PORT AND OCEAN ENGINEERING UNDER ARCTIC CONDITIONS
TECHNICAL UNIVERSITY OF NORWAY

UTILIZATION OF PRESTRESSED CONCRETE IN ARCTIC OCEAN STRUCTURES

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The proper development and exploitation of the resources of the waters of the Arctic requires structures which are capable of surviving the extremely severe environment, and ice loading conditions, which are capable of rapid construction at the site, yet which still remain within practicable limits of cost.

The arctic regions are dominated by ice in its various forms, from drift ice and shore-fast ice on up to ice sheets, with their rafting and pressure ridges, and even the possibility of ice islands. Failure of ice in crushing develops a cycle within the resonant frequency of many types of structures. Local pressures require rigidity against deformation and buckling. Ice may cause severe abrasion, including "plucking" of particles from the surface wherever there are discontinuities.

The low temperatures prevalent in the Arctic place severe demands on ductile behavior under impact.

Waves, while generally less severe in height and period than in the upper temperate zones, may still be limiting criteria especially during the construction period. In the shallow waters of the Arctic Ocean, storm surges can raise the water level 2 to 3 meters.

Many areas of the Arctic Ocean are subject to seismic disturbances. The structure is then subjected to combinations of loading, including its own acceleration, the acceleration of the adjacent water (virtual mass), and the acceleration of or crushing of the ice. Consideration must therefore be given to probabilities and risk evaluation, including the acceptability of minor lateral displacement of the structure.

Any structure founded on the soil becomes part of a ice-water-structure-soil system. The interaction between these elements, and especially between structure and soil must be carefully evaluated. Permafrost beneath the surface and its possible degradation due to the heat from oil production may present special problems. The possibility of liquefaction of the soil under seismic disturbance or during construction must be considered. Other papers at this conference are devoted to more detailed discussion of these environmental considerations. It is the purpose of this paper to concentrate on the structure and to determine the ways in which prestressed concrete may be most effectively utilized for the construction of structures in this environment.

It is important that consideration be given to the nature of failure of the structure under overload or accident conditions. Brittle and catastrophic types of failure are extremely undesirable; ideally, partial failure will cause a redistribution of loads and will be self-localizing. The width of cracks must be restricted by reinforcement or prestressing. Safety against pollution of the environment may be of more ultimate importance than safety of the structure itself.

The above criteria are analogous to those controlling the design and construction of nuclear reactor pressure vessels. The same general approach of limit states, with varying factors of safety, depending on probability and consequences, should be employed.

A number of structures have been studied for utilization in the Arctic waters for various purposes: exploratory drilling platforms, production drilling and processing platforms, offshore oil storage, shipping terminals, bridge piers, tidal power stations and even submarine tanker hulls. For these, concrete and especially prestressed concrete has proven to be the most suitable material. With it, structures of large mass can be economically constructed. Shapes involving cones and double-curvature (as necessary to minimize ice pressures), are readily fabricated. The behavior of prestressed concrete at very low temperatures is still ductile, as shown by the tests for cryogenic applications. Concrete inherently possesses rigidity. Freeze-thaw resistance can be assured through the use of adequate air-entrainment. Natural vibration periods are out of the range of possible resonance with ice crushing.

Abrasion, and plucking due to adhesion of the ice, may present problems: these can be overcome by the employment of "armor" of steel sheets or other suitable materials.

As in the case of nuclear reactor pressure vessels, failure under overload may be localized and contained by well-distributed reinforcement and especially multi-axial prestressing. Ductile steel or epoxy liners may be utilized to span across any cracks and thus provide a leak-tight membrane.

Such concrete structures can be prefabricated in a warm water port, as floating barges, caissons, or vessels. They may then be towed to the site in the Arctic during open water, and sunk and secured in place. Securing to the soil can be accomplished by gravity, obtained by water ballast or sand and gravel fill, or grout-intruded aggregate; by prestressing to the soil; by pin piles; by anchors; or by sinking the structure into the soil as a caisson. A combination of these may be employed to successively stabilize the structure against the loadings which may occur immediately after installation, and those which will occur later in the season.

Water ballast, followed by dredging within the structure and its sinking as an open caisson, has many favorable aspects, especially if ice loading may occur shortly after installation.

The prestressing technique may also be beneficial in the assembly of modules at the site. Individual barges or caissons of a suitable size and shape for towing would be placed in proper position relative to each other after arrival at the site, and the segments would be then post-tensioned together. The assembly and joining procedure might thus resemble present practice in subaqueous vehicular tunnel construction.

Any anchors which are used, as for example in shallow water, will require prestressing to ensure equal distribution of loading and to restrict the displacement of the structure within allowable limits.

Prestressing enables the designer to control the behavior of the concrete sections under non-uniform loads, for example, by forcing the structure to act as a shell. The typical cone section for an Arctic Structure may have a shell 3 to 4 m thick . Under external loading, the shell tends to fail by in-plane lamination and implosion. Prestressing may be used to equalize strains across the section.

Prestressing may also be used to resist high shear forces, both by increasing the normal compressive force and as direct shear reinforcement.

Because prestressing permits generally thinner structural sections to be obtained, due to its greater efficiency as compared with unstressed mild or high-yield steel reinforcement, it reduces the dead weight and thus reduces draft for towing in critical areas such as around Point Barrow.

Prestressing offers a direct economy over conventional steel in many cases, i. e. a saving in material cost. Because the time of installation of an equivalent resisting force is greatly decreased, prestressing may make possible a reduction in the time required for prefabrication.

