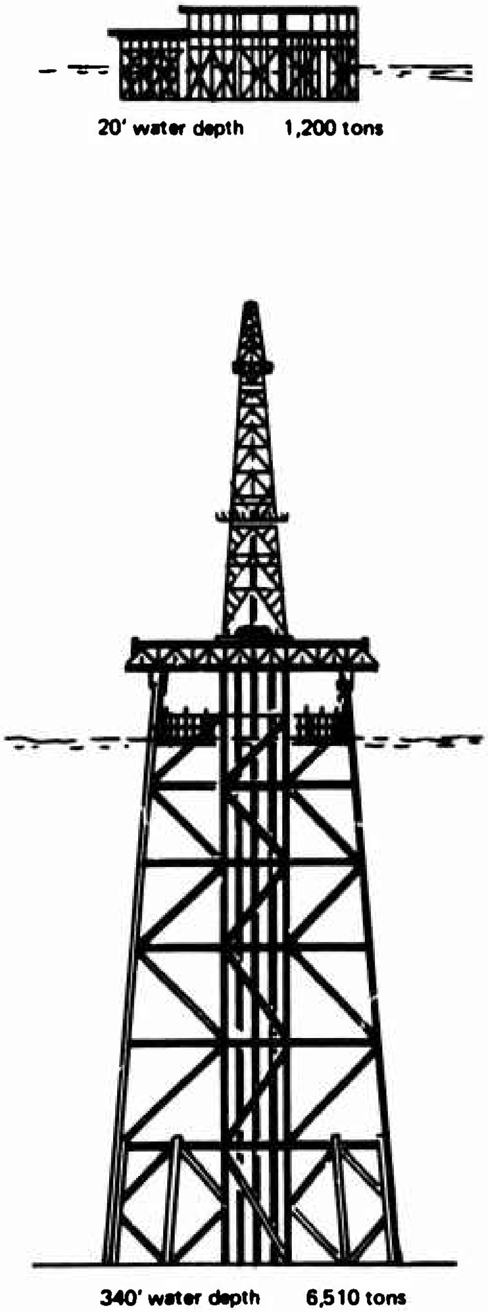


Figure 34. Typical offshore platforms for shallow and deep water. (From Schmid, 1969.)

24-foot-high building. The site is located 27 miles south of Bermuda in 193 feet of water. Sediments are dense coral sands. The platform is supported on four 30-inch-diameter by 5/8-inch-thick steel piles drilled approximately 50 feet into the sediment and then grouted. No foundation problems have been reported.

Khazzan Dubai I. Khazzan Dubai I is a large submerged oil storage tank with a capacity of 1/2 million barrels (Chicago Bridge and Iron, 1969). Pumping and control facilities extend above the water surface. Its physical appearance is that of an inverted funnel, 270 feet in diameter and 205 feet high (Figure 36 and 37). Khazzan Dubai I was installed in August 1969, 58 miles off the shore of Dubai in the Arabian Gulf. The 30,000,000-pound open-bottom structure rests on a perimeter footing in 160 feet of water. The perimeter footing also contains guides for 30 anchor piles spaced around the perimeter. These 36-inch-diameter piles penetrate 90 feet into the seafloor. The structure–foundation interface was designed to withstand the scouring action caused by a 3-knot bottom current. No problems have been reported to date.

NSRDL Towers. The Naval Ship Research and Development Laboratory in Panama City, Florida, has operated two oceanographic towers off the coast of Florida since 1957 (Mine Defense

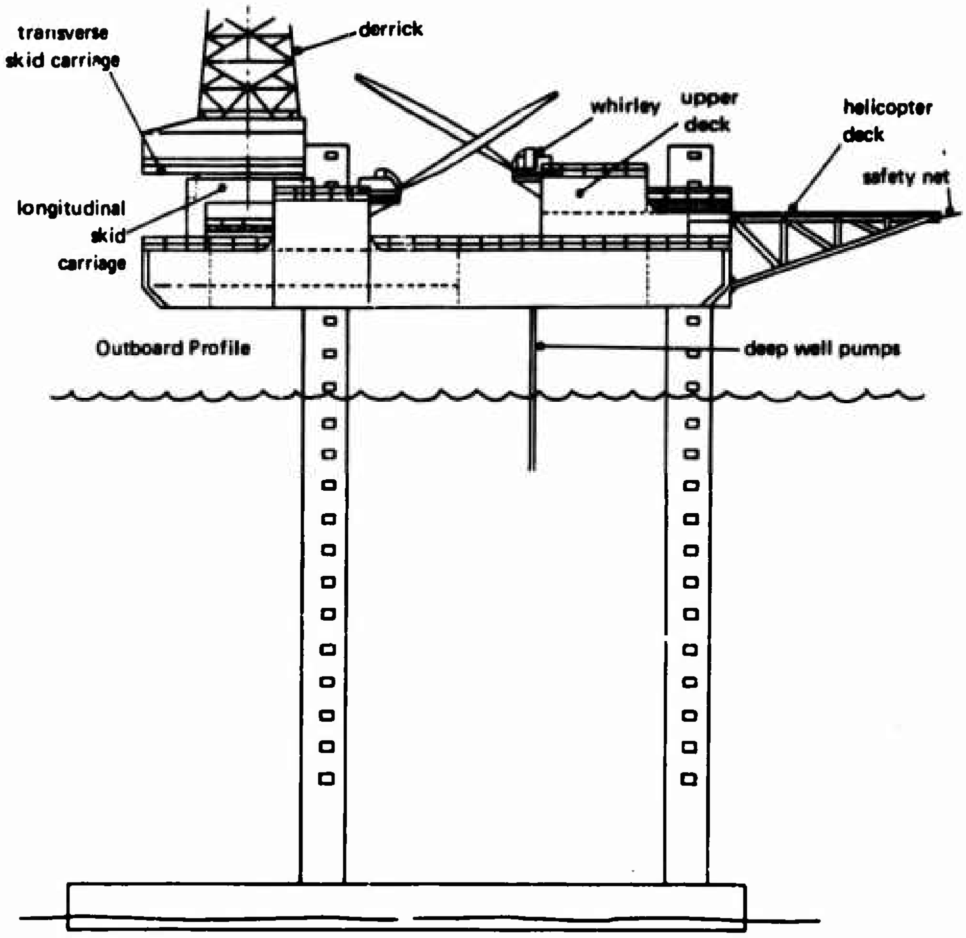
Laboratory, 1964; Toske, 1969). The larger tower, Stage One, is located in 100 feet of water and has overall dimensions of 105 by 105 feet. The structure is supported by sixteen 30-inch-diameter piles embedded 60 feet into a medium dense to very dense gray silty sand. Pile capacity is 760,000 pounds.

