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PRESTRESSED CONCRETE OCEAN STRUCTURES AND SHIPS

COVER PHOTO:

Ekofisk oil storage caisson under tow to Ekofisk field in the middle of the North Sea. Structure is now in service, storing up to 1,000,000 barrels of crude oil and supporting re-injection equipment to further conserve energy resources.

PRESTRESSED CONCRETE OCEAN STRUCTURES AND SHIPS

A Presentation of the Expanding Use of Prestressed Concrete for Ocean Structures and Ships with Guides to Effective Design and Construction Practice

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Post-tensioned, prestressed concrete ferro-cement yacht (22 x 5.86 m) owned by Dr. Tony Fisher, Sydney, won the Ocean Classic "Sydney to Hobart, 1973".

I. OBJECTIVE

The purpose of this brochure is to introduce information on the rapidly growing use of prestressed concrete for ocean structures to engineers, constructors, and user industries.

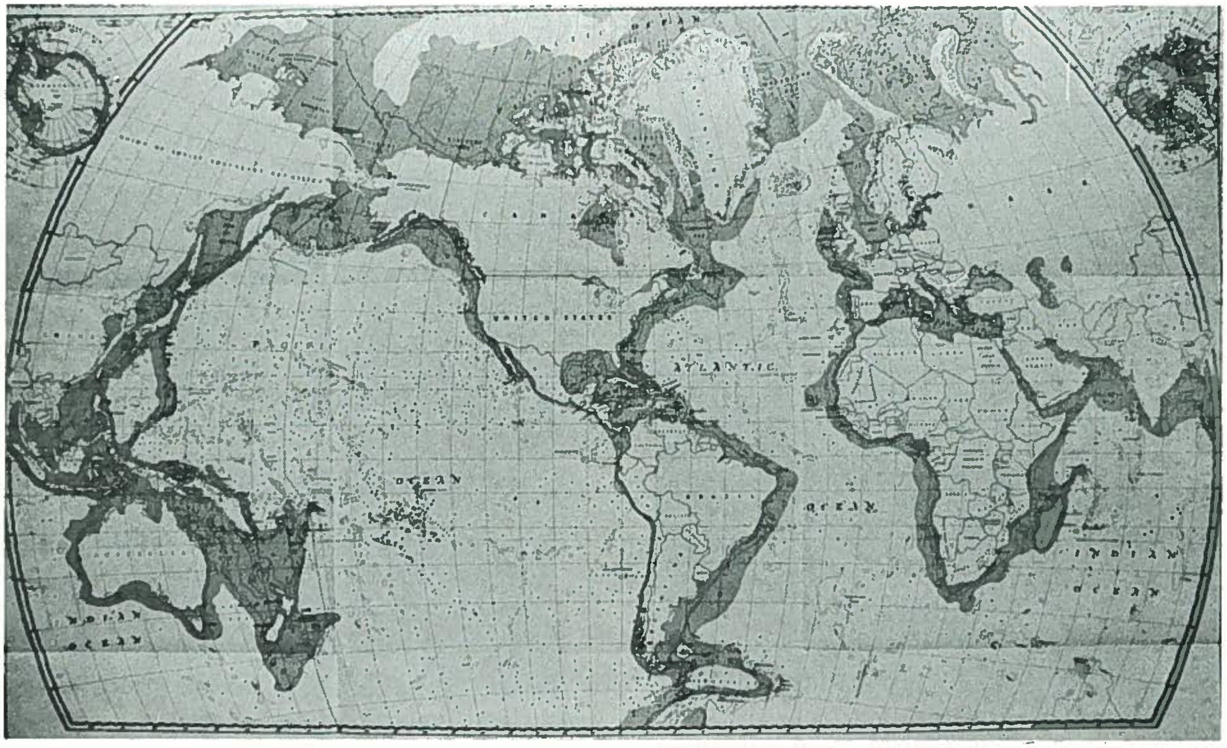
Although concrete has been extensively used since 1900 for marine and coastal structures, its full utilization in sea structures has depended on the advent of prestressing techniques and high strength concrete materials.

The extreme demands of the severe environment and deep water of the North Sea oil field development, coupled with similar experience in offshore terminals has stimulated concentrated research and development of concrete sea structures and has translated these into actual practice on a large and growing scale.

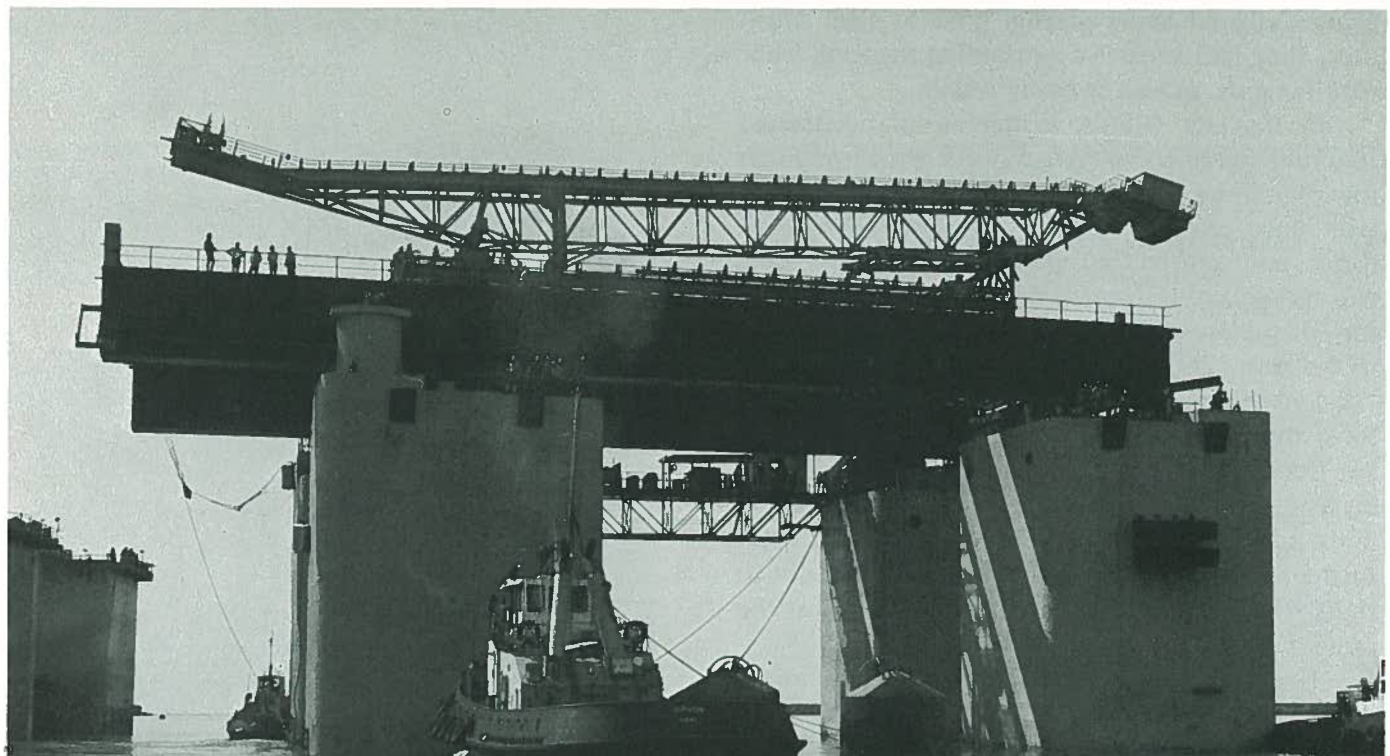
Application to ocean structures involves new considerations, both within current concrete technology and by integration with the work of other disciplines. In this brochure, a number of these aspects are examined and guidelines are indicated for the most effective design and construction practice.

The projected exploitation of the continental shelves and slopes, the challenge of the Arctic Ocean, and the changing needs of industry and society will apparently continue to present a demand and opportunity for sea structures. Prestressed concrete is expected to play a major role in carrying out these programs in a practicable, timely, economical and safe manner.

The Prestressed Concrete Institute is therefore presenting this brochure to provide background information and technical guidelines relative to the major factors involved in the effective use of prestressed concrete in an ocean environment.



Continental margins of the seas contain vast resources for the benefit of mankind, and present a need for concrete sea structures.



Caisson for offshore coal shipping terminal, Queensland, Australia. The steel shiploader girders and trusses are supported on prestressed concrete caissons.

II. HISTORY OF CONCRETE SEA STRUCTURES

The Romans used pozzolanic cement concrete for the underwater piers of river bridges which still stand. John Smeaton invented Portland Cement for use in the Eddystone lighthouse in 1756. Lambot first used reinforced concrete for small boats in 1848 and one of his later boats is still afloat.

Marine structures of concrete have been numerous worldwide since the early 1900's and recent inspections confirm the long-term durability and integrity of many of these pioneering structures, in the USA, USSR, and Europe. [1]

Reinforced concrete ships were built by the hundreds in World Wars I and II and gave excellent performance under severe marine exposure. Some of the World War I vessels are still available for inspection and test: one of these, the Selma, grounded on the beach in Galveston, in 1921, was built of expanded shale lightweight concrete, with minimum cover, yet still displays good durability. However, these ships were uneconomical due to being designed along parallel lines to steel ships: thus, they had excessive reinforcing steel and labor requirements, as well as heavy weight.

In the late 1950's, a number of prestressed concrete ocean-going barges were constructed in the Phillipines and have seen continuous service ever since, with notable records of low maintenance and satisfactory performance. Prestressing was recognized as presenting a special opportunity for adequately countering the cyclic dynamic loads of the seas. [2]

Lighthouses of concrete, constructed as caissons, towed out into the ocean and seated on the sea floor, were constructed in the 1960's in Scandanavia, Ireland, England, Germany and Canada. Some of these used post-tensioning to anchor them to the sea floor and to provide greater strength to the shafts. These were the true forerunners of the present North Sea caissons.

The history of concrete in the sea environment is as old as concrete itself. Its applicability has long been recognized for harbor and coastal structures, and thus, by utilizing the best of our knowledge and new techniques, its use can be confidently extended to the deep oceans.

In June, 1973, the Ekofisk Caisson, 86,000 cu.m. of prestressed concrete, was emplaced in 70 meters of water, one hundred kilometers off the coast of Norway. Its success immediately unleashed a flood of interest (and contracts) in concrete ocean structures, not only for the North Sea, but for fixed and floating offshore terminals. As of this writing, (June, 1975), 12 huge prestressed concrete caissons are under construction for the North Sea, for depths up to 150 meters; a 10-caisson coal loading terminal of prestressed concrete offshore Queensland, Australia, is nearing completion; and a 70,000 ton displacement prestressed concrete floating terminal for LPG is under construction in Washington, to be towed to the Java Sea.

Other structures and vessels are under design for a variety of purposes in the oceans: these are examined in Section VI, Future Developments.

The technological advances which make modern concrete sea structures possible are firmly rooted in the advances in other applications of prestressed concrete, such as Long Span Bridges and Nuclear Reactor Pressure Vessels.

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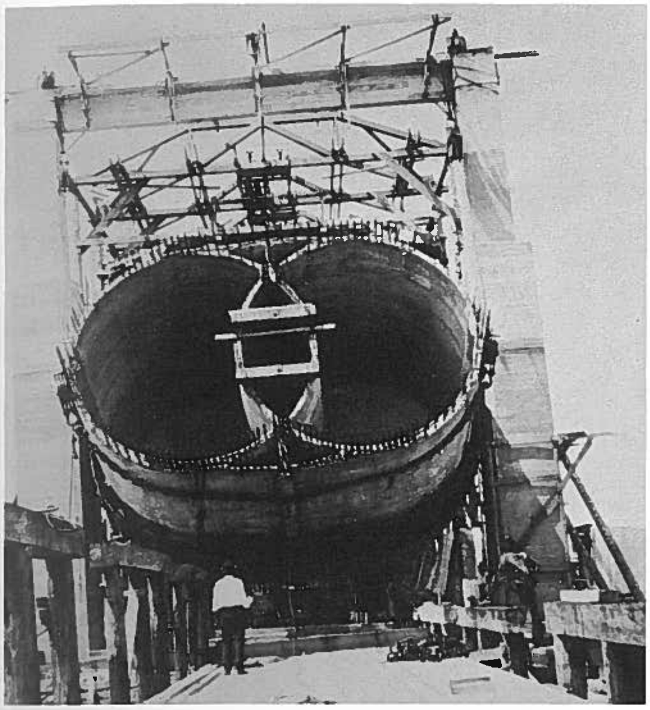
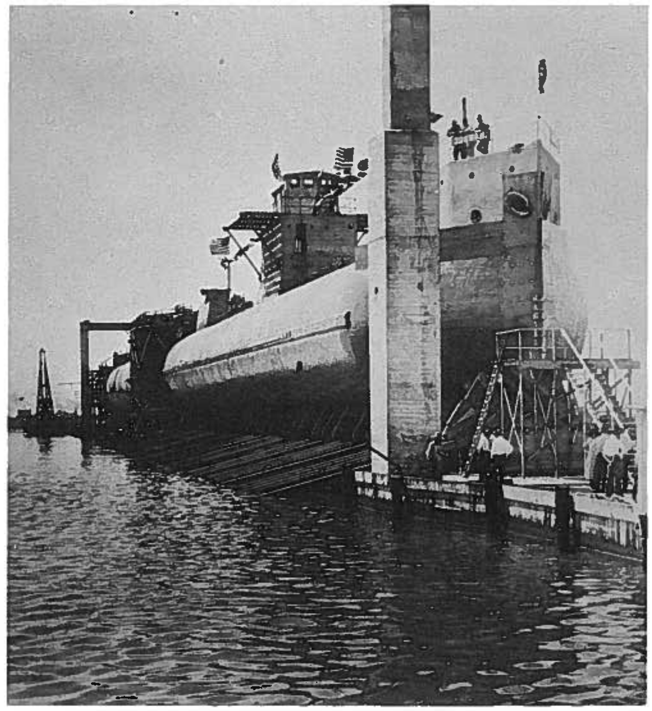
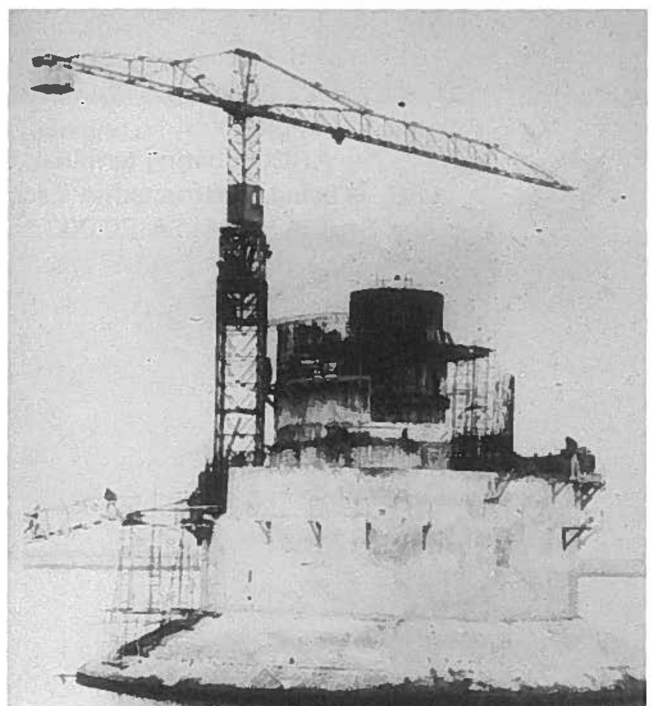


Reinforced Concrete Ship Hull – World War I.



World War I Concrete Ship.

Reinforced Concrete Light Structure "Nab Towers", Portsmouth, England. Built in 1918 as a U-Boat barrier for the Dover Straits, but installed as a lighthouse in 1920 following the Armistice. Still in service and in good condition despite thin walls and minimal concrete cover.



Kish Bank Lighthouse, Ireland, 1966, now installed in the Irish Sea. This is a telescoping structure: after landing on the sea floor, the shaft and lighthouse are raised to full height and permanently fixed to the base.

III. CURRENT APPLICATIONS

Current applications of prestressed concrete sea structures include the following notable examples.

Twelve drilling and production caissons or "gravity-platforms" completed or under construction for the North Sea, in water depths to 148 meters, each consisting of about 100,000 cubic meters of concrete, containing about 3000 tons of prestressing steel.

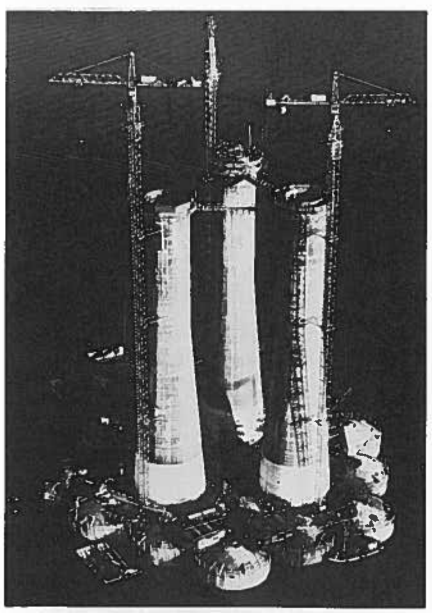
The Ekofisk caisson, installed in June, 1973, which has successfully weathered two 25-year and one 50-year storms, with performance and behavior strikingly close to that predicted in the design. It is now used both for oil storage and as a major platform for gas processing, etc.

The Beryl A Condeep Structure, installed in July, 1975 in 120 meters of water in the UK Sector of the North Sea is to serve as a drilling, production, and storage facility.

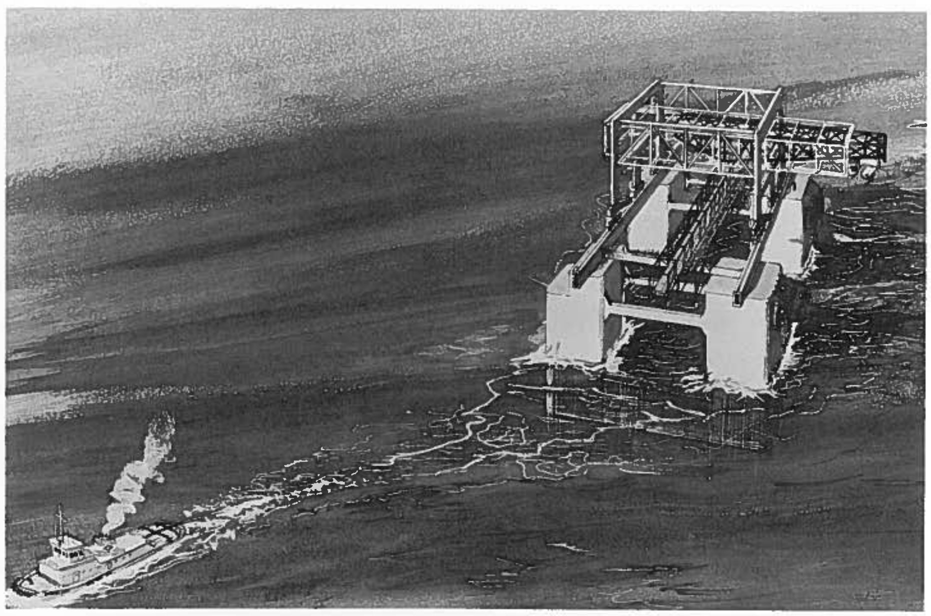
A major coal loading terminal, located in exposed seas off the coast of Queensland, Australia, is founded on 10 prestressed concrete caissons, now nearing completion.

The ARCO floating terminal, for refrigeration, storage, and processing of LPG, is being constructed in Tacoma, Washington, and will be towed to the Java Sea, Indonesia. A 70,000 ton displacement vessel of prestressed concrete, it employs segmental precast composite shell construction.

ARCO Floating LPG Terminal.



Condeep Brent B as seen from Beryl A.



Coal loading terminal, Queensland, Australia, founded on 10 prestressed concrete caissons.

IV. ADVANTAGES OF CONCRETE FOR SEA STRUCTURES

1. Properly designed and constructed prestressed concrete structures offer many advantages for use in the sea. These include:
   a. Durability and reduced maintenance.
   b. High resistance to fatigue.
   c. High resistance to compressive forces, such as those imposed by hydrostatic pressure.
   d. Excellent cold weather and low temperature qualities.
   e. Inherent rigidity and freedom from ovalization and vibration.
   f. Favorable mode of failure under accident conditions.
   g. Good thermal insulating qualities.
   h. Highly resistant to fire.
   i. Adjustable to imposed deformations through relatively low elastic modulus and creep.
   j. Wide availability of materials and labor skills.
   k. Ability to mold to complex double curvature.
   l. Economy.
2. There are some less favorable properties of prestressed concrete which require special consideration and which may necessitate use of special reinforcement details. Among these are:
   a. Low tensile resistance in direct tension, flexure, and diagonal tension (shear).
   b. High weight to strength ratio.
   c. Limited ultimate strain.
3. Prestressed concrete sea structures must therefore be designed on a rational basis, utilizing the properties of the materials, selecting configurations appropriate to concrete, utilizing prestressing and other special techniques where applicable. Loads and forces should be those developed from a rational evaluation of the sea environment. Rather than attempt to apply or extrapolate from steel structures and ships, prestressed concrete should be treated in its own right.

   Guides for accomplishing this are presented in Section VI. Technical Guides to Proper Design and Construction Practice.
4. Certain features of modern prestressed concrete sea structures stand out.
   a. The advantageous use of high strength concrete.
   b. Prestressing of massive precast and cast-in-place concrete sections by use of post-tensioning.
   c. The advantages of precasting and segmental construction methods for achieving high quality, economy, and speed.
   d. The mobility of sea structures: they can be constructed in one location and towed great distances to the site of use.
   e. The opportunity for integration of complete systems into a concrete sea structure — the "Systems" potential.

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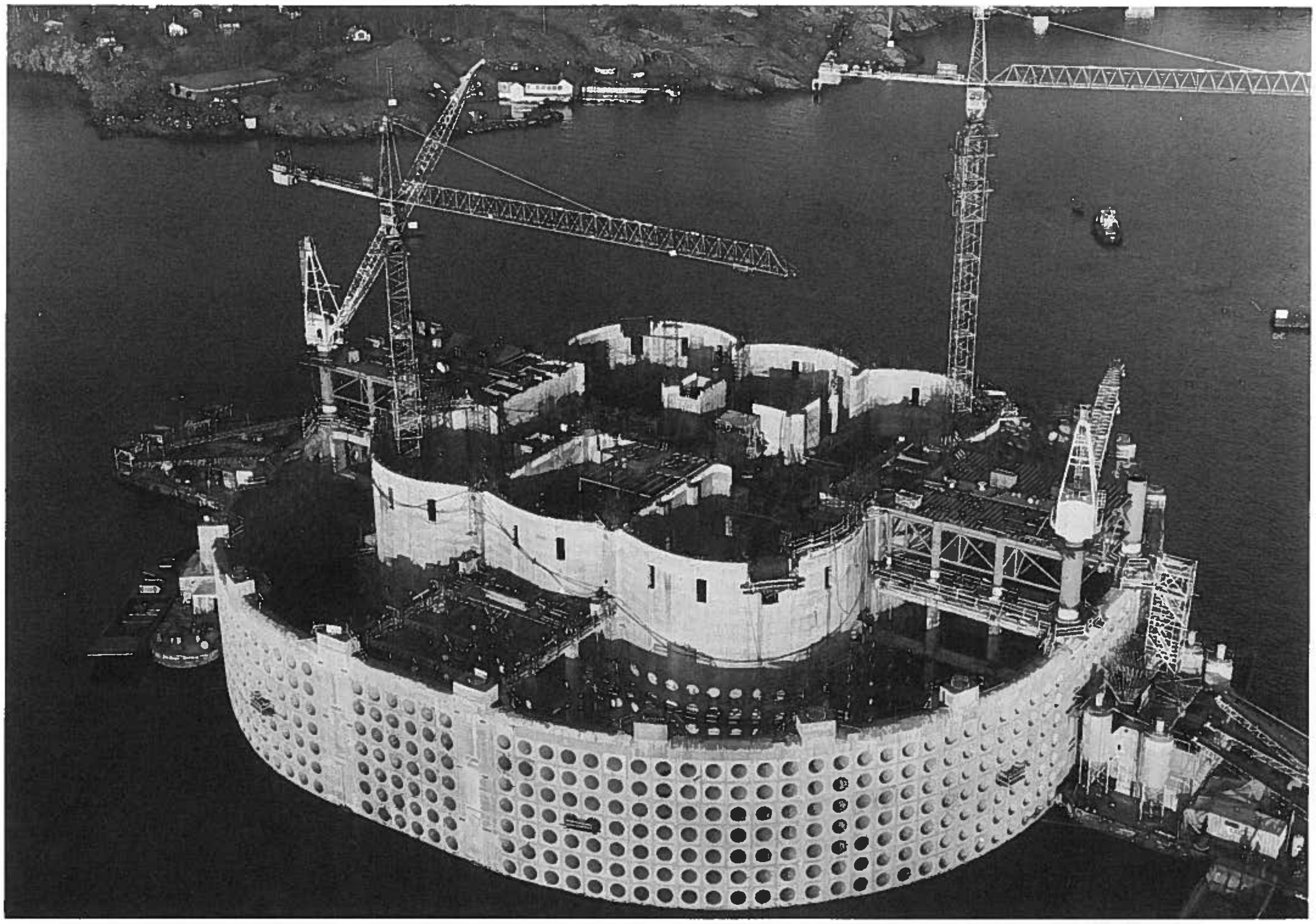

Ekofisk oil storage caisson under construction — 86,000 cubic meters of high quality prestressed concrete were used.

Condeep Beryl A: This huge concrete structure, largely submerged at this stage, has just "picked up" the 12,000 ton deck structure.

V. ECONOMICAL CONSIDERATIONS

The Economy of Concrete Sea Structures must be evaluated from a functional or performance viewpoint, in order to make a proper appraisal. It is seldom a question of direct comparison of a specific structural member, but rather an overall analysis of both first cost and operational costs.

Prestressed concrete will indeed often be found to achieve a direct first cost saving. This is particularly true with respect to deeply-submerged structures, subject to high hydrostatic loads, where the concrete may be found to represent only about half the cost of the comparable structure in steel. For structures subject to flexure, the difference may be smaller, from a 20% saving down to zero.

Substantial savings are usually realized in maintenance costs. Over the structure's life cycle, the reduced cost of the maintenance of concrete over steel may in some cases equal the capital cost.

