Offshore Concrete Gravity-Based Structures

ACI Committee 357 members report on updates to ACI 357R

by Widianto, Erik Åldstedt, Kjell Tore Fosså, Jonathan Hurff, and Mohammad S. Khan

A gravity-based structure (GBS) is a massive foundation placed on the seabed to serve as the base for offshore structures. These structures can be relatively compact, such as a wind turbine, or quite extensive, such as an integrated oil drilling and production platform (topsides), which generally also includes oil-storage caissons. For the latter case, a GBS typically consists of a concrete caisson and multiple shafts (Fig. 1). The caisson can be built up using several circular cells or straight walls, or a combination of cells and walls, and its bottom and top are usually closed by domes or slabs. The shafts extend above the caisson to a safe level above water, where they support the topsides.

Design and Construction Challenges

More than 30 major GBS systems have been constructed for oil and gas production. Ekofisk, the oldest GBS, was installed in the North Sea, Norway, in 1973. Hebron, the newest GBS, was installed in the Grand Banks, Canada, in 2017.[1,2] Offshore concrete GBSs have several distinct features that pose unique challenges during analysis, design, and construction:

- GBS components are typically constructed in dry dock and near shore to minimize expensive offshore construction. Therefore, various floating stages are required during construction, including complex marine operations, to allow transport to and installation at the site (Fig. 2);
- Platforms can be massive in size. The Troll A platform, which was installed in the North Sea, Norway, in 1995, had a 370 m (1213 ft) tall GBS. The platform is the tallest structure ever moved.[4] The Gullfaks C platform, which was installed in the North Sea in 1989, is known to be the heaviest man-made object ever moved, weighing 1.5 million tonnes (1.65 million tons), including solid ballast and water ballast during towing to the installation site[5,6];
- GBS systems have complex geometries, containing a considerable number of "Disturbed" or D-regions such as connections among various

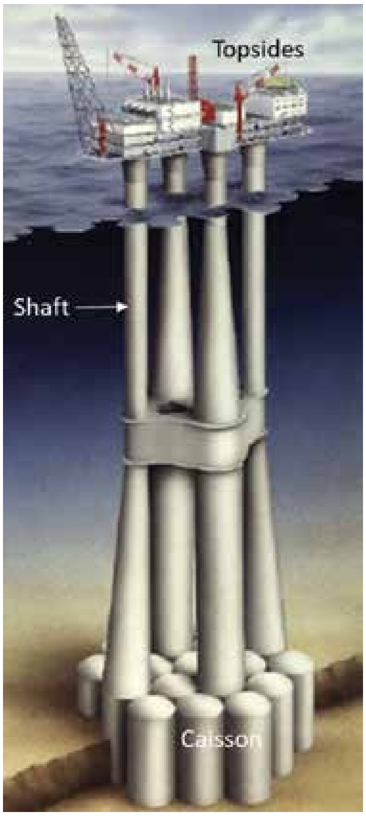

Fig. 1: A rendering of the Troll A platform. Its topsides systems include drilling equipment, production and processing facilities, and living quarters

Fig. 2: The Hebron float-over and topsides-GBS mating operation. The project set an industry record for the heaviest marine float-over and topsides-GBS mating operation[3]

Fig. 3: Slipforming of the Hebron GBS, Newfoundland and Labrador, Canada

Fig. 4: Sea ice impacts the Sakhalin II LUN-A Platform, Russia *(photo courtesy of Kvaerner)*

concrete components and the connection between the topsides structure and the GBS shaft. The loads imposed at the topsides-GBS connections are generally quite high. The Hebron GBS, for example, has the heaviest topsides with an operating weight of 65,000 tonnes (71,000 tons) supported on a single shaft,[1] which results in a reaction force of up to 20,000 tonnes (22,000 tons) at one connection;