Prestressing may generally best be applied by the use of large concentrated strand tendons for principal reinforcement, with the tendons encased in rigid watertight steel ducts, later filled by controlled grouting. For secondary forces such as shear, high tensile bars, protected by grout or bitumastic compounds, are generally suitable. Principle tendons may be circumferential, placed in segments, with the anchors on the inside of the shell, or they may be helical and crossing, as employed in prestressed concrete nuclear reactor pressure vessels.

Special care must be given to the concrete, including the use of a rich, dense, mix; containing air entrainment in the zone which will be exposed to the atmosphere, and using aggregates of known frost-resistant quality. Anchorages for post-tensioning tendons should be recessed and filled with epoxy mortar. If heating ducts are used, they must be of steel, as embedded copper or aluminum might produce electrolytic corrosion of the tendons.

A review of some specific structures studied for Arctic utilization will illustrate these principles.

DRILLING AND PRODUCTION PLATFORMS FOR SHALLOW WATER (Fig. 1)

The required shape for such a structure in place is usually a polygon, giving maximum work area with minimum frontal area opposing the ice. To accomplish this and still have towable vessels, two barges can be placed side by side and joined.

In shallow water, the ice becomes locked to the bottom. Maximum ice pressure will occur during spring break-up, with rafting and pile-up due to wind. The barges, therefore, must be designed to minimize pile-up and protect the drilling and production equipment from damage. If a berm is provided on which the piled-up ice collects, its weight will help to increase the stability. Sloping sides will minimize initial pile-up forces whereas vertical sides may force the pile-up to remain seaward of the barge side.

While the over-all load on the barge side may only be 7 Kg/cm^2 or so, local concentrations may reach 25 Kg/cm^2. The barge sides must therefore be designed to resist local forces of this magnitude in shear and bending.

The cells must be protected against internal freezing and bursting either by draining, or by providing expansion-cushioning material such as styrofoam.

Prestressed lightweight concrete may be used to reduce draft to enable access to very shallow water.

CAISSONS FOR DEEP-WATER DRILLING AND OFFSHORE TERMINALS

In the deeper waters outside of the offshore islands, the structure must be designed to withstand the load of the solid ice sheet and of pressure ridges. It becomes necessary to select a structural configuration which will minimize the total load. The use of a cone section is attractive from both a structural and an ice viewpoint. With a cone, the advancing ice sheet tends to ride up and fail in tension, with both radial and circumferential cracks. The cone should re-curve at the top in order to prevent excessive ice ride-up.

For many locations, such as the Beaufort Sea, maximum ice loadings may occur within a short period after start of installation. Thus it becomes necessary to adapt a concept that will achieve stability within 2 to 3 days time. The dredging and placement of a sand or gravel bed may be required in areas of weaker soils.

Concrete caissons embodying the cone principle were selected for the proposed offshore terminal module for Humble Oil Co., Fig 2. This structure, located about 40 kilometers north of Prudhoe Bay, Alaska, in 30 meters of water, would consist of a reinforced concrete caisson 85 meters in diameter. The lower portion of the caisson was to have been constructed in a basin in Puget Sound, and launched with a draft of about 6 meters. It would then be taken to an adjacent outfitting dock in deep water where its walls would be extended upward, giving it a draft of some 20 meters at completion. For towing across the Gulf of Alaska, special towing skegs were to be added to prevent yawing and rotation. After passage around Point Barrow, the caisson would be taken to the site, sunk by water ballast, and immediately filled with sand and gravel.

Concrete caissons of similar configuration, but with an enlarged base have been given serious study for deep water drilling and production platforms, Fig 3, 4, 5.

OFFSHORE STORAGE

To augment such a loading terminal, underwater storage may well be employed. The constant temperature of the water (about -2°C) is beneficial in preventing gelling of the oil. The tanks will preferably be built of prestressed concrete because its weight can be used for gravity stabilization against lateral forces, it is economical, non-brittle at low temperatures, and has rigidity against local load concentrations. Finally, multiaxial prestressing and/or reinforcing provides security against catastrophic ripping and oil spillage under accident conditions.

The only ice loading that must be resisted is that of pressure ridges and possibly ice islands. Fortunately, only the lower portion of the ridge will impinge on the underwater storage vessel, and here the ice is normally weak and porous.

A proposed surface terminal incorporating underwater storage is shown in Figs 6 and 7.

INTERCONTINENTAL PEACE BRIDGE

The proposed Intercontinental Peace Bridge across the Bering Straits, although possessing little if any economic justification, stands as a potential monument, a symbol of the joining together of the continents of the world, a re-establishment of the Bering Land Bridge over which man first came to the Western Hemisphere, and a linking of the United States and the U.S.S.R. in a joint construction effort.

Such a bridge has now become technologically feasible. It can employ many of the concepts originally developed for the Northumberland Straits Bridge in Eastern Canada, whose construction has unfortunately been indefinitely delayed.

The Intercontinental Peace Bridge, as presently envisioned, would utilize caisson piers of prestressed concrete, manufactured in an open-water port, towed to the site, up-ended and sunk, then post-tensioned to the bottom through holes drilled from the structure itself. Such a system lends itself to the short working season, exposed location, and extensive repetition of operations. These caissons would be of cylindrical cross-section, surmounted by cones and ice-deflectors, Figs 8, 9, and 10.