Concrete has a high weight-to-strength ratio and concrete structures which must float (ships) have a significantly greater displacement for the same cargo capacity as compared with steel. However, this does not necessarily imply an operating-cost disadvantage.

a) For lightweight cargoes (liquefied gas) and for service in the Arctic, high displacement may actually be an advantage.

b) For ships, the lower deadweight-to-displacement ratio may be offset by the use of a lower block coefficient, through the use of double curvature in the hull.

The durability of concrete to aggressive substances and the high resistance to abrasion makes concrete attractive for use in carrying and storing chemicals and for use with mechanical loading and unloading devices. Once again, annual costs of maintenance may be substantially reduced.

Concrete sea structures can be and usually are built independently of shipyards. They do not depend on extensive facilities and installations. High quality concrete materials are available in most areas of the world. While skilled labor and supervision is required for a number of highly-technical operations, the greater portion of a typical concrete sea structure can be constructed utilizing normal construction contractors and labor. The required construction equipment is also that commonly used in general engineering construction.

Of particular attraction in many developing countries is the extensive use of local materials and indigenous labor.

Where special conditions apply, as in Arctic Ocean service, or with cryogenic gasses, the economy of prestressed concrete may be dramatic, due to its favorable properties at low temperatures.

Less immediately apparent but of great significance is the previously mentioned facility with which concrete sea structures can be integrated into an overall system.

Prestressed concrete sea structures can generally be constructed more rapidly than their steel counterparts. They lend themselves to rapid installation on the sea floor and to the carrying out of installation activities from the structure itself. These are perhaps the dominant considerations in their initial selection for the North Sea.

Frequently, where prestressed concrete has been selected solely on the basis of lowest first cost, the other advantages described above turn out to be even more significant.

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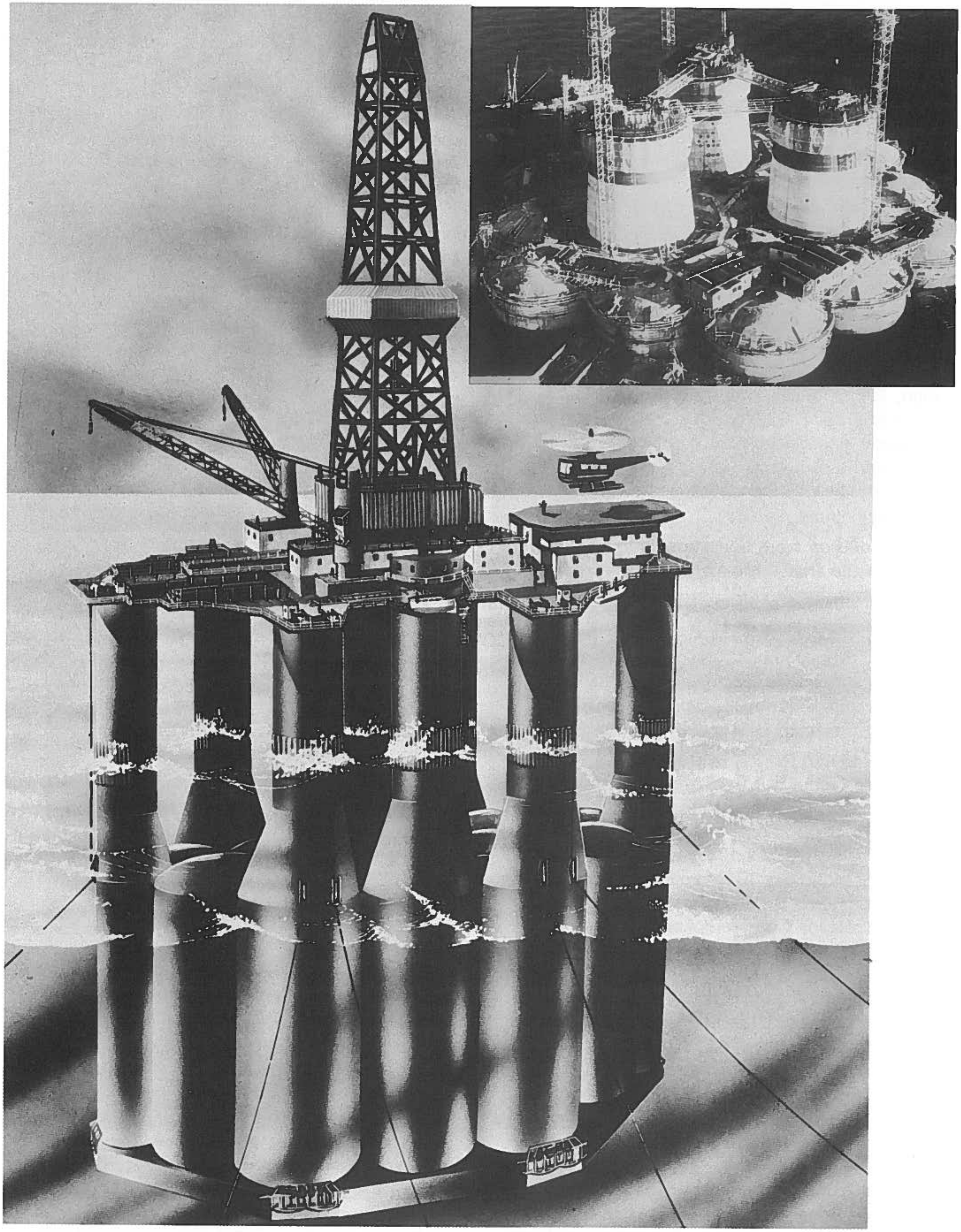

Condeep shafts rise above prestressed concrete domes which constitute the roof of the caisson storage cells (upper right). Proposed floating concrete caisson Condrill (lower left) for drilling for oil/gas in very deep water.

VI. TECHNICAL GUIDES TO PROPER DESIGN AND CONSTRUCTION PRACTICE

A. Design Criteria

Basic design criteria for determination of loads and forces are set forth in the FIP Recommended Practice for Design and Construction of Concrete Sea Structures, 2nd edition, 1974. [1]

A companion document, Recommended Practice for Design and Construction of Concrete Ships, is currently under preparation by FIP. In the interim, Ref [2] below, may be utilized as a guide.

Det Norske Veritas has published "Rules for Design, Construction and Inspection of Offshore Structures," 1974, [3], which closely parallels the FIP Recommendations, but contains useful additional quantitative requirements.

Additional loading conditions now under consideration include:

1) Collision from boats known to be working in the area — (no major damage criterion).
2) Accidental collision from large vessels — (non-catastrophic damage criterion).
3) "Dropped object" — a large piece of equipment is accidentally dropped on the structure during operations.

For seismic zones, the basic loadings for design are presented in reference [4].

For ice loadings in the Arctic and sub-Arctic regions, the types of loads are presented in reference [7]. More up-to-date quantitative information has been published in subsequent preprints of the Offshore Technology Conference and has been further developed by proprietary research of the Arctic Petroleum Operators Association, Calgary, scheduled for public release within the next year or so.

For determining the capacity of reinforced and prestressed concrete to resist these "sea" loadings, the ACI Building Code — ACI 318-71, with supplements to date, (ref. [5]), may be utilized. In other regions of the world, applicable national codes may be utilized for most considerations, but the ACI Building Code is considered preferable for shear design.

Special consideration has to be given to concrete that is under water, subject to high hydrostatic loading, and saturation. Saturation reduces strength and alters the volume-change properties.

Shear for underwater concrete must be given special consideration at construction joints and in regions which also experience high moment. (See Section VI-D.).

Implosion resistance (buckling or lamination type failure) under high hydrostatic loads is discussed in Section VI-D.

Structural regions subject to cyclic and dynamic loads require special consideration of fatigue in the submerged condition (See Section VI-E.).

Impact resistance, both in the minimal damage and ultimate, post-cracking condition, requires special consideration (See Section VI-F.).

For the steel portions of sea structures, for example, hybrid steel and concrete structures, the latest edition of API-RP2A, ref. [6], and applicable provisions of the DNV Rules, ref. [3], should be used.

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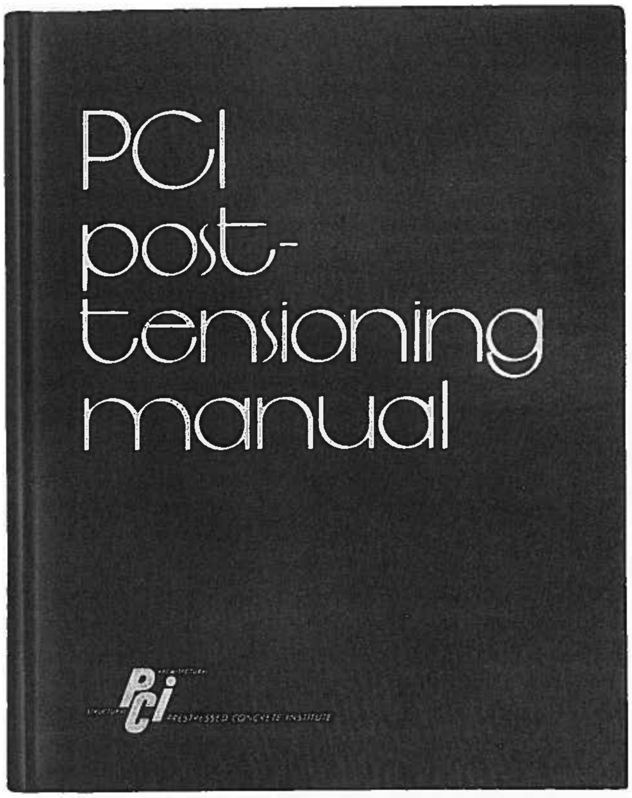

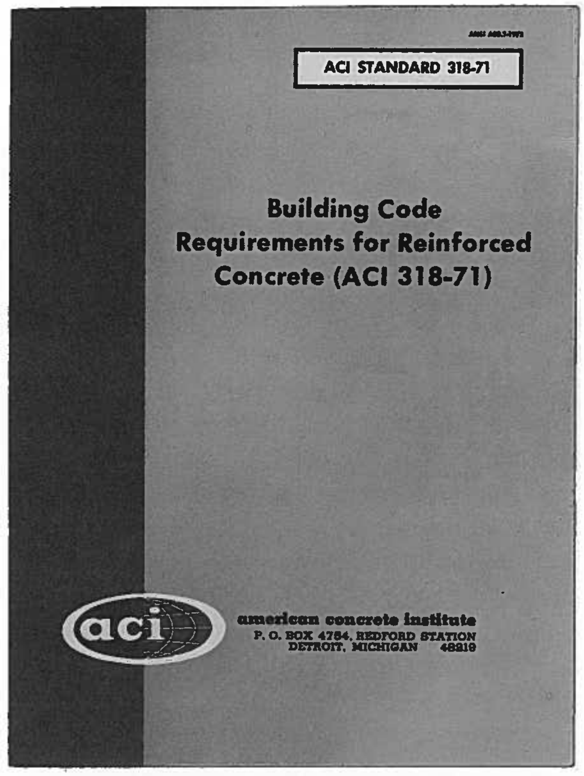

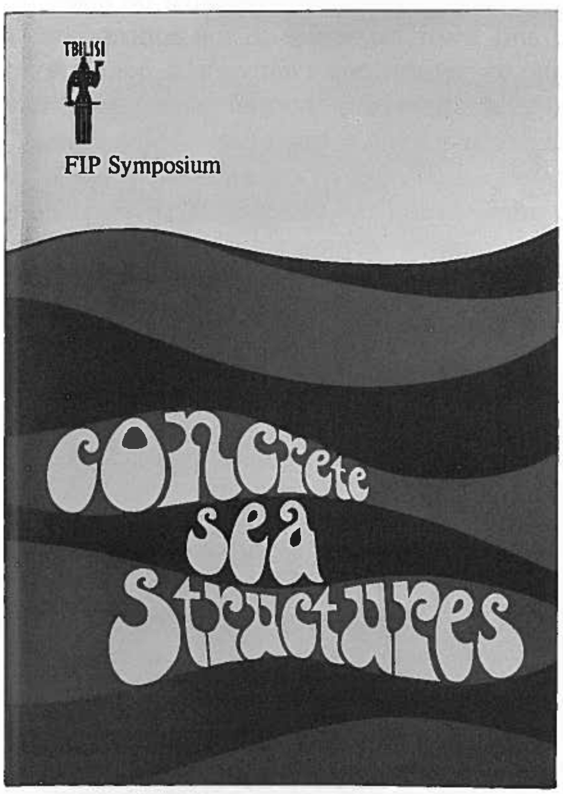

Extensive references and specifications have been published which are directly applicable to design and construction of prestressed concrete ocean structures and ships.

B. Concrete Materials, Mixes, Transport, and Placement

The principal properties desired in concrete for sea structures are high compressive and tensile strength, light unit weight (if possible), impermeability, abrasion resistance, and durability.

Conventional sand - and - gravel or sand-and-crushed rock concrete can be produced in most areas of the world to give strengths of 6000 psi for cast-in-place concrete and 7500 to 8000 psi for precast concrete (ref. [1]). Use of high cement factors, very low water-cement ratios, thorough compaction and good curing are required. The recommendations of the ACI Manual of Concrete Practice ref. [2] should be followed.

The new "super" water-reducing agents, recently made available to the concrete industry, permit significant reductions in water-cement ratios while giving adequate workability for placement.

Pozzolans may be substituted for a portion of the Portland Cement. These reduce the heat of hydration and enhance the durability. Tests must be carried out to verify the compatability of specific pozzolans with specific cements, and to ensure that adequate early strength can be developed for the construction stages.

Conveyance of concrete for sea structures must be given special study to ensure against adverse temperature changes, loss of workability, and segregation. Long-distance transport by pumping is particularly difficult to control.

Placement may also present difficulties due to the congestion of reinforcing bars and prestressing ducts on multiple axes. Small coarse aggregate, a slightly over-sanded mix, high cement factor, and use of retarding admixtures are all frequently required, along with closely-spaced access in the forms for placement and vibration.

Ferrocement techniques are applicable to small structures, e.g., boats up to 65 feet or so in length. The principle advantage of ferrocement is its high apparent tensile strength, and its ability to accept large deformations with well-distributed micro-cracks. This technique uses closely-spaced layers of wire mesh, with fine aggregate concrete applied by hand trowelling or by shotcreting. Ferrocement is often limited in application by the cross-plane shear resistance, but the technique has interesting potential for use in special doubly-curved zones of concrete sea structures and ships, where it may be employed compositely with the principal concrete structure.

Other fibers used to give greater tensile strength and ultimate strain are alkali-resistant glass and some of the organic fibers (e.g., nylon, polypropylene, etc.)

Polymer-impregnation of concrete (ref. [4]) presents the potential advantage of extremely high strength combined with impermeability and high abrasion resistance. Practical methods of achieving polymer-impregnation are being developed for concrete bridge decks and will presumably be applicable to sea structures and ships.

A related development, polymer-concrete, using inert rock flour as filler and polymer as the sole cementing agent, also offers attractive potential but its long-term performance must be substantiated.

Structural lightweight concrete (ref. [5]) is very attractive for many concrete sea structures, especially where low weight is required and the minimum thicknesses are determined by practical considerations of cover and placement of steel and ducts. Special consideration must be given to tensile and shear capacities in the appropriate conditions of saturation. Lightweight concrete makes available improved, thermal insulating properties (see Section VI-G.). Use of small size coarse aggregate and high cement contents, with water reducing admixtures, can produce lightweight concrete with strengths comparable to those of normal weight concrete.

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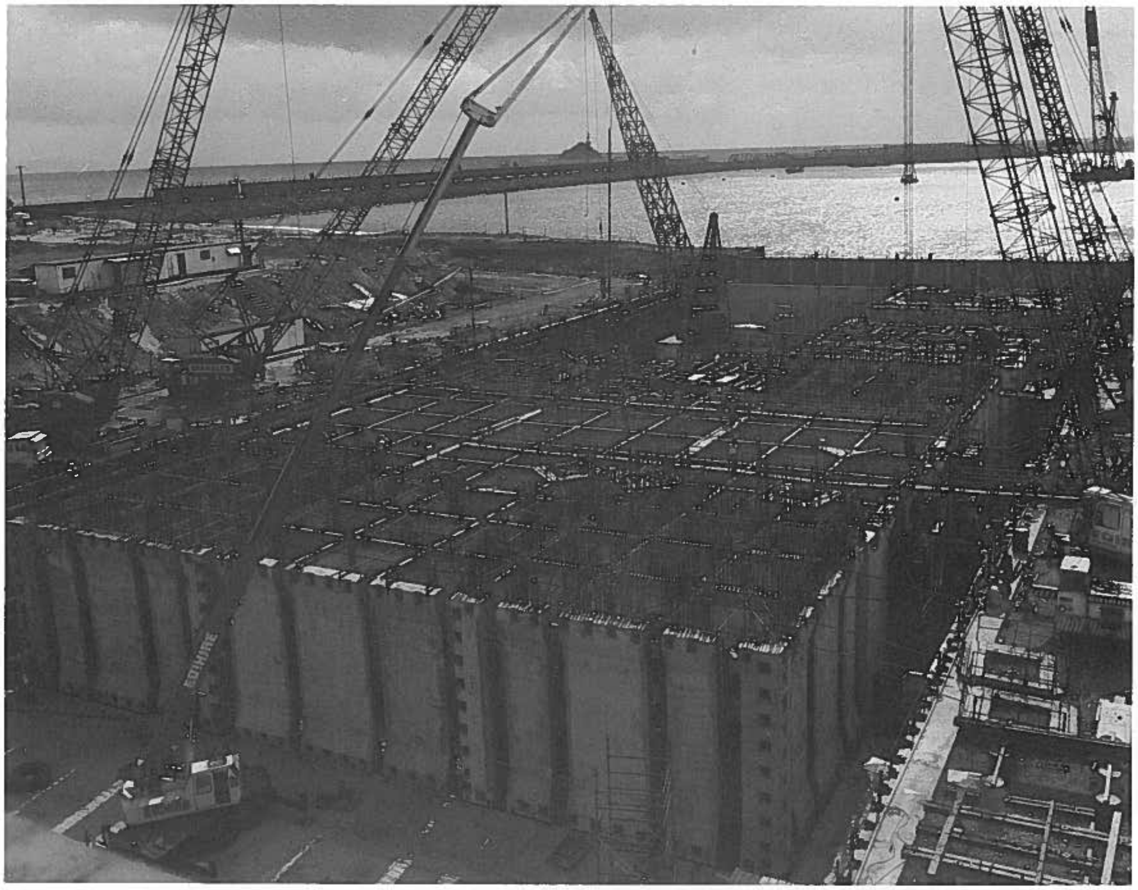
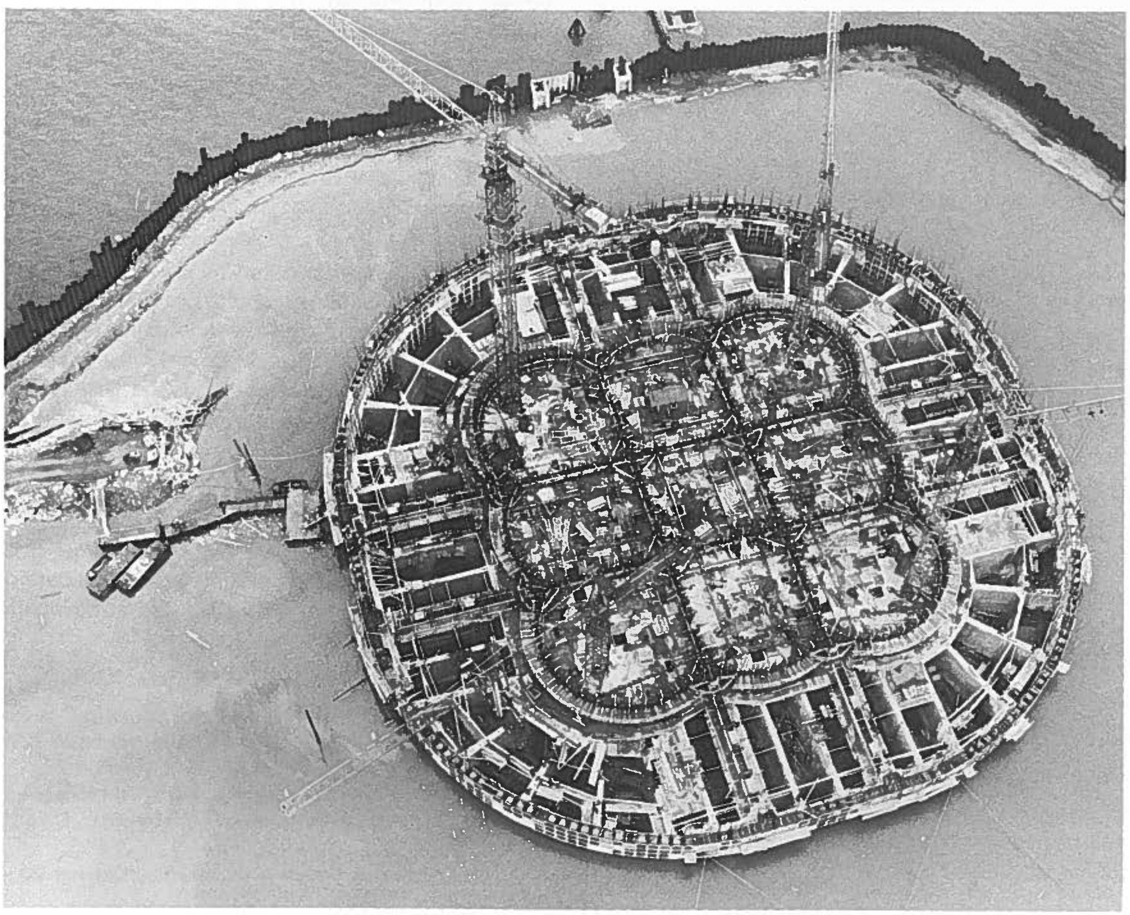
4. Polymers in Concrete, American Concrete Institute Publication SP-40, American Concrete Institute, Detroit, 1973.
5. "Lightweight Concrete," American Concrete Institute Publication SP-29, American Concrete Institute, Detroit, 1971.

Construction of prestressed concrete terminal caissons in graving dock, Queensland, Australia. Precast concrete elements are joined by cast-in-place joints and post-tensioning.





Ekofisk caisson base raft, ready for tow out of construction basin for completion afloat.

C. Durability and Corrosion Resistance

The sea is a notoriously adverse environment for all materials. Fortunately, well-designed and constructed concrete can be among the most durable and maintenance-free of all structural materials.

Durability must be viewed in its actual context of steel encased in concrete. Concrete provides a high pH adjacent to the steel and seals off the surface from rapid replenishment of oxygen.

Corrosion of steel depends primarily on three factors: water, to act as an electrolyte; chlorides, to lower the pH; and oxygen, or more specifically, an oxygen gradient.

The concrete itself is subjected to sea water attack in which the calcium aluminate hydrates are replaced by magnesium hydroxide and calcium sulfate in a complex reaction.

Three major zones are identified for attention on typical sea structures: the splash and atmospheric zone (which, it is believed, should be treated as one zone); the submerged zone, and the sea floor zone. This last, usually ignored, may be especially sensitive because of the oxygen gradient.

A few simple but highly important rules will ensure long-term durability of prestressed concrete in the sea.

1) Cement should have C3A (tri-calcium aluminate) content between 4% and 8%.

2) Water-cement ratio should be below 0.45 and preferably below 0.42.

3) Cement factor should be at least 620 lbs per cu. yd. (370 Kg/m^3).

4) Cement should have restrictions on alkali content, similar to ASTM Type II.

5) Aggregates should be sound, as shown by sodium-sulfate soundness test and actual experience in coastal or harbor structures. They should be non-alkali-reactive. Aggregates should be selected for hardness and abrasion resistance.

6) Cover of concrete over steel should normally meeting the following:

   a) Thick-walled structures (over 30 cm):

      Passive reinforcement (conventional) and pre-tensioned steel

      Submerged Zone (50 mm)

      Splash and atmospheric zones (62.5 mm)

      Post-tensioning ducts (75 mm)

   b) For thin-walled structures (30 cm and less):

      Passive reinforcement and pretensioned steel; 2.0 times the normal maximum size of coarse aggregate, plus the allowed tolerance in cover, or

      2.0 times the nominal diameter of reinforcement, plus the allowed tolerance in cover, whichever is greater.

      Post-tensioning ducts: add 12.5 mm to above values.

   Where thinner covers are required, protective coatings should be applied.

   The exact amount of cover required depends on impermeability of cover, tolerance of steel placement, and number of surface defects (blow holes, bug holes, etc.).

7) Chlorides shall be strictly limited in the mixing water and on the aggregates, with special attention paid to the fine aggregates from desert and beach deposits.

8) Within the splash zone, if it is subjected to freezing, air entrainment (4%–6%) should be employed.

9) Post-tensioning anchorages should be recessed, painted with epoxy and encased in epoxy mortar, or in concrete which is tied into the structure and sealed against leakage.

10) Post-tensioning ducts should be ferrous metal and they may be galvanized. The ducts should be watertight and not less than 0.6 mm thick in the submerged zone, 1.00 mm in the splash zone. Tendons and ducts should be protected from salt deposits and from corrosion during storage and installation, until grouted. VPI powder and Water Soluble oils may be used. The tendons should be grouted with cement grout. Particular attention must be paid to complete filling of vertical ducts, since accumulation of bleed water may occur at the top. Stage grouting and use of thixotropic admixtures are viable solutions.

11) Construction joints should be prepared by sand-blasting or water jet to remove laitance and to roughen the joint to a depth of 6 mm. A bonding coat of epoxy should be applied at the start of the next pour. Alternatively, the succeeding pour may be commenced with an enriched mix, for example, the coarse aggregate omitted from the first 15 cm. The exterior faces of the joint should preferably be coated with epoxy sealant.

12) Thorough curing, as by water, over several days, may significantly enhance the impermeability and the ultimate durability.

13) Coatings of epoxy or polyurethane may be beneficially applied in the splash zone and atmospheric zone to reduce permeability.