Stage Two, the smaller tower, is 60 by 84 feet and is located in 60 feet of water. Eight 24-inch-diameter steel piles arranged in a 60- by 60-foot square support the structure. The upper 50 feet of sediment at the site contain medium dense blue, green, and gray coarse sands. Below that depth is a dense gray silty sand. Each pile, which has a capacity of 540,000 pounds, is embedded approximately 70 feet. No foundation problems have been reported.

NELC Tower. An oceanographic research tower was constructed for Naval Electronics Laboratory Center (formerly the Navy Electronics Laboratory, San Diego) in 1959 (LaFond, 1965). The tower is located in 60 feet of water off Mission Bay, San Diego. The main tower extends 90 feet above the waterline. Four 12-3/4-inch-diameter open-end steel piles support the structure. Maximum load on each leg is 140,000 pounds compression and 115,000 pounds tension.

Subsurface exploration with probing and drilling techniques was utilized at the site to establish sediment logs (Dames and Moore, 1959). Water-jet probing reached 63 feet below the seafloor. A weathered conglomerate was encountered at that depth. Borings were made approximately 10 feet from the probings. A log of one of the borings is shown in Figure 38. Undisturbed samples were taken and tested. In addition to routine tests for soil engineering properties, the laboratory study established friction characteristics between soil and steel. An effective angle of friction of 21 degrees was measured between steel and medium- to coarse-grained sands with shells (material found in the upper 30 feet), and a value of 19 degrees was measured between steel and loam and fine-grained sands (material found below 30-foot depth). No foundation performance problems have been reported.

Tektite I Pile Guide System. During the on-site preparation phase of the Tektite I program, a pile foundation system was used in 32 feet of water for stabilizing and guiding a habitat-transporting barge (General Electric, 1969; Hallanger, 1970). After the barge was flooded and lowered, the habitat was to be floated off. A steel pile (about 21 inches in diameter) was driven to refusal through each of the four corner guides on the barge. The barge was left moored and floating in this condition overnight with plans to commence the controlled flooding and lowering operation the following morning. Seas were reported to be calm during the night; however, the next morning it was found that all four piles had snapped off at the mudline. Subsequently, the piles were redriven, and the flooding and lowering operation commenced immediately. This approach was successful.



Mat and Drilling Platform

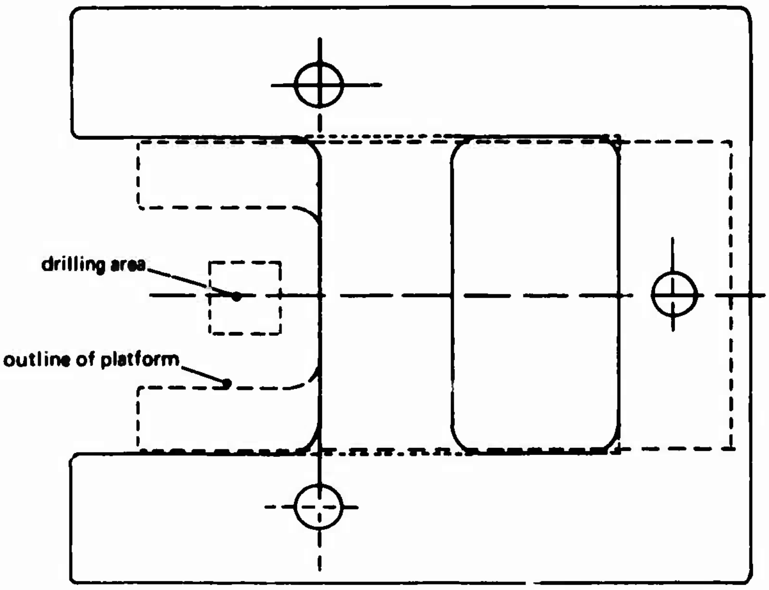


Figure 35. Typical jack-up rig with mat foundation. (From Schmid, 1969.)

