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DEEP-OCEAN PILE EMPLACEMENT SYSTEM: CONCEPT EVALUATION AND PRELIMINARY DESIGN

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ABSTRACT

A previous review of the state-of-the-art of seafloor pile emplacement indicated that three types of mechanical systems could be developed for deep-ocean seafloor pile emplacement. The systems are: vibratory drivers, screw piles, and jack-in piles. Conceptual designs for multiple-pile emplacement systems utilizing each of these mechanical systems were developed and compared. The comparison showed that screw-piles would be the most effective in meeting the given operating requirements. A preliminary design for a pilot-model screw-pile emplacement system is presented.

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INTRODUCTION

It is expected that future Navy seafloor and subsurface installations will require foundations and anchorages of greater capacity and reliability than are provided by the foundation or anchorage systems ordinarily used (e.g., spread footings, mats, dead-weight anchors, and drag-type anchors).[1] Piles and pile groups can often be designed to provide the required increase in capacity and reliability. However, the Navy has no means for emplacing piles in water deeper than about 100-150 feet. Few commercial organizations can emplace piles in water depths beyond 150 feet, and these operations are very expensive. Since further seafloor and subsurface installations frequently will be in greater water depths it will be necessary to develop economical means of emplacement to permit the use of piles for these installations.

Background

A review of the state-of-the-art of seafloor pile emplacement has shown that only marine drilling techniques could be adapted to emplace piles or pile groups for an immediate requirement in water deeper than 1000 feet.[2] Pile emplacement using other state-of-the-art methods (e.g., underwater pile hammers and vibrators or surface-driving with followers) is currently limited to about 1000 feet by logistics problems. However, only moderate effort is required to develop a pile emplacement system operable to 6,000 feet. Three existing mechanical concepts were shown to be possible candidates for further development: vibratory drivers, screw piles, and jack-in piles.

Scope

In this report conceptual designs for pile emplacement systems based upon each of the three mechanical concepts are presented, and the advantages and disadvantages of each are summarized. A comparison of the advantages and disadvantages led to the selection of screw piles as the best system for further development. A preliminary design is presented for a pilot-model emplacement system based upon the use of screw piles.

SELECTION OF PILE EMPLACEMENT SYSTEM CONCEPT

Operating Requirements

The operating requirements for a seafloor pile foundation were designed to apply to a generalized installation rather than a specific seafloor structure. This was done to ensure that the choice between alternatives would not be influenced by the special characteristics or design requirements of a given installation. In the initial phase of the selection process, the operating requirements were given as follows[2]:

1. The system must be operable in water depths to 6,000 feet.

2. The system must be able to emplace several piles in a multi-sided structure in correct relative positions.

3. Each pile must be within 2 degrees of plumb.

4. Pile emplacement must be possible in sea states up to and including sea state 3.

5. Each pile should have an ultimate uplift or bearing capacity of 200 kips.

Based upon these criteria, concepts for several emplacement methods were developed and compared. The primary emphasis in the initial phase was upon the effectiveness of the emplacement device (i.e., vibratory driver, impact hammer, etc.) rather than upon the performance of an overall system. Details of the initial-phase comparison are given elsewhere.[2] It was determined that vibratory driver, screw pile, and jack-in systems were feasible for development.

The emphasis in the second phase was upon the performance of a complete pile emplacement system utilizing each of the three emplacement methods. In this comparison the operating requirements were modified to reflect the characteristics of the complete system. The operating requirements relating to water depth, verticality of the piles, and sea state were retained without change. For each system only the minimum required number of piles was considered. The minimum number for vibratory-driver and screw-pile systems is three piles; for the jack-in system, five piles are required. The minimum capacity requirement was reduced to an ultimate load capacity for the system of 150 kips in uplift or bearing, and a 75-kip ultimate lateral load requirement for the system was added.

In addition to the above requirements, the following design goals were established:

1. The submerged weight of the system should be less than 40 kips to permit use of the NCEL-developed motion-compensating winch.

2. The power required for pile installation should be less than 100 horsepower.

3. The system should require less than two hours of on-bottom time to emplace the minimum number of piles. The time limit includes system checkout, leveling, etc.

4. The system should be able to emplace piles in a wide range of seafloor types; i. e., soft to stiff cohesive soils and loose to dense cohesionless soils.

5. The system should be capable of expansion in size (plan dimensions of structure) and number of piles.

6. All components should be within the state-of-the-art; i.e., minimum development required.

7. The system should utilize a minimum of mechanical operations and control functions.

8. The system should be handled by a single ship or a single tug-barge combination. Required deck space is a function of the plan dimensions of the installation, but the minimum space is approximately 12 ft x 12 ft for the emplacement system, 4 ft x 8 ft for a control van, 10 ft x 10 ft for a crane, and 10 ft x 20 ft for winches, prime mover, and miscellaneous equipment. The vessel must have a 20-ton crane to place the system overboard.

Table I summarizes the operating requirements.

Common Design Characteristics

A schematic representation of a seafloor pile emplacement system is shown in Figure 1. The system comprises five subsystems:

1. The foundation/anchorage subsystem, which includes a template, piles and connections.

2. The installation subsystem, which includes the emplacement mechanism (i.e., vibratory drivers, or jack-in or screw-in mechanisms) and associated power conversion and distribution equipment (i.e., hydraulic pumps, lines, valves, reservoir, gears, etc.).

3. The electrical subsystem, which includes submerged electric motors, transformers, electrical cable, and generator.

Table 1. Summary of Operating Requirements for a Seafloor Pile Emplacement System

Water Depth	6000 feet
Verticality Tolerance	±2 degrees
Sea State Capability	Sea State 3
Capacity - Uplift or Bearing	150 kips ultimate
Lateral Load	75 kips ultimate
Submerged Weight	40 kips maximum
Power Required	100 HP maximum
Emplacement Rate	2 hours maximum to emplace all piles
Number of Piles	At least 3 piles placed in proper relative position*
Seafloor Soils Adaptability	Soft to stiff cohesive soils; loose to dense cohesionless soils
Versatility	Adaptable to emplacement of more than the minimum number of piles; adaptable to changes in plan dimensions of structures
Required Development Effort	All components should be reasonably within the state-of-the-art; minimum development time desired
Complexity	Minimum number of mechanical operations and control functions desired; possibility of automation
Ship Support	Single ship or single tug-barge combination; approximately 500 sq. ft. deck space and 20-ton crane required

* The jack-in system requires 5 piles for operation.

4. The control subsystem, which includes the controls of all submerged and surface equipment and any required instrumentation such as attitude sensors, safety alarms, etc.

5. The load handling and surface support subsystem, which includes the cable, winch, surface vessel, crane, etc.

The most influential requirement related to the physical configuration of the pile emplacement system is that several piles be emplaced in a given pattern. This necessitates the use of a template to properly position the piles, because the cost and difficulty involved in remotely positioning separate piles in a pattern in 6000 feet of water would be unreasonably large. The template provides a temporary base for power conversion and control equipment and acts as a guide to maintain verticality of the piles. It also can be designed to remain in place as part of the major structural support system. Thus, the seafloor installation need not have as heavy a base structure, and the installed weight of the installation can be reduced.

The template will constitute a major portion of the weight of the emplacement system. Since all of the conceptual designs were based upon essentially the same installation plan dimensions, the weight of the template can be taken as constant. Differences in total system weight are thus due to differences in the weight of the emplacement mechanisms, the piles, and possibly the instrumentation and control systems required. The pile weights may vary because of different cross-sections and lengths required to obtain the specified load capacity.

Because the piles are designed to be normal to the template the requirement concerning pile verticality is essentially a requirement for a maximum inclination of the template of ± 2 degrees. It was concluded that the installation system would hang from the cable in an essentially vertical condition. Thus, if the piles are allowed to free-fall the final 3 to 5 feet they will enter the soil approximately vertically. This can be accomplished by providing a bottom-sensing probe and trip mechanism to release the piles. Also, a supplementary footing may be necessary to stabilize the template while one of the piles is being driven. The bottom-sensing probe and supplementary footing are shown in Figure 1.

It was determined that hydraulic power is the optimum form for each of the three emplacement mechanisms. The use of hydraulic power at the planned water depth is not common, but the state-of-the-art was advanced considerably by the design for the NCEL seafloor deep corer[3]. It was determined that the best method of supplying power was by electrical transmission from the surface to a submerged electric motor driving a hydraulic pump[4]. This eliminates the difficulties involved with handling long hydraulic lines. The use of an electromechanical cable appears desirable to avoid cable entanglement problems. Control for the hydraulic motors and cylinders can be telemetered down the power cable. For the power levels tentatively proposed the use of a seafloor source of electric power does not appear feasible.

In the following sections, brief descriptions of conceptual designs based upon each of the emplacement mechanisms are presented. The relative advantages and disadvantages of each conceptual design are discussed, and a semi-quantitative method is employed to compare the designs and select the best system.