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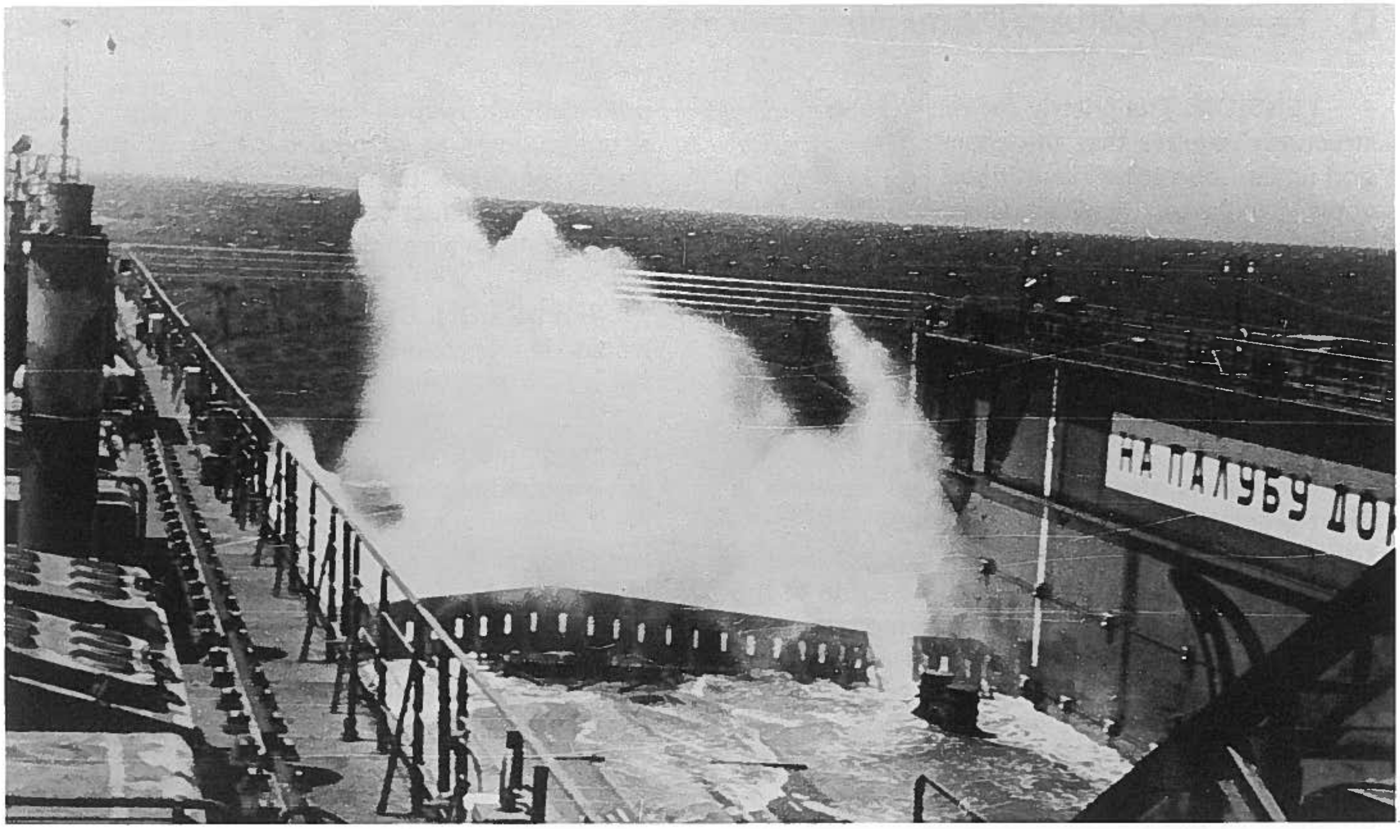
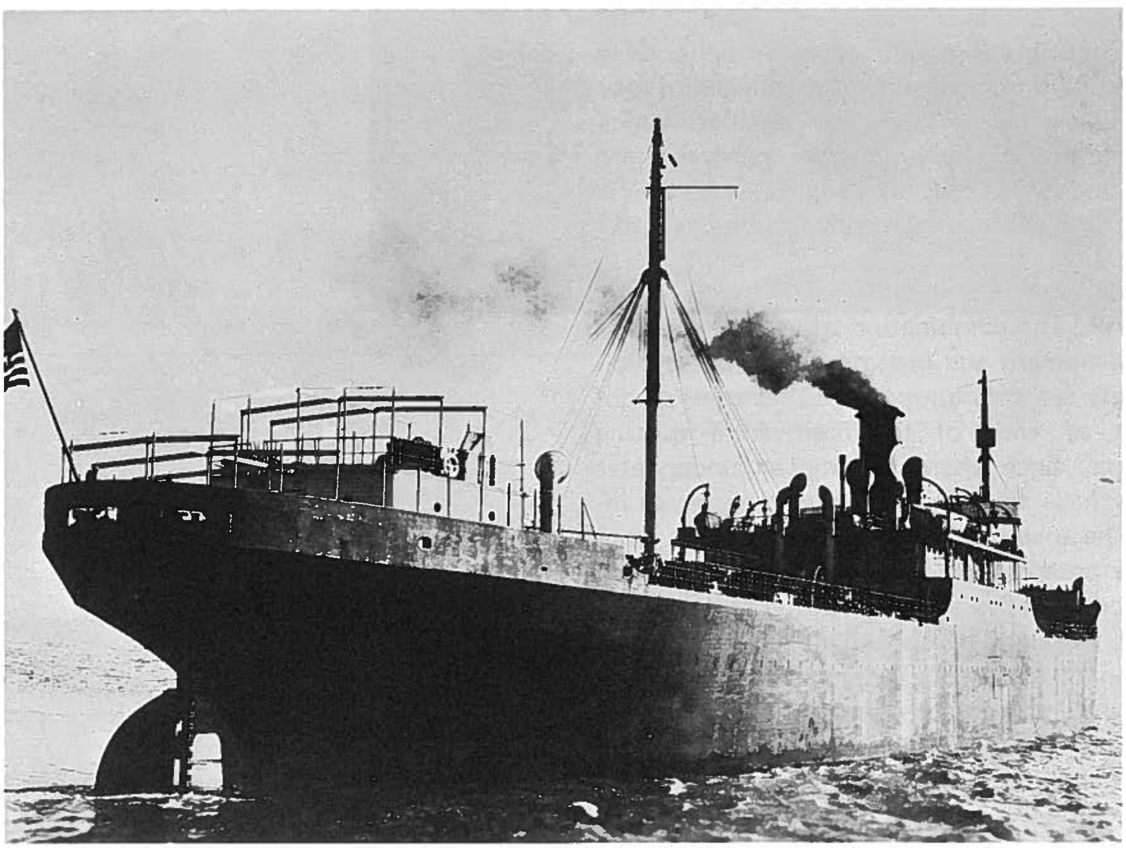


Floating drydock of prestressed concrete enroute across the Black Sea in storm.



This 7500 ton vessel (U.S.S. Selma) of expanded shale lightweight concrete is still sound after 54 years of exposure to the sea. Vessel is grounded on the beach at Galveston, Texas.

D. Tension, Shear, and Implosion

TENSION. The criteria for many concrete sea structures requires that the concrete have no tension under "operating" conditions, and no cracking under "extreme" environmental conditions. In some cases, these requirements control the design, being a more severe limitation than the compressive strength, despite the use of prestressing.

In any event, for sea structures, it is suggested that a flexural tensile strength requirement be placed on the concrete as well as the more usual compressive strength requirements.

The tensile strength of saturated concrete is slightly greater than for dry concrete. The tensile strength of dry structural lightweight concrete is lower than that for normal weight concrete of the same compressive strength but when moist or saturated, is approximately the same. These phenomena are both related to the favorable effect of absorption in reversing drying shrinkage and microcracking at the aggregate/paste interface.

The flexural tensile strength of concrete may be enhanced by proper selection of aggregates with particular consideration of their surface characteristics, by low water-cement ratios, and by thorough and extended curing. There is an indication that concrete subjected to compression during its early curing stages (as in pretensioned construction) may develop higher tensile strengths. Members which have exceptionally heavy passive reinforcement may develop reduce tensile strength due to the restraint of the bars, leading to early micro-crack formation.

SHEAR. The combination of very heavy shear with high moment and high normal forces is typical of many sea structures. It requires careful consideration of each of the basic shear-resisting mechanisms, since after cracking, an underwater zone may have significantly reduced aggregate interlock. The shear capacity of a compression zone loaded in compression to values approaching the ultimate compressive strength will be reduced, not enhanced, as might be concluded from the direct application of some code formulae. The establishment of the location for computation of shear at an arbitrary distance away from the support, as given in many building codes, is not necessarily applicable under conditions of high hydrostatic loads.

Particular care has to be given to the shear at construction joints, since for many sea structures, practical construction considerations require a construction joint at or near the zone of maximum shear. The "shear-friction" approach appears applicable, with a reduction in the friction factor due to the saturated environment.

IMPLOSION. Cylinders, domes, and shells subjected to high hydrostatic loads may fail in buckling or by in-plane lamination. This is a complex multi-axial stress condition, affected by the strength, modulus of elasticity, reinforcement, out-of-roundness and thickness tolerances. A rational approach to computation of implosion strength is given by ref. [2]. Recent tests indicate that the capacities computed according to this reference may be slightly conservative. On the other hand, the influence of out-of-roundness effects on implosion strength may be somewhat greater. Since implosion can be catastrophic, a conservative and thorough evaluation is warranted.

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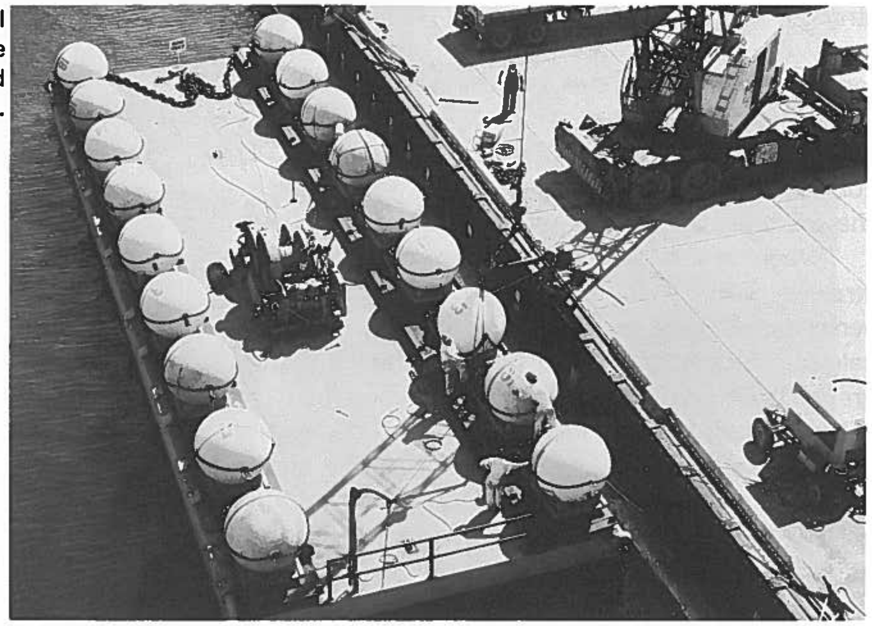
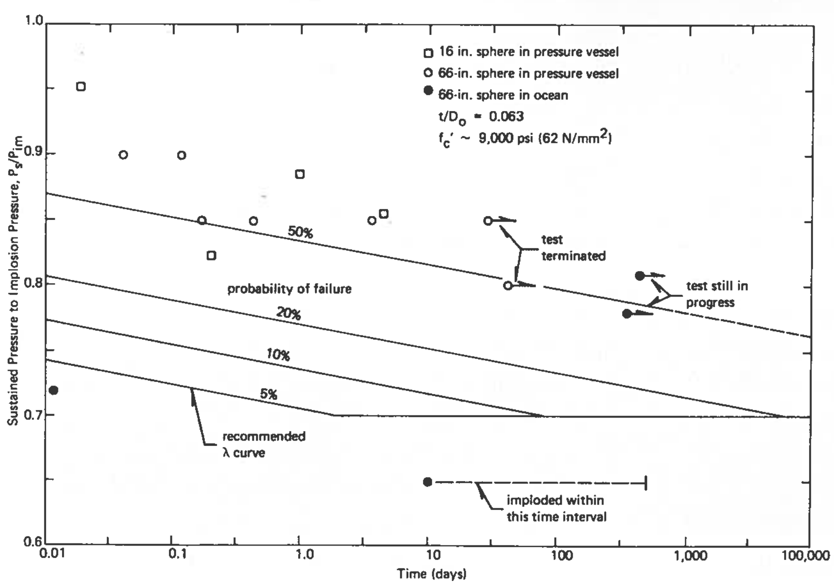
NCEL test habitat, submerged for six months at 600 feet.

56" diameter thin-wall concrete spheres which have been subsequently installed at sea in depths to 3000 feet.





Relation of implosion strength to duration of submergence.

E. Fatigue

A typical concrete sea structure or ship may see 1.7 x 10^8 waves in its lifetime, of which less than 10% (or about 10^7) may create significant changes in stress. The highly corrosive environment in the splash zone, and full saturation below sea level, both affect fatigue life.

As long as the concrete does not crack, then the range of steel stress, both reinforced and prestressed, can be shown to be well within the endurance limit, with full consideration for the environmental conditions (ref. [3]).

Concrete, itself, shows an endurance limit of about 60% in compression: in fact, cyclic loading below this level will actually enhance the fatigue strength of the concrete, especially when the concrete experiences "rest periods" between high ranges of cyclic loading, and when the applied stresses are variable.

Hence, for the design wave, an upper limit of concrete stress of 60% f'_c and a lower limit equal to the modulus of rupture, will insure against fatigue.

Where the concrete can crack, as in non-prestressed sections, then the water may have an adverse wedging action, and corrosive actions can accelerate steel fatigue. Even so, where crack widths are kept below 0.1 mm (at the reinforcement), a fully satisfactory endurance life of 10^7 cycles and more is believed to be available. Flexible epoxy coatings on the surface of the concrete may be used to provide additional protection to reinforcement in this corrosive environment.

Where cracking is permitted, a careful analysis must be made of the cumulative fatigue properties, based on Miner's hypothesis, and considering both minimum and maximum stress levels.

Anchorages for post-tensioning tendons require special consideration and must be proven by acceptance tests (ref. [1]). Grouting of ducts, which transfers stress reversals by bond, minimizes the effects of load cycling on the anchorages.

Zones subject to cyclic loading in both high shear and moment, such as the base of towers and shafts, should be confined by transverse reinforcement, such as spirals or well anchored stirrups, just as is required for seismic-resistant structures. In addition, longitudinal mild steel should be of adequate percentage to insure ductility.

All reinforcement, both stressed and unstressed, which is subject to high cyclic loading, should be well anchored: a rule of thumb being twice the anchorage length normally used for static loads, since loss of bond is one of the early manifestations of fatigue in concrete structures.

Properly designed and constructed, prestressed concrete can be said to have excellent properties of fatigue resistance.

REFERENCES

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2. "Hardened Concrete, Physical and Mechanical Properties," Chapter 9 (Fatigue Strength), American Concrete Institute Monograph, No. 6, Detroit.
3. Leonhardt, F., "Prestressed Concrete," Wilhelm Ernst and Sohn, Berlin, 1964, pp. 40, 41; 197-202; 515-517.
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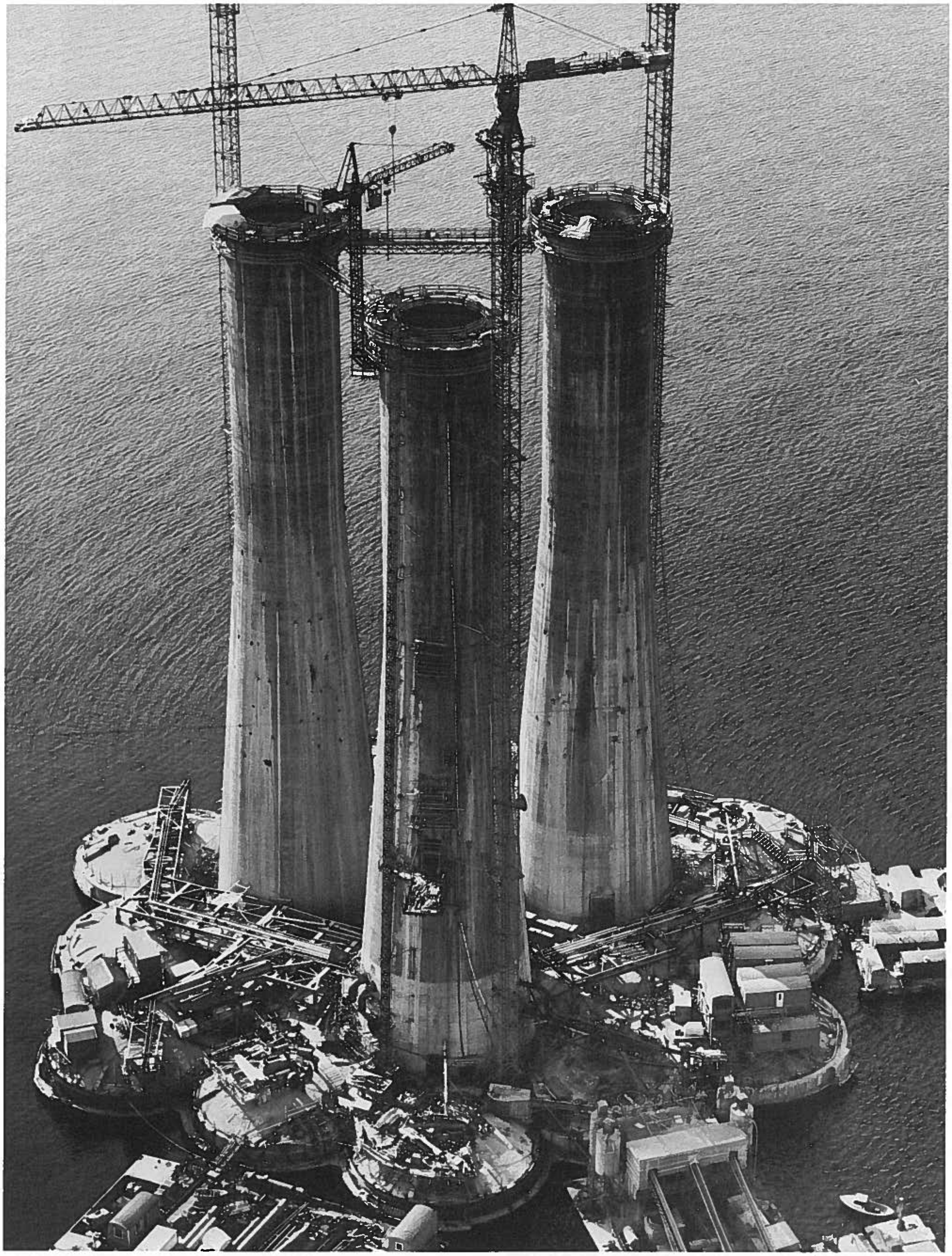

The cyclic dynamic loading of storm waves on towers such as these of Condeep, requires design to prevent fatigue.

F. Impact and Collision

A fixed sea structure is subject to occasional impact from the work vessels and supply boats, etc., working to support operations. Similarly, a concrete vessel or ship is subject to impact from docking. For these types of "service" impacts, no structural damage should ensue. The structure should be designed to resist these impacts within the elastic range. Local abrasion and spalling can be prevented by use of special coatings, rubbing strips, or fenders.

Typically, criteria are established for the size of vessel, speed of impact, and amount of energy assumed to be absorbed by the impacting boat in rotation and deformation. The structure is then designed to resist this impact within the maximum and minimum possible water levels, by use of both prestressed and mild steel. Transverse reinforcement such as stirrups may be found necessary to resist the local shears, and in-plane prestressing may be useful in resisting both shear and impact.

A second type of impact is that of the accidental kind, which has a very low degree of probability. Here the size and impact velocities may be significantly greater. For such an accident, the structure may be allowed to sustain damage as long as it is non-catastrophic, doesn't lead to progressive collapse, and is repairable. This type of impact may be best resisted by closely-spaced grids or mesh of reinforcement and by confinement with stirrups.

The structure or vessel as a whole must have damage-arresting reinforcement and sufficient redundancy to maintain structural integrity after such a severe collision.

For floating structures, stability in the damaged condition must be verified.

A third type of impact is that from a "dropped object," for example, oil-well casing or a pump dropped during transfer from a supply boat to the platform. Such objects hit with relatively high velocity despite the drag of the water, and can cause holing.

The resistance of well-reinforced concrete to impact was shown in the grounding on a breakwater and accidental collision of the thin-shelled prestressed concrete barges in the Phillipines, by the ability of one of these same barges to withstand a mine explosion during the Viet-Nam War with holing but readily repairable damage, and by the recent tests of the Sandia Corporation for the U.S. Atomic Energy Commission for missile-hazard impacts against the walls of nuclear reactor containment and pressure vessels. The LNG Storage Tank on Staten Island, of prestressed concrete, has been designed to take the impact of a 747 engine falling at 200 mph.

Well-reinforced and prestressed concrete does not experience catastrophic ripping, but rather a well-dispersed pattern of multiple cracking. The impact energy is absorbed by the following mechanisms:

1) Aggregate interlock and shear friction across multiple small cracks.
2) Deformation (both elastic and plastic) in the concrete and steel.
3) Dowel action of steel across cracks.
4) Tensile strain of the steel.
5) Crushing of the concrete.

Experience from prestressed concrete piling under multiple hammer blows shows the effectiveness of prestressing to resist impact when well confined by spirals. The experience with the foundation for a large forge hammer is also instructive. The International Nickel Company, in their West Virginia plant, has utilized a tri-axially prestressed concrete base which has resisted 100 g acceleration for over 3×10^8 cycles, taking the blows of an 8-ton forging hammer. It is questionable whether any other material could take such impacts.

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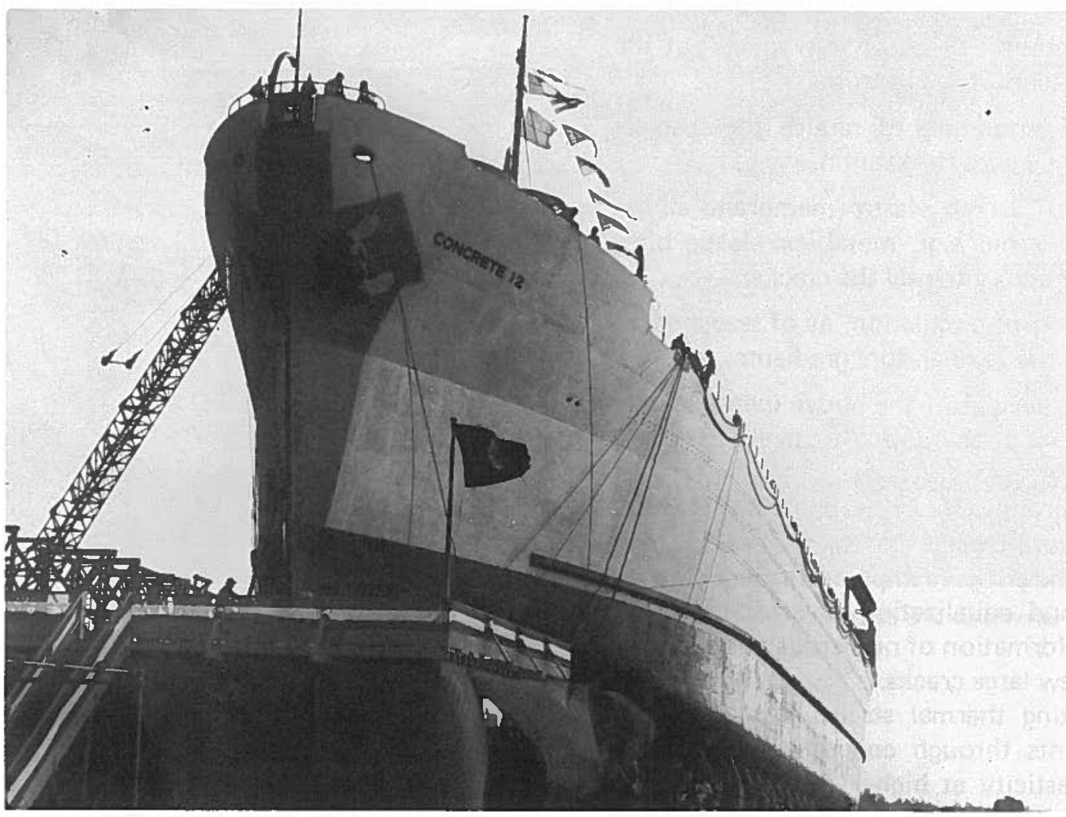
1. Proceedings of Symposium on the Application of Prestressed Concrete to Machinery Structures. Federation Internationale de la Precontrainte, January, 1964.

Prestressed concrete fuel barges and cargo barges used for 10 years in the Philippines have successfully survived groundings on breakwaters and collisions.



One of 104 lightweight concrete ships built during World War II

G. Thermal Strains

Concrete structures subjected to in-service or accidental temperature changes will experience strains across the section and global or overall expansion-contraction.

Thermal differences across a section impose a curvature: where this is restrained by the structural configuration, as at the intersection of a roof and a wall, bending occurs and tensile strains develop. These may be beyond the tensile strain capacity of the concrete and cause cracks to form.

Thermal strains of this kind are thus self-limiting: the cracks reduce the stiffness (ref. [1]) of the joint, and rotation takes place, alleviating the strain.

Practical solutions to this kind of thermal strain problems are:

a) Provision of well-distributed passive reinforcement in the critical zones to limit the size of cracks.

b) Prestressing to offset these strains (as carried out in nuclear reactor pressure vessels).

c) Adoption of an overall configuration that distributes strains more uniformly by eliminating concentrated restraints.

d) A purposeful hinge or thin section at the corner, permitting rotation.

e) Use of insulation to reduce the thermal gradient across the section.

f) Provision of an elastic membrane at the critical zone; e.g., metal, or elastic bitumen or epoxy to seal the cracks.

g) Provision of circulation, as of seawater, to reduce the temperature gradients.

In practice, several of the above methods may be used in conjunction more effectively than one alone.

Concrete structures can be benefited by slow initial temperature change and by several cycles of change below the critical temperature. This permits readjustment and equalization of strains through creep and the formation of numerous micro-cracks rather than a few large cracks.

In calculating thermal strains, the non-linear thermal gradients through concrete, the reduced modulus of elasticity at higher temperatures, and the increased creep rate at higher temperature should be considered: in many cases they will be favorable.

For the global or overall expansion or contraction, thermal stresses (strains) may be offset by prestressing. Configurations may be selected which allow expansion and contraction with minimum restraint. Frequently, the mechanical systems for filling and removal can be scheduled so as to minimize the effects, e.g., filling a number of compartments simultaneously rather than one at a time.