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Table 4. Offshore Towers and Platforms

Name	Operator	Installation Year	No. of Structures	Depth (ft)	Location	Foundation Type	Load Per Foundation Member	Fo
Argus Island	Navy	1960	1	193	27 miles south of Bermuda	piles		four
Khazzan Dubai I		1969	1	160	near Dubai Arabian Gulf	footing and piles		27 foc pil arour
NSRDL Towers	NSRDL (Naval Ship Research and Development Laboratory)	1957	1	100	off west coast of Florida	piles	760,000-lb capacity	sixtee
			1	60	similar	piles	540,000-lb capacity	eight
NELC Tower	NELC (Naval Electronics Laboratory Center)	1959	1	60	Mission Bay near San Diego	piles	140,000-lb compression 115,000-lb tension	four
Tektite I (Pile Guide System)	Navy, Department of Interior, NASA, General Electric	1969	1	32	Lameshur Bay, Virgin Islands	piles		four
Texas Towers	Air Force	1955 and 1956	3	55	St. George's Bank east of Cape Cod	caissons	5,300,000-lb compression 720,000-lb horizontal 1,800,000 ft-lb bending moment	thre
				55	off Nantucket Shoal	caissons	7,100,000-lb vertical 1,100,000-lb horizontal 33,000,000 ft-lb bending moment	thre
				180	75 miles southeast of New York Harbor	caissons	6,800,000-lb vertical 820,000-lb horizontal negligible bending moment	thre

Offshore Towers and Platforms

dation pe	Load Per Foundation Member	Foundation Size	Embedment Depth (ft)	Sediment Type	Bearing Capacity (psf)	Remarks
les		four 30-in.-diam	50	dense coral sand		No foundation problems.
g and es		270-ft-diam footing with piles spaced around perimeter	90			No foundation problems.
es	760,000-lb capacity	sixteen 30-in.-diam	60	very dense gray silty sand		No foundation problems.
es	540,000-lb capacity.	eight 24-in.-diam	70	medium dense blue-green coarse sand		No foundation problems.
es	140,000-lb compression 115,000-lb tension	four 12-3/4-in.-diam	63	medium to coarse sand above black silty loam		No foundation problems.
s		four 21-in.-diam	driven to refusal	coral sand		Piles snapped off during night.
ns	5,300,000-lb compression 720,000-lb horizontal 1,800,000 ft-lb bending moment	three 15-ft-diam	48	loose sand above dense sand	≈24,000 at 30-ft penetration	Dismantled.
ns	7,100,000-lb vertical 1,100,000-lb horizontal 33,000,000 ft-lb bending moment	three 14-ft-diam	60	similar to above		Dismantled.
ns	6,800,000-lb vertical 820,000-lb horizontal negligible bending moment	three 12-1/2-ft-diam				Destroyed by sea-action, structural failure.

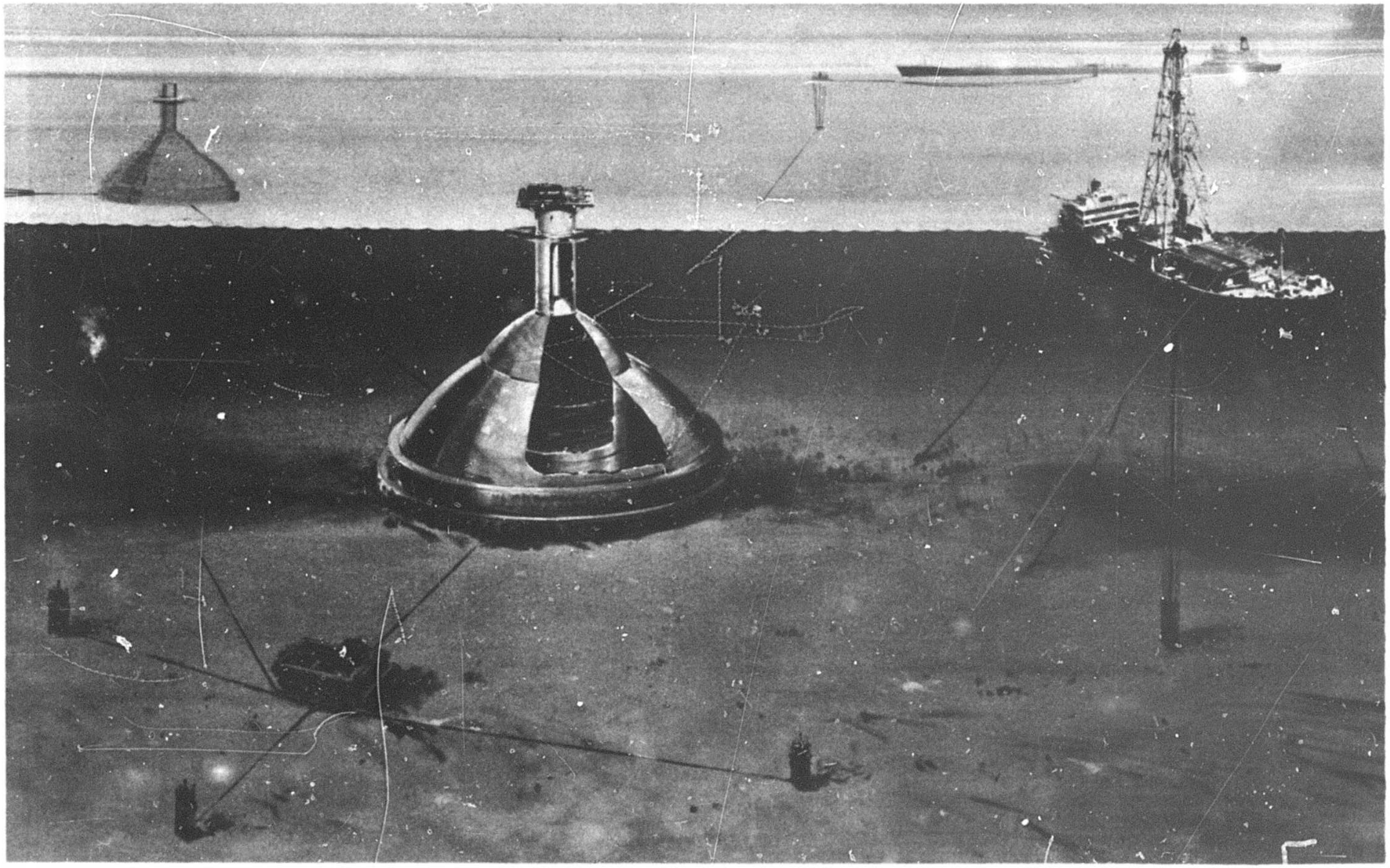

Figure 36. Artist's conception of submerged oil facility. (From Chicago Bridge and Iron, 1969. Photo courtesy of Chicago Bridge and Iron Company.)