Vibratory Driver Systems

For vibratory driver systems, several designs are possible depending upon the specific type of vibrator utilized and upon the mode of operation of the system. Two general types of vibrator are available: eccentric-weight drivers and linear oscillators[2]. Although the devices operate quite differently it was concluded that either could be used in an underwater system, and that neither type offers any significant advantage in meeting the operating requirements listed above. This factor was thus eliminated from the conceptual design. However, it should be noted that eccentric-weight devices have been developed to a greater extent than linear oscillators, which gives the eccentric-weight drivers a cost advantage.

Three general modes of system operation were considered. In the first mode all of the piles are lowered with the template, and a separate vibrator is provided for each pile. Electric power would be supplied from the surface and converted to hydraulic power at the seafloor. The control system would direct the power to one vibrator at a time. At the end of driving, the vibrators, electrical and control subsystem components would be detached and retrieved for reuse.

In the second mode the system utilizes a single vibrator to drive all piles and an indexing system to position the driver from one pile to another. All piles are lowered with the template, as above. The electrohydraulic power system is also essentially the same as the first mode. The control system must control the indexing system as well as the power to the vibrator. It would also be necessary to provide a device for clamping the vibratory driver to the head of each pile, and for detaching the driver at the end of each driving cycle. This device must provide a rigid coupling of driver to pile for best efficiency of the vibratory driver.

In the third mode the piles are lowered with the template and a single vibrator is handled on a separate line from the surface vessel. The system must provide means for locating and positioning the driver on the piles. The locating could be done acoustically, and the positioning by water jets on the driver. The positioning could also be done by submersibles, either manned or unmanned. However, because of the likelihood of cable entanglement and the expense of submersible operations, this mode was eliminated from consideration.

Jack-In System

The jack-in concept for seafloor pile emplacement is shown schematically in Figure 2. This concept was developed to eliminate the need for a large reaction mass against which to jack.[5] As indicated in Figure 2, the system uses five piles in a regular pentagonal template. At each corner of the template a jacking mechanism controls the position of the pile relative to the template. Piles are driven by jacking on one pile at a time in the sequence shown by the circled numbers in Figure 2. The reaction is derived from the weight of the emplacement system plus the skin friction on the two piles adjacent to the one being driven.

Several types of jacking mechanism are feasible for this system. One promising concept uses a winch-and cable mechanism. Other possible mechanisms include rack-and-pinion jacks, chain jacks, and hydraulic cylinders. It was concluded that the specific type of jacking mechanism would not influence the choice between the conceptual designs.

The control system for the jack-in concept would direct the power to one jack at a time. Several repetitions of the jacking sequence will probably be necessary because a given pile may meet a level of resistance that will overcome the available reaction, and that corner of the template will begin to rise. Jacking on that pile should be discontinued when the template reaches a predetermined inclination, and the next pile in the sequence should be jacked. The control system should permit the skipping of a given pile in the event it reaches maximum penetration before the other piles. At the end of driving the power and control subsystems would be detached and retrieved.

Screw-Pile System

A screw-pile system is shown schematically in Figure 3. The piles have one or more helical blades at the lower end, and are emplaced by rotating them about the longitudinal axis. The piles would be rotated individually to minimize power requirements. The driving torque would be resisted by lateral forces on the other piles in the template. At least two sequences of pile rotation may be required because the torque might be great enough to overcome the lateral soil resistance in the early stage of driving. Thus, the control subsystem would be quite similar to the jack-in system described above.

As shown in Figure 3, the screw piles are square and are rotated by a kelly drive that allows longitudinal motion of the pile while it rotates. An alternative drive system was considered with which two piles are driven at the same time by a drive unit attached at the upper end of the piles. The piles are counter-rotated to absorb the torque. It was concluded that this system is much less desirable than the kelly-drive system because the weight would be concentrated so far above the template, and the free-fall of the piles would be hindered.

Comparison of Conceptual Designs

Each conceptual design was carried only far enough to provide a reasonable basis for comparison. Because of the large number of operating requirements that a seafloor pile emplacement system must meet, and because the four conceptual designs may differ in the manner or degree in which they fulfill any given requirement, a quantitative method of comparing the systems is necessary. The method adopted is essentially the same as was used to select the three emplacement mechanisms[2]. Relative weights are assigned to each of the operating requirements identified in Table 1 to reflect the degree of importance they exert in concept selection. Then each system is rated according to how well it meets each operating requirement, employing a numerical rating scale, called an effectiveness number. The effectiveness number and the weight are multiplied and the products are summed for each system. The resulting aggregate number reflects comparative effectiveness of the systems.

It was determined that all of the systems could be designed to meet the requirements for water depth, sea state capability, capacity, number of piles, and ship support in an equivalent manner. Thus, these requirements can be neglected in comparing the various systems.

The weights assigned to each of the remaining operating requirements are shown in Table 2. It should be noted that the requirement concerning versatility has been divided into two categories. The most important factors in comparing the systems are submerged weight, development required and complexity. The submerged weight has a large effect upon the handling system, the range of choice of surface support system, and the likelihood of successful emplacement. The required development effort affects both the time and overall cost of procuring a prototype emplacement system. Systems utilizing the greater number of state-of-the-art components are superior, provided of course, that all other criteria are met satisfactorily. Complexity is related primarily to the reliability of the system and secondarily to cost. In general, systems utilizing fewer mechanical operations and control functions are more reliable and less costly; such systems are superior. The other operating requirements have relatively less effect upon system comparisons, as reflected by the weight assigned.

Table 2. Relative Weights of Operating Requirements for Concept Selection

Requirement	Weight
Submerged Weight	3
Power Required	2
Emplacement Rate	2
Verticality	1
Seafloor Soils Adaptability	2
Versatility - Greater number of piles	1
Versatility - Variable plan dimensions	2
Required Development Effort	3
Complexity	3

A scale of 1 to 5 was adopted for assigning effectiveness numbers. As noted above, the effectiveness number attempts to quantify the degree to which each conceptual design fulfills the operating requirements listed in Table 2; the larger the number, the better the system meets the requirement. For the first four requirements, quantitative limits can be established for each of the effectiveness numbers, as shown in Table 3. For the remaining requirements, the effectiveness number represents the judgment of the relative quality of each conceptual design, Table 4 summarizes the conceptual designs, the effectiveness number assigned for each requirement, and the overall effectiveness rating of each system.

Discussion

All of the conceptual designs can meet the requirement that the submerged weight be less than 40 kips. However, the multiple-vibratory driver system will be just below this limit and is down-rated compared to the other systems, as shown in Table 4. The weight estimates for the vibratory systems are based on a driver-to-pile weight ratio of 3 to 1. This ratio is about average for successful commercial vibratory drivers.

The required power is estimated to be the least for the jack-in system and the greatest for the vibratory systems. However, the vibratory systems have a potentially greater emplacement rate and may permit shorter on-bottom operation times. The lower relative rating of the emplacement rate of the jack-in and screw-in systems reflects their status as "static" emplacement methods.

The jack-in system is rated much superior to the others in ability to assume and maintain a vertical pile attitude (i.e., level template attitude), because the jacks at each corner can be used to level the template at the beginning and end of the pile-jacking sequence. The attitude of the other systems depends upon how nearly vertical they hang when the piles are released from the template to free-fall the final 3-5 feet.

The screw-in emplacement method is believed to be the most adaptable to differing soil conditions. Industry experience with this means of emplacing ground anchors for electric utility lines and pipelines has shown that screw piles can be configured to penetrate dense cohesionless and very stiff cohesive soils at the proposed power levels[6]. The vibratory driver systems are relatively inefficient in cohesive soils and would probably penetrate the stiff cohesive soils only with considerable difficulty. The jack-in system is not expected to operate effectively in cohesionless soils because the point resistance of the driven pile would increase too rapidly with depth for the skin friction on the adjacent piles to provide sufficient reaction force.

Table 3. Rating Scales for Effectiveness Numbers

Requirement	1	2	3	4	5
Estimated Submerged Weight, kips	>40	30-40	20-30	10-20	<10
Estimated Power Required, HP	80-100	60-80	40-60	20-40	<20
Emplacement Rate, ft/min	-	-	<5	5-10	>10
Verticality, Degrees	-	<±2	-	-	<±0.5
Seafloor Soils Adaptability	Loose Cohesionless; Soft Cohesive	Medium Cohesionless; Medium Cohesive	Medium-Dense Cohesionless; Stiff Cohesive	Dense Cohesionless; Very Stiff Cohesive	All except rock
Versatility - Number of Piles	Essentially unadaptable; major effect on operation or cost	-	Not readily adaptable; moderate effect on operation or cost	-	Easily adaptable; minimum effect on operation or cost
Versatility - Plan Dimensions	Essentially unadaptable; major effect on operation or cost	-	Not readily adaptable; moderate effect on operation or cost	-	Easily adaptable; minimum effect on operation or cost
Development Effort	-	Less than 60% state-of-the-art components; more than 4 years to prototype	More than 60% state-of-the-art components; approx. 3-4 years to prototype	-	80% state-of-the-art components; approx. 2 years to prototype
Complexity	-	Large aggregate number of mechanical operations and control functions	-	Moderate aggregate number of mechanical operations and control functions	Small aggregate number of mechanical operations and control functions