The effects of a sudden impingment of liquefied gas on concrete are discussed in Section VI-K.

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1. Behavior of Concrete Under Temperature Extremes, American Concrete Institute Publication SP-39, Detroit, 1973.

Oil storage tanks such as Ekofisk must accomodate the thermal strains of hot oil inside and cold water outside.

H. Abrasion and Marine Fouling

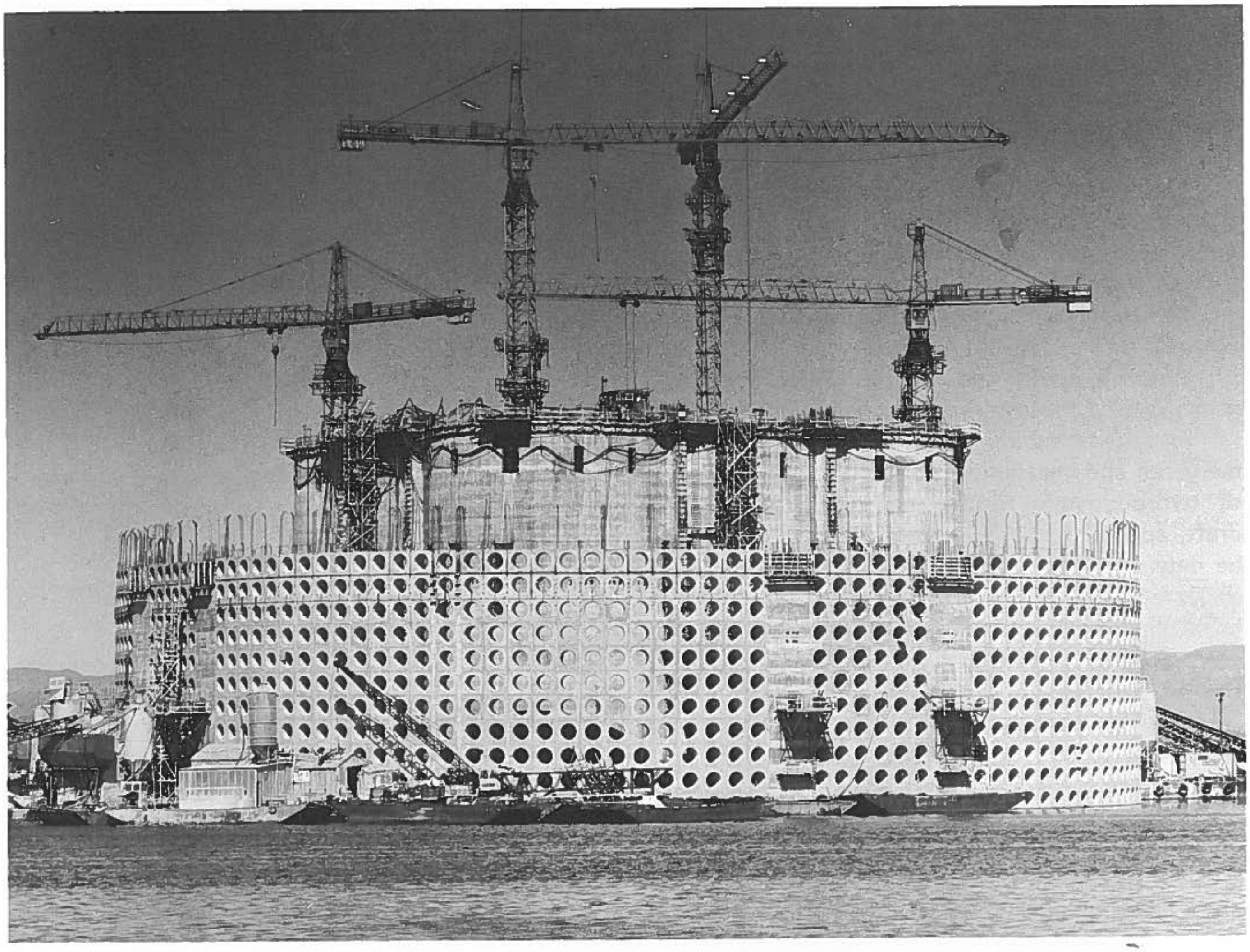
Sea structures are subject to abrasion, from moving water carrying sand, or silt, rolling gravel on a stream bed, and from ice. Concrete is essentially highly abrasion resistant, but this may be enhanced by selection of hard, abrasion-resistant aggregates, and dense mixes of low water cement ratio.

Structural lightweight concrete is subject to "plucking" of coarse aggregate particles from the surface. This may be minimized by thorough curing (to increase the bond between paste and aggregate); and provision of wire mesh or closely-spaced reinforcement near the surface.

Very high abrasion resistance may be obtained by polymer-impregnation of the concrete. Another approach is to use coatings or wear plates. Wear plates of mild steel, attached by embedded bolts have been much used in the past. The new dense polyurethane and dense epoxy coatings (applied without solvent) are apparently highly wear-resistant.

All structures in the sea are subject to fouling by marine organisms. Concrete with a compressive strength above about 3000 psi is apparently free from holing by rock-boring molluscs. Compared to steel, concrete in the sea experiences much reduced fouling from marine growth due to its alkalinity. Concrete blocks removed from the Los Angeles breakwater after 67 years of exposure still showed the form marks after the barnacles, etc., were removed, showing little corrosive attack by the secreted acids.

The dense polyurethane coatings referred to above are reported to greatly reduce the adherence of marine growth to the surface, enabling easy removal by underwater jet or brush.



Ekofisk caisson breakwater must withstand abrasion and cavitation of breaking waves. The multiple perforations are a concept developed by M. Jarlan to convert the static wave force with dynamic turbulence, and thus reduce the total forces on the structure.

I. Wave Forces, Hydrodynamic and Foundation Considerations

The design of sea structures for storm waves at sea requires specialized knowledge and techniques.

For large concrete structures, the single regular wave approach, with a deterministic height and period, will give a reasonably close approximation of forces. For a more accurate approach, especially for towers, columns, etc., a wave spectrum analysis should be employed. The dynamic amplification due to interaction of structure and waves should be included in the analysis.

For towers and cylinders of relatively low D/L ratio, Morrison's equation can be used, since the forces are determined by both drag and inertia.

The design of caissons and bases is largely governed by inertial forces. The forces acting on such structures are determined by diffraction analysis (ref. [1]).

The local forces of breaking waves may reach 20 to 30 tons per square meter.

Vortex shedding and ovalization effects should be considered for towers and shafts.

Structures during construction, towing, submergence and installation are subjected to a variety of hydrodynamic forces and effects. Stability, draft, applied forces and structural strength must be determined at every stage of construction. The stages of tow-out, construction afloat, progressive ballasting, submergence for deck mounting or other installations should be carefully analyzed. Use may be made of internal pressurization or lightweight "buoyancy" fluids to offset the extreme hydrostatic head. Other considerations include: towing, heeling, the dynamic forces from roll and pitch, "squat," the potential impact caused by a broken tow line, stability and dynamic effects of breaking waves during submergence, and possible "suck down" and sliding effects as the structure nears the sea floor. Usually the most critical stages for stability occur as the structure is submerged across abrupt reductions in the waterplane area, e.g., as the roof of an enlarged base passes below the sea surface.

On founding, the structure may experience concentrated forces under the base due to "hard points" which may be seafloor boulders, outcrops, or just high spots of dense sands. Penetration resistances and lateral forces during installation must also be considered. Finally, the lateral and overturning forces of the sea must be transmitted through the structure to the ocean floor: therefore, the base of the structure must be adequately reinforced. Uniform bearing is often provided by grout injection under the base, using special thixotropic grout mixes. In service, the structure must have adequate resistance to sliding and to overturning. Long term settlements must be within acceptable limits. Liquefaction of underlying sands and mud slump of soft clays under storm waves or earthquakes must be prevented. Scour protection must be provided.

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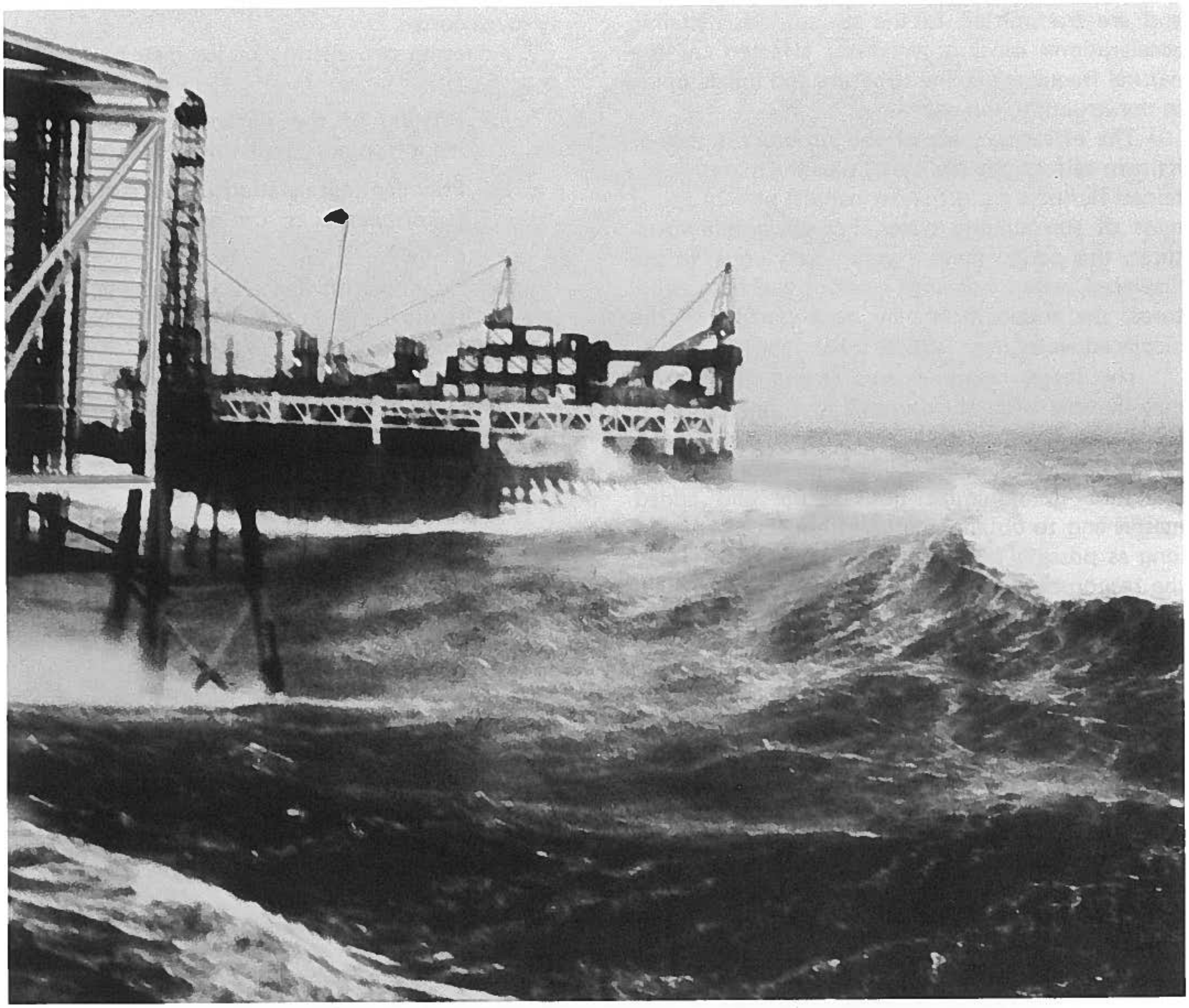

Photo taken by Det Norske Veritas surveyor Ragnar Sune during the storm in the Ekofish oil field North Sea from November 15th to 19th, 1973.

J. Seismic Behavior — Ice Behavior

SEISMIC. The performance of fixed concrete sea structures in seismic areas requires special consideration. Most important are the lateral, vertical, and torsional forces due to the seismic acceleration. These accelerations in the bed rock are attenuated and amplified in the overlying sediments, and are transmitted to the structure as dynamic accelerations causing responses affected by the natural frequency of the structure and the damping in the structure, soil and water.

The effective mass of the structure is that of its own self-weight (air mass) plus the mass of contained fluids (e.g., salt water ballast) plus an added mass of surrounding water. For tower-like structures, this added mass is very nearly equal to the displaced water. For large caissons and base structures, the added mass may be a portion of the displaced water (e.g., 25% to 50%).

The forces resulting from strong earthquakes may be very large, sometimes 2 to 4 times those of the design storm wave. The effect of earthquake forces may be reduced by careful design of the structure to minimize both actual and added masses and to obtain a natural frequency period as long as possible. The upper limit on this is set by the response to the large impulses: thus a median range of 3 to 6 seconds natural period may be found most satisfactory.

Another solution is to permit controlled decoupling during a strong earthquake when the forces exceed those due to the design storm. Floating and moored structures are, of course, automatically decoupled to an appreciable extent.

Other seismic phenomena to be considered are:

a) The tsunami waves, which increase the apparent hydrostatic pressure.

b) Acoustic overpressure shock wave, which may give a surcharge equal to the hydrostatic pressure.

c) Liquefaction or slumping of the supporting soils.

ICE. Ice forces occur in sub-Arctic and Arctic seas, and off the mouths of fresh-water rivers.

Moving ice exerts less over-all force than completely frozen ice sheets, but may give local impact.

Ice sheets moving against a vertical surface develop forces equal to the failure of the ice in compression, at a period of about 1 second. The mass of concrete structures is generally favorable in resisting the large forces developed.

Inclined faces, such as cones, may enable the ice to break in tension, which develops significantly lower forces.

Adhesion or collaring of ice may be reduced by:

a) Heating of the surface through embedment of pipes circulating hot water.

b) Polymer-impregnation of the surface with a full coating of the polymer on the surface.

c) Coating with dense polyurethane, as currently used on the new USCG icebreaker ships.

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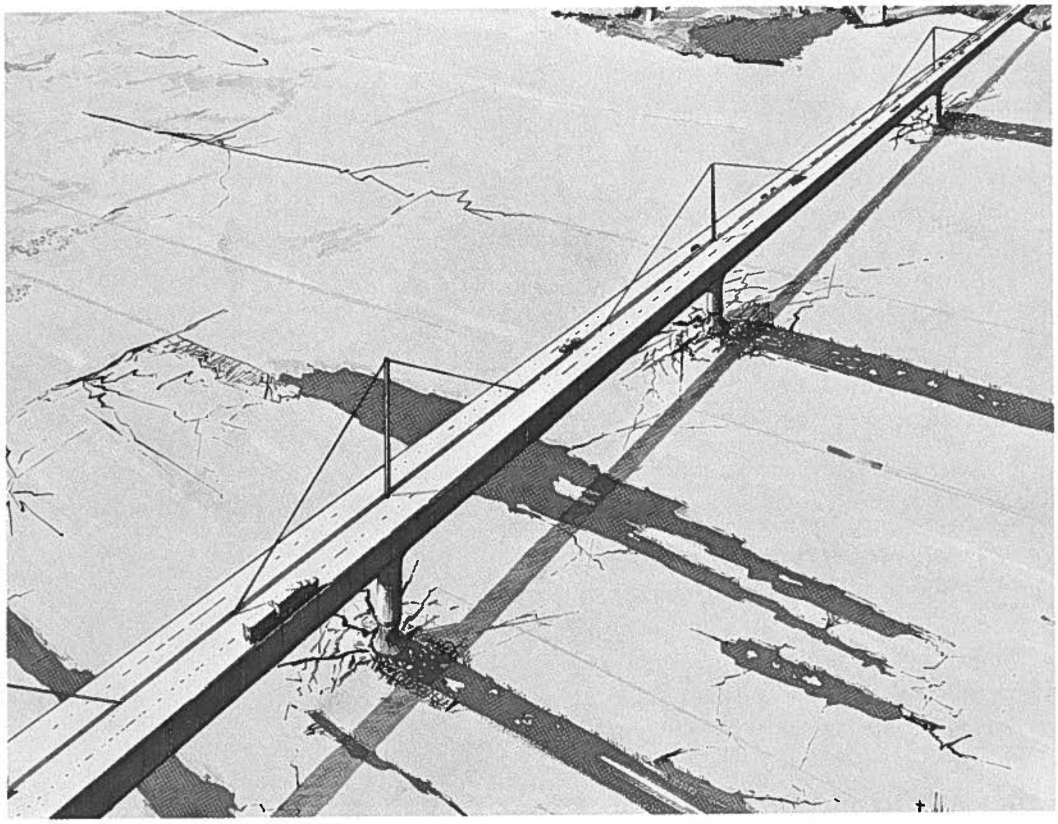
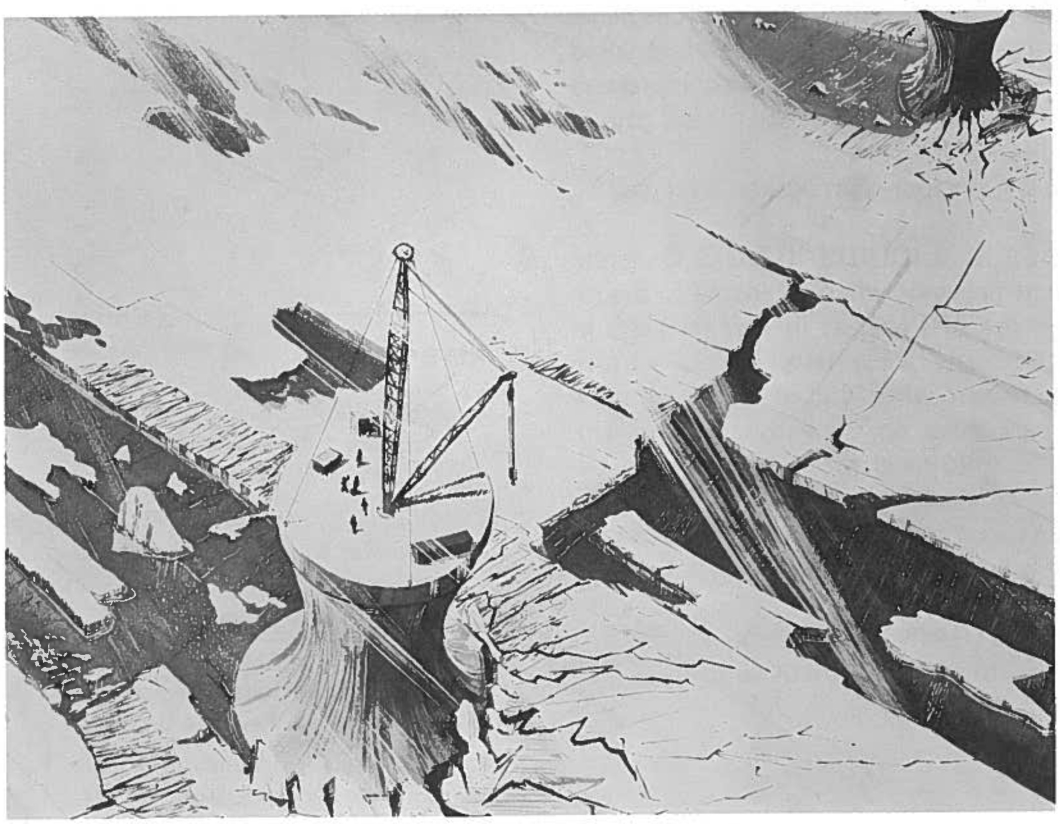


Bridge proposed by T.Y. Lin across Bering Straits, Alaska to Siberia.



Pier construction for bridge proposed by T.Y. Lin across Bering Straits depicted above.

K. Effect of Salt Water, Oil, and Cryogenic Liquids (LNG)

SALT WATER. Salt water affects concrete in a number of ways.

The saturation of concrete by salt water slightly reduces the effective concrete strength, eliminates drying shrinkage, and reduces creep.

The magnesium ions may replace calcium ions in the cement causing a loss of strength. The chloride ions reduce the passivation (pH) which the cement gives to the embedded steel. For a discussion of these two aspects, see Section VI-C. Durability.

OIL. Oil and petroleum products have little aggressive effect on concrete as long as they do not contain an excessive amount of acids, sulphides, or fatty oil substances. A general rule is that the saponification index should be less than 0.50 and the neutralization index should be below 0.25.

Unlined concrete structures can be satisfactorily used to store typical crude oils, diesel oil, etc. The effect of the alkalinity of the concrete on the product and its additives should be verified in the case of refined products.

If the concrete is not already saturated with water, oils will penetrate, with light fractions penetrating most deeply. Physically, concrete soaked with oil will suffer up to a 12% loss in compressive strength, but experiences a somewhat lesser gain in flexural tensile strength.

Concrete is not vapor-tight against light gas.

CRYOGENIC LIQUIDS (LNG). Concrete shows excellent behavior when subjected to the direct impingement of LNG, as in a spill. Tests in France and Germany show only minute surface spalling. Cold-drawn wires and strands and some prestressing bars show no transitional loss of impact resistance. Mild steel reinforcements are believed to give satisfactory performance under extreme cold temperatures, if well embedded in concrete, since it is not subject to transverse impact.

THERMAL STRAINS. The thermal strains due to prolonged exposure to hot oil or cold LNG, etc., are discussed in Section VI-G.

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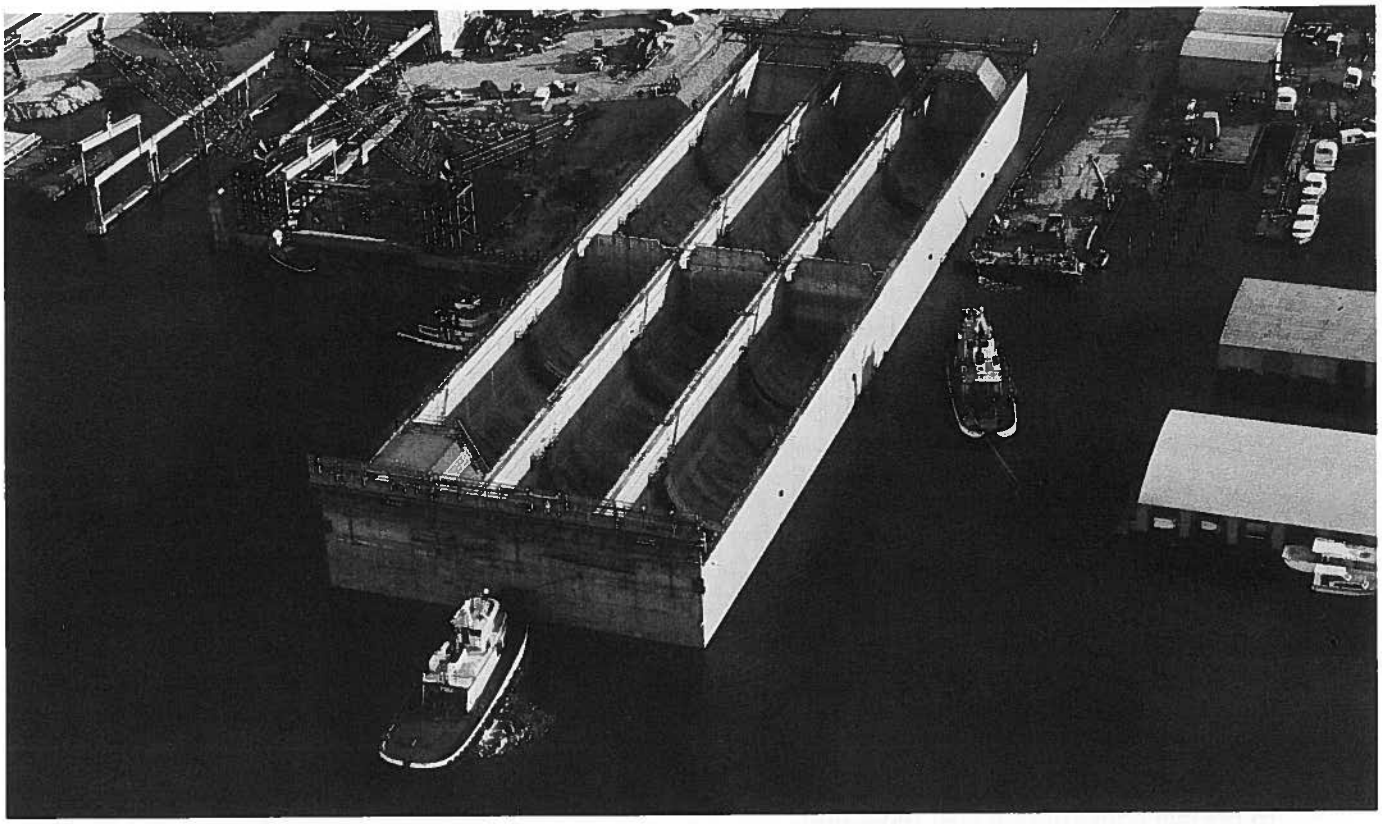
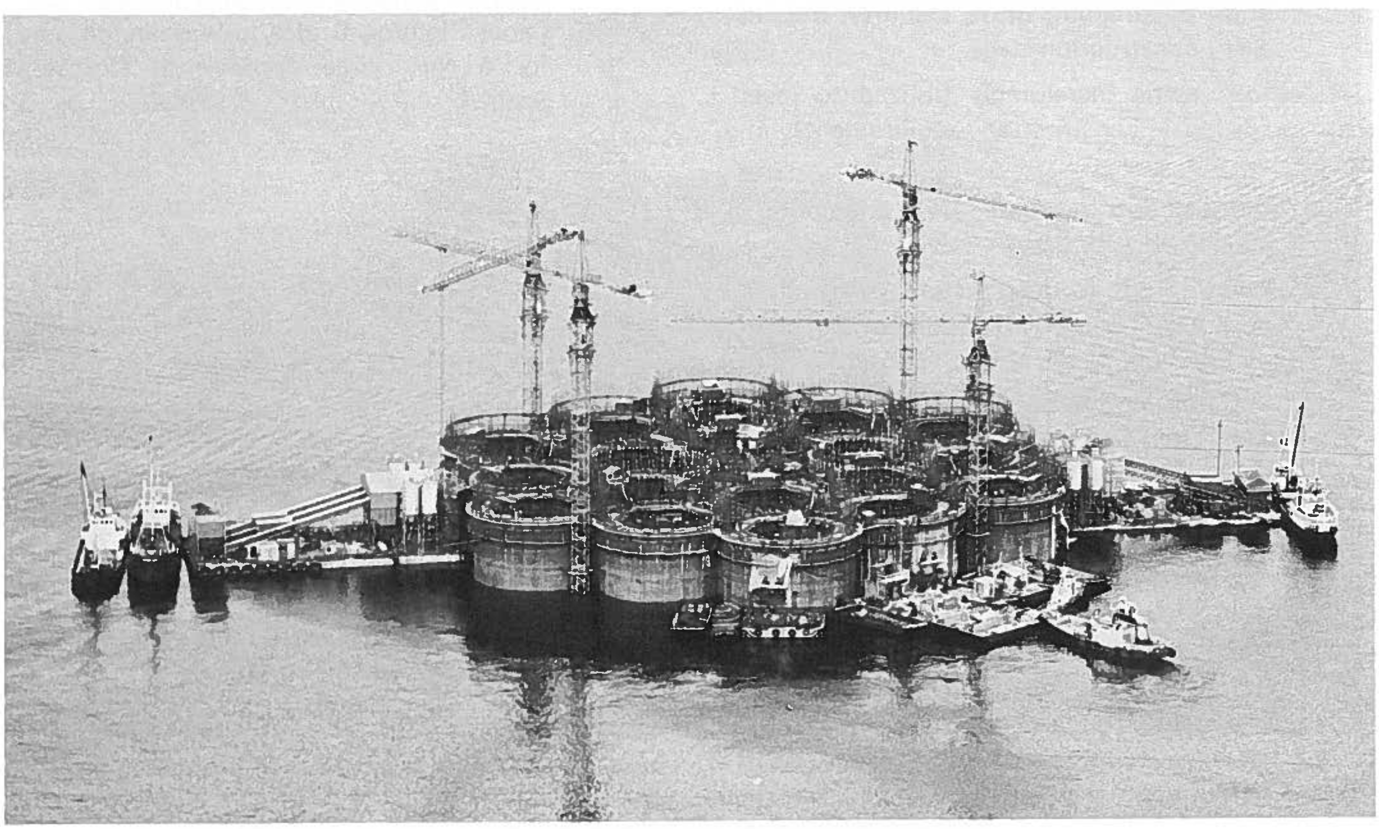


ARCO LPG terminal barge uses prestressed concrete as secondary barrier.