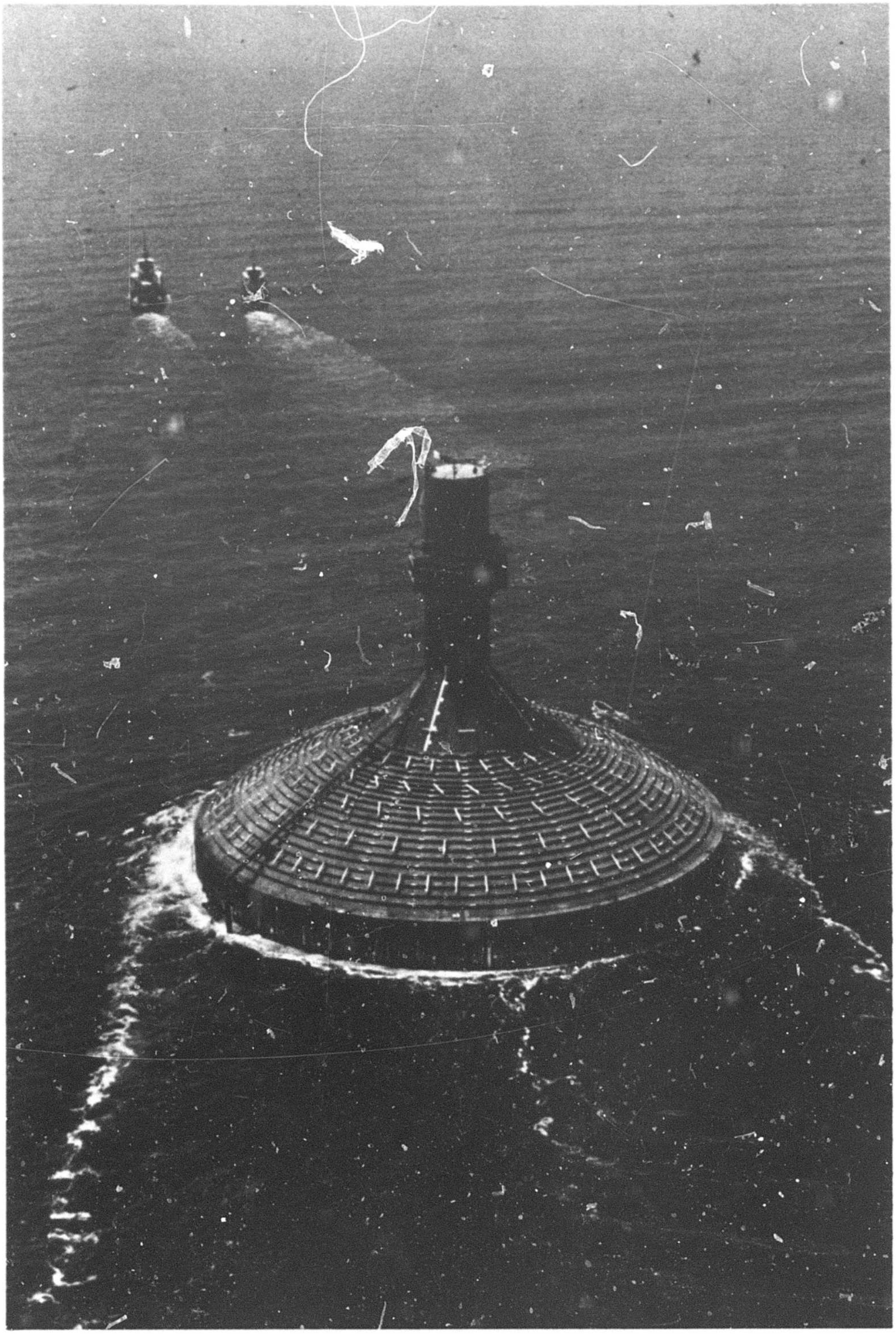

Figure 37. Khazzan Dubai I being towed to site. (From Chicago Bridge and Iron, 1969. Photo courtesy of Chicago Bridge and Iron Company.)