NEW DEVELOPMENTS

In the materials field, a very interesting development is taking place with polymer-impregnated concrete. Precast concrete, immersed in a monomer, is then exposed to irradiation or thermal treatment which converts the monomer to a polymer. The resultant concrete is very high strength, up to 1600 Kg/cm^2, impermeable, and with excellent abrasion resistance. While commercial production has not yet commenced, and the detailed application to barges and caissons must be worked out, this material would appear to be of major significance for future structures in the Arctic.

Another development having important implications for Arctic Structures is that of concrete containing dispersed polypropylene or wire fibers, (e.g. Wirand, developed by Battelle Development Corp.). Fiber-reinforced concrete possess greater tensile, shear, and impact resistance.

Further investigation and development is needed into the matter of adhesion resisting surface materials. Perhaps fiberglass or teflon or neoprene coatings could be utilized effectively.

SUMMARY

High quality prestressed concrete appears to be especially well suited for the construction of a wide variety of Arctic structures. It possesses excellent properties for resisting the environmental loadings and conditions, and is inherently practicable and economical. As further development of the Arctic Ocean and its adjoining waters takes place, prestressed concrete will undoubtedly play a major role.

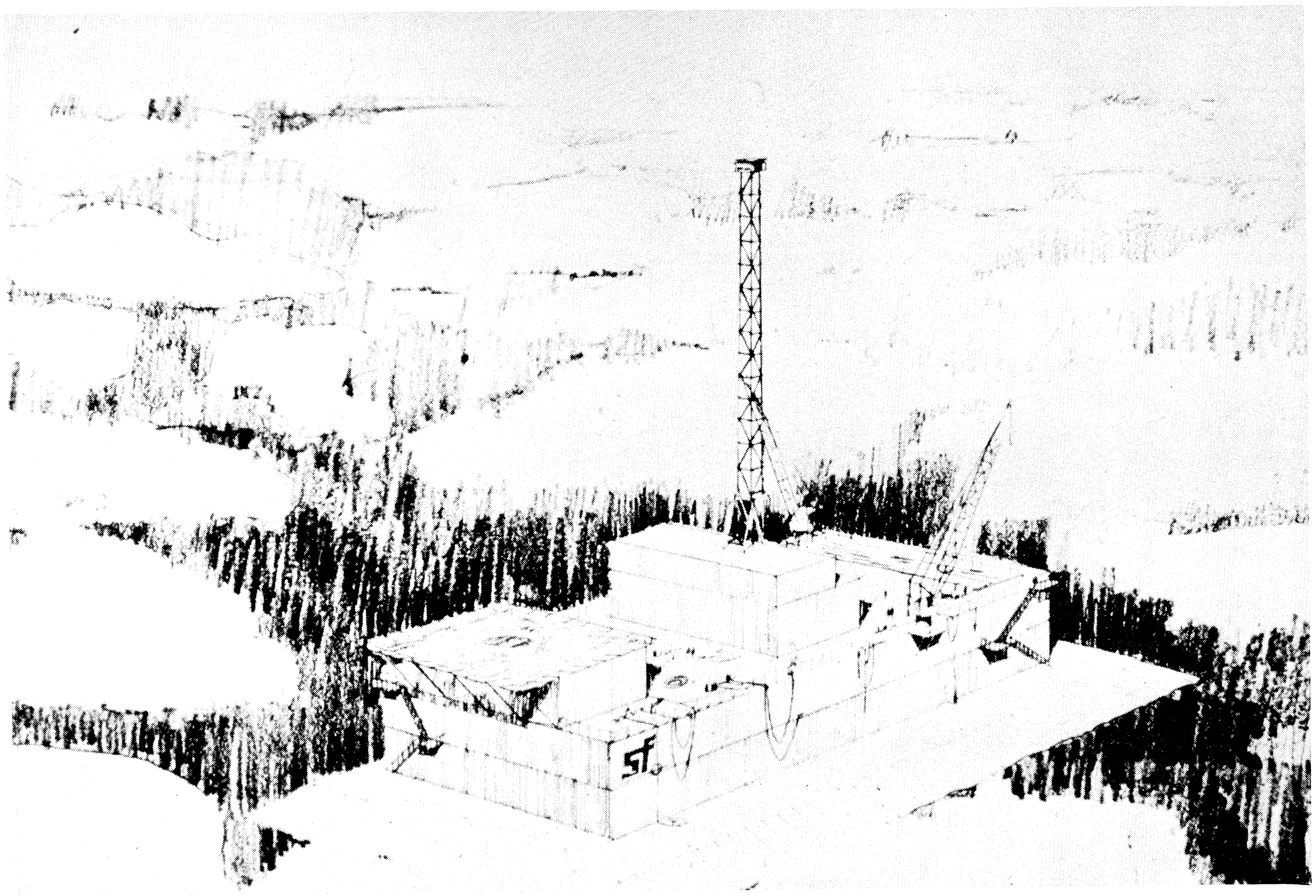

FIGURE 1. DRILLING AND PRODUCTION PLATFORM FOR SHALLOW WATER

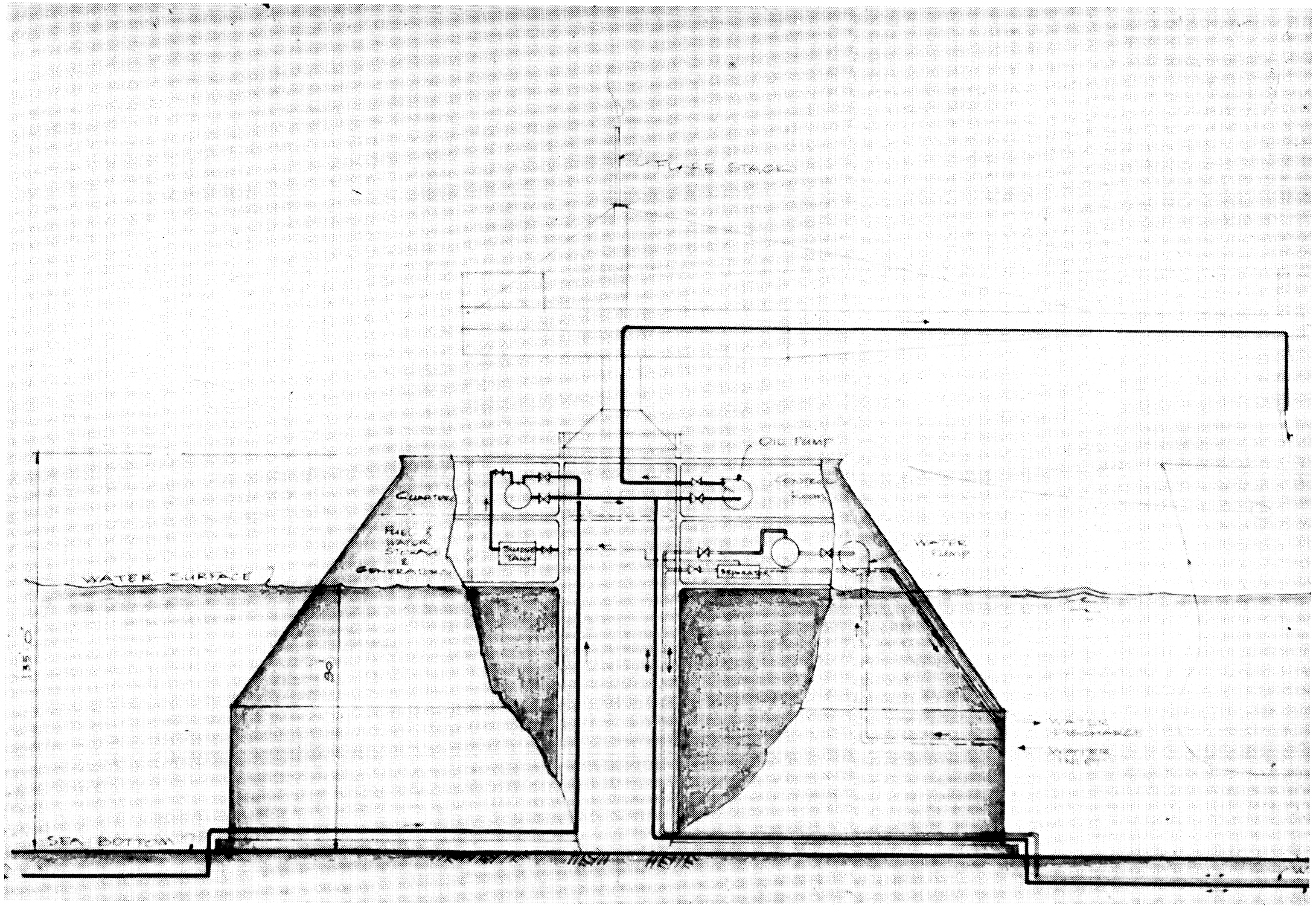