Table 4. Comparison of Overall Effectiveness of Pile Emplacement System Conceptual Designs

Requirement	Weight	Conceptual Design			
		Multiple Vibratory Driver	Single Vibratory Driver	Jack-in	Screw-in
		Effectiveness Number			
Estimated Submerged Weight	3	2	4	4	4
Estimated Power Required	2	2	2	4	3
Emplacement Rate	2	4	4	3	3
Verticality	1	2	2	5	2
Seafloor Soils Adaptability	2	3	3	2	4
Versatility - Number of Piles	1	1	5	5	5
Versatility - Plan Dimensions	2	3	3	5	5
Development Effort	3	3	3	3	5
Complexity	3	4	2	4	5
Overall Effectiveness	-	54	58	71	79

The screw-in, jack-in, and single vibratory driver systems are estimated to be equivalent in versatility for use in a foundation requiring more than the minimum number of piles. The multiple vibratory system is rated as essentially unadaptable because of the excessive weight of additional drivers. The screw-in and jack-in systems are rated equivalent in versatility related to varying installation plan dimensions. The screw-in system can be readily adapted for varying foundation sizes and shapes; i.e., triangular, square, rectangular, circular, etc. The jack-in system must retain its basic circular shape (i.e., the vertexes of the regular pentagon lie on a circle) for best efficiency but the dimensions can be varied with no loss in efficiency. The vibratory driver systems are judged to be less adaptable to changes in foundation size and shape.

The screw-in system is estimated to require the least development. Nearly all of the components are easily within the state-of-the-art and industry experience with submerged pipeline and electric utility line anchoring provides sufficient guidelines for expeditious development. The jack-in system would not require much component development but would require more testing to prove the concept. The vibratory systems would require both component development and rather extensive testing.

The overall complexity of each system was evaluated by first determining the mechanical and control functions for the operation of each system. The complexity of each function was appraised as either simple or complex, and was assigned a numerical rating of 1 or 2, respectively. The ratings for each system were summed, and the aggregate number for each system was taken as a measure of the system complexity. The screw-in, jack-in and multiple vibratory driver systems are judged to be relatively simple systems, and the single vibratory driver systems is judged to be quite complex.

Finally, the last line in Table 4 summarizes the overall effectiveness of each system. It is evident that the screw-in system rates the highest, closely followed by the jack-in system. The two vibratory driver systems are rated considerably lower. The screw-in system was chosen for preliminary design.

PRELIMINARY DESIGN OF PILOT-MODEL EMPLACEMENT SYSTEM

General

For the preliminary design of the pilot-model emplacement system, the shape and the overall plan dimensions could be chosen arbitrarily because the use of a pile foundation/anchorage is not limited to installations of a certain class or size range. It was decided to base the design on the minimum number of piles because the operation and utility of the screw-pile emplacement method could be demonstrated adequately and at minimum cost with a three-pile system. An equilateral triangle is the obvious choice for shape. A pile spacing of ten feet, center-to-center, was chosen because the resulting foundation/anchorage is at once large enough to be representative of a prototype system and small enough to be handled over the side of a moderate-sized ship. The overall length of one of the sides of the triangle formed by the template is about 14 feet.

The length of the piles and the size and number of the helical blades can be varied within limits to suit the expected soil conditions at the proposed site. It is believed that piles longer than 50 feet will be too difficult to handle, and a minimum length of about 25 feet will be necessary to provide adequate embedment of the blades. The blade diameter can be varied from about 16 inches to 30 inches. The minimum diameter is limited by the cross-sectional dimensions of the pile shaft. The diagonal dimension of the planned pile cross section (10 inches by 10 inches) is approximately 14 inches. If a smaller pile cross section is desired, bushings would be necessary to reduce the size of the hole in the kelly drive. (A smaller pile cross section would reduce considerably the lateral load capacity of the foundation/anchorage.) The maximum diameter of the helical blades is limited by the installation torque available. The use of multiple blades to aid penetration is common in commercial screw anchor installations[6].

The required installation torque was estimated from a theoretical analysis, and from results of installation and load tests of actual screw anchor installations. The theoretical analysis suggests required torque of 10,000 to 15,000 ft-lb for adequate penetration of all expected seafloor soils. Industrial users of screw anchors commonly utilize power equipment with a stalling torque of 8,000 to 10,000 ft-lb to emplace high-capacity anchorages[7]. The larger torque value of 15,000 ft-lb was adopted for the preliminary design to ensure full pile penetration. In order to estimate the required power, a minimum pile rotation speed of 10 rpm was established. At 10 rpm the 15,000 ft-lb torque requires 28.6 horsepower to be delivered to the pile. Assuming reasonable efficiency of the electrohydraulic power system, approximately 60 horsepower must be delivered at the surface to emplace each pile.

The general operation sequence for the screw-pile emplacement system is shown in Figure 4. As indicated, the piles and template will be lowered together as a unit, Figure 4a. As the unit nears the seafloor, a bottom-sensing trip mechanism releases the piles to free-fall a short distance for initial embedment in an approximately vertical attitude. The template is supported on the piles by one-way grips that permit the piles to move only downward with respect to the template, Figure 4b. The one-way grips are designed to be completely automatic mechanical devices and will not require control telemetry. The auxiliary footing is necessary to stabilize the unit when one of the piles is being rotated, Figure 4c. When the pile is fully embedded, an automatic mechanical connection is made between the pile and the template, and subsequent piles are emplaced. When all piles are in and the load-bearing connections are established, the emplacement system is detached from the template and retrieved, Figures 4d and 5. If a given installation must be more nearly horizontal than is possible with the planned pile free-fall method, a leveling system can be included; the leveling would be done before the piles were emplaced. Figure 6 shows the system block diagram for the pilot-model system.

In the following sections the five subsystems are described and the major components of each subsystem are defined.

Foundation/Anchorage Subsystem

The foundation/anchorage subsystem consists of the template, the piles, the main load-transfer connections, the one-way travel grips and auxiliary footing, the pile release mechanism, and guide bearings that keep the piles aligned in the template, Figure 7. For the preliminary structural design of the template each side of the template was assumed to be a beam with ends partially restrained against rotation, supporting a centerpoint load of 75 kips. For a span of 10 feet, the required beam is approximately 18 inches deep and weighs 50 pounds per foot. The template will be of all-welded, steel construction and the sides can be fabricated as trusses, as shown in Figure 7, or from standard rolled sections.

The pile cross section must resist compression, tension, bending, and torsion loadings. However, the maximum values of these loadings are not expected to occur simultaneously, and the effects of combined loadings will be negligible. The loading that controls the cross-section dimensions is the maximum bending (lateral) loading of 25 kips per pile. For the preliminary design a 10-inch, square-tube cross with a wall thickness of 3/8 inch was chosen. A lateral load analysis indicates that this cross section is adequate. Failure will be induced in the soil rather than the piles.

The vertical capacity and emplacement torque of screw piles of several different configurations were estimated for various likely seafloor soil conditions. As noted above, these calculations indicate that the helical blades should range in size from about 16 inches to 30 inches in diameter. The calculations also indicate that more than one blade per pile will be required for adequate capacity and proper installations in all likely seafloor soils. The calculations show that pile penetrations will range from a minimum of about 15 feet in dense cohesionless soils to about 50 feet in soft cohesive soils.

The main load-transfer connectors transfer the shear load from the template into the piles. They are designed to be automatic mechanical locks that will function when the piles reach full penetration relative to the template; i.e., each pile must travel a given distance downward relative to the template. Because of the necessity for a given amount of travel, the installation system is purposely overpowered to ensure full penetration. The preliminary design of the main load-transfer connectors is shown in Figure 8. As indicated in Figure 8, the grips ride on the sides of the pile as the pile moves downward, until aligned with corresponding openings in the pile walls. A light spring force drives the grips into the openings. The openings will be reinforced to resist the bearing pressures caused by the shear connectors. Each half of the connector shown in Figure 8 is designed to take the full design shear load of the joint. The connectors are designed to transfer the load through the guide bearing assemblies to avoid relative rotation between the piles and the connector.

The one-way travel grips, Figure 9, are simple pawl and ratchet devices that permit the piles to move only downward relative to the template. The pawls are designed to be installed on the guide bearing assemblies to preclude relative rotation of the grips and piles. A ratchet bar or chain is attached to the sides of the piles to complete the grips. In conjunction with the auxiliary footing these grips stabilize the system during emplacement. When a given pile is being emplaced, no shear is transmitted between the pile and the template; the footing and the other two piles support the weight of the pile emplacement system. The one-way grips permit shear transfer at the non-rotating piles. The auxiliary footing is a simple spread footing designed to support about 60 percent of the weight of the template and installation unit.

The pile release mechanism is designed to operate automatically as the template nears the seafloor. A bottom-sensing trip mechanism releases spring-loaded pins that hold the piles in the template. The free-fall permits initial penetration of the piles in an essentially vertical attitude.