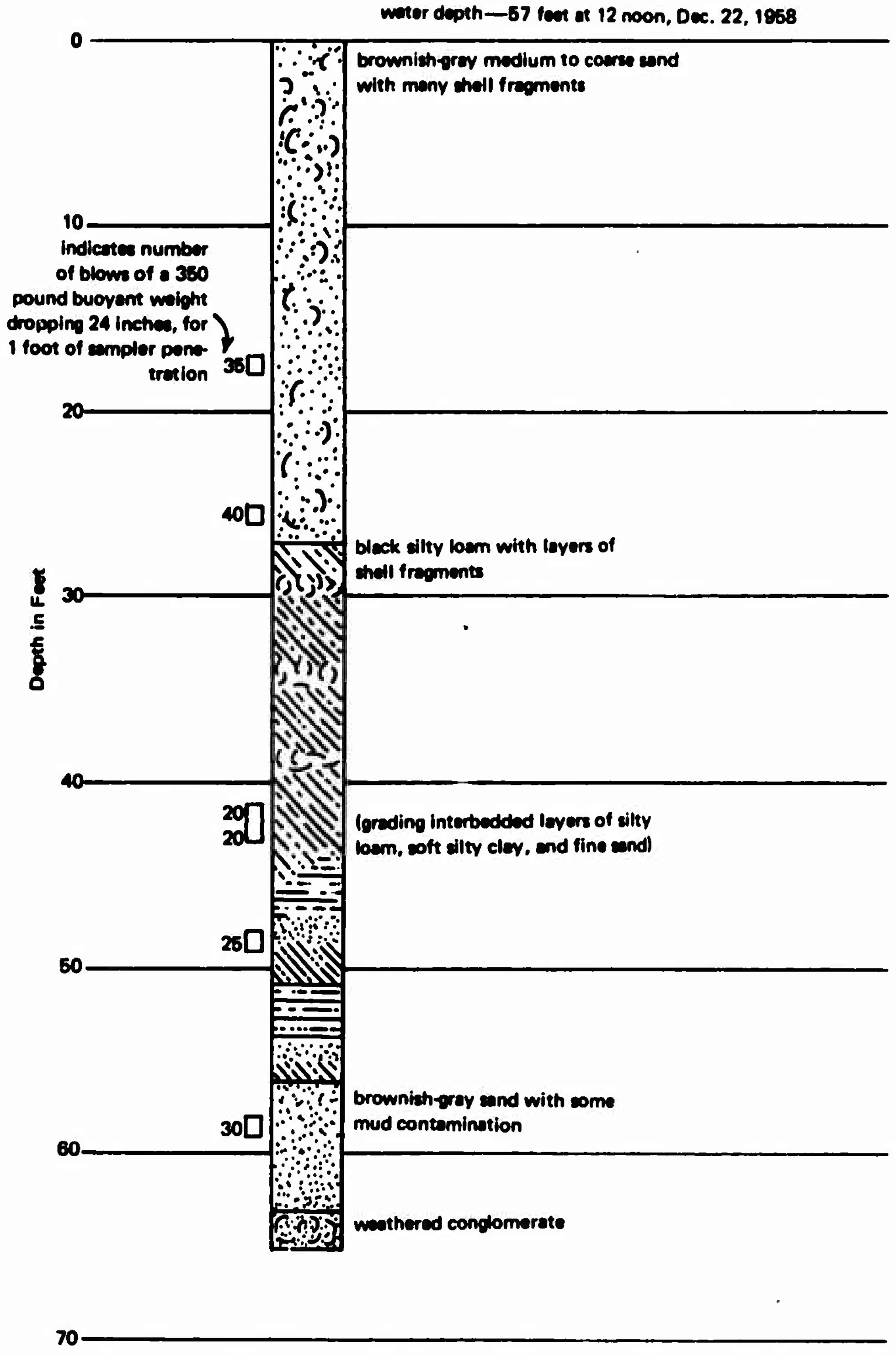

Figure 38. Boring log at NELC tower site. (From Dames and Moore, 1959.)

Texas Towers. During 1955 and 1956, three offshore radar platforms, Texas Towers, were installed along the East Coast of the United States as part of an Air Force early warning defense system (Anderson et al., 1954; Rutledge, 1956 and 1969).

The first tower was constructed in the summer of 1955. It was located on St. George's Bank approximately 95 miles east of Cape Cod, Massachusetts. The mean depth to the seafloor was 55 feet. Bottom sediments at the location consisted of 10 feet of loose sand underlain by over 150 feet of dense sand. Scattered through the area were pockets of organic clays and silty clays. The bearing capacity of the sand at a depth of 30 feet or more below the sea bottom was estimated at 24,000 psf. The three legs, each 15 feet in diameter at the base, were sunk as caissons 48 feet into the seafloor. Maximum design loads for each caisson were: 5,300,000 pounds vertical compression, 720,000 pounds horizontal force, and a bending moment of 1,800,000 ft-lb.

The second Texas Tower was located off Nantucket Shoal approximately 45 miles southeast of Cape Cod. Foundation conditions were essentially the same as were found at St. George's Bank. The tower was supported by three 14-foot-diameter legs sunk as caissons to a depth of 60 feet. Each caisson was designed for maximum vertical loads of 7,100,000 pounds, maximum horizontal force of 1,100,000 pounds, and maximum moment at the seafloor of 33,000,000 ft-lb.

The location of the third Texas Tower was approximately 75 miles southeast of New York Harbor in water 180 feet deep. The structure was designed with 12-1/2-foot-diameter legs and an underwater bracing system. The three legs were sunk simultaneously as caissons. Each caisson was designed for maximum vertical force of 6,800,000 pounds, maximum horizontal force of 820,000 pounds, and negligible bending moment.

On January 15, 1961, the radar tower off New York was destroyed by sea action. Cause of failure was attributed simply to "structural failure of the supporting system." Subsequently, the two remaining towers were dismantled.

General Petroleum Experience. The vast majority of offshore platforms belong to the petroleum corporations and related companies. As a result, specific information on design or performance is often considered proprietary and therefore not available. Much information of a more general nature and of great value to a study such as this is, however, available (Noorany, 1969; Reese, 1969; Smoots, 1969; Kochler, 1969).

Of several hundred offshore permanent platforms, only a few failures are known (Howe, 1968 and 1969; McClelland, 1969; Lubinsky, 1969). These failures have usually occurred during severe storms. Several failures not related to storms have also occurred however.

During placement of the platform substructures, which typically utilize footing or caisson configurations for temporary support, penetrations of up to 8 feet have been recorded. In some instances the actual penetration, or immediate settlement, has been as much as 3 feet more than expected.

After the piles have been driven and grouted in, settlements have occurred in many instances. At several locations where the soil profile was considered competent and rather firm, total settlements of up to 3/4 inch and differential settlements of up to 1/2 inch occurred over periods ranging from 1/2 to 2 years (Busher, 1969).