Condeep "Statfjord A" has storage capacity for 1,000,000 barrels of crude oil in concrete cells.

L. Construction Methods

Construction of concrete sea structures differs from that of conventional engineering construction in several ways.

a) The structures are usually very large and massive, yet must eventually be moved to the sea, that is, usually to a site other than that where they were constructed.

b) Weight control and dimension tolerance control is usually very important: excessive over-thickness may not be acceptable.

c) Quality control is extremely important to assure strength, durability, and impermeability. Particular care must be exercised at construction joints to keep them watertight.

d) The concentration of construction effort in a limited space may require emphasis on prefabrication and other methods of site labor reduction, over and above that due to normal construction cost reduction.

e) Critical parts of the construction must be performed afloat, requiring careful evaluation of strength, draft, stability, etc., at every construction stage.

Methods being increasingly utilized to meet these additional construction requirements include:

a) Construction of a base raft in a temporary graving dock or basin.

b) Floating out to deep water, using a temporary air cushion to reduce draft. Completion of the remaining structure afloat.

c) Slip-forming vertical walls, shafts, cells, etc., allowing the recently completed structure to submerged progressively and thus develop the necessary buoyancy to support the additional weight.

d) Prefabrication of relatively large segments of precast concrete, handled into position by large crane barges or stiff-legs. Jointing with epoxy coating of matched-cast sections as in long-span bridge construction, or by cast-in-place concrete, and by post-tensioning.

e) Composite construction, using the prefabricated elements of (d) as supports for cast-in-place concrete. Joining the two by bond or stirrups, etc., to ensure monolithic behavior.

Because of the cost of a large basin or graving dock, and the draft restrictions at launching, other methods are being utilized on special structures for the initial launching.

a) Construction on a large barge, then launching by sinking of the support barge in shallow water or under the control of buoyancy tanks.

b) Excavation of a basin without dewatering, backfilling with selected sand. Construction of the new structure, then lowering it through the sand by dredging, pumping, jetting and airlifting. This is the so-called "Sand-Jack" method.

c) Construction of the base in smaller sections, launching them individually, and connecting them afloat into a monolithic raft or vessel. Such a principle is used today to join supertanker hulls of steel. This method has been used successfully for prestressed concrete structures for the Hood Canal Floating Bridge in Washington, and for a very large drydock in Northern Spain.

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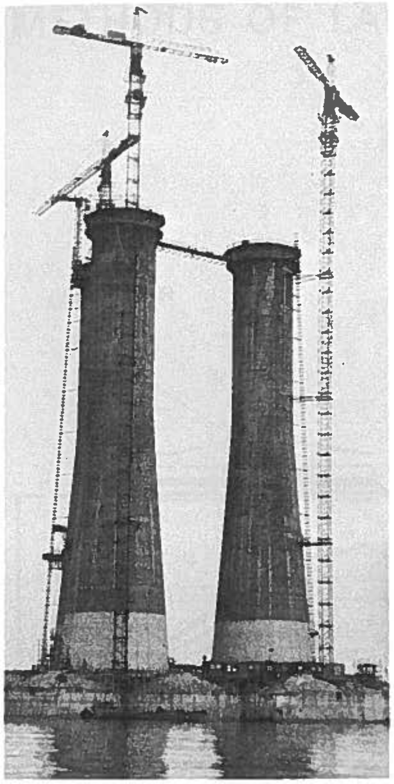
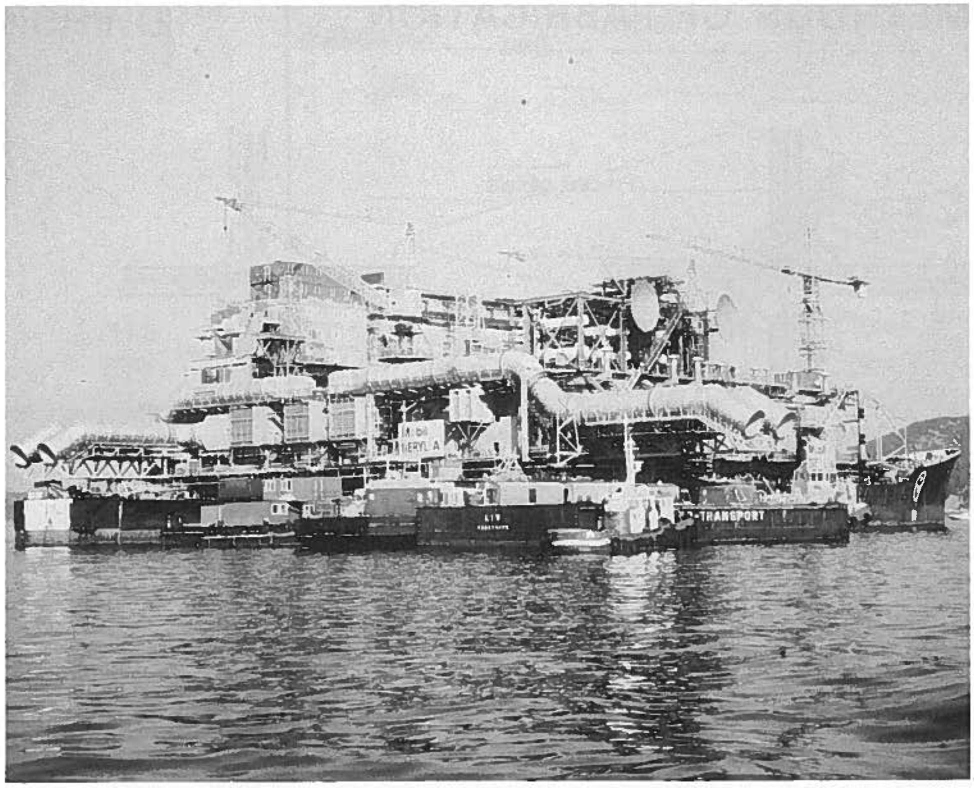
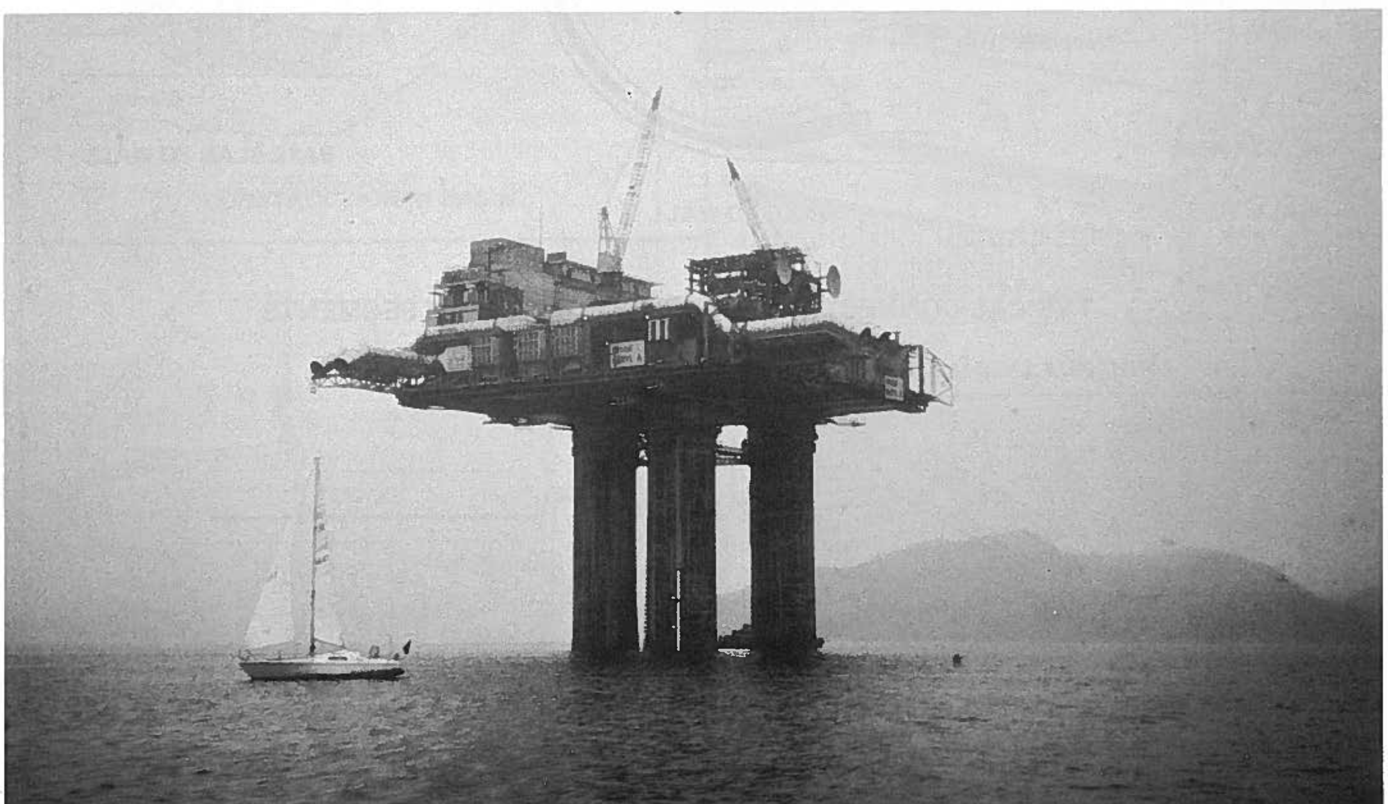
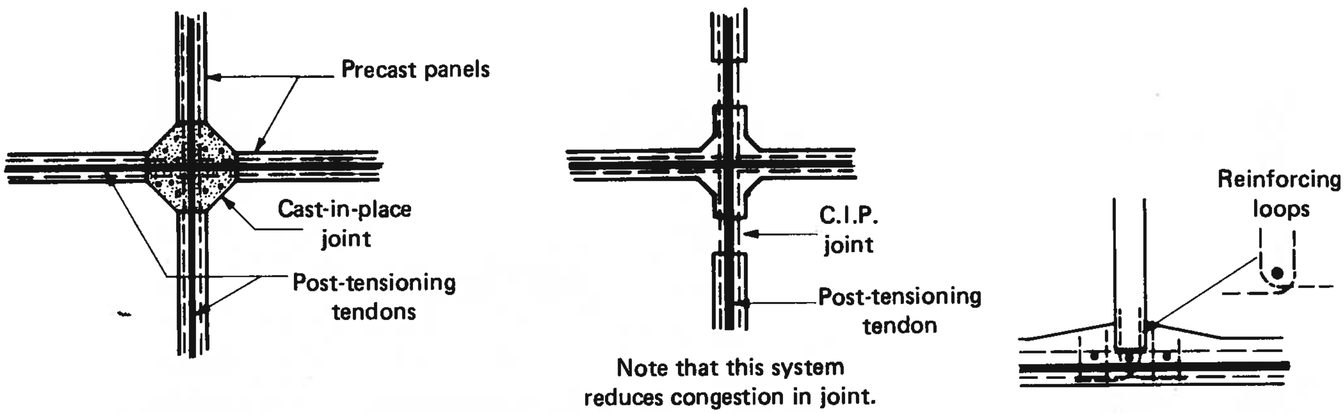




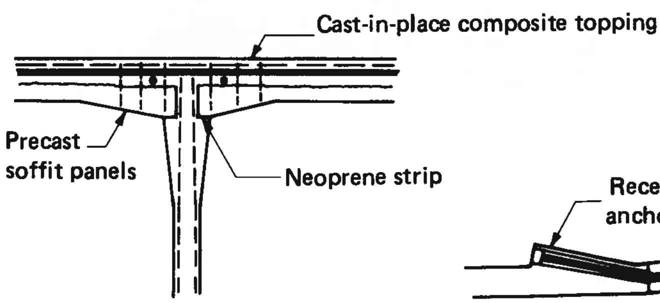


This sequence of three photos show [top-left] concrete structure completed and ready to be submerged to full-depth; [top-right] integrated steel superstructure floated over top and resting temporarily on two tanker hulls; [bottom] concrete caisson deballasted to pick up superstructure, ready for use.