The guide bearings, Figure 9, serve to keep the piles aligned with respect to the template, while allowing the rotation of the piles. The bearing assemblies also transmit the shear from the main connectors and one-way grips to the template, as previously noted. Solid bearings utilizing low-friction polymeric bearing surfaces are planned rather than roller or ball bearing units.

Installation Subsystem

The installation subsystem, Figure 10, consists of the kelly drives, the hydraulic motors, piping, valves, pump, and reservoir, and the handling frame and equipment housing. The kelly drive is essentially a large gearwheel with a square central hole through which the pile passes. The gearwheel is driven at its perimeter by the hydraulic motor through a speed reduction system. The degree of speed reduction required depends upon the specific hydraulic motor chosen and upon the design stalling torque/speed, but ranges from about 20:1 to 60:1. The ten-inch square central hole will be lined with a low-friction polymeric material to aid the longitudinal motion of the piles.

The hydraulic system is designed as a pressure-compensated, closed-loop oil hydraulic system, similar to the hydraulic design for the NCEL seafloor deep corer.[3] The reservoir is designed to contain the hydraulic valves and pump and the electric pump motor in addition to the hydraulic fluid. A fixed-displacement gear pump delivers a flow of 40 gallons per minute at a maximum pressure of approximately 1600 pounds per square inch. The hydraulic piping required is nominal one-inch I.D. steel tubing with a wall thickness of 0.134 inch. The piping will be supported and protected by the radial members of the handling frame. The system is designed to operate with only four valves that will require surface control -- a bypass valve and function valves controlling the three motors. The location of the valves within the hydraulic reservoir minimizes the amount of electrical wiring and number of electrical penetrators exposed to the ocean environment. Three internal-gear hydraulic motors are used to rotate the kelly drives. Assuming a speed reduction of 20:1 the motors must develop approximately 750 foot-pounds of torque at 200 RPM. A single-acting hydraulic cylinder or rotary actuator will be used to trigger the release mechanism that detaches the installation unit from the template. A simplified hydraulic circuit diagram is shown in Figure 11.

The handling frame is the permanent base for the installation subsystem components and is the intermediate member through which the load of the emplacement system is transferred to the cable. The major loading condition is the shear load through the frame-to-template connectors as the system is being lowered to the seafloor. Although the static load per connector is only about 6.7 kips, the likelihood of dynamic loading during lowering requires that the connectors be designed to resist about 40 kips each.

Electrical Subsystem

The electrical subsystem includes the electric motor driving the hydraulic pump, the surface and submerged transformers, the electric transmission portion of the electro-mechanical (E-M) cable, and the generator unit. The entire subsystem is similar to the corresponding design for the seafloor deep corer. In fact, the generator unit, surface transformer, and E-M cable for the corer could be utilized directly, provided that the subsurface electrical components and the control subsystem are designed to be compatible with the existing hardware.

As noted previously, approximately 60 horsepower (electric) must be provided at the surface to supply the required 28.6 horsepower at the kelly drive motors. Electric power would be generated at 440 volts and transmitted over the E-M cable at 2300 volts. A submerged stepdown transformer would provide the power at the appropriate voltages for the pump motor and the control and feedback functions.

The electric motor would be located within the hydraulic fluid reservoir, similar to the NCEL seafloor deep corer design. The design is a standard modification of an industrial three-phase motor.

Control and Feedback Subsystem

The control and feedback subsystem includes the controls and feedback instrumentation of all submerged and surface equipment. The subsystem presents the greatest potential for simplification and cost reduction by judicious choice of the required control and feedback functions and the balance of automatic and operator control. The preliminary design presented herein is probably not optimum but is a good basis for the final design. The major effort required is the analysis of the subsystem for the most cost-effective balance of automatic and operator control. The goal is to minimize or eliminate the need for multiplexing of control or feedback signals on the E-M cable.

The preliminary functional design of the control and feedback subsystem is shown in Figure 12. Control functions are shown as dashed lines and feedback functions as dotted lines. A total of four control channels and nine feedback channels are required for the envisioned system. Each channel is simply an on/off channel; no proportional controls or feedback are needed.

The four control channels are utilized to operate solenoid-controlled hydraulic spool valves -- one for each of the three hydraulic motors, and one for a bypass valve (Figure 11). Each of these valves requires a feedback channel to verify its operation.

A fifth hydraulic valve operates the installation unit release mechanism as described above (Installation Subsystem). It is controlled by the pile travel limit switches -- when all three piles have reached maximum travel and have tripped limit switches the installation unit release is automatically activated.

The pile travel limit switches are also connected to the motor valves. As each pile reaches its maximum travel the limit switch closes the corresponding motor valve and opens the bypass valve. This prevents the rotation of the pile after it reaches full depth and minimizes soil remolding. The feedback channels for the motor valves thus function as the feedback for the pile travel limit switches.

Feedback channels are also designed for the pile release mechanism (Foundation/Anchorage Subsystem), an attitude sensor, and two pressure sensors. One of the pressure sensors would be a pressure release valve to prevent excessive system pressures. The second sensor would be used to indicate a given level of torque at the piles. The torque level can be chosen arbitrarily. However, it would probably be a torque corresponding to the estimated lateral resistance of the two stationary piles during the initial phase of pile emplacement. If the sensor indicated that the torque might overcome the reaction forces, driving of the pile could be discontinued until the other piles were emplaced deeply enough to resist the torque.

Many other control and feedback functions are possible and would be valuable, but the cost of providing additional functions is believed to be too great to be justified for the pilot-model system. Testing with the pilot model will determine the need for additional control or feedback in a prototype system.

Loading Handling and Surface Support Subsystem

This subsystem includes the surface vessel, the E-M cable, the winch, handling slings, shipboard cranes, and related items. As previously indicated (Operating Requirements) the overall system will require a minimum of 500 square feet of deck space and a 20-ton crane for over-the-side handling. This definitely limits the vessels from which the system can be operated since few "ships-of-opportunity" have installed, or can support, a 20-ton crane.

It is expected that the system will be lowered with either the NCEL seafloor deep corer winch or the NCEL motion-compensating winch. The E-M cable for the NCEL deep corer could be utilized for the pile emplacement system, or a new cable with a minimum 80,000-pound breaking strength could be designed and purchased. The decision concerning a new cable must be made during final design of the control and feedback system on the basis of a trade-off study of the relative costs of adapting the controls to the corer E-M cable versus providing a new cable.

SIMPLIFIED, LIMITED-CAPABILITY SYSTEM FOR ANCHORAGES

In the course of developing the preliminary design presented herein a concept for a simplified system with a limited capability evolved[4]. If the requirements for vertical downward load capacity and lateral load capacity are eliminated the cross-section dimension of the pile can be reduced because the buckling resistance of the 10 by 10-inch cross-section is no longer required. The system becomes an uplift-resisting anchor. By using a 4 by 4-inch cross-section the required installation torque is approximately halved. If the rotation rate is also reduced from 10 rpm to 2 rpm the horsepower requirement is reduced from about 28.6 horsepower per pile to about 3 horsepower per pile. By driving all three piles at once the total horsepower requirement is 9 horsepower. For approximately one-half hour of driving time the power could be supplied by a submerged battery pack. Approximately 12 kilowatt-hours of electric energy would be required, and ultimate uplift capacities of approximately 120 kips in cohesive soils and 90 kips in cohesionless soils would result.

This system would utilize a much-simplified control system since a single valve would control all three motors. All controls would be automatic and would be contained on board the installation system. Thus, the need for an electro-mechanical cable is eliminated. The operation would be as described below.

Arrival at the bottom would be sensed by a pad as previously discussed. The pad could be made to release all three kellys so that the augers would penetrate the loose surface layers by gravity. The vertical aspect of the platform (level) could be controlled by a buoy, rigidly attached but well above the platform. In principle, the entire assembly could be lowered in free-fall with the buoy limiting the rate-of-descent.

The "contact pad" could with very simple mechanical valving or electric relays activate an automatic sequence to simultaneously drive all three piles to full depth. Upon full penetration, a simple spring-loaded pawl at the lower end of the kelly drive would fix the platform with respect to the piles.

The power components, if inexpensive enough, could be left on the platform. If it were desired to retrieve the power components, a platform could be released by a time mechanism or command from the surface. The buoyancy element would probably require releasing and removal to provide a clear foundation for subsequent mounting of equipment or a structure.

While free-fall appears to be practical using a buoy as described, a minimum cable to establish the foundation's location would be desirable. This would also be useful in guiding the buoy and power components to the surface, as well as in guiding a structure to the installed foundation.