Of the more than 100 mobile jack-up rigs fabricated, at least 30 have been involved in major mishaps (Howe, 1968). Six of these mishaps have been attributed to foundation or soil problems. In one incident, a rig utilizing a 65- by 97-foot mat and applying a pressure of 180 psf to the sediments was involved in a bearing capacity failure and was subsequently lost. At the time of this failure (1958), it was apparently the accepted practice of many operators to forego detailed soil investigations at each specific work site. Since most operators worked primarily in one area, for which their rigs and foundation systems had in many cases been specifically designed, the expense of additional soil investigations was considered unjustifiable. The usual practice was to move onto a site, jack the rig up, and then preload the foundation for a period of time before commencing actual drilling operations. The rig involved in this failure penetrated as much as 9 feet into the soft Gulf of Mexico soils during preloading (Beaupré, 1969).

For other jack-up rigs, some of which use caisson configurations with diameters ranging from 20 to 50 feet, penetrations of up to 30 feet have been experienced before adequate bearing capacity was achieved. Pilelike configurations have been used on some similar jack-up rigs, but penetrations in several cases were considered excessive. Two rig losses have been attributed to excessive penetration of piles. To overcome excessive penetration, spud cans have been added to the piles on some of these rigs to increase their bearing area (Howe, 1968).

As a result of these and other incidents, more attention is being paid to in-situ investigations and foundation analyses for such rigs. It is known that in at least one case the insurance underwriters now require sampling at the site, laboratory evaluation of the unconfined compressive strength of the soil, and a satisfactory calculation of a suitable factor of safety.

Another problem for such rigs is scouring action caused by bottom currents or surge. Scouring is assumed to be a major problem only in water depths of 400 feet or less. Massive steps are sometimes necessary to prevent undermining of the foundations by this phenomenon. Rip-rap and other materials are used to form a protective blanket in some instances. In other cases, scour curtains have been built into the periphery of mat foundations.

Mats have been designed with a streamlined configuration to reduce scour effects. Mats currently in use range up to 185 by 200 feet in size. Spud piles are sometimes built in to increase lateral stability; peripherial scour curtains help in this regard also. These foundations have been exposed to tropical storms and hurricanes in at least 82 instances; and in only three cases were horizontal displacements detectable.

ANALYSIS OF CASE STUDIES

Foundation Performance Problems

The seafloor structures discussed in the Case Studies section have encountered performance problems in the following three areas: soil behavior, environmental conditions, and deployment techniques. Unsatisfactory performance in each of these areas has been of sufficient magnitude to impair the performance of an entire structure. In several cases, a minor initial performance problem generated other, more serious performance difficulties. In almost all cases the unsatisfactory performance could have been prevented or minimized if environmental parameters had been properly measured and effectively used before design or during deployment. It is hoped that a summarization of the major problems encountered by existing seafloor structures will be helpful in reducing the number and degree of future unsatisfactory performances.

In almost three-fourths of the situations involving foundation problems, the structure or object was placed on the seafloor before an adequate investigation of the sediment properties had been performed. In many cases, no sediment samples were taken at the site. The design engineer, consequently, did not know whether the foundation was being placed on, for example, soft cohesive clay, medium dense sand, or fractured rock. The resulting foundation design reflected the obvious lack in data.

When sediment samples were taken at a site before the foundation was designed, the percentage of successful performances increased. However, foundation difficulties such as excessive settlement or tilting were still experienced. These difficulties were attributed to either the failure of data obtained from the soil sample to represent conditions at the entire site or the inability of analytical techniques to predict performance.

The soil sample fails to represent conditions at the entire site when (1) the soil properties vary vertically and laterally from the point of investigation, (2) methods for obtaining the samples alter the properties of the material, or (3) laboratory testing techniques cannot adequately reproduce behavioral parameters. In many foundation designs, the validity of the sample with respect to actual conditions was never established. A single core was often assumed to represent the material surrounding the site. Neither sample disturbance nor areal variability was considered in analysis. Consequently, structures located near the site did not always perform as expected. Some laboratory analyses consisted solely of classifying the soil according to grain size and mineral constituents. Design was based strictly upon the expected performance of the soil type. Since the range in behavior for a soil type was large, a conservative design technique was employed. More sophisticated laboratory testing techniques often failed to consider the low effective strengths of the soil. Early attempts at performing consolidation tests missed the behavior of the soil in the low pressure ranges.

Even when relatively undisturbed representative samples were evaluated for strength and consolidation characteristics, in-situ behavior often deviated from analytical predictions. In most cases, the difficulties were attributed to the inability of analytical techniques to predict performance. For example, the bearing capacity of cohesive soils has been found to be lower than often anticipated. Keller's model footings penetrated to a depth greater than predicted by calculations based upon the undisturbed strength of the soil. However, calculations employing the remolded strength of the soil predicted the depth of penetration rather closely. Apparently the penetrating blocks progressively remolded the soil. Jack-up rigs designed to apply a bearing pressure of less than 200 psf have failed in the underconsolidated soils of the Mississippi Delta area. The factors of safety against bearing capacity failure (undisturbed strength) for these soils were thought to be significantly greater than one. However, at other sites traditional bearing capacity estimating techniques are sometimes conservative. Results from the NCEL plate bearing device and the ESSA plate load device indicate that the bearing capacity for cohesionless materials is larger than predicted by methods suggested by Terzaghi and Peck (1964). Foundation designs based upon these latter calculations are conservative from a soils standpoint.

Techniques for predicting the settlement of a structure have also been found to differ from in-situ performance. The LOBSTER tests conducted by NCEL suggested that a large amount of secondary compression occurs in seafloor soils. A settlement analysis based on laboratory consolidation tests therefore underestimated settlement.