FIGURE 2. PROPOSED OFFSHORE TERMINAL MODULE FOR HUMBLE OIL CO. AT PRUDHOE BAY

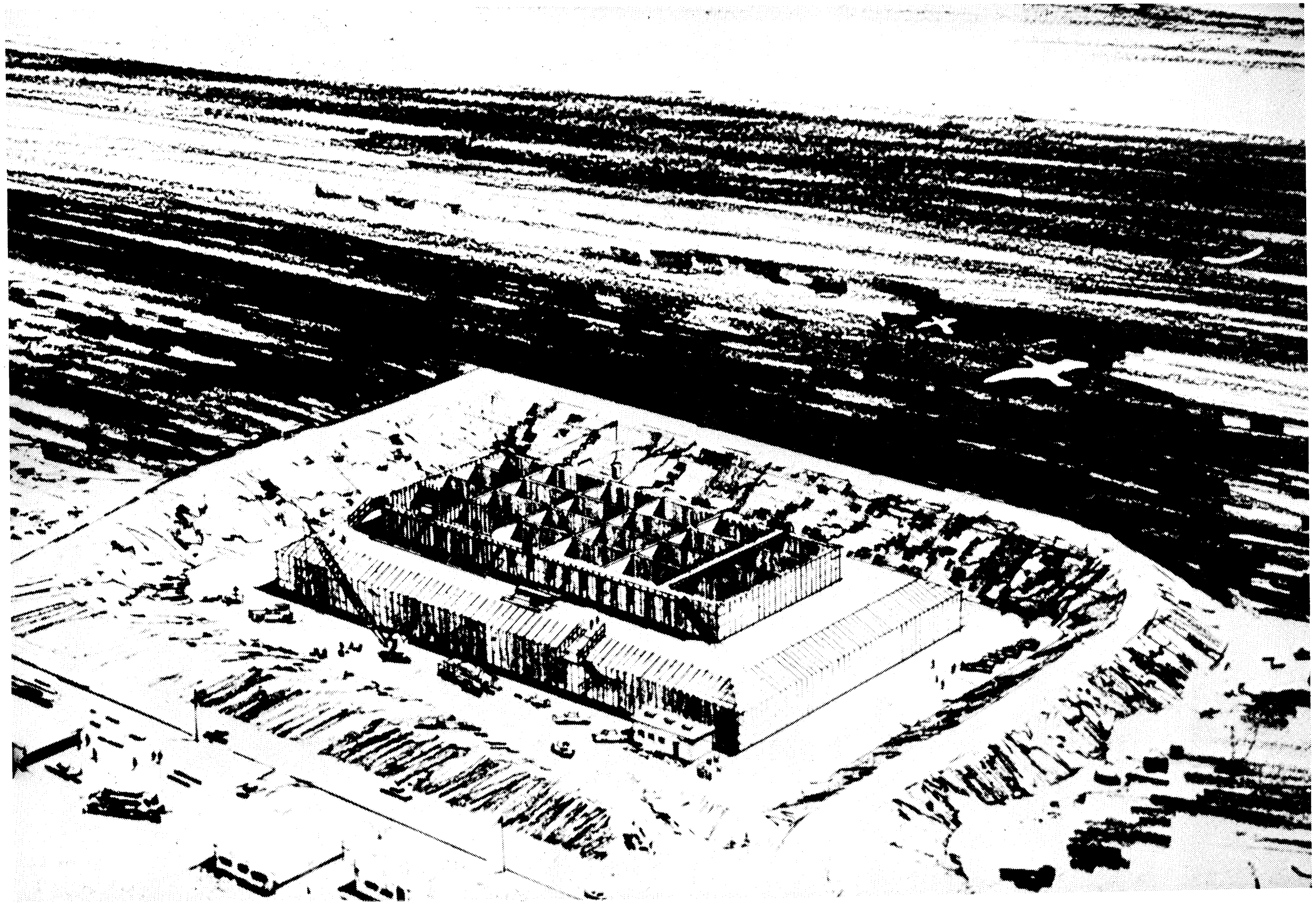

FIGURE 3. CONSTRUCTION OF CAISSON BASE WILL BE PERFORMED IN BASIN AT WARM WATER PORT

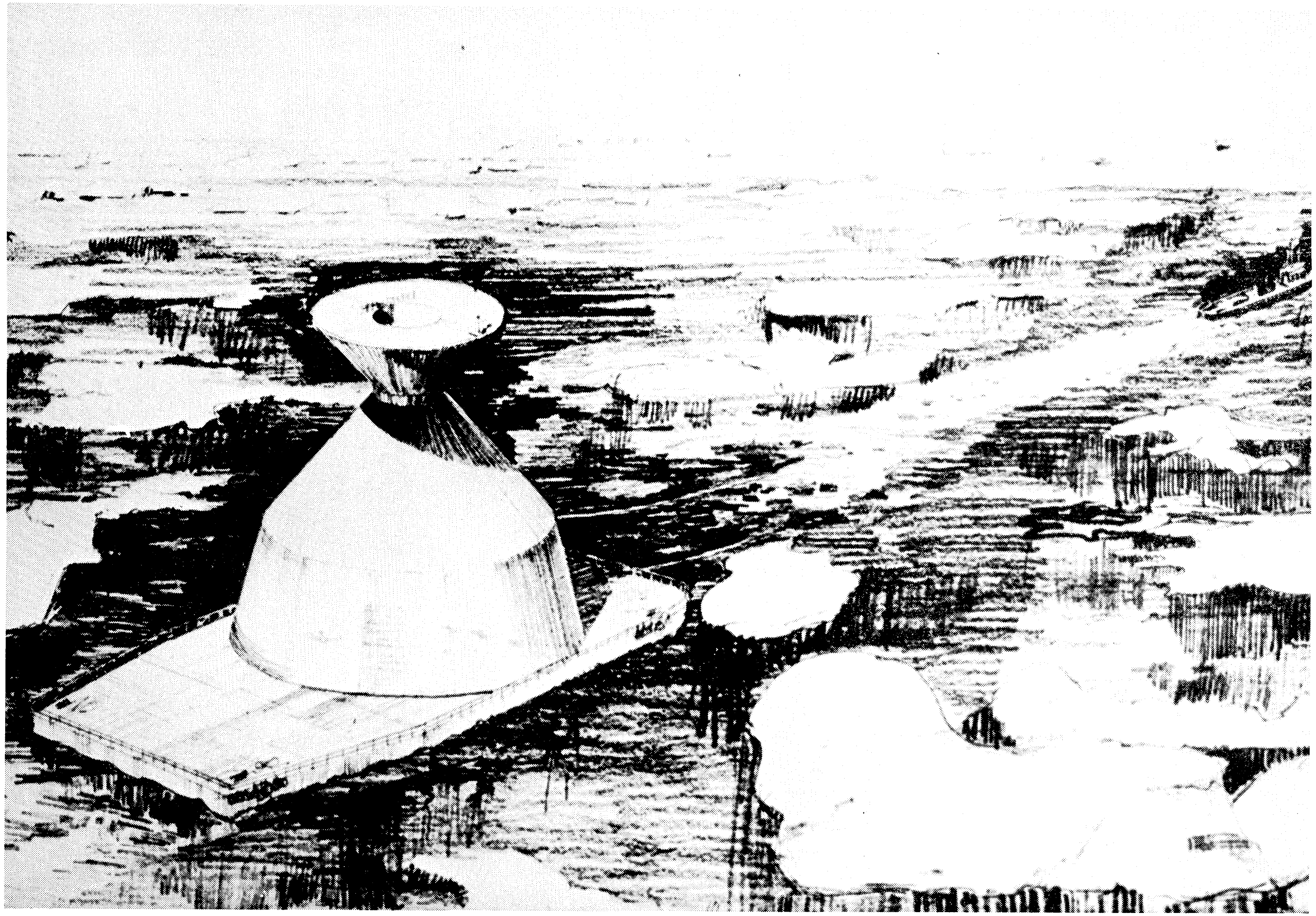

FIGURE 4. TOWING OF CAISSON TO SITE

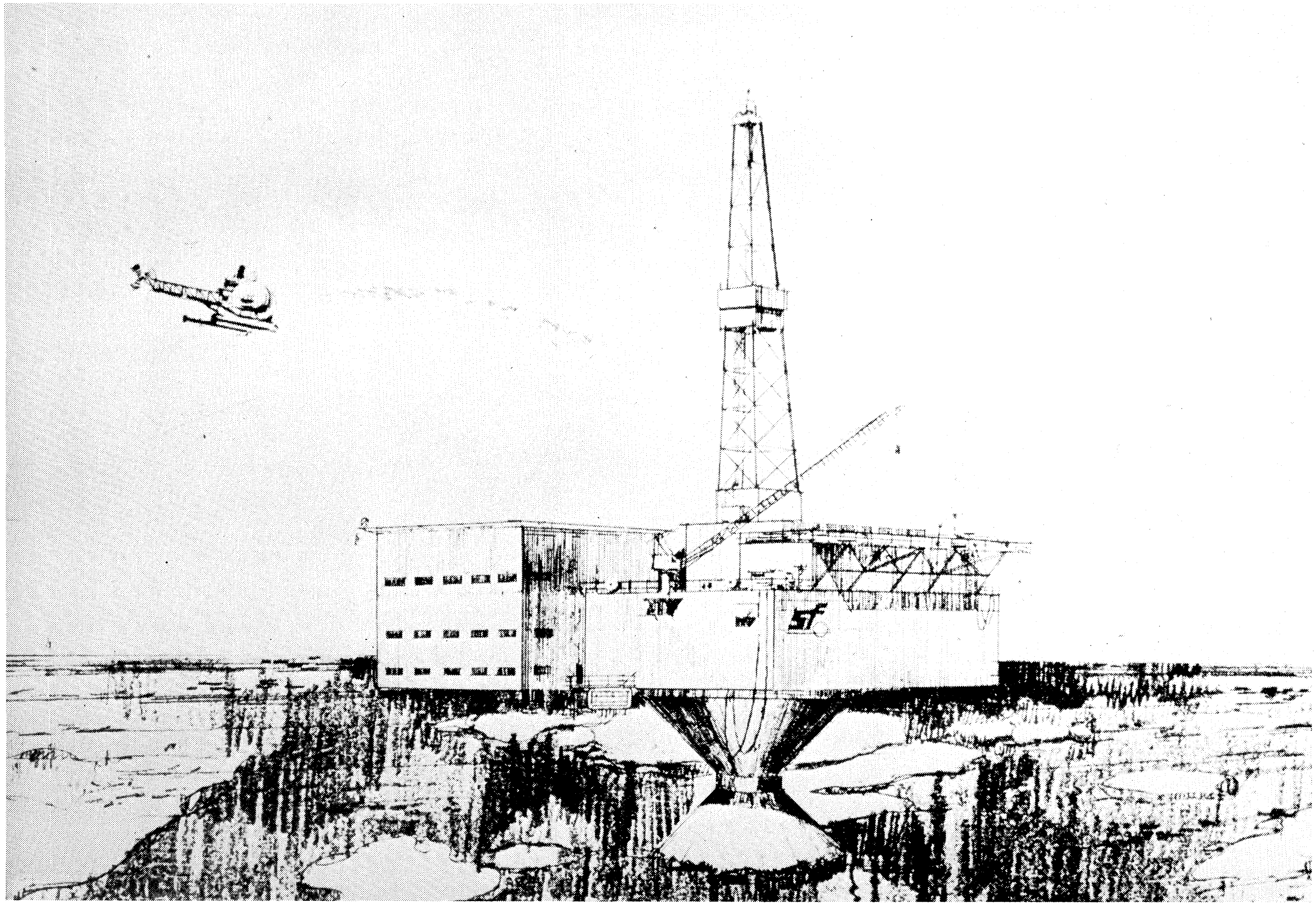

FIGURE 5. CONCRETE CAISSON IN PLACE TO SUPPORT DRILLING AND PRODUCTION OPERATIONS

FIG. 6. PROPOSED TERMINAL INCORPORATES UNDERWATER OIL STORAGE