Furthermore, a simpler drive system can be utilized with the smaller cross-section piles. This system is shown in Figure 14. The square kelly is replaced with a round pile in which are machined two grooves circumferentially at the top and bottom. At the middle of the figure (Figure 13) is shown the lower end of the pile, with the driving spline not aligned with the driving groove; the pile is thus held from dropping. As the pile is rotated by the hydraulic motor the driving spline enters the driving groove and no longer prevents the pile from falling. When the pile achieves full penetration, the driving spline enters an annular groove at the upper end of the pile; all rotation of the pile stops even if the motor continues for a short time. The vertical position of each pile is maintained by the driving spline in the annular groove, as well as by a spring-loaded locking pawl, a simple but sure method of preventing the platform from moving with respect to the piles under vertical loading should the driving spline line up with the driving groove upon stopping of the motor. The illustrated configuration of pawl is descriptive; in the actual case, a broad latch which would span the driving groove would probably be used. Only two control functions, both of which could be made automatic, are necessary. First, the hydraulic motor drive would be actuated by a mechanical valve or limit switch when the contacting pad reached soil. Second limit switches (3 in series) or comparable/mechanical hydraulic sensors would shut off the hydraulic motor when all three piles were fully driven; these could readily be combined with the locking mechanism.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the evaluation of design concepts for a seafloor pile emplacement system it was concluded that a screw-pile emplacement system would be the most effective in meeting the given operating requirements. Most of the system components have already been developed, and the difficulty involved in system integration is small.

A preliminary design for a pilot-model screw-pile emplacement system was developed and is presented. It is recommended that this pilot-model be developed. The development can be conducted in several stages. For instance, the control and feedback subsystem should be developed first by "breadboarding" to study the most effective balance of automatic and operator control. Following this study final decisions can be made concerning use of multiplexing versus hard-wire controls and the use of the corer E-M cable versus purchase of a new cable. The installation and electrical subsystem could then be developed, followed by development of the foundation/anchorage subsystems. Staged development would permit the greatest flexibility for the final design and would also permit relatively low annual budgets.

ACKNOWLEDGEMENTS

The efforts of Mr. E. J. Beck on the mechanical design aspects of this program, and in particular on the concept for a simplified system for anchorages, are gratefully acknowledged.

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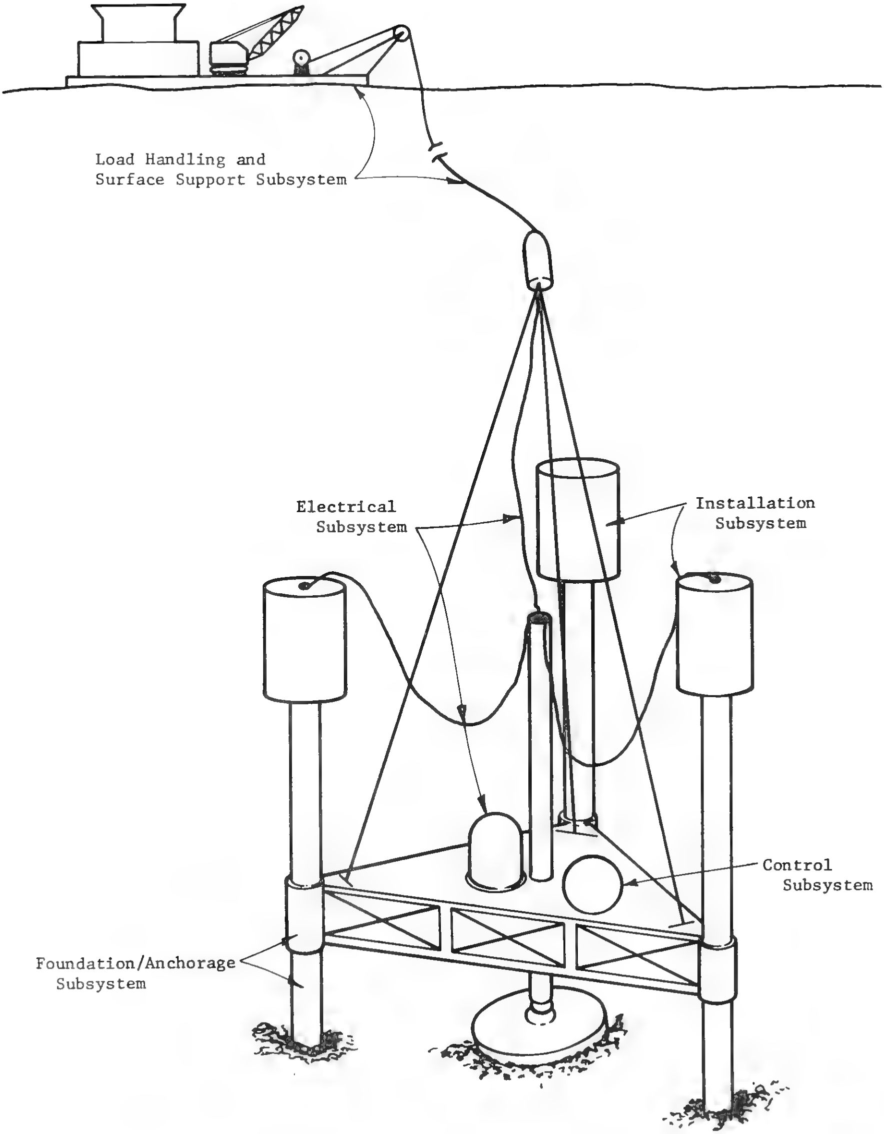


Figure 1. Schematic view of a seafloor pile emplacement system.

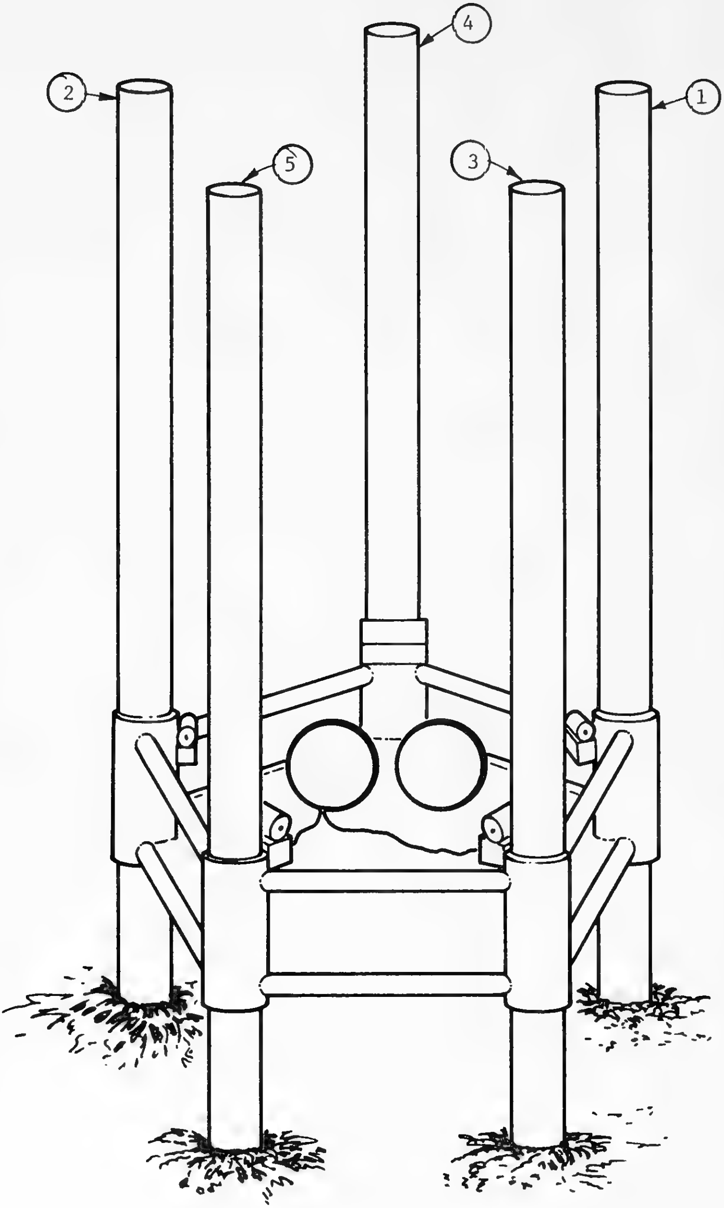


Figure 2. Concept for a jack-in emplacement system.