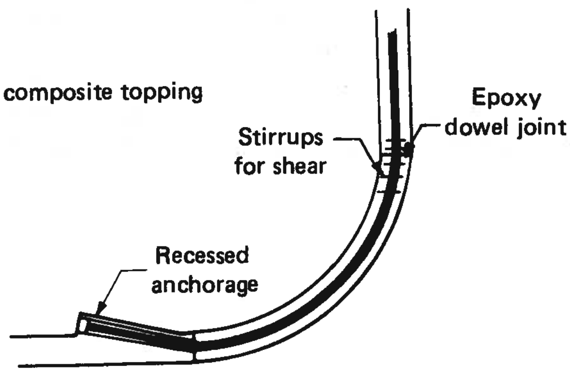
METHODS OF FABRICATION



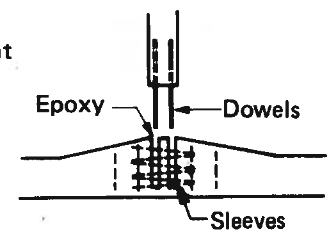
INTERSECTING WALLS



WALL TO ROOF

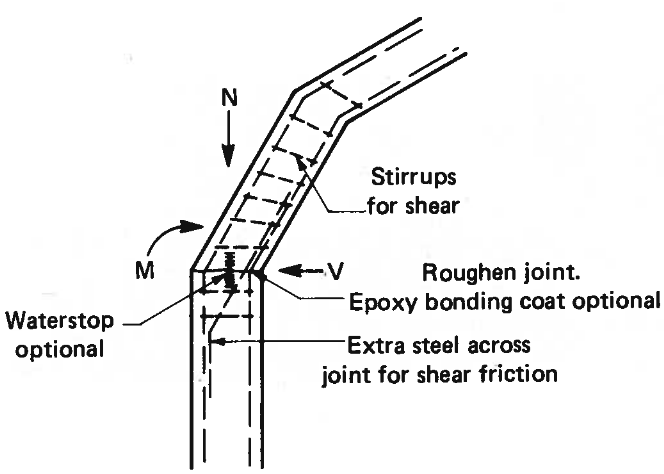


WALL TO WALL

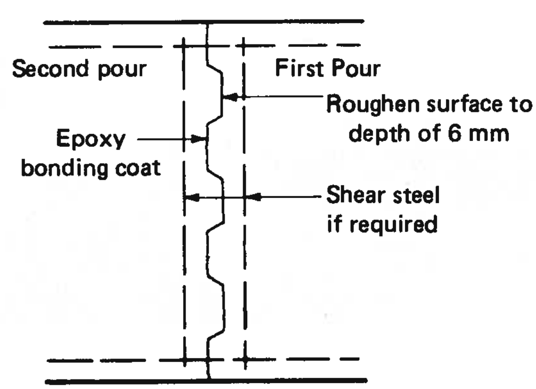


BASE SLAB TO WALL

TYPICAL CONNECTION DETAILS FOR PRECAST SEGMENTS

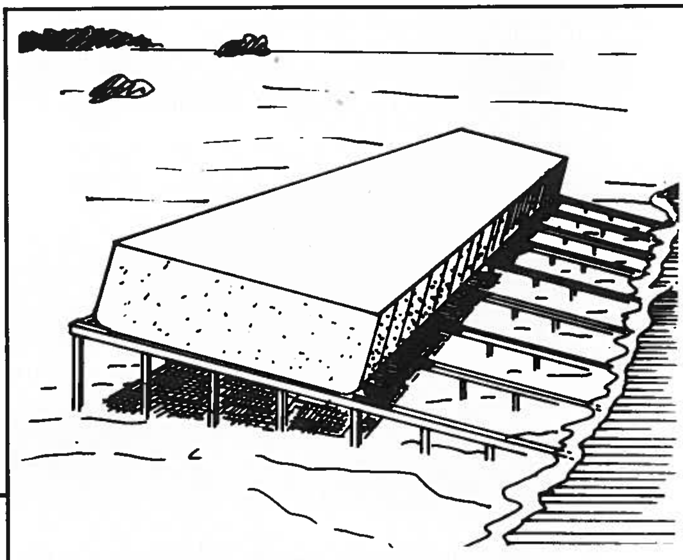


HORIZONTAL CONSTRUCTION JOINT

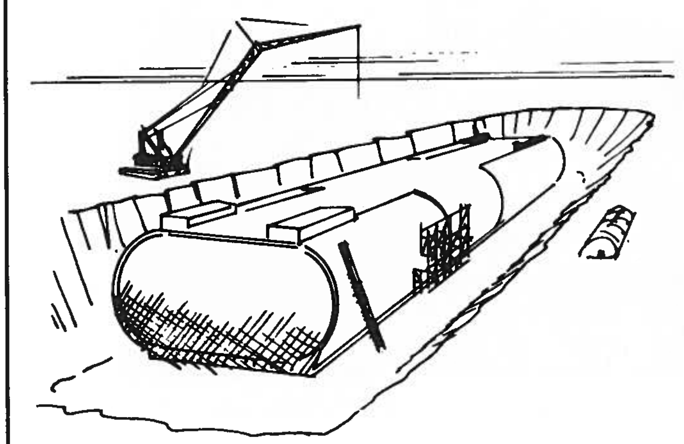


VERTICAL CONSTRUCTION JOINT

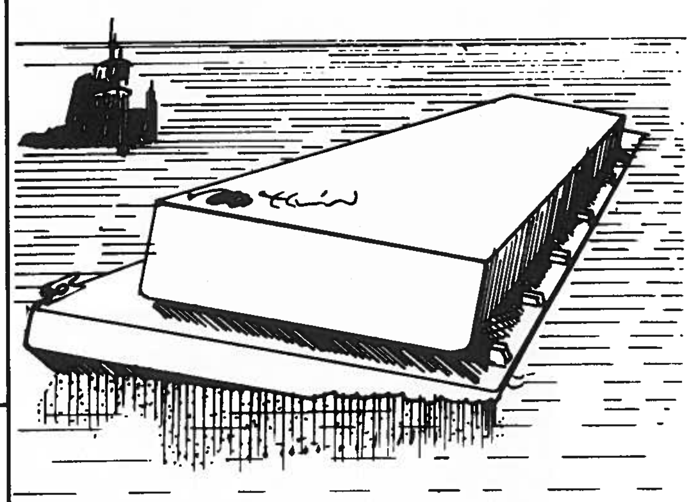
METHODS OF LAUNCHING



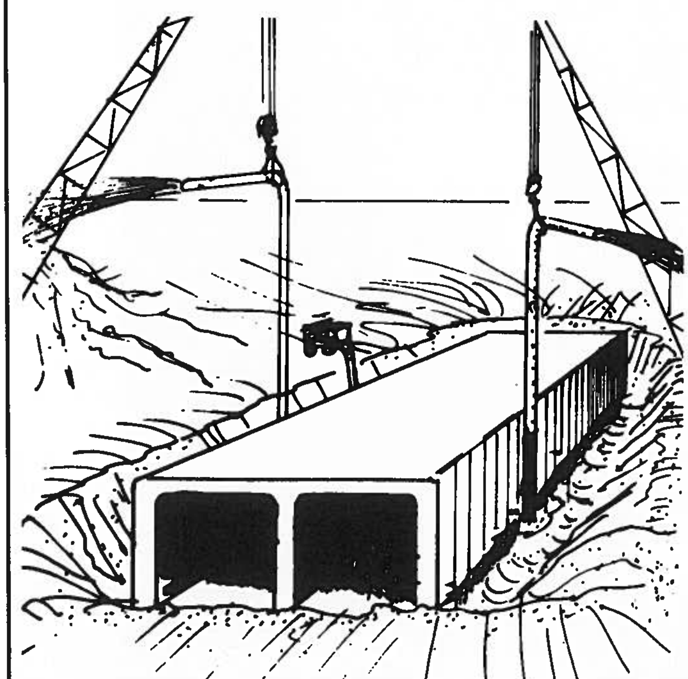
SIDE LAUNCHING



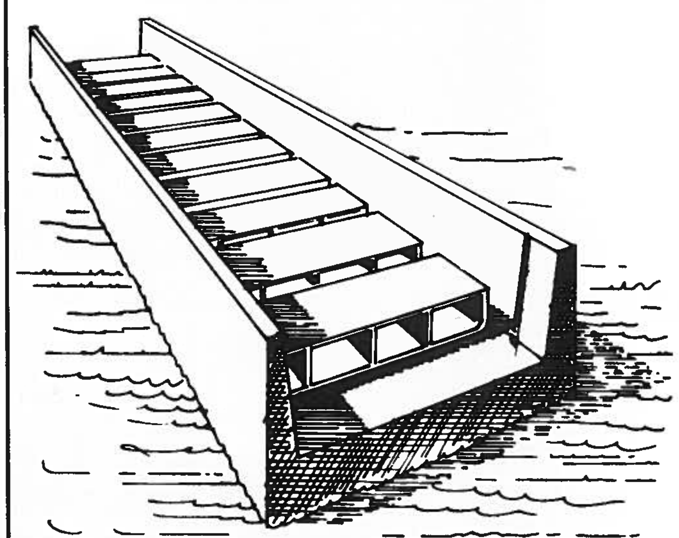
CONSTRUCTION IN BASIN



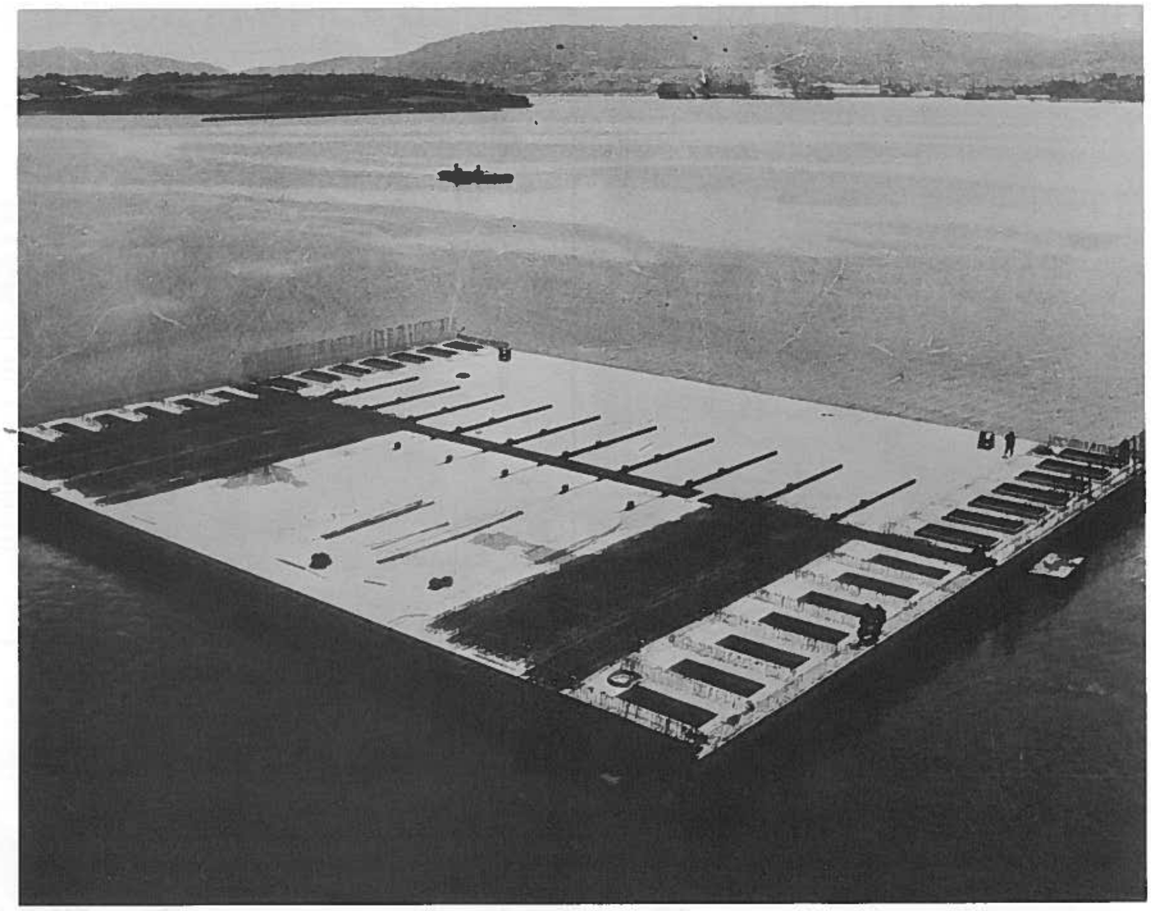
BARGE LAUNCHING



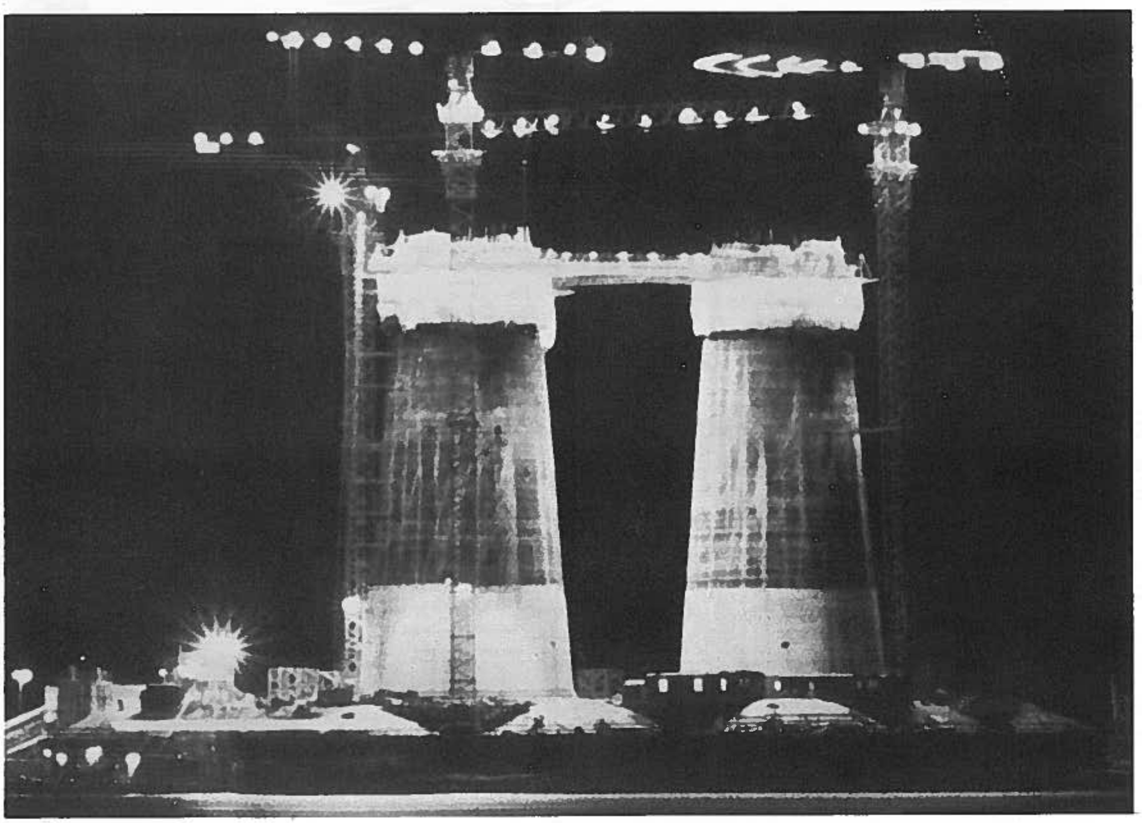
SAND JACK



ASSEMBLY IN DRYDOCK OR GRAVING DOCK

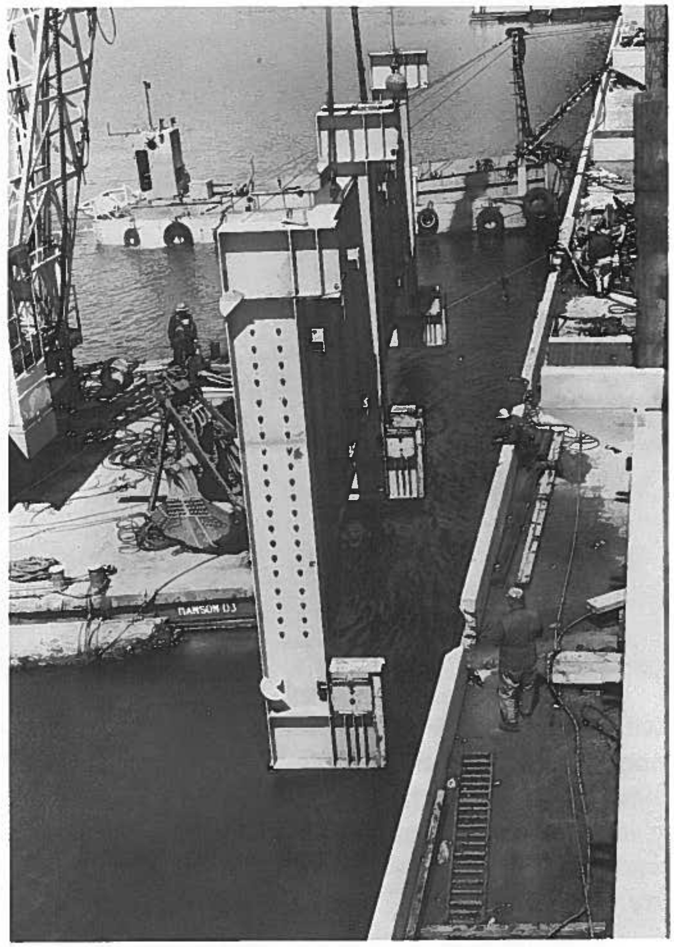


Prestressed concrete drydock pontoons, assembled afloat by post-tensioning. (Northern Spain)

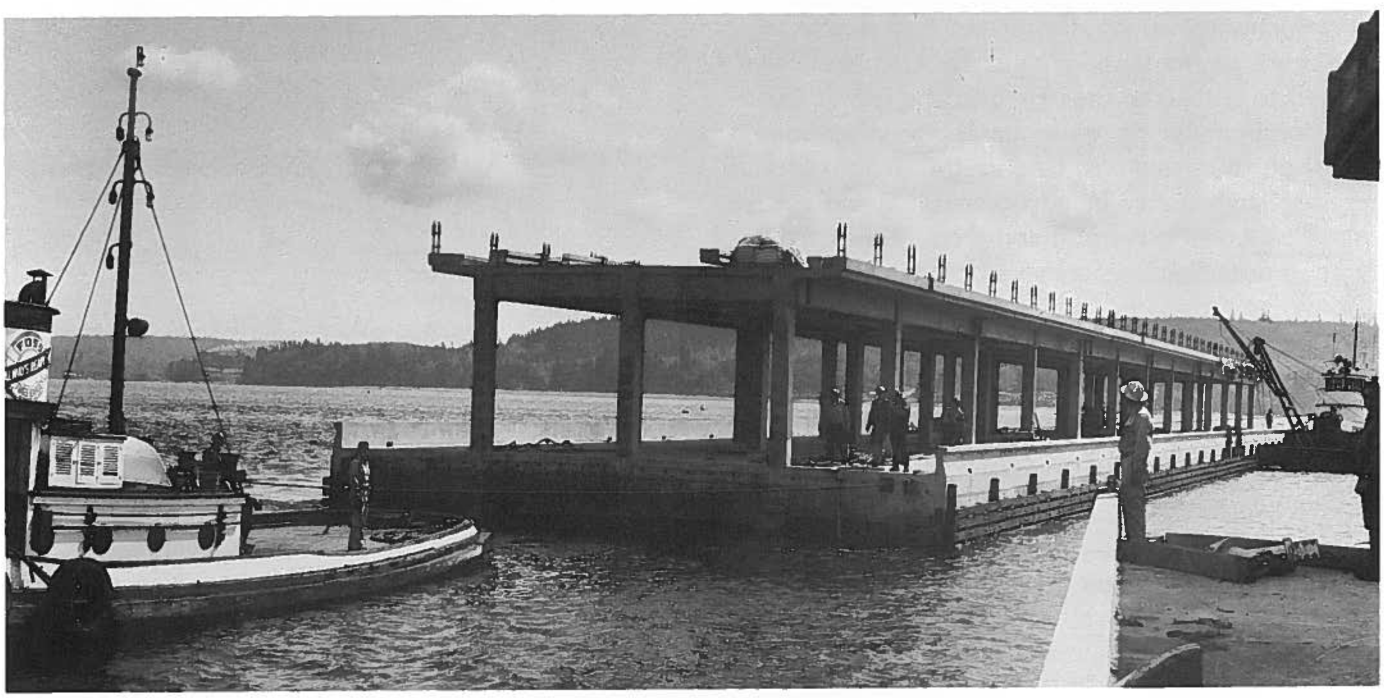


Slipform construction of prestressed concrete towers continues night and day to completion.

Hood Canal Bridge pontoons were assembled afloat into rigid structures by post-tensioning and epoxy.



Sixty foot long steel strongback used on both sides of pontoon joint to provide rigidity at the joint during the pouring and curing of the epoxy grout.



Towing pontoon F into position for connecting to pontoon E of the Hood Canal Floating Bridge.

M. Post-Tensioning

Post-tensioning has had a major, if not a decisive role, in extending the use of concrete to sea structures. It assures that the concrete will remain free from serious structural cracking, thus preventing fatigue in those critical zones subjected to cyclic loading. Post-tensioning permits the creation of a favorable state of stress to later resist imposed forces or strains. Finally, its efficiency permits the effective use of higher strength concretes and thinner sections.

Post-tensioning may be effectively employed to join precast segments or to join entire sections, as, for example, base raft or vessel sections which are to be joined afloat.

Stage-stressing techniques of post-tensioning tendons may be applicable, to counter temporary high stress conditions imposed during construction.

In typical sea structures, some critical zones will be subjected to alternate high tensile forces and high compressive forces. In evaluating the ultimate strength of the section, consideration can be given to the favorable reduction in prestress when under high compression due to strain compatability.

Shear is often critical in sea structures. Post-tensioning for shear will often be found effective.

Because of the sea environment exposure, proper precautions must be taken to ensure durability. See Section VI-C.

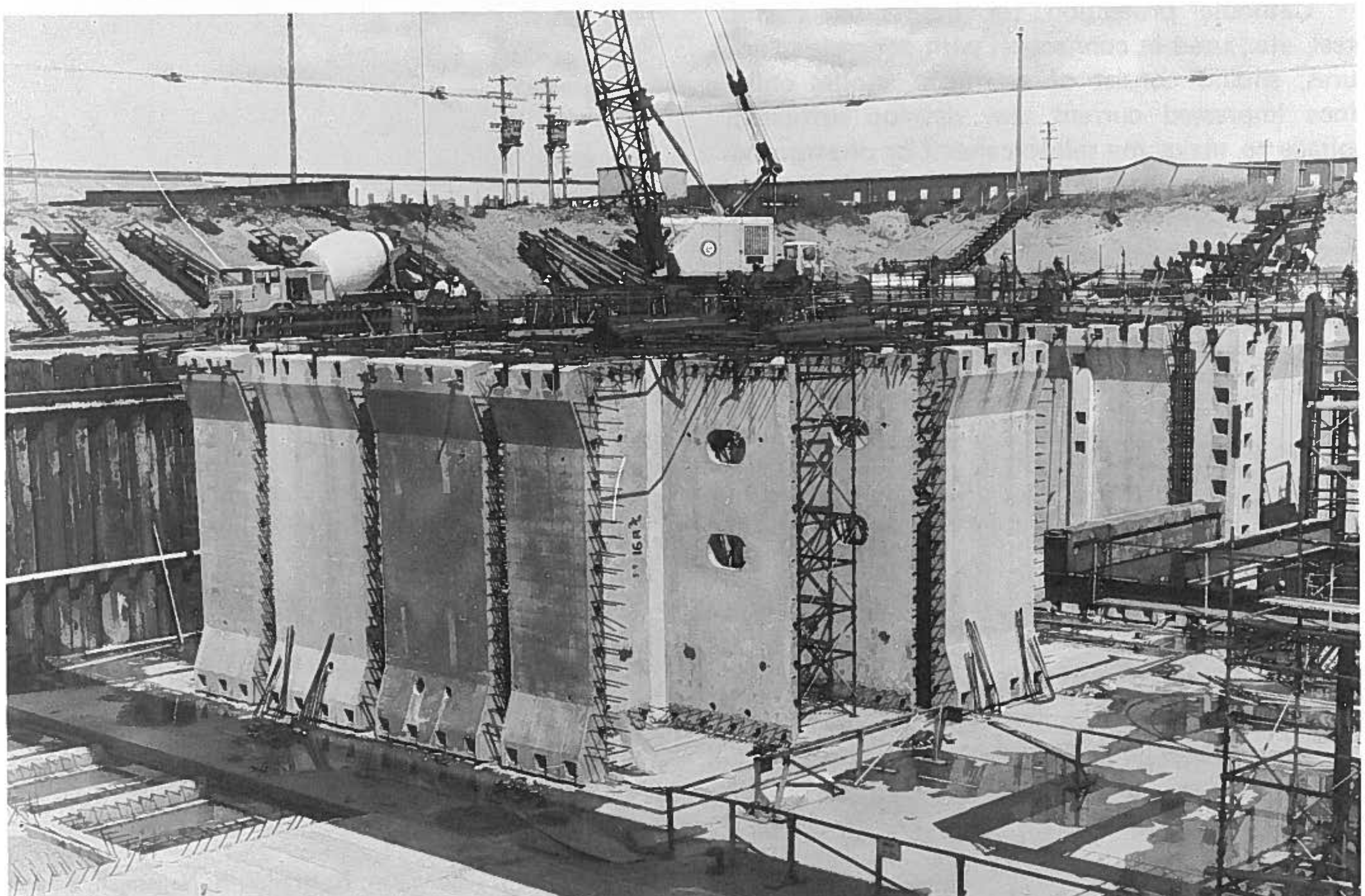
Anchorage zones and locations of short-radius curvature in the tendons must be adequately reinforced to withstand the high bursting forces. Bursting forces must be given particular attention in relatively thin sections. One useful technique is to precast such zones or anchorages. Particular care must be taken to ensure complete filling of ducts with grout. Because high vertical ducts are commonly employed in sea structures, measures to overcome bleed problems must be utilized. See Section VI-C. Durability.

Since post-tensioning is often employed on a very large scale in sea structures, under difficult, corrosive, and congested conditions, yet where its performance is extremely important, it is especially necessary to exercise careful control of duct, anchorage, and tendon installation; as well as stressing and grouting procedures.

REFERENCES

1. PCI-Post-Tensioning Manual, Prestressed Concrete Institute, 1972.
2. Recommendations for Acceptance and Application of Post-Tensioning Systems, Federation Internationale de la Precontrainte, London, 1972.
3. Recommendations for Acceptance and Testing of Steels for Prestressing. Federation Internationale de la Precontrainte, London, 1974.
4. Precautions to be Taken During the Storage, Handling, and Positioning of Prestressing Tendons, FIP Commission on Practical Construction, Proceedings of the VII Congress, Federation Internationale de la Precontrainte, London, 1974.

Over-water extension for La Guardia Airport was constructed of precast pretensioned segments, connected by post-tensioning and cast-in-place concrete for monolithic behavior.



Precast concrete wall units being assembled into caissons for offshore terminal by concreted joints and post-tensioning.

N. Passive Reinforcement and Inserts

Passive (non-prestressed) reinforcement will consist of mild steel reinforcing bars (including high-yield strength bars), and welded wire mesh.

Welding of reinforcing bars should be avoided as it reduces the strength under cyclic and fatigue loads.

Bundling of reinforcing bars can be effectively used to minimize the adverse aspects of congestion and to permit proper placement of the concrete.

Galvanized reinforcement may be employed provided it has been passivated in manufacture by a chromate wash. Alternatively, chromate wash may be applied at the site or a chromate admixture added to the concrete (ref. [1]).

Inserts, plates, penetratons, etc., should be epoxy coated or galvanized for protection from sea water corrosion. They and any anchors attached to them may require spacing (separation) from the adjoining reinforcement of the structure, e.g., by 6 cm of concrete.

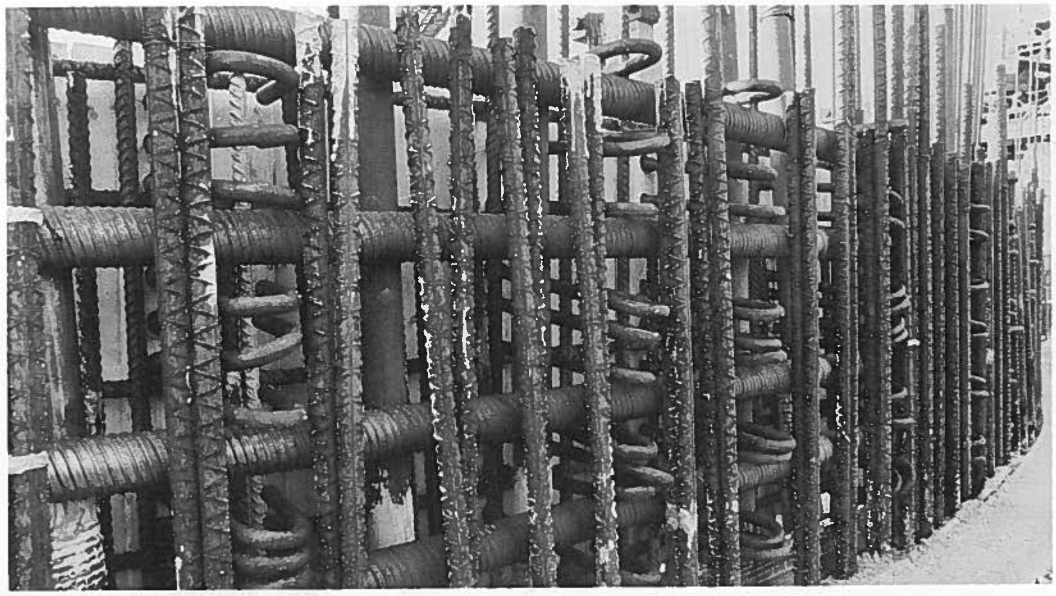
Cathodic protection for inserts, structural steel, etc., used in connection with concrete structures, should consist of sacrificial anodes only, since impressed current may develop sufficient voltage to make the reinforcement or prestressing steel act as an anode. Alternatively, mesh "screens," designed by electrical specialists, may be used to shield the structural reinforcements.

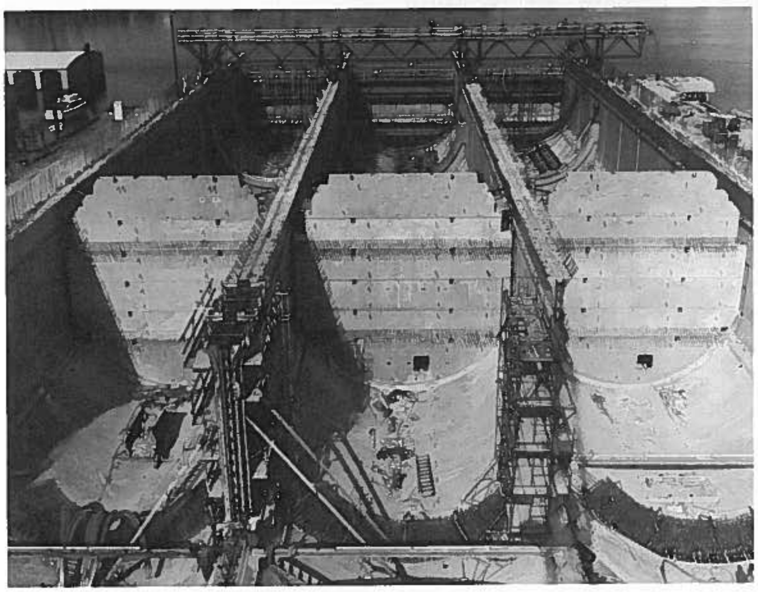
All inserts, structural steel additions, etc., should preferably be attached to the concrete structure by post-tensioning to prevent fatigue.

REFERENCES

1. Cornet, I; Williamson, R; Bresler, B; Nagarajan, S., and Christiansen, K., "Chromate Admixture To Improve Performance of Galvanized Steel In Concrete Sea Structures," Proceedings, FIP Symposium On Concrete Sea Structures, (Tbilisi), Federation Internationale de la Precontrainte, London, 1973.

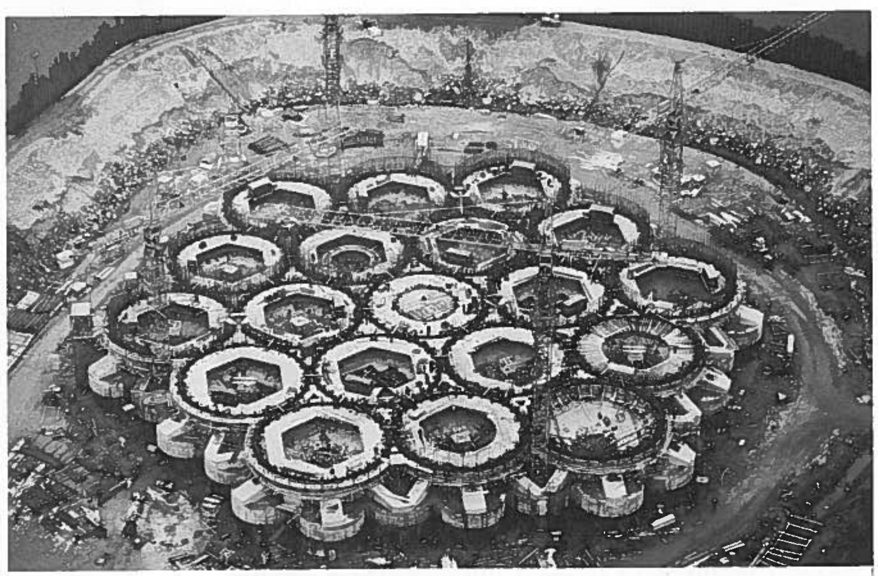
Ekofisk caisson tank walls under construction showing reinforcing steel and post-tensioning ducts.





Construction of Arco prestressed concrete LPG terminal barge in graving dock using a combination of precast segmental construction and cast-in-place construction, post-tensioned on all three axes

Construction of base raft in basin, Condeep Statfjord "A", combines precast and cast-in-place concrete on steel skirt rings.



O. Inspection, Instrumentation and Repairs

Concrete sea structures generally are built to conform to the requirements of Governmental Regulatory agencies and/or insurance requirements. This often requires that the inspection procedure during construction and during service must be established as part of the design process.

The specificiations should set forth allowable tolerances in detail: concrete quality, wall thickness (plus and minus), out of roundness, deviation from a best-fit circle and from a true circle, verticality, true position, etc. For reinforcing steel and ducts, tolerances in placement and in cover should be established.

Some small cracking during construction may be inevitable, due to drying shrinkage and heat of hydration. Such cracks may be acceptable if they are in zones that later will be in compression but may not be acceptable in zones subject to cyclic loadings, etc. Crack widths should be defined. Surface defects due to escape of bleed water and entrapped air should be recognized and limits set on depth and size.

If more serious defects occur than those established above, the specifications should set forth acceptable means of repair. Does that portion of the structure require removal and replacement, or can it be repaired by epoxy coating? Establishment of such provisions at the time of original design will go far towards prevention of unnecessary delays and focus attention where it is most important.

Inspection in service requires the establishment of periodical inspections and for inspection after severe storm or accident. Locations that are particularly critical should be noted by the designer and the type and characterisitics of potentially serious defects, such as shear cracks, should be noted. Provision should be incorporated in the original structure for access to the critical areas, and methods of inspection set forth.

Instrumentation should be provided in the structure as an aid to control the construction and installation and as a means for monitoring the structure in service. Strain gages may be placed on reinforcing steel and on concrete surfaces, thermocouples installed, etc. Reliability is far more important than measurement of small variations.

In utilizing these instruments, there must be sufficient redundancy and sufficient cross-check between readings to prevent unnecessary alarm developing from a malfunctioning instrument.

Repairs to a sea structure after damage both above and below water, are feasible and practicable. Typical repair methods should be set forth by the designer as part of the original design, so that later they can be instituted without unnecessary delay.

Epoxy injection, using special penetrating epoxies that bond even to a damp or wet surface, has been used with great effectiveness in the repair of cracks in sea structures up to about 1 mm in width. This includes inclined cracks in compressive zones.

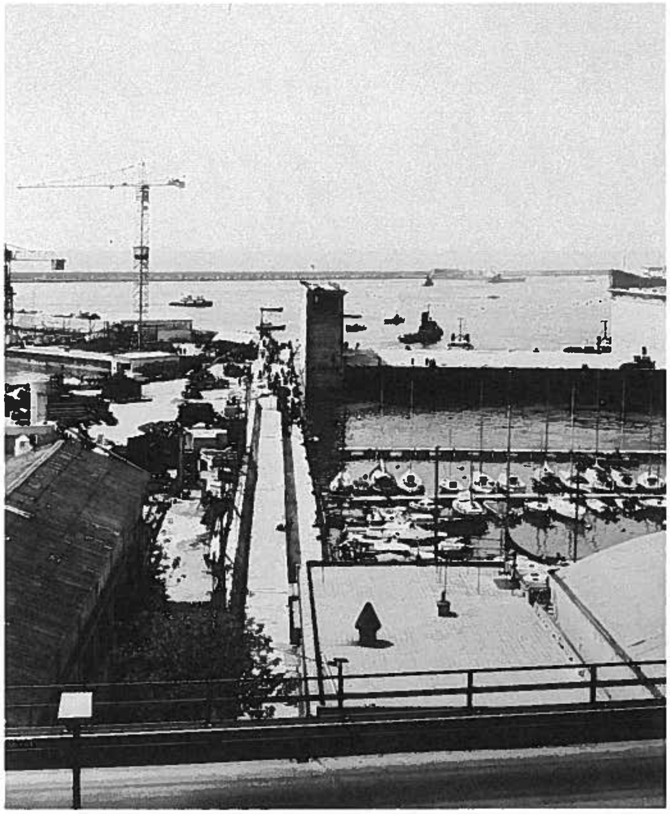
Shotcrete may be used to build up surfaces, but great care must be taken to prevent entrapment of rebound, especially behind reinforcing bars. Porous shotcrete can lead to accelerated salt-cell corrosion.

Grout-intruded aggregate (Prepakt) has been successfully employed for the resotration of cavity-type damage.