In other case histories, no reliable analytical technique was found to be applicable to the particular condition in question. The Tektite project, for example, abandoned the use of embedment anchors as a foundation for the Tektite habitat when performance data were found to be nonexistent. An acoustic array in the St. Croix Range slid nearly 1,000 feet down a gentle slope because the surface strength of the soil was insufficient to resist the lateral component of the structure's weight. The sliding problem was not anticipated, since slopes were between 10 and 15 degrees. Now that a foundation failure of this type has occurred and there is general awareness of this problem, special footing configurations have been fabricated to minimize the possibility of future occurrences. However, an analytical technique for designing such features has not been established. Foundation breakout has proven to be a problem of concern in at least one case. Conshelf Three personnel experienced anxious moments on the bottom when the habitat refused to break free after ballast was released. Several of these areas (breakout, anchor capacity) are currently being investigated. Once a reliable analytical technique for predicting performance is developed, it will be essential to verify the technique with field experience.

The second major cause of foundation problems involves the effects of various environmental factors. Many of the problems are associated with wave forces; however, other factors such as marine life and topography have influenced the integrity of certain systems. In shallow-water areas (less than 400 feet), the seafloor surge resulting from surface waves has caused extensive scour and fill about some footings. Up to 50% of the area beneath some LOBSTER footings and about 25% of the area beneath the Hydrolab were undermined. In the case of the LOBSTER footings, large differential settlements followed as the footing tipped into the scour pit. Fill caused by current action has, in turn, deposited several inches of material over the NUSL transponder block. The same wave forces have disrupted the normal arrangement of cables for acoustic arrays at the BARSTUR range. Surface waves also affected the performance of one and possibly two other structures. Four piles driven through the corners of a floating barge into the sediment at the Tektite site failed in fatigue after being subjected to the oscillatory motion of a barge floating in the water. In another instance, a mooring line attached between a surface ship and the Hydrolab may have permitted the motion of the ship to transmit an oscillatory force to the habitat. The resultant force variation could result in a partial liquefaction of the sandy material beneath the foundation.

In deep water, the seafloor surge action caused by surface waves decreases; however, a more uniform current may still affect the integrity of the structure. In addition to causing scour or fill about an object, the currents may impart significant lateral loads to the side of the structure. At the Canadian Range, the lateral loads, in turn, caused excessive differential movements of the structure.

Another rather unusual parameter which led to the unsatisfactory performance of a foundation was the undermining action by marine life. Animals which burrowed beneath a few of the LOBSTER footings caused substantial differential settlements. Results of another experiment at the same site (Muraoka, 1970) suggested that U-shaped wormholes in the area may have contributed to excessive footing settlements.

Rough topography has also caused unsatisfactory performance of several seafloor foundations. Rock terrain near the Conshelf Two site prevented use of the conventional bearing pad foundation. The large slope at the Sealab II site was the cause of the habitat tilting.

The last major area of consideration involves deployment techniques. The number of foundation difficulties associated with this parameter seems to vary with structural size and depth of deployment. Small structures such as the SCARF hydrophone arrays have apparently been tipped over during the installation phase. Another problem often associated with the deployment technique involves the final location of the device. In several situations, the final position of the object was substantially removed from the area of the soil's investigation. Properties and surface consistencies varied between the two locations.

Unique Foundation Features

These performance problems generated several new approaches to design and deployment. Of greatest apparent benefit has been the realization that performance problems do occur and that, if performance is to be satisfactory, some form of analysis should be performed before deployment. More accurate site surveys, which include better soil analysis, and updating of analytical techniques have been two other more immediate results. Several unique foundation designs for combatting the more unusual performance problems also evolved. In some cases these unique designs were based upon the results of analytical calculations. However, in most cases an empirical approach to design was employed. Regardless of their origin, these unique designs, summarized in the following paragraphs, have increased the performance reliability of some seafloor structures. The design engineer should, therefore, consider incorporating some of these preventive actions if soil, environmental, or deployment difficulties are anticipated.

The bearing capacity problems associated with the low-strength, cohesive materials of river deltas and deep-sea areas have been avoided by decreasing the net bearing pressure on the soil. Various buoyant objects such as syntactic foam modules or buoyancy chambers have been attached to the structure to decrease the total unit weight. This approach is typically employed on smaller, lightweight structures since the amount of buoyancy achieved varies directly with the amount of fluid displaced and the module's weight. Two typical seafloor systems employing this buoyancy concept are the Canadian and St. Croix hydrophone arrays and the manned habitats (Sealabs, Conshelfs).

Several different techniques were used to avoid bearing capacity problems when structural loads were large. Typically the organizations involved in design recommended larger bearing surfaces or pile group support. If these measures failed to prevent performance difficulties, the spud-can technique was employed. This procedure consisted of counteracting immediate penetration by installing large-diameter bases to the lower end of cylindrical legs. The large-diameter legs were forced into the sediment as the structure was deployed until sufficient load capabilities were developed to support the structure.

Problems involving excessive total and differential settlements have been handled in several ways. The petroleum industry found that total settlements of mat foundations could be minimized by preloading the foundation. This technique involved subjecting the foundation to excessive loads for an extended period of time. Before actual operations began, the foundation loads were reduced. This concept assumes that all settlements would occur during the period of preloading. Since loads are reduced prior to commencing actual work, any subsequent settlement is thought to be small.

Differential settlements have been controlled by employing universal joint systems. For example, the hydrophone arrays at the Canadian Range are located between a buoyant sphere and a universal joint. As the structure settles differentially, the sphere rotates the hydrophone about the universal joint back into a vertical orientation. A second technique for reducing differential settlement involves the use of a wide spread on the footing. The larger spread tends to reduce the rotational movements developed by a differentially settling structure. Some proposed seafloor structures (MUS, for example) will incorporate level-compensating devices to control differential movements.