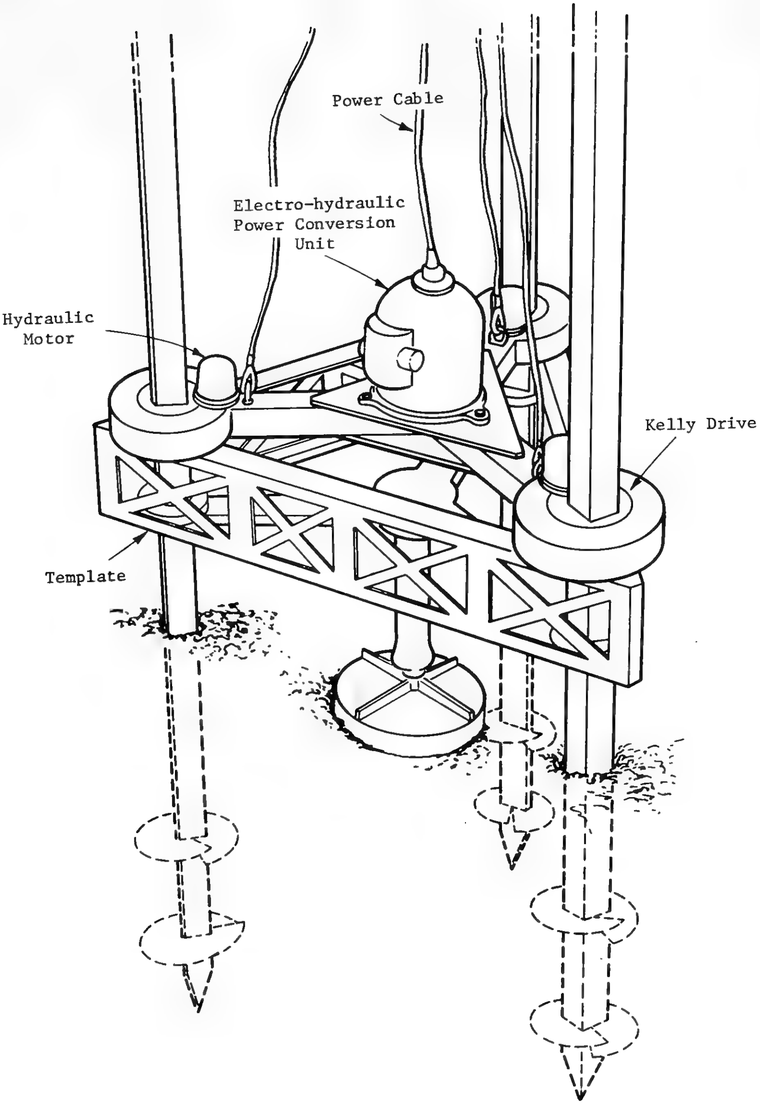
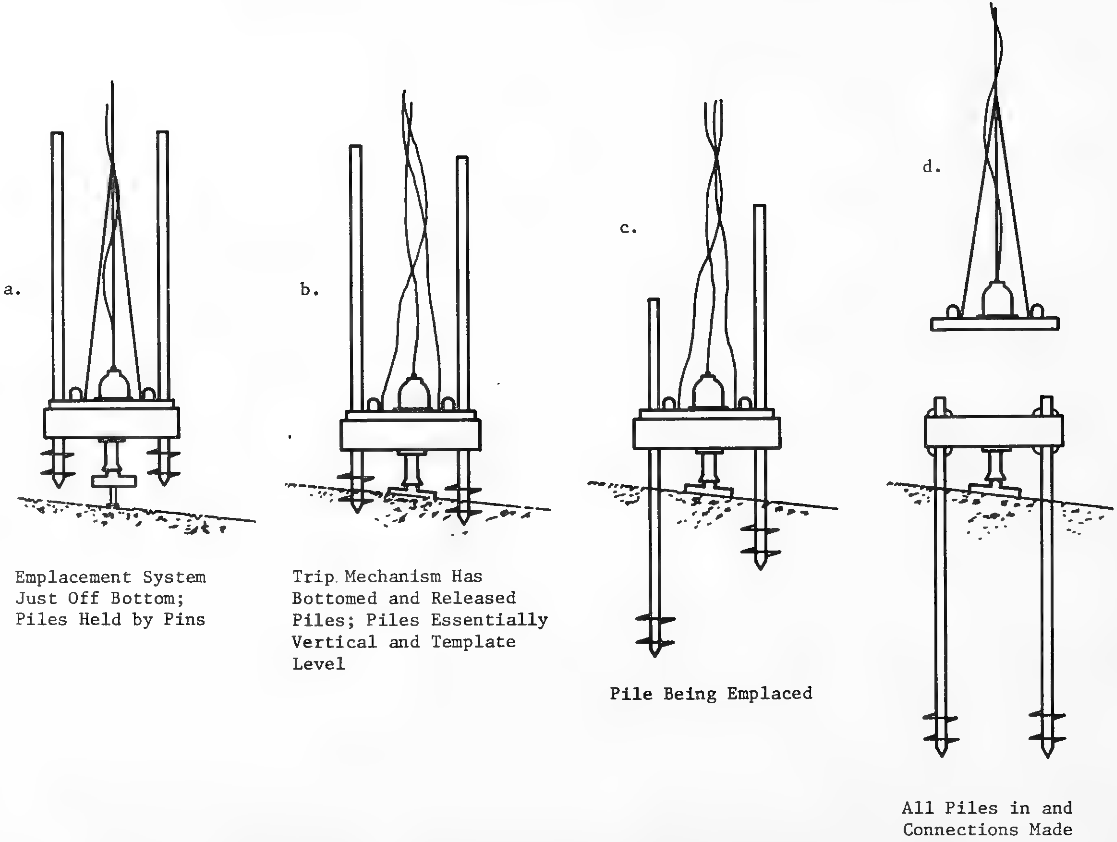


Figure 3. Conceptual design for a screw pile emplacement system.



Emplacement System
Just Off Bottom;
Piles Held by Pins

Trip Mechanism Has
Bottomed and Released
Piles; Piles Essentially
Vertical and Template
Level

Pile Being Emplaced

All Piles in and
Connections Made

Figure 4. Operational sequence for deep-water, screw-pile emplacement system.

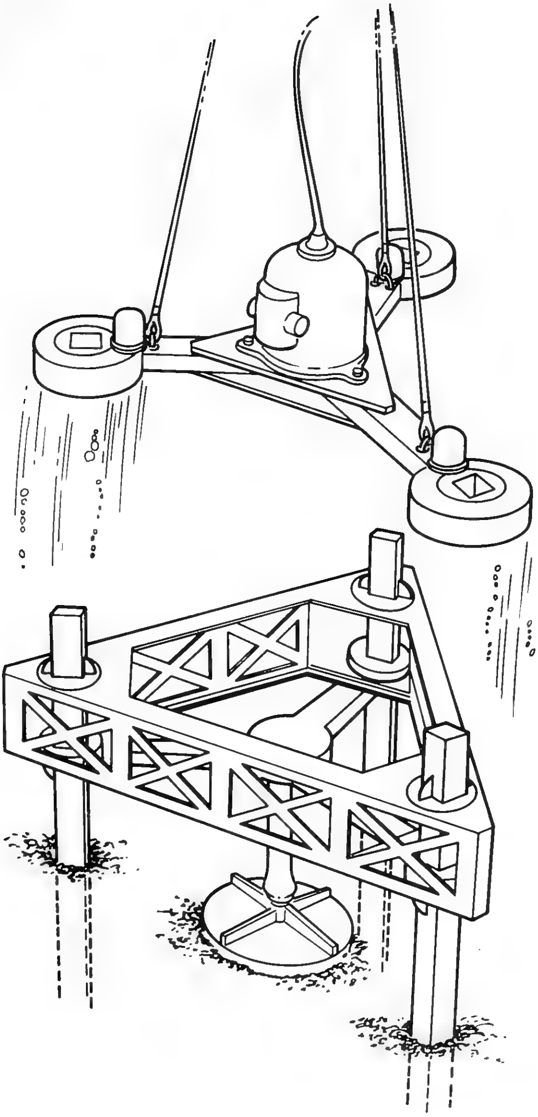


Figure 5. Pile foundation/anchorage in place.

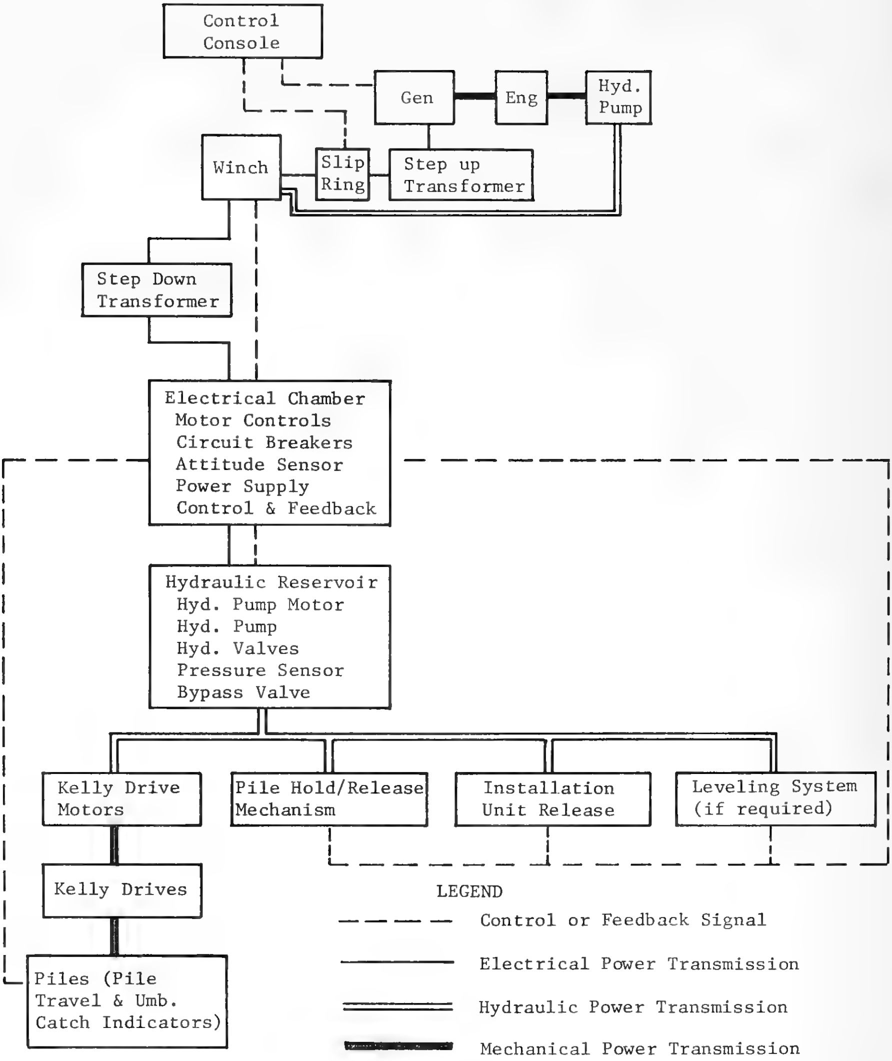


Figure 6. System block diagram for pilot-model seafloor screw pile emplacement system.