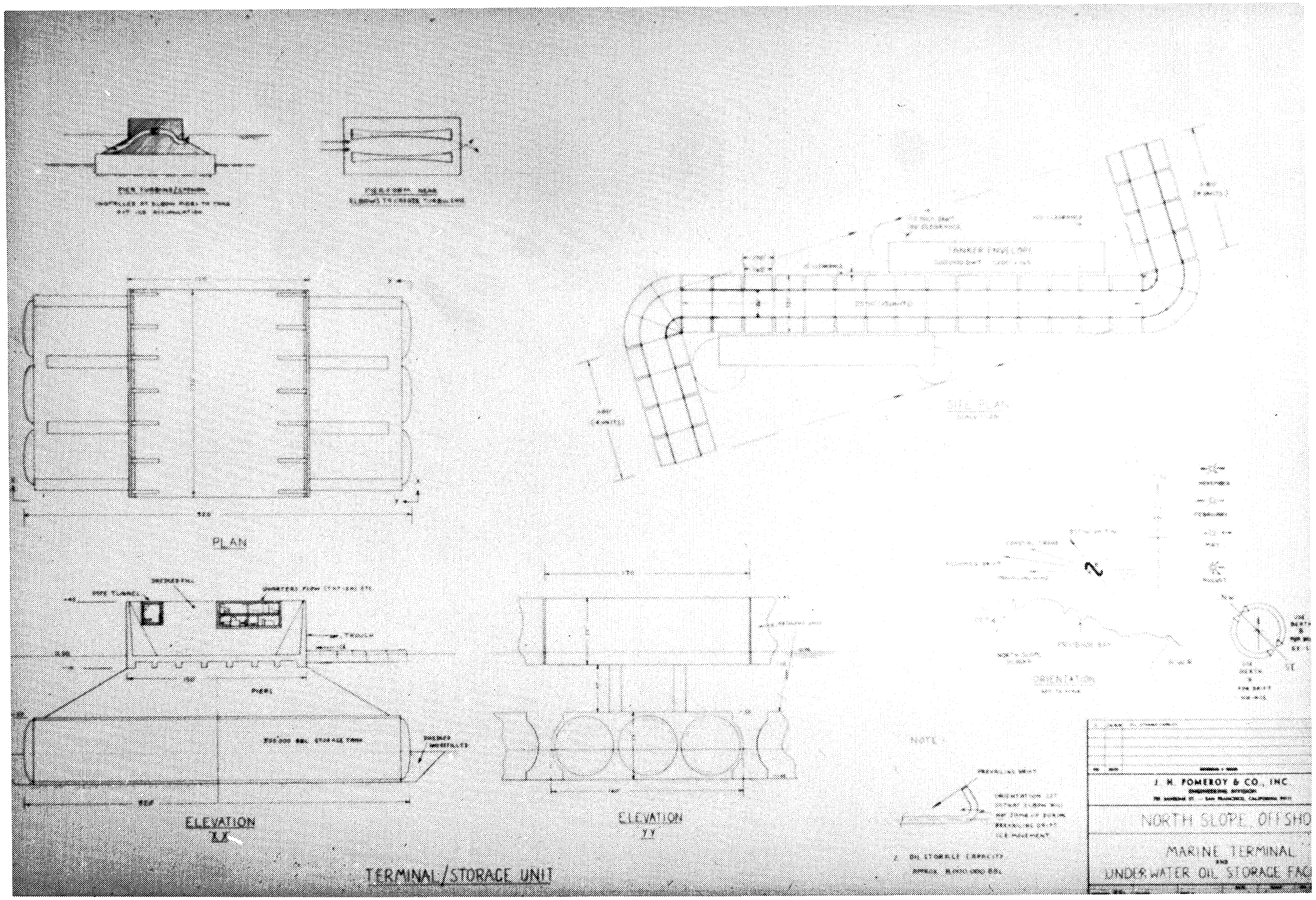

FIGURE 7. DETAILS OF PROPOSED Z TERMINAL

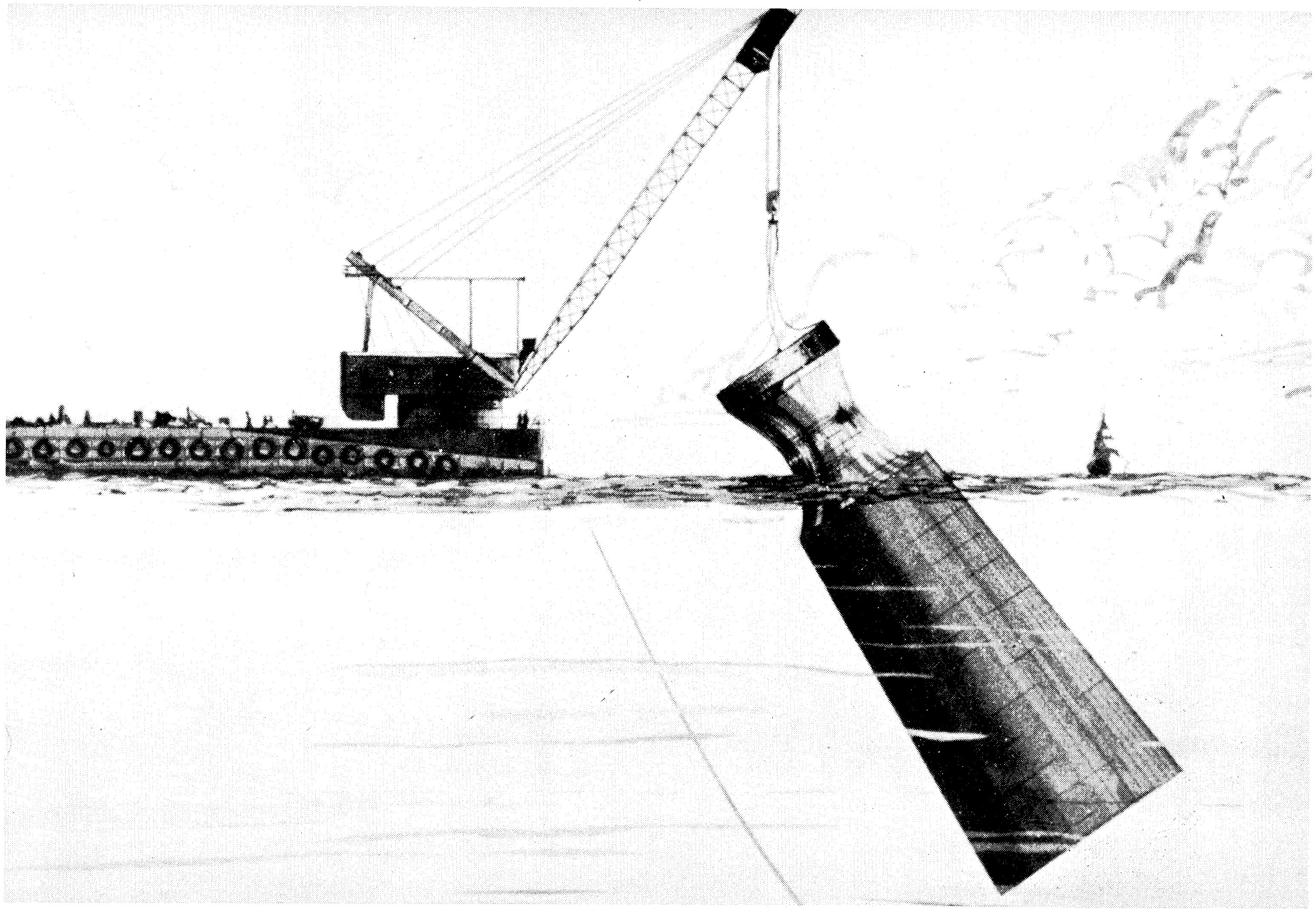

FIGURE 8. UP-ENDING OF CAISSON PIER FOR PROPOSED BERING STRAITS BRIDGE

FIGURE 9. PRESRESSED CONCRETE CONE WOULD BE POST-TENSIONED TO SEA FLOOR ROCK

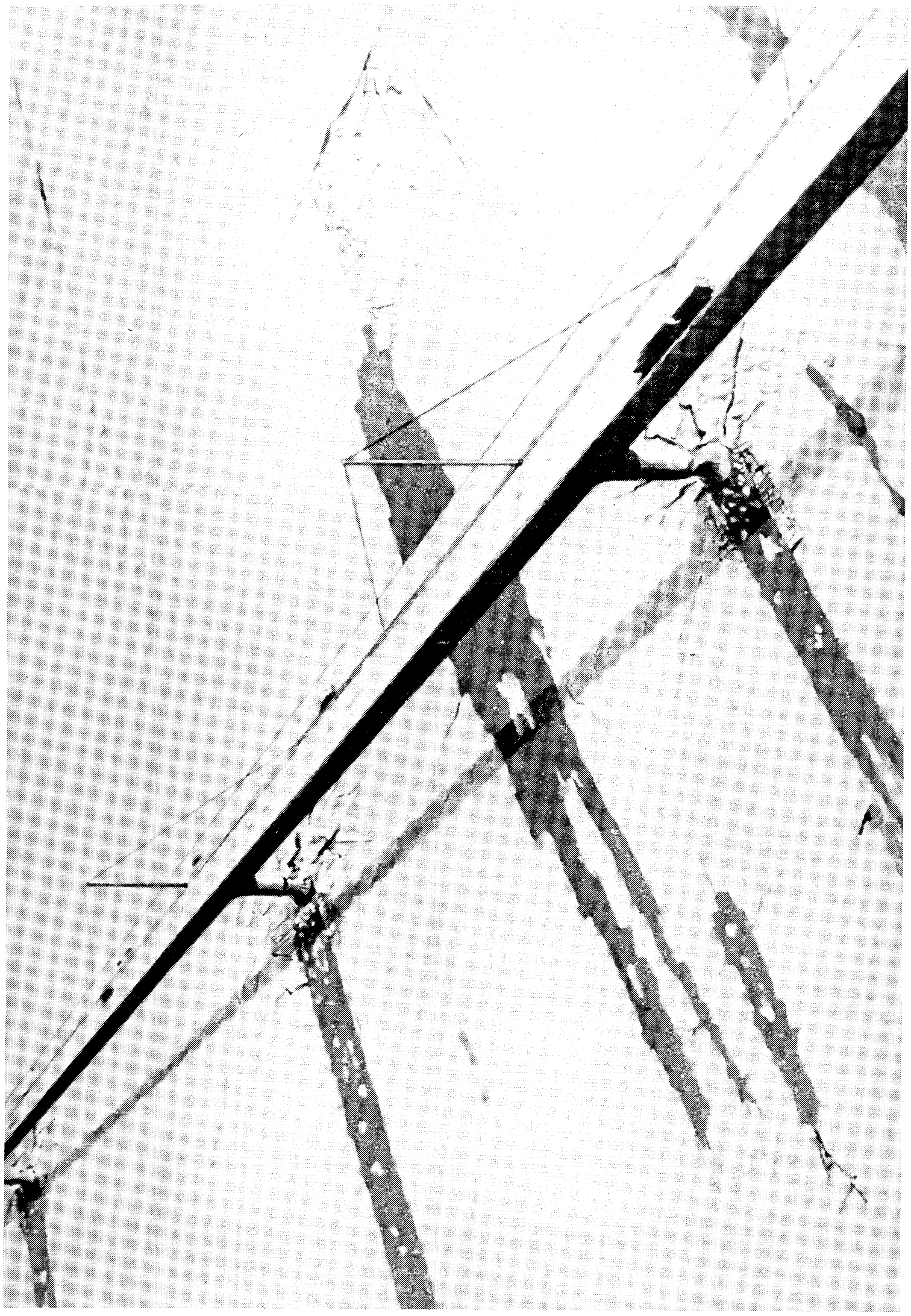

FIGURE 10. INTERCONTINENTAL PEACE BRIDGE JOINS ALASKA AND SIBERIA