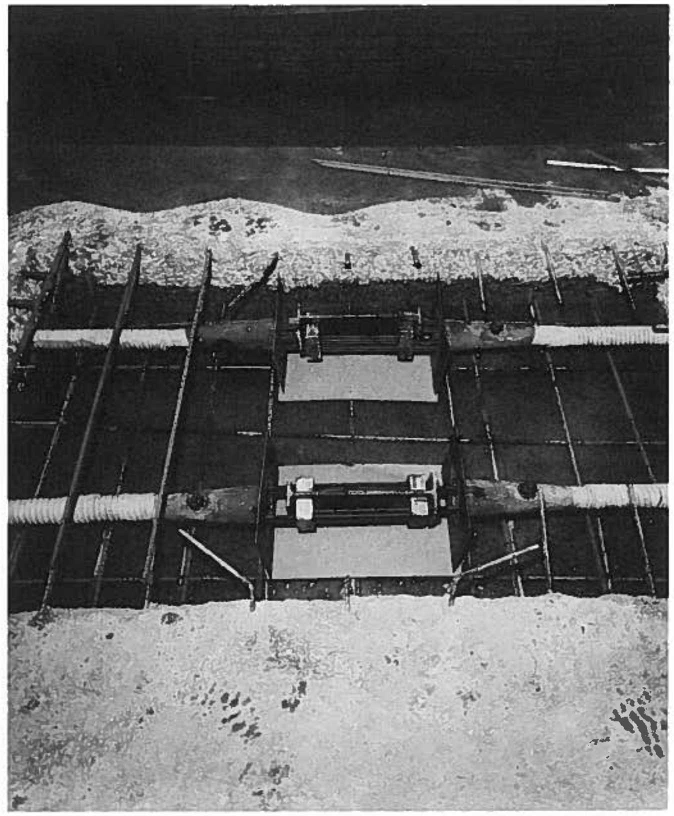
Concrete barges have been successfully repaired underwater by the use of rapid-setting cement mortar and replaced in service without the need for docking. Underwater-setting epoxy coatings may be similarly used.

REFERENCES

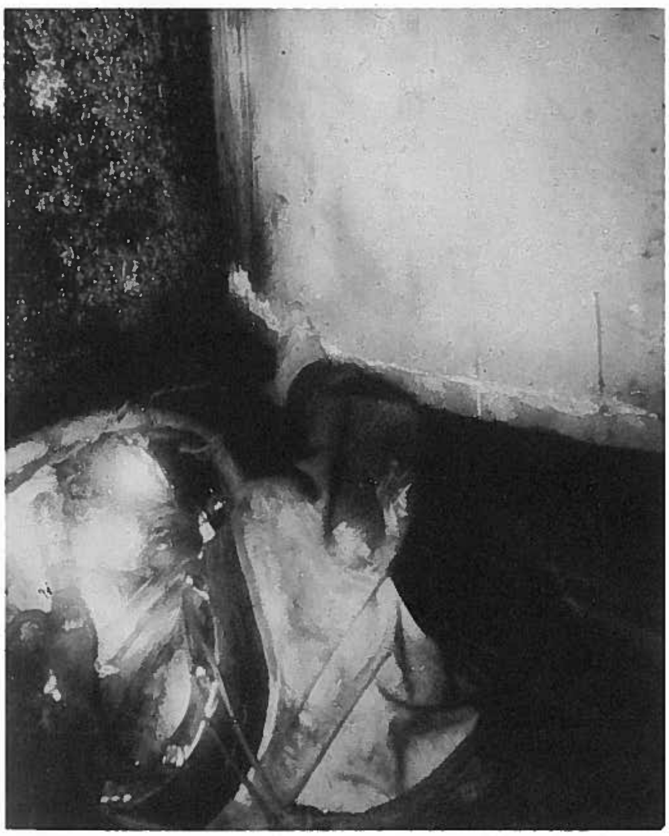
1. Proceedings, FIP Symposium on Concrete Sea Structures (Tbilisi), Federation Internationale de la Precontrainte, London, 1973.
2. ACI Manual of Concrete Practice, Part I, American Concrete Institute, Detroit, 1974.
3. Manual of Concrete Inspection, American Concrete Institute, Publication SP-2, Detroit, 1961.



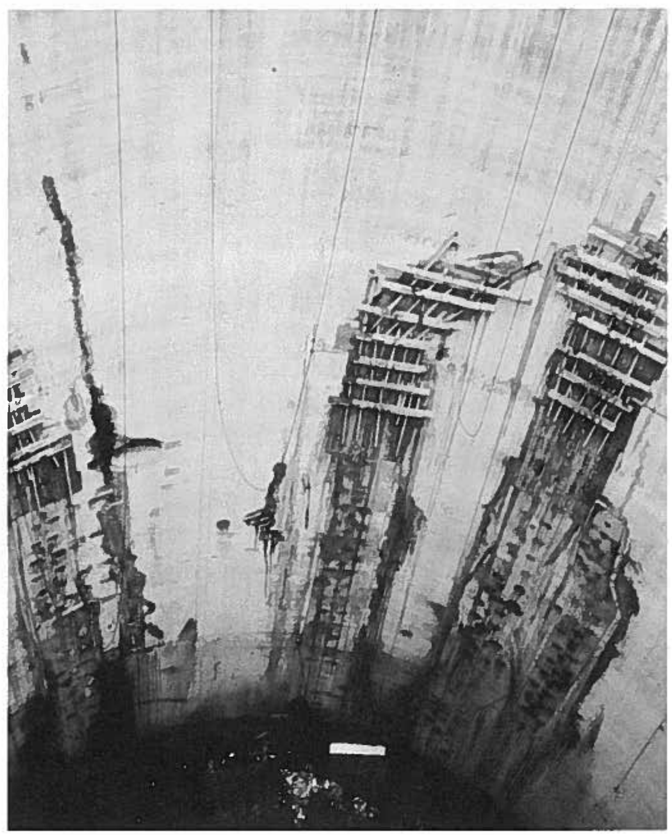
Prestressed concrete floating drydock under construction in Genoa, Italy. This structure had to meet stringent requirements for capability of being repaired to full strength in event of explosion or other accident.



Test repair of damage for Geona, Italy, floating drydock. The Italian government authorities required proof that the structure could be fully restored even after a hypothetical explosion in service.



Diver inspection of underwater assembly of precast concrete.



Repairs in progress to walls of caisson base. Damage was due to incorrect ballasting/construction procedure. Completely restored and certified by combination of grout-intruded aggregate concrete and epoxy injection.

P. Quality Assurance

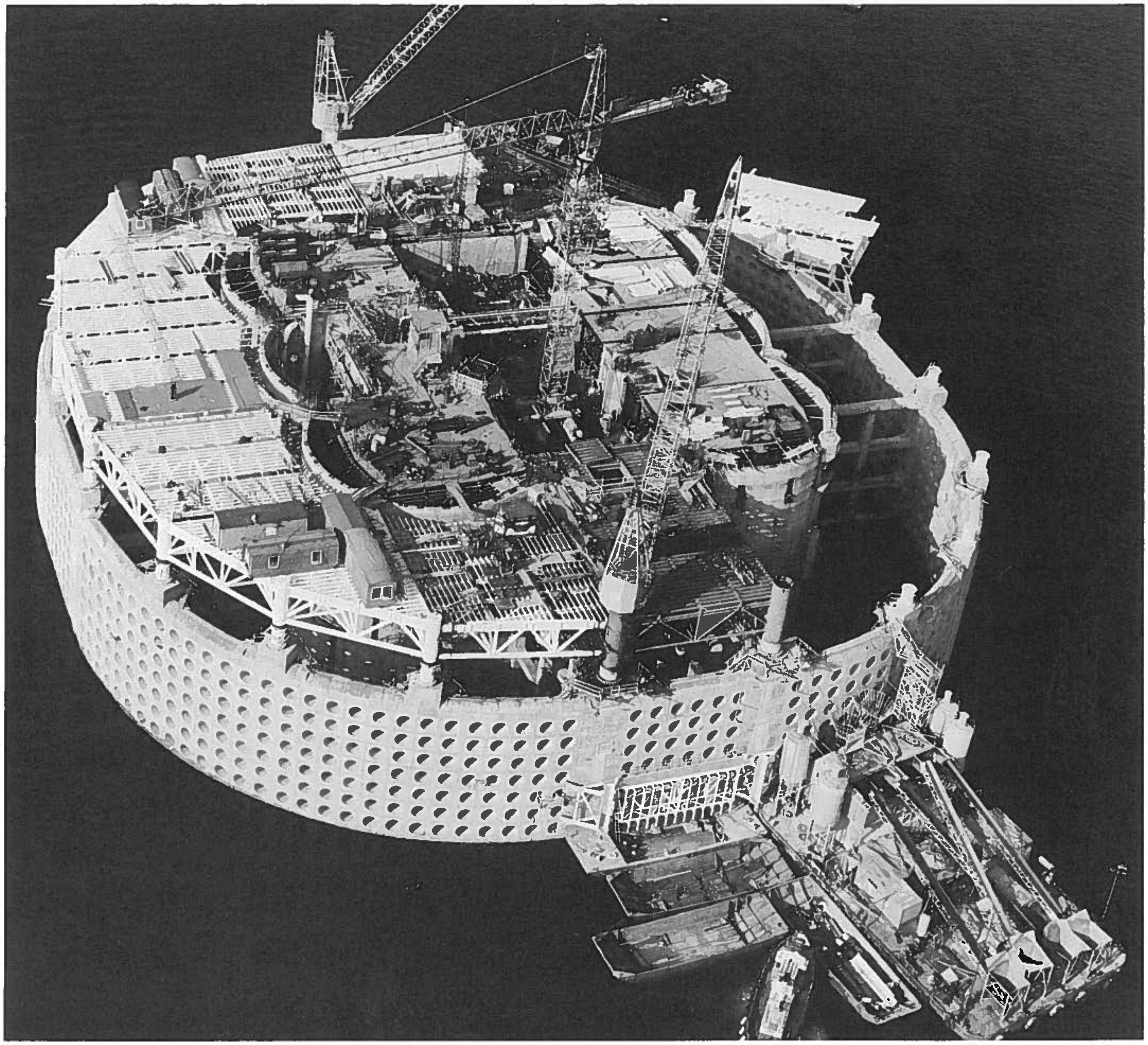
In many respects, large complex sea structures are similar to nuclear reactor pressure vessels. In addition, they must perform in an adverse environment under a wide range of loadings. Collapse or serious damage can have effects that extend far beyond the structure itself, such as enforced shutdown of an entire system, environmental pollution, and loss of life. Therefore, a quality assurance program must be established and implemented, ensuring that all materials and all work are in conformance with design requirements.

A quality assurance program has two divisions, that of carefully planned inspection and testing (see Section VI-O.) and that of Documentation for Control. This latter is of especial importance for sea structures because, by their nature, the supply of materials and components and even the design and construction are often multi-national in character, which compounds the problems of identification during procurement, fabrication, inspection, shipping and installation.

Therefore a comprehensive Quality Assurance program must be an integral part of the design and construction process.

REFERENCE

1. Code for Concrete Reactor Vessels and Containments, Section III, Division 2, Nuclear Power Plant Components, American Society of Mechanical Engineers, New York, 1975.



Complex structures such as the Ekofisk caisson require thorough implementation of a quality assurance program.

Q. Safety Considerations

Sea structures and ships must be designed with a high probability of safety during both service conditions and extreme or accident conditions. For the latter, a value of one event per 100 years is usually assumed, although even longer periods are assigned where an accident could cause widespread loss-of-life (e.g., floating nuclear power plant).

The various factors of safety – material factor, capacity reduction factor, load factor, etc. – must all be carefully evaluated and selected. Extreme loads may be limited in specific cases by the water depth, yet the "load factor" commonly employed also includes an allowance for the accuracy by which the design analytic method represents the true behavior. Not only variations in material quality, but tolerances of construction are involved. The consequences of failure enter into selection of the proper factors. Since many sea structures cannot be thoroughly inspected on a periodic basis, the existence of undetected deficiencies must be considered. Guides to the selection of appropriate factors are provided by refs. [1] and [2].

Each major element and the structure itself must be checked for its capacity in both the service "elastic state" and ultimate state, through all stages on construction and service. Above all, a brittle mode of failure must be avoided: post-cracking ductility is essential, that is, a range through which the structure will have integrity even after the design "ultimate" load has been exceeded and major damage sustained.

This ductility concept permits a redistribution of loads and provides energy absorption.

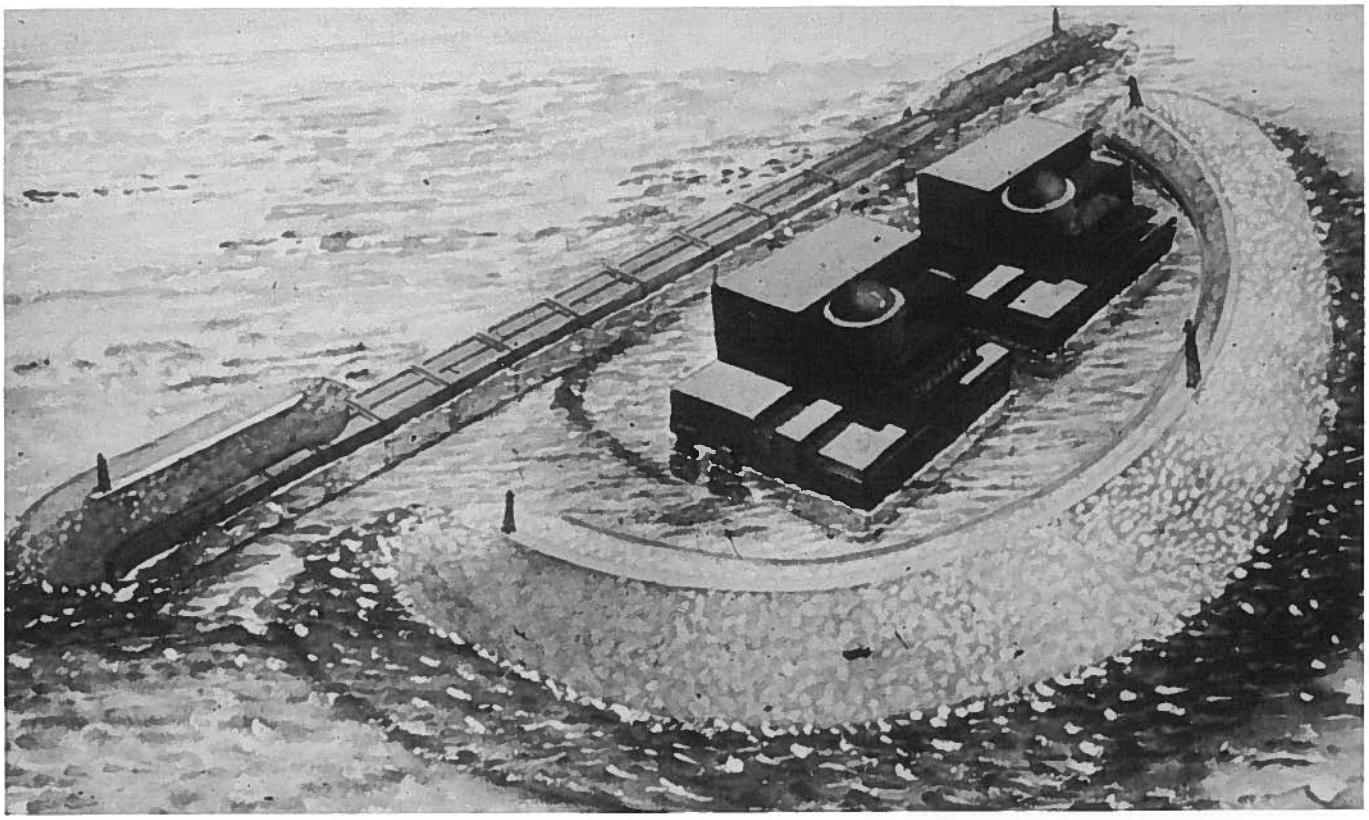
Damage should not be progressive: strong points or elements should be built in at rational intervals. Stability must be maintained. Redundant members may be installed.

Under such "post-ultimate" condtions, severe damage is acceptable, both repairable damage and, in appropriate cases, un-repairable damage, just as long as life safety, etc., is assured.

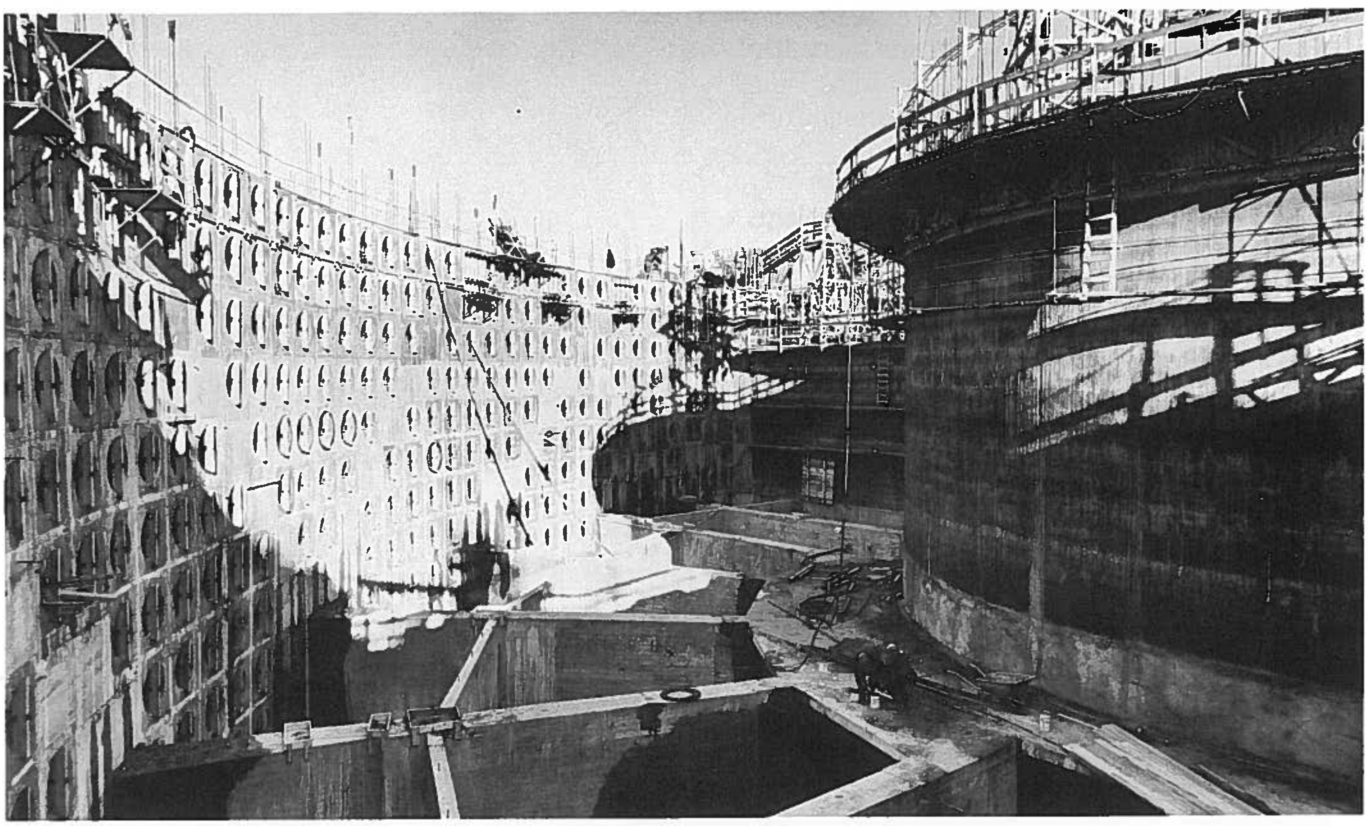
Studies such as the above are often classed as "Failure-Mode Effects Analyses" and "Risk Analyses."

REFERENCES

1. Recommendations for the Design and Construction of Concrete Sea Structures, Federation Internationale de la Precontrainte, Second Edition, London, 1974.
2. Rules for the Design, Construction and Inspection of Fixed Offshore Structures, Del Norske Veritas, Oslo, 1974.



Proposed Atlantic generating plant will be protected by concrete breakwater caissons and large concrete Dolose units, in order to ensure safety in extreme hurricanes and in event of supertanker grounding.



Permeable breakwater protects Ekofisk oil storage from direct wave impact and collision.

VII. FUTURE DEVELOPMENTS

The striking success of prestressed concrete in its application to sea structures presents exciting opportunities together with severe demands.

These advances have been made possible largely through the technological developments in reinforced and especially prestressed concrete. Thorough integration of many disciplines has been evoked: naval architecture, hydrodynamics, structural engineering, materials technology, geothecnical engineering, construction engineering and management. It is the effective blending together of these interactive aspects that constitutes the present achievement.

The future now presents its challenges. More research is urgently needed on the actual behavior of concrete structures under heavy loadings and dynamic loadings in the hydrosphere. A better understanding is needed of the environment-structure-soil system under extreme conditions such as earthquakes. In order to permit more efficient and refined techniques, concretes of higher compressive and tensile strengths are required as well as continued development of schemes for the effective integration of prefabricated elements into molithic behavior.

The structures currently needed and demanded do indeed present challenging opportunities. Those under serious study and design at the present time include:

— Floating structures to support entire plants, such as an LNG liquefaction facility and terminal

— Offshore nuclear power plants: breakwaters and moorings

— Arctic Ocean drilling and production terminals

— Floating tunnels for highway and rail transport across deep-water straits

— Ocean thermal energy plants

— Piers for bridges across arms of the ocean or exposed seas, such as the Honshu-Shikoku Bridges across Inland Sea, and the Intercontinental Peace Bridge across Bering Straits

— Fixed offshore terminals for storage and production

— Cargo submarines

— Mobile offshore research laboratories and logistics/repair bases

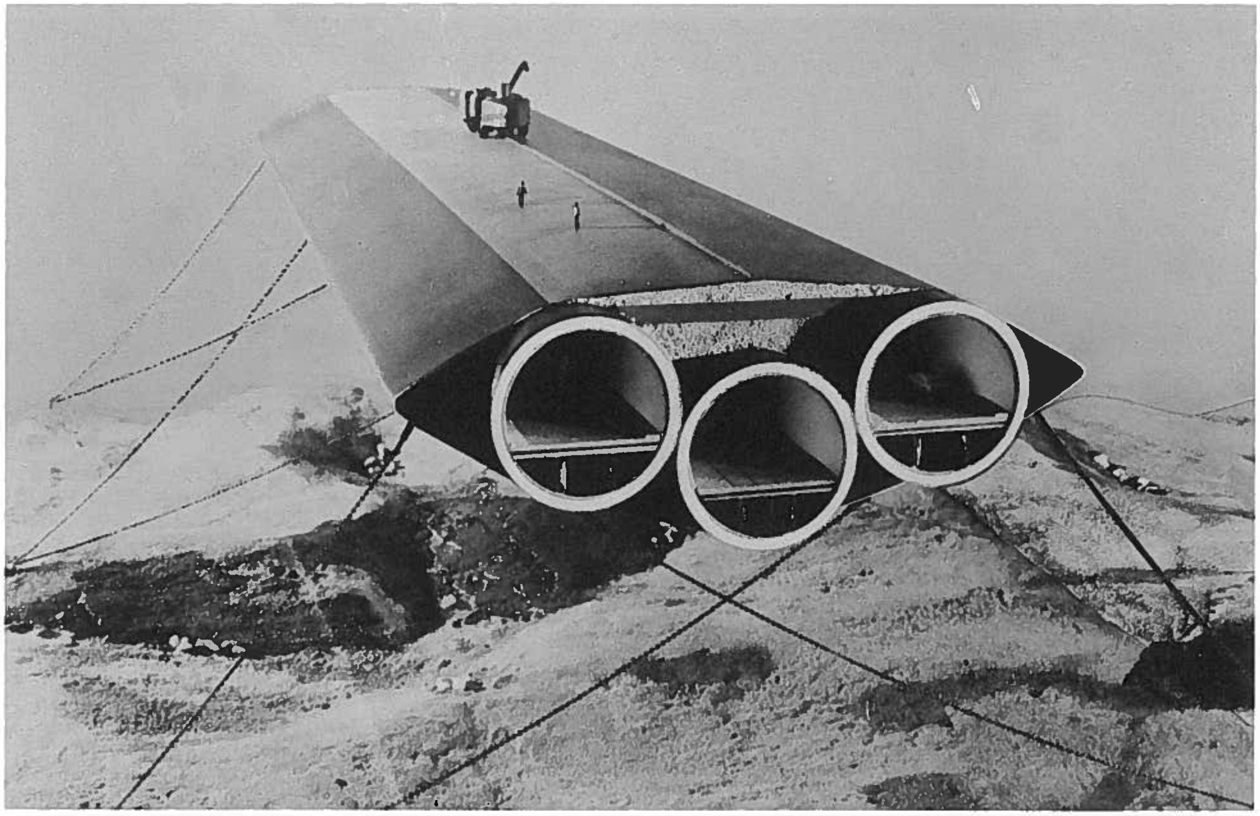
— Semi-submersible drilling and production vessels such as Condroll, Conprod, Trosvik, etc.