The lateral stability problems encountered by APL in the St. Croix Range were overcome by designing subsequent foundations with keying edges. These structures, which had perimeter cutting edges attached to their bottoms, were dropped from above the seafloor to increase the depth of key penetration. Sealabs II and III incorporated a similar keying edge on each of the bearing pads. Since ring- or box-type keys (such as those employed at the St. Croix Range) also function as hydrostatic anchors during removal, NCEL engineers have proposed the use of screens or slotted keys for dissipating the immediate breakout forces.

Several unique designs have been developed for handling environmental problems. Foundations located in shallow water were streamlined to minimize the turbulent motion of bottom currents about the footings. This action reduced, in turn, the degree of undermining by scour. In another case, a protective blanket of coarse-grained material was spread about the foundation. Since bottom currents were not of sufficient magnitude to displace the coarse particles, scour was controlled. A third technique for controlling scour involved perimeter curtains around the foundations. These curtains extended the depth of scour necessary for causing structural undermining. The latter two techniques also could be effectively used to prevent undermining by marine animals.

The other environmental problem which necessitated unique foundation designs involved the irregular topography of the seafloor. Proposed habitats (MUS) will incorporate adjustable, articulated legs for leveling the structure on uneven slopes and maintaining bearing contact. The Tektite and Sealab I projects avoided some problems associated with irregular topography by physically leveling the sites. A screed-type apparatus removed the high points and filled in the low points before the habitats were placed.

Deployment problems were generally related to the handling of the structure at the surface and the correct positioning of the structure on the bottom. Handling problems have been reduced by equipping the various habitats with buoyancy tanks. These tanks permitted the habitats to be floated to the site. By flooding the tanks, negative buoyancy was achieved, and the habitats sank to the bottom. Positioning problems have been reduced by employing either cable or pile guides. The rate of descent was controlled during deployment by hanging weights beneath the structure (Makai Habitat). Once the weights came in contact with the bottom, the net negative buoyancy was decreased. The rate of descent was thereby reduced to a more controllable level.

SUMMARY AND CONCLUSIONS

This report describes a number of seafloor installations with respect to basic foundation design parameters and foundation performance. These installations include offshore towers, manned habitats, acoustic arrays, and various research test units. All of these seafloor structures, or installations, require some form of foundation through which vertical and horizontal forces are transmitted to, and resisted by, the seafloor.

Performance problems have been encountered by a number of these foundations, and failures have occurred in a few cases. Of the approximately 400 installations for which information was found to be available, 4% experienced performance problems and an additional 3% failed. Numerous other seafloor foundations performed satisfactorily, but the factors of safety incorporated in their design were very high so that the cost of fabrication and deployment may have been excessive.

The objective of this effort was, therefore, to collect and summarize all available information on the performance of seafloor foundations. This information, along with appropriate analysis, could be expected to contribute significantly to improving the capability for designing safe, reliable, and economical seafloor foundations.

It was not possible to satisfy totally this objective because of a general lack of available detailed knowledge concerning design and performance of existing seafloor foundations. However, based on the available general information, it is possible to make the following generalizations concerning foundation design parameters:

1. On cohesive soils, excessive total or differential settlements have been the causes of inadequate performance much more often than have bearing capacity failures.

2. Bearing pressures as low as 180 psf have caused bearing capacity failures in cohesive soils. Known installations supplying pressures in the 40- to 100-psf range have experienced no such failures although, in some cases, they have been subject to large settlements and other performance problems such as undermining resulting from scour or biological activity, downslope skidding, and improper installation.

3. On granular soils, where static bearing capacities are much larger, other factors have been the source of most performance problems—these factors have included scour due to bottom currents or surge, errors or unforeseen difficulties during installation and construction, excessive current or surge forces, inadequate knowledge of topography, and biological activity.

The general analysis of the experience to date with seafloor foundations has pointed out foundation systems which have been successful and those which have not been. This analysis has also drawn attention to conditions unique to the seafloor environment which must be considered in the design of foundations. As a result of this analysis, the following three general conclusions have been reached:

1. In many cases there has been insufficient, or total lack of, reference to foundation design principles.

2. Although most foundation performance problems have not resulted in catastrophic failures of the installation, they have often necessitated very expensive remedial actions.

3. The number and sophistication of seafloor installations are increasing; therefore, the importance of improving the reliability of foundation performance is becoming more critical.

RECOMMENDATIONS

Results of this study suggest several areas for additional effort.

1. Efforts should be made to draw attention to foundation engineering principles which have been determined for the seafloor (see, for example, Hironaka and Hoffman, 1970; or Herrmann, 1971) so that these can be utilized in all seafloor foundation designs.

2. Foundation performance monitoring should be increased. Devices such as the Foundation Performance Monitoring System should be employed whenever possible; however, less sophisticated techniques (such as photographs or diver observations) also provide valuable information and should be utilized when the mission of the installation cannot justify specialized monitoring equipment.

3. Efforts should continue to develop and improve guidelines for seafloor foundation design. Particular attention should be given to the deep ocean, because costs are much higher in this area. These efforts should include in-situ sampling and testing, soil analysis, and development of the proper analytical models of soil behavior required for the foundation design process.

4. New concepts for seafloor foundations and their emplacement should be developed.

5. The effort to collect, analyze, and summarize case studies of seafloor foundation performance should continue.

ACKNOWLEDGMENT

The cooperation and assistance of numerous Navy activities, federal agencies, private corporations, and individuals are gratefully acknowledged; without such cooperation, a summary such as this would not be possible.

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