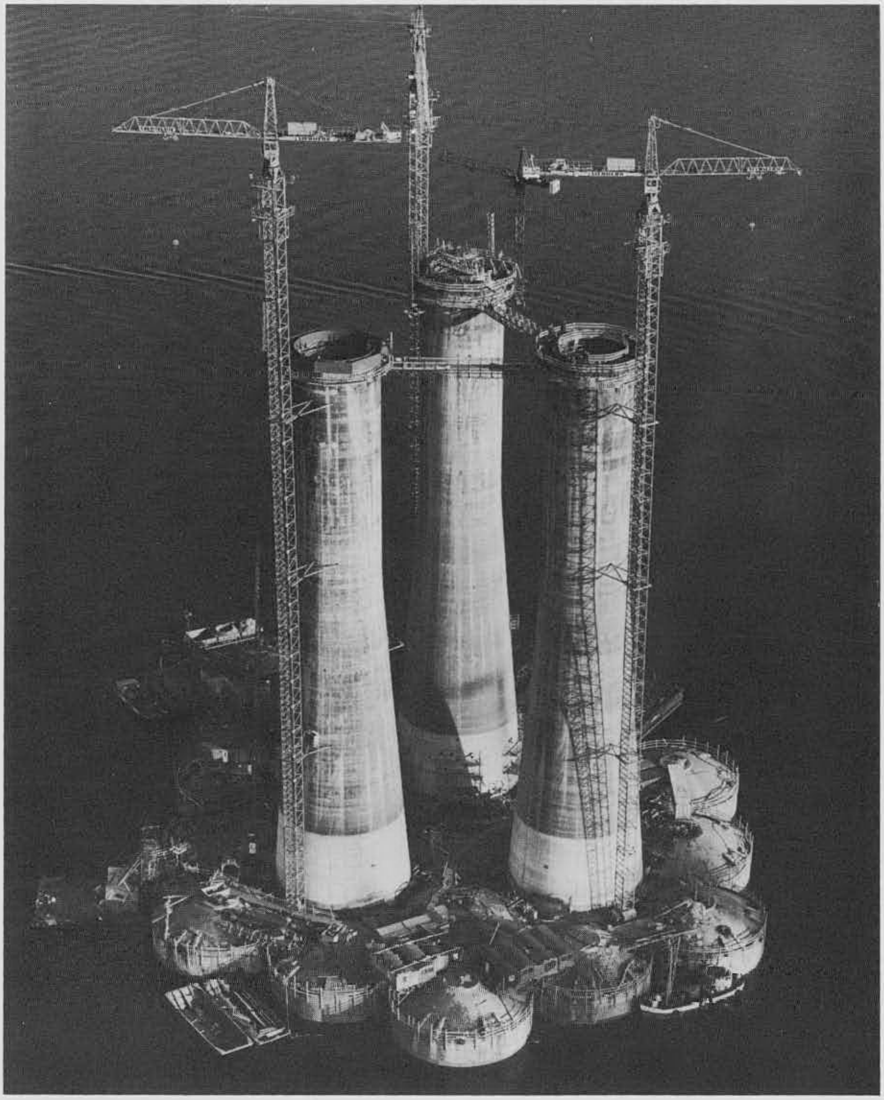

DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES IN THE NORTH SEA

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For the development of a number of major oil fields in the North Sea, prestressed concrete caissons have been selected. These huge structures have bases up to 100 meters square and stand 200 meters from sea floor to deck level. A typical structure will contain 100,000 cubic meters of prestressed concrete and provide storage for 1,000,000 barrels of oil. These are among the most complex and sophisticated structures ever undertaken, and require the integration of many engineering disciplines for their accomplishment.

These structures pass through many design stages during construction and service: fabrication in a dewatered basin, launching, completion afloat, submergence to mount the steel deck structure, towing to the site, submergence to the sea floor, and founding, followed by alternate filling with hot oil and displacement by cold water. Most important of all, they must safely weather the repeated severe storms of the North Sea.

The new oil discoveries in the North Sea lie almost exactly half-way between Scotland and Norway, in water depths of 70 to 160 meters, and are exposed to some of the worst sea and wind conditions in the World. The proper development of these fields has required consideration of many factors. The trend is to the construction of very large integrated platforms, capable of supporting drilling and production operations, processing of gas for transmission, reinjection of gas or water, and interim storage of oil. Such a platform may support a large number of deviated wells drilled from it in addition to adjacent sea-floor completion satellite wells. The newest platforms must support almost 40,000 tons of equipment on top.

The development of these concrete sea structures has been very radical and very sudden. The first such caisson, Ekofisk, was commenced in 1971 and is now in place and in service, showing excellent performance in full accord with predicted values, during the storms of the last two winters. The successful installation of Ekofisk unleashed an intensive effort in design of concrete caissons for deeper water and more severe conditions. Twelve such structures are now under construction, with valuations ranging from 100 to 350 million dollars each.

It is important to recognize the contributions of various organizations in responding to this challenge: the enterprise of Norwegian, French, and British constructors, the critical roles played by U. S. engineers in providing technical expertise, the work of Det Norske Veritas in providing certifica-

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*Professor of Civil Engineering, University of California, Berkeley tion capability and of Lloyds in providing insurance. A particularly important need was filled by FIP, the International Federation of Prestressing, in the timely holding of International Symposia on Concrete Sea Structures and in promulgating Recommended Practices for Design and Construction.

The over-riding determinant in the design of these structures is the wave force. Typically, the 100-year design wave may be 30 meters with a 16.5 second period, exerting a lateral force of 40,000 tons. Attention is also paid to the energy distribution in the wave spectra to ensure that maximum design forces are accurately calculated for the various portions of the structure. Dynamic amplification of the structure-soil system is added.