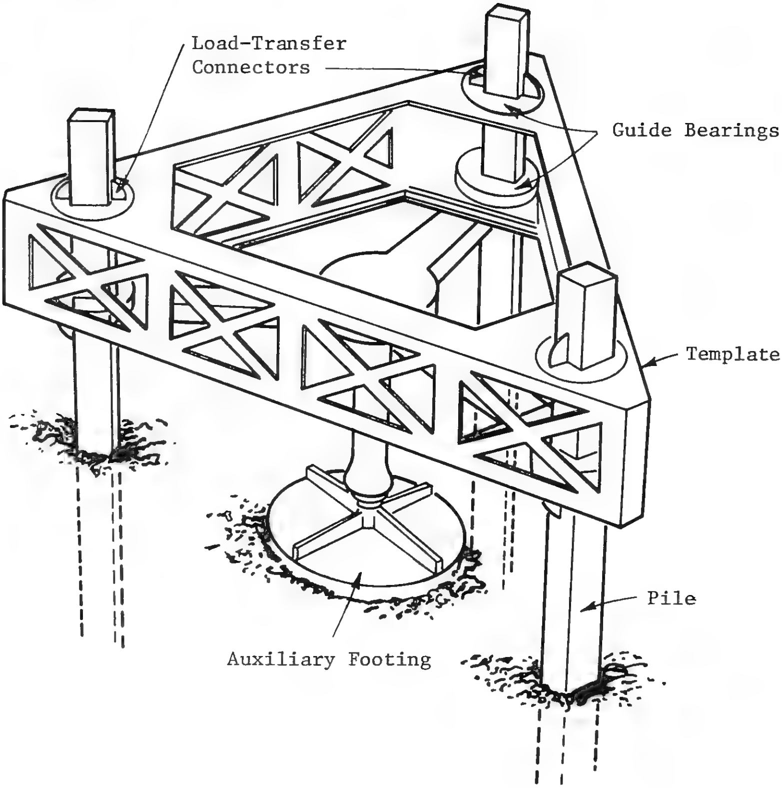


Figure 7. Foundation/anchorage subsystem in place.

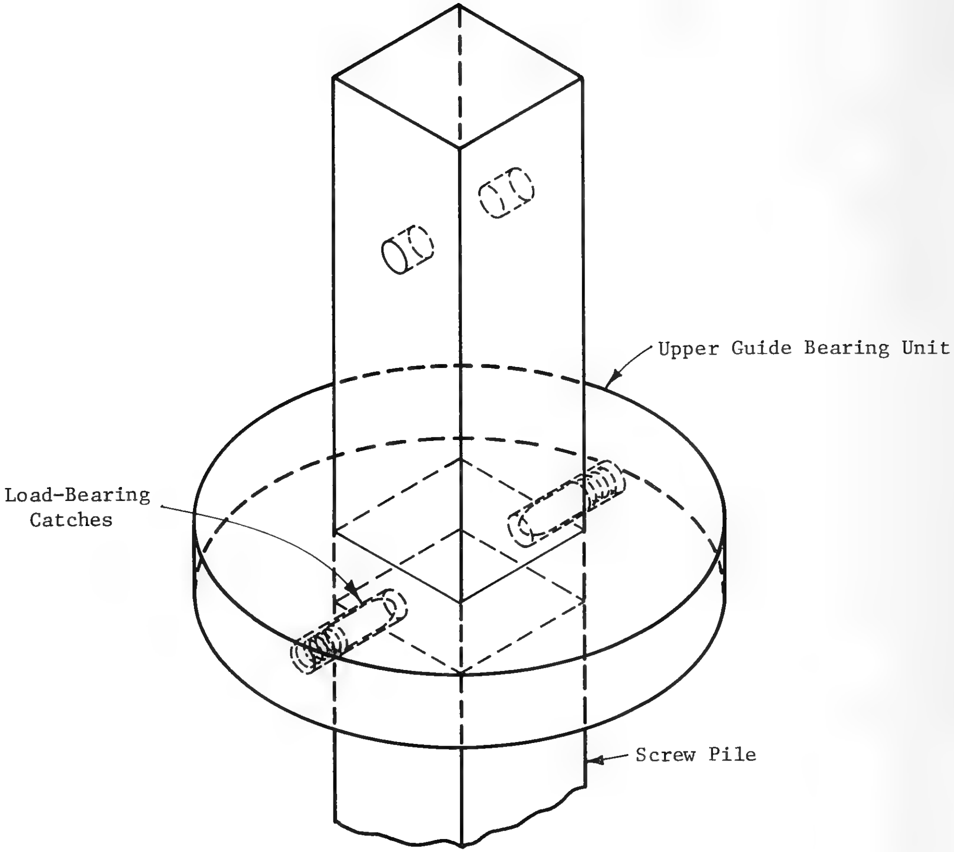


Figure 8. Schematic design of pile-to-template load-transfer connectors.

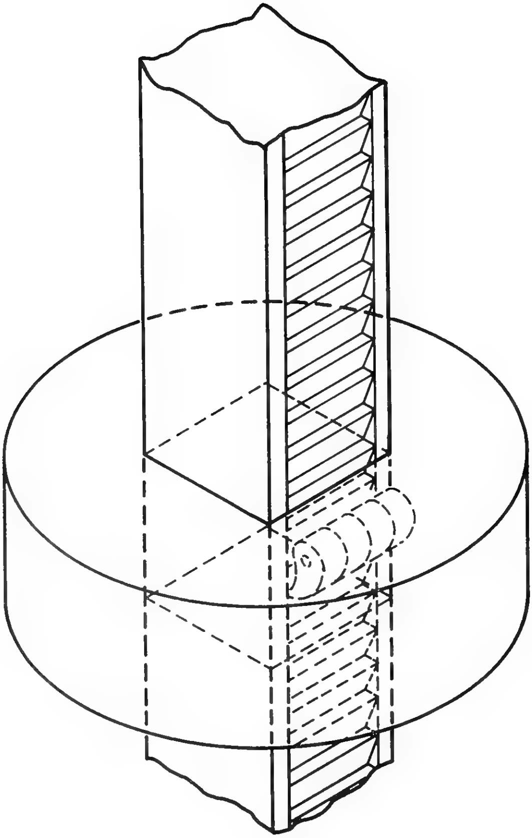


Figure 9. Schematic view of one-way travel grips.

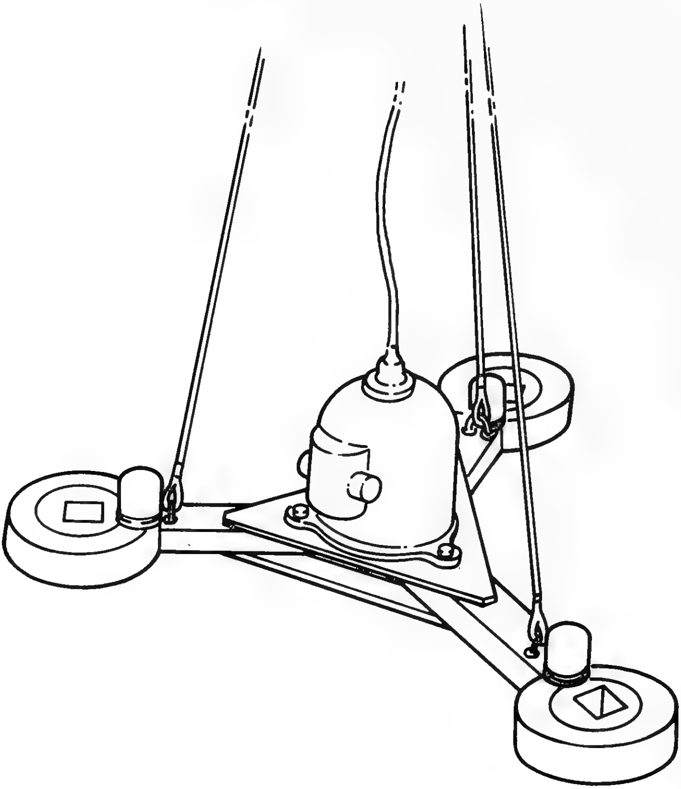


Figure 10. Installation subsystem of the pilot-model pile emplacement system.