— Concrete ships for transport of bulk cargoes and liquefied gasses

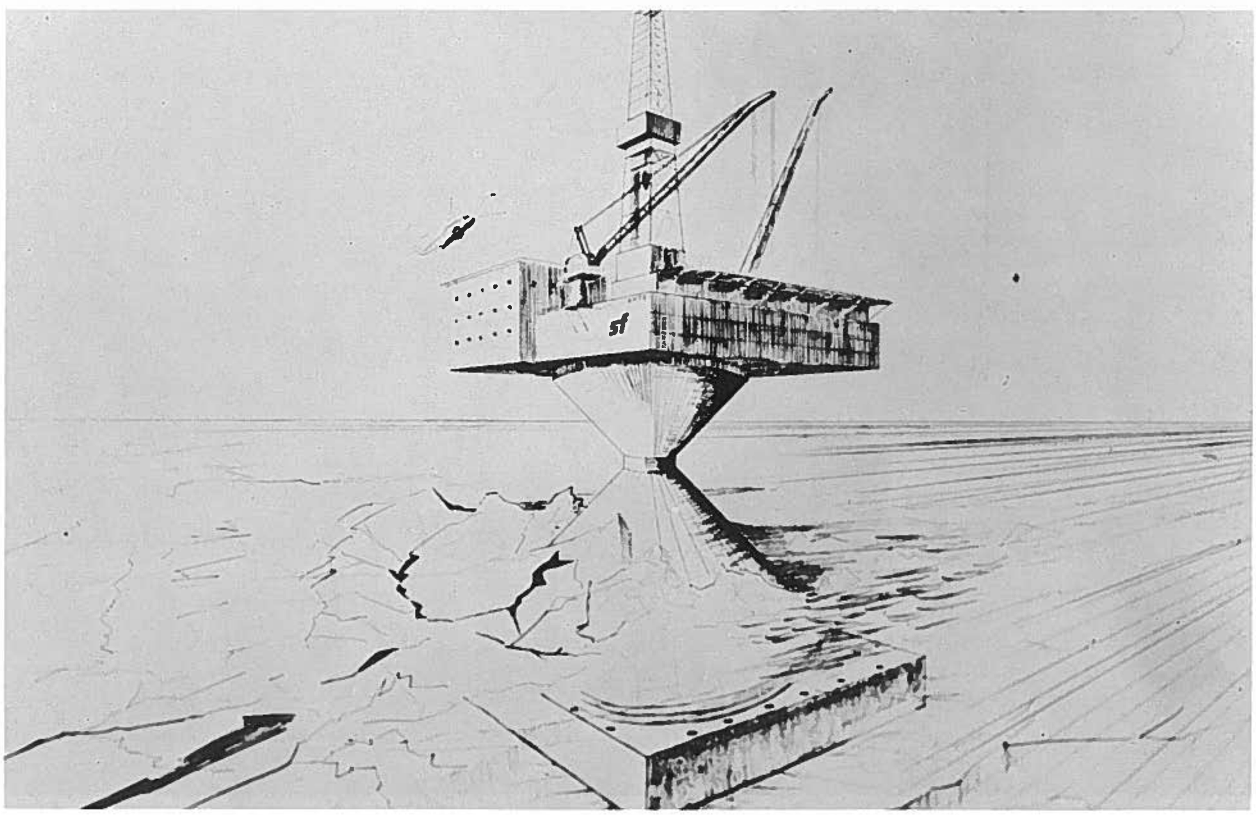
The future is indeed promising. Yet the risks are correspondingly great and therefore require a sophistication of engineering, construction and control that will require a major effort on the part of the prestressed concrete and construction industries. The seas present a challenge and an opportunity for industry and society.

REFERENCES

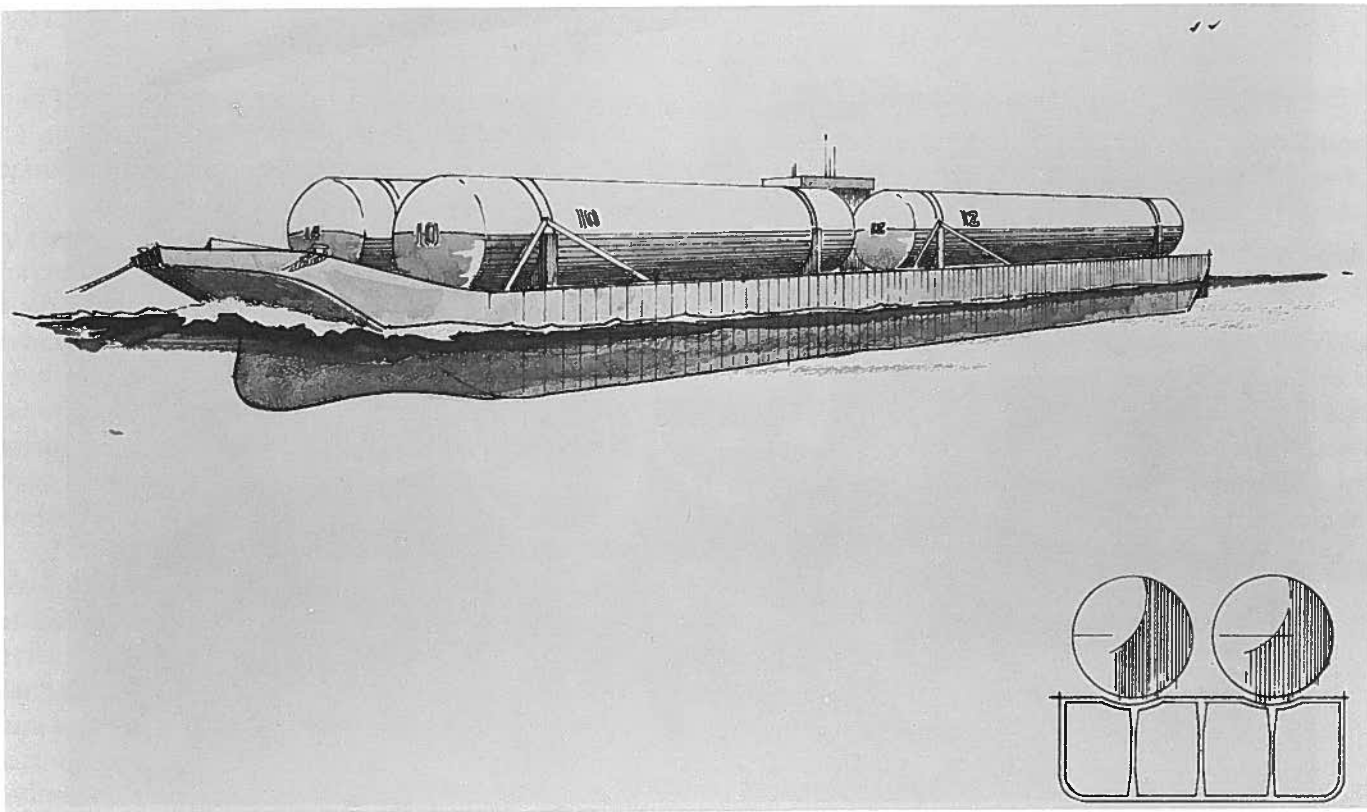
1. Concrete in the Oceans, Parts I and II, Cement and Concrete Association, London, 1974.
2. Gerwick, B.C. Jr., "Concrete Structures: Key to Development of the Oceans," Journal of the American Concrete Institute, V. 71, No. 12, December, 1974, pp. 611-616.



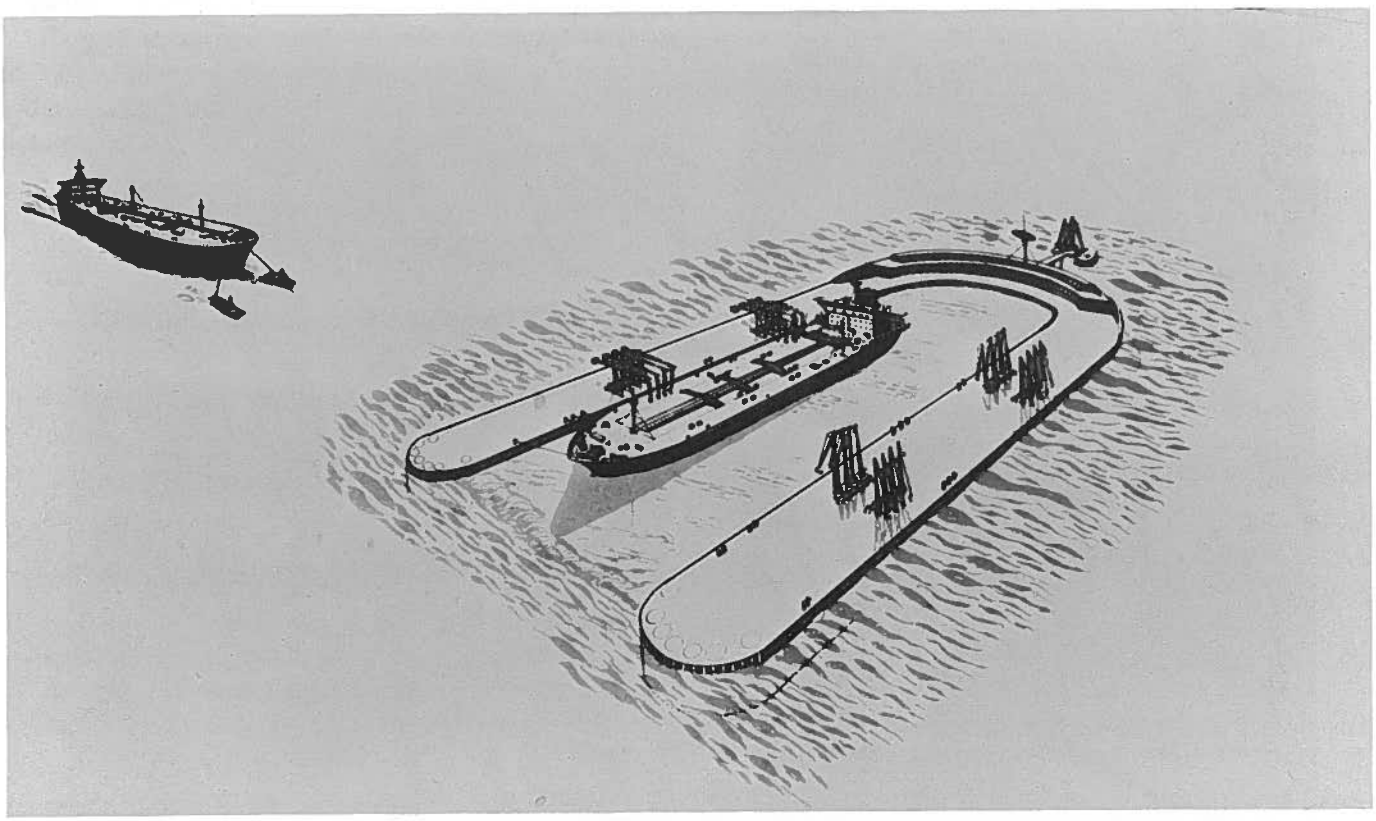
Proposed floating concrete tunnel under the Straits of Messina.



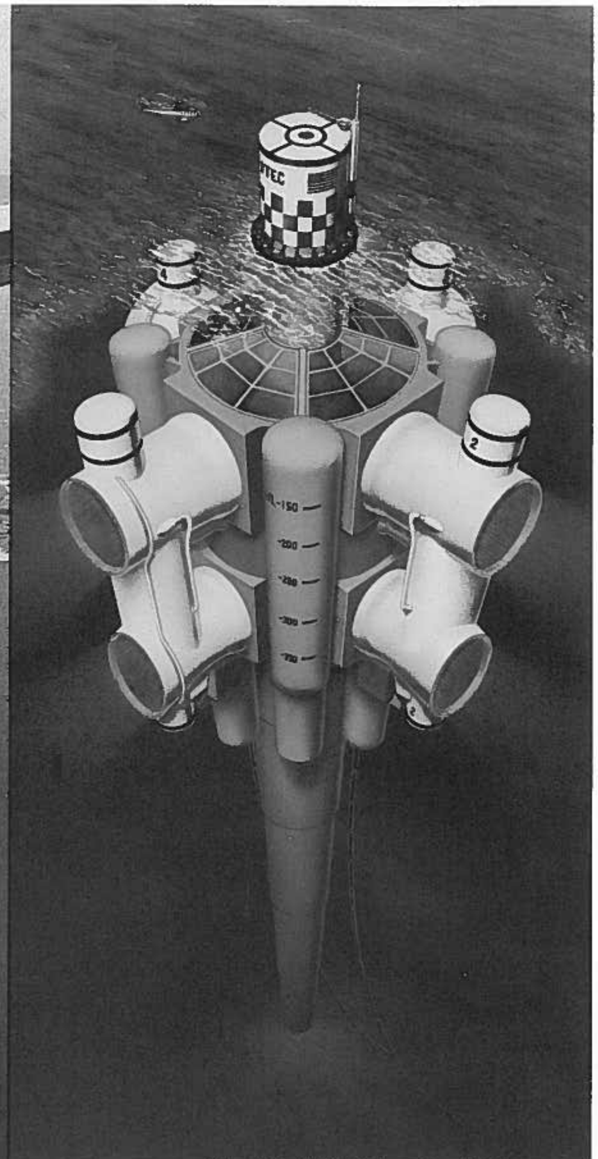
Proposed drilling and production platform for Arctic Ocean.



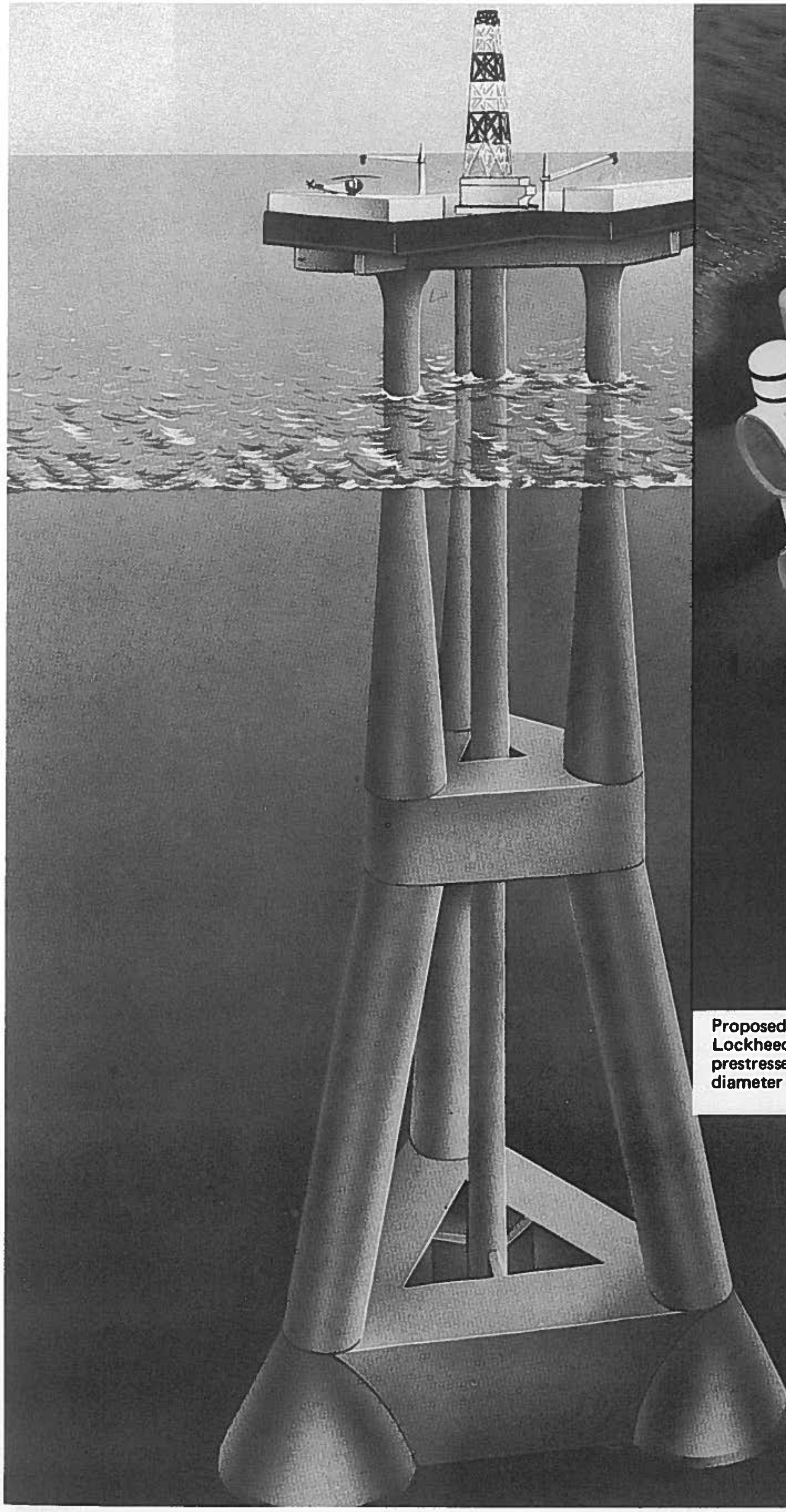
Prestressed concrete transport vessel has been approved "in principle" by the U.S. Coast Guard.



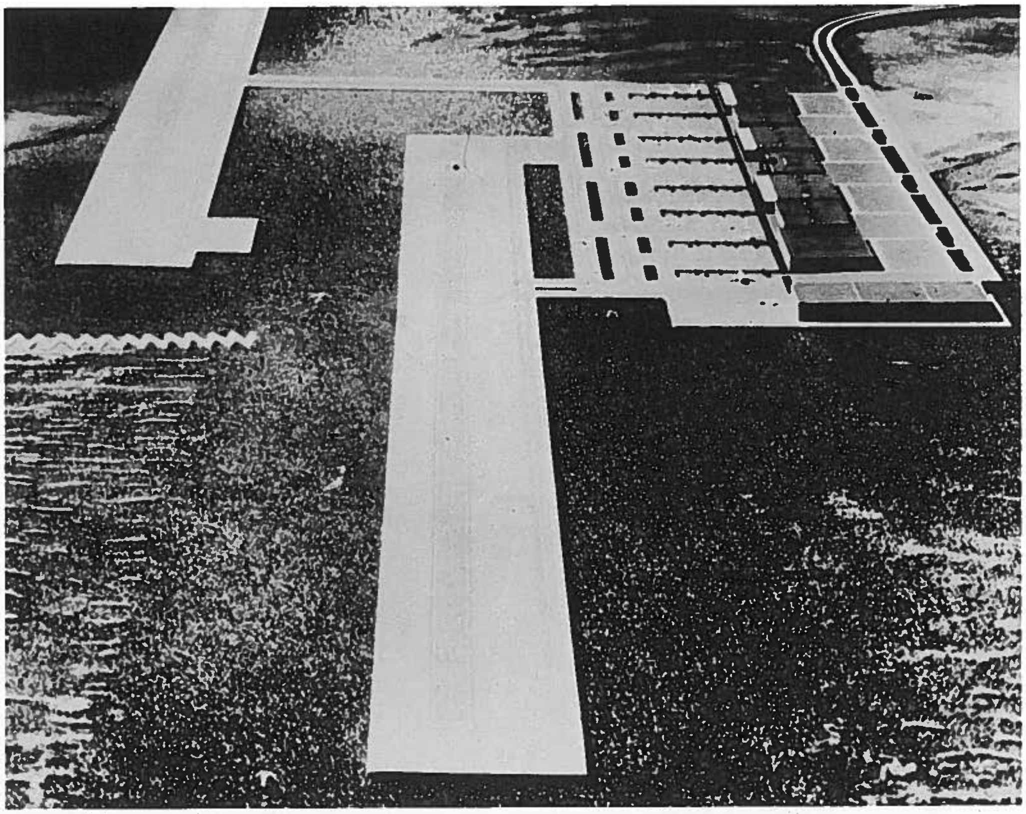
Prestressed concrete offshore floating supertanker harbor proposed by Finsterwalder.



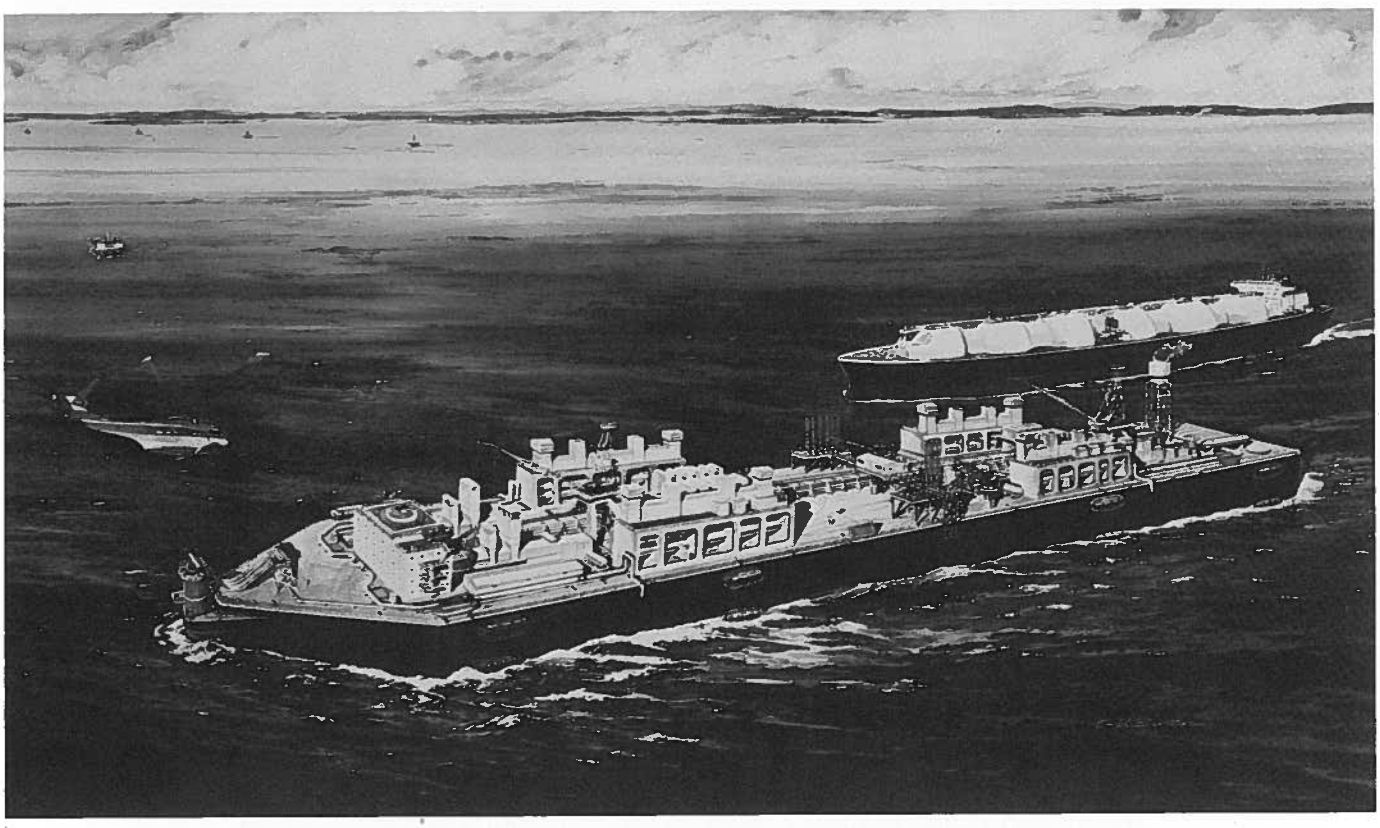
Proposed offshore thermal energy conversion plant by Lockheed Missile and Space Co. and T.Y. Lin, Inter. A prestressed concrete caisson from which hangs a 100 foot diameter by 1000 foot long concrete intake pipe.



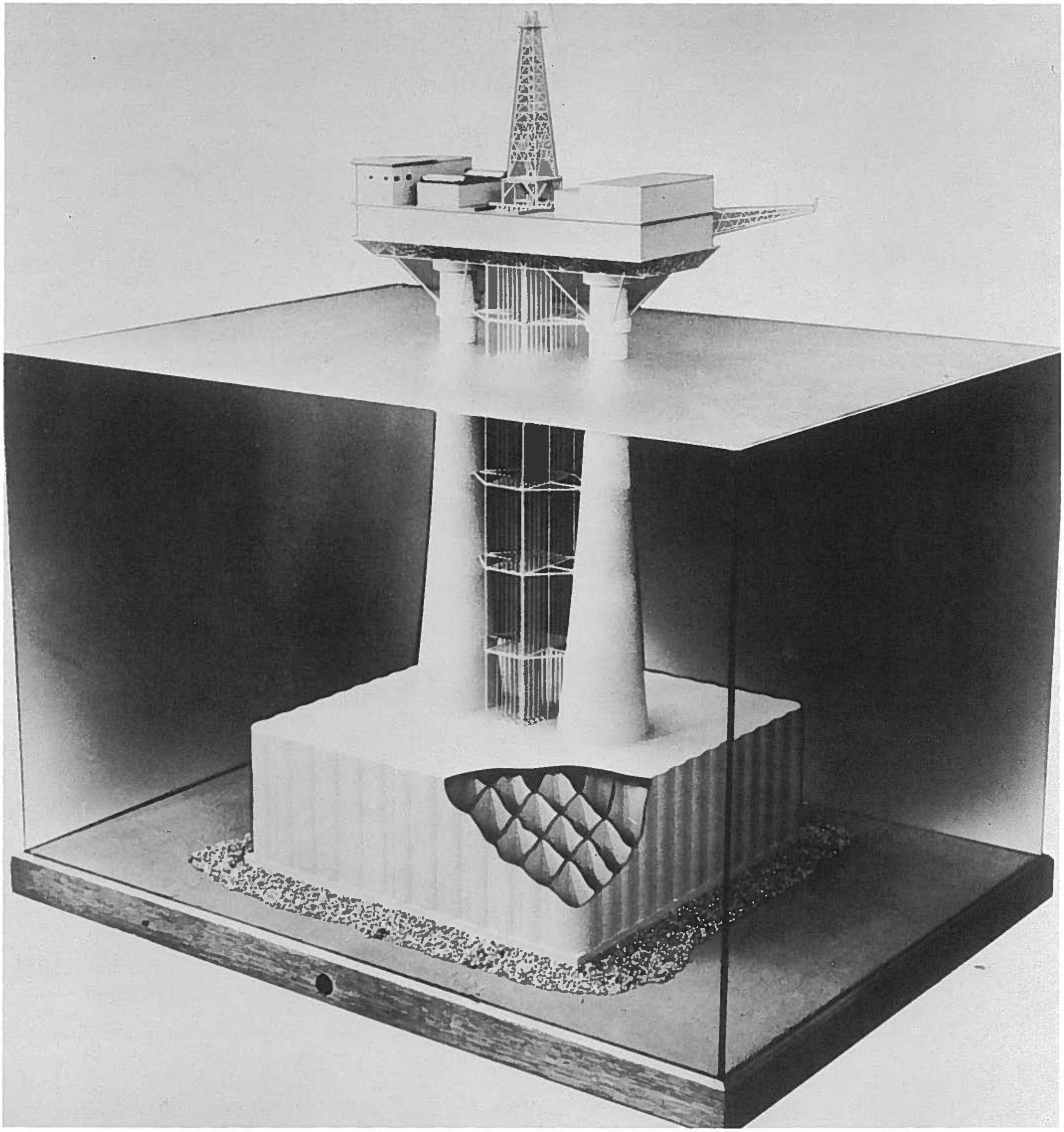
Deep water structure proposed by Selmer A/S for up to 300 meters water depth. Post-tensioned concrete construction of base, columns and deck.



Proposed floating airport of prestressed concrete pontoons
by Shell, UK and Harris & Sutherland.



Floating concrete facility for production storage and loading of
Liquid Natural Gas by Global Marine Development, Inc.



Model of a twin-towered prestressed concrete production platform, built to a scale of 1/200th exhibited by Sir Robert McAlpine & Sons Ltd., at the Offshore Technology Conference, Houston, Texas, 1975. It represents a platform with a base 368 feet square and 131 feet high, and with the completed tower will be 465 feet above the seabed.

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