Uplift forces, as the wave passes, will frequently equal or exceed the lateral forces, but fortunately are out of phase with them.

These wave forces are almost entirely inertial in character, heavily influenced by the mass of the enlarged base. They tend to cause sliding of the structure, aggravated by their cyclic nature and rocking and overload of the soil in bearing.

Obviously the foundations for such structures are critical. Soil sampling and investigation is extremely difficult and there are usually far less good data developed than desired. Fortunately, North Sea soils are quite strong, being of glacial origin, and hence can usually provide adequate bearing. Thus potential shear or sliding failure under cyclic loading may determine the size of the base. To improve this aspect and also to prevent scour, steel or concrete skirts are provided which penetrate 3 to 6 meters or so into the sea floor. Permanent drainage is provided for sand strata to prevent pore pressure build-up under storm waves, with risk of liquefaction.

To resist the dynamic loads of the waves without fatigue, the towers or columns of such structures must be prestressed. The hugh hollow base is used to provide flotation during construction, tow, and installation, and oil storage thereafter. Compartments of this base are subjected to very heavy external hydrostatic forces during construction and installation: of the order of 100 to 150 tons per square meter (20,000 to 30,000 psf). When the structure is landed on the seafloor, local hard spots may produce concentrated loads on the base which are two to three times as great. Thus shell design (cylinders, domes, haunches, etc.) is employed, and detailed studies must be made of moments and especially of shears. Existing programs and codes have proven inadequate and recourse must be made to fundamental theory, especially in determining ultimate shear capacity of the sections in question.

The construction of such structures is carried out in a sequence: the base is constructed in a basin to a height of 10 meters or so, then floated out to deep water and completed afloat. Various construction techniques are employed and combined, including slipforming, panel forms, precast concrete segments, etc.

Very high strength concrete is employed, and strict quality control is exercised throughout. Frequently 600 or more skilled workmen will be employed to carry out the many aspects of work required.

While the concrete structure is being constructed, the steel deck, about 7000 tons to box girder construction is being fabricated. The concrete structure is now ballasted down in protected but deep water, until only a few meters of the column tops protrude above the surface. The deck is now floated in over the top, on barges, and the structure de-ballasted to transfer the deck to the columns. This is generally the most critical stage in the structure's life; due to the extreme hydrostatic pressures on the base.

One of the advantages of the caisson concept is that all the oil and ballast piping, controls, and much of the equipment can be installed and tested while the structure is still afloat in the fjord. Then, during the best weather season (June-July and perhaps August), the structure is towed out to sea. The largest tugs in the world are used, 12,000 to 20,000 shp, and up to 5 are used in parallel to move the huge mass which draws about 60 meters and displaces 500,000 tons. Once arrived at the site, perhaps 7 days after leaving, the tugs fan out to hold the structure in position while it is ballasted down to the sea floor: a process that usually takes 12 hours or so. By over-loading (ballasting) the structure, the skirts on the lower part of the base are forced into the soil. Uniform bearing is then achieved by underbase grouting, using special mixes.

Control and supervision of such a large and complex undertaking requires highly qualified engineers at all levels. Management of the operation requires detailed schedule control, especial attention to advance procurement, and meticulous planning.

The detailed design of these structures has to date been carried out simultaneously with construction, necessitating special contractual arrangements by which responsibilities and risks are clearly defined.

As could be expected with such accelerated schedules for unprecedented structures, problems have developed and there have been many anxious moments. Fortunately, as of now, all of these have been met and the next group of offshore concrete structures is on schedule, with tow out scheduled for the summer of 1975.

For example, the Ekofisk structure encountered problems with thermal cracking due to high heat of hydration. These cracks were filled with epoxy. Shears where found to be excessive for founding on the seafloor, where local "hard spots" might produce concentrated loads of 200 tons/square meter. A second heavily-reinforced concrete slab, one meter thick, was placed above the original slab and tied to it by thousands of drilled-in dowels.

On another structure now under construction, during one stage, differential ballasting was employed. Due to misunderstanding between the constructor and designer, certain empty cells were subjected to very high hydrostatic heads in the wrong direction, with consequent severe cracking. These cracks were successfully repaired in a major program of epoxy injection, grouted pre-placed aggregate, and structural modifications.

The three-dimensional analysis of the complex shell configurations for two current structures has proven extremely difficult, with the result that shears and moments at the juncture of domes and cylinders were under-estimated. Fortunately this was caught in time. Structural strengthening is now being carried out and internal air pressurization will be employed.

The successful identification and meeting of these critical developments is a tribute to the engineering and construction profession. While the majority of these problems are the result of pushing ahead so rapidly into new uncharted areas, they would never have been even recognized as potential problems if some enterprising individuals and groups had not had the courage to move ahead boldly and with confidence. Our knowledge in all the fields involved is increasing by leaps and bounds due to the dedication of those involved to ensure that the structures will have a high degree of safety for all conditions.

Additional design criteria and structural analyses are now being developed: collision from service vessels, cyclic thermal changes in the storage tanks, the impact of equipment or supplies dropped overboard during handling, and even possible sabotage. Such criteria are very real, but have not previously been widely applied to offshore structures. Risk analyses and failure-mode effect analyses are being carried out on a far more thorough basis.

These offshore structures represent a significant advance in engineering and construction and set a whole new pattern for offshore facilities of many types: offshore terminals, floating nuclear power plants, ocean energy facilities, and facilities for increased production of petroleum from the continental shelf and eventually from the continental slope. Perhaps of greatest long-range import, they have forced the integration of the diverse disciplines of structural engineering, foundation engineering, materials technology, mechanical engineering, naval architecture, hydrodynamics, construction engineering and management, all within a framework that requires full consideration of economic, political, and environmental factors.