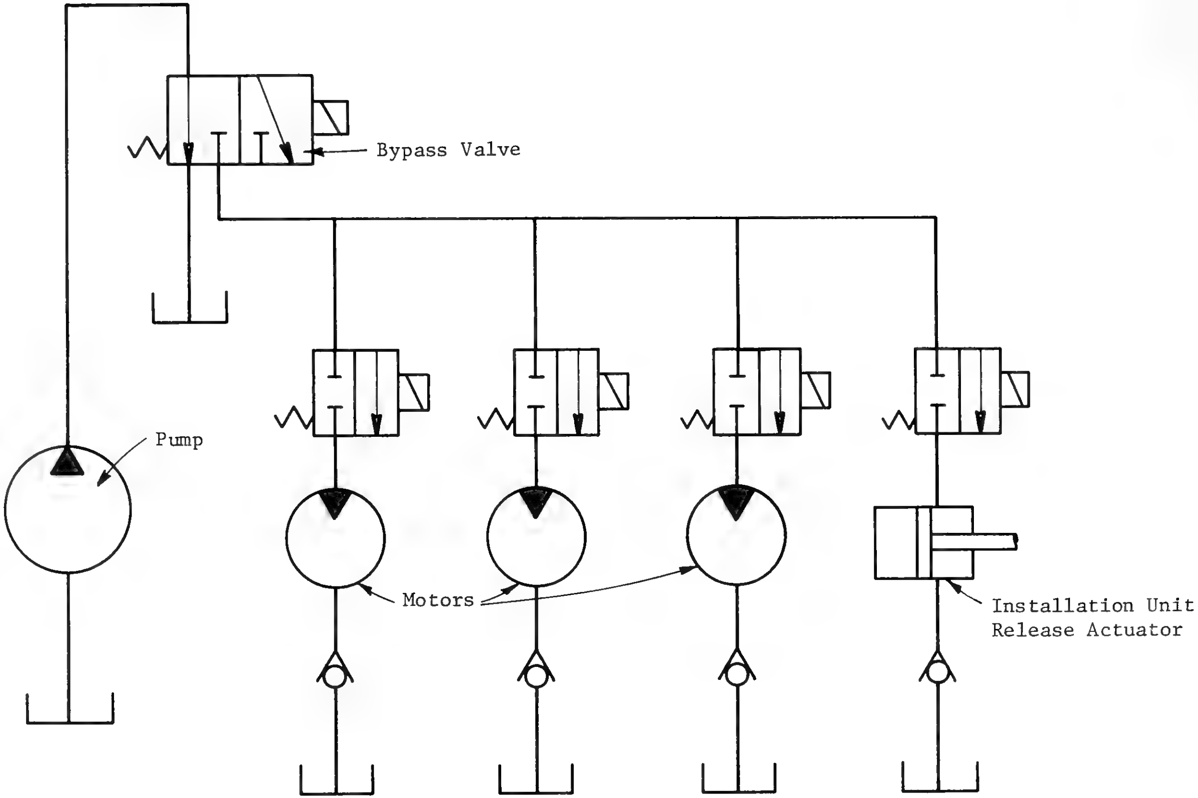


Figure 11. Preliminary hydraulic circuit diagram.

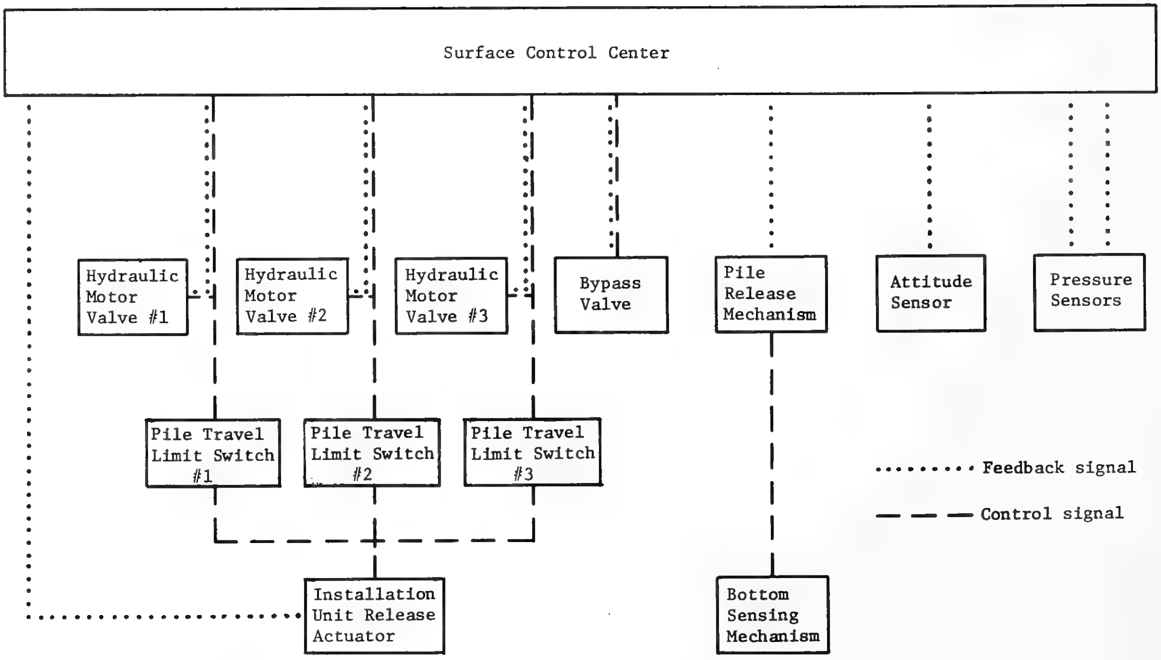


Figure 12. Preliminary functional design of control and feedback subsystem.

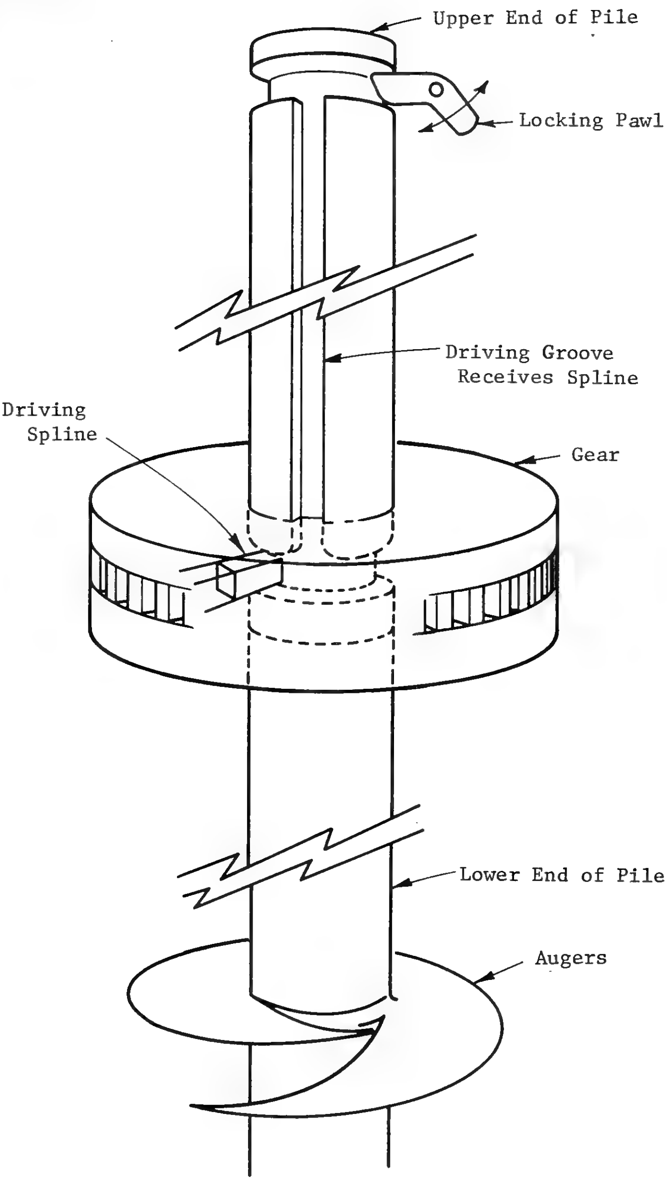


Figure 13. Simplified drive for limited-capability system.

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13 ABSTRACT

A previous review of the state-of-the-art of seafloor pile emplacement indicated that three types of mechanical systems could be developed for deep-ocean seafloor pile emplacement. The systems are: vibratory drivers, screw piles, and jack-in piles. Conceptual designs for multiple-pile emplacement systems utilizing each of these mechanical systems were developed and compared. The comparison showed that screw-piles would be the most effective in meeting the given operating requirements. A preliminary design for a pilot-model screw-pile emplacement system is presented.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Ocean bottom						
Deep water						
Emplacement techniques						
Pile driving						
Design						