- Slipforming is commonly used for the construction, with continuous concrete and reinforcing bar placement (Fig. 3). While this minimizes the construction schedule and construction joints (and thus minimizes risk of water seepage), it creates huge logistical and staffing demands. The largest slipforming operation in history is believed to have been carried out for the Gullfaks C GBS in Norway at its deep-water construction site. With a total slipform length of more than 3 km (1.9 miles) to construct more than 2/3 of the height of the entire 24 cells (each with 28 m [92 ft] inner diameter) at the bottom of the GBS, about 115,000 m^3 (150,000 yd^3) of concrete was cast in a continuous slipforming operation over 42 days[7];
- GBS systems have highly reinforced structural elements, with average reinforcement density of over 300 kg/m^3 (19 lb/ft^3), well above the density of 75 to 150 kg/m^3 (5 to 9 lb/ft^3) for typical buildings and bridges. Also, a GBS will contain many access openings and pipe penetrations that will require additional reinforcement to replace interrupted bars. This results in local reinforcement densities that can be as high as 600 kg/m^3 (37 lb/ft^3);
- Offshore structures are exposed to waves, and many are exposed to ice and iceberg impacts. Defining design loads generally requires site-specific statistical analyses and model tests, and these loads can be huge. For example, wave loads can exceed 1000 MN (225,000 kip) and iceberg impact loads can exceed 500 MN (112,000 kip). To resist wave loads, Troll A GBS has concrete skirts that penetrate 36 m (118 ft) into the seabed. Among the current GBS installations, only the Hibernia and Hebron structures were designed to resist iceberg impact loads. However, the Sakhalin I Arkutun Dagi, Sakhalin II LUN-A (Fig. 4), and Sakhalin II PA-B structures in Russia were designed to resist moving sea ice; and
- GBS cells in some platforms are used to store oil, so leak tightness is a functional requirement. To minimize cracking resulting from large differential pressures and temperatures, post-tensioning and special reinforcement detailing are needed.

Concrete Materials

Concrete mixtures for recent GBS projects have required concrete strengths of up to 100 MPa (14,500 psi). Mixtures must exhibit long-term durability in a seawater environment. Deleterious factors always include chloride and sulfate ions and may include exposure to freezing and thawing. To ensure good consolidation in the heavily reinforced structures, mixtures must have high slumps (nearly self-consolidating) without segregation. Relative to more conventional structures, the high reinforcement density in a GBS results in a much slower slipforming rate and an increased risk of surface damage due to adhesion between the concrete and the formwork sheathing.

To meet these extensive demands, concrete mixtures typically include slag cement, fly ash, and silica fume; high-range water-reducing admixtures; an air-entraining agent; and a retarder.

Update to ACI 357R

ACI 357R, “Guide for the Design and Construction of Fixed Offshore Concrete Structures,”[8] covers structures founded on the seabed that rely on gravity to achieve stability (specifically, GBS systems). The document places emphasis on special considerations for the analysis and design, material specifications, and construction of these structures. While it was reapproved in 1997, it has not been updated since it was first published in 1984.

A task group within ACI Committee 357, Offshore and Marine Concrete Structures, is currently updating the document. The task group consists of practicing engineers and educators who have extensive experience in the design and construction of major offshore facilities. Many are members of various committees that have developed international standards for GBS.

Most of the updates are needed to reflect lessons learned from more recent GBS projects as well as to reflect changes in applicable international standards. Concrete materials and mixtures changed significantly since 1984, so updates will include discussions of lightweight aggregates, current admixtures, and self-consolidating concrete. Durability requirements have also changed, so updates will include discussions of prequalification of materials, considerations for slipforming, duct and grouting requirements for post-tensioning tendons, large-scale testing, and mockups. In addition, data will be updated to reflect concrete strengths that are currently specified for GBS construction.

Structural analysis discussions are being updated, as well as load categories and load factors, to be consistent with current international standards. Also, a discussion is being added regarding the required multidisciplinary coordination to define loads resulting from, for example, marine operations, pipes penetrating on concrete walls, and drilling equipment.

A more detailed discussion is being added regarding serviceability requirements such as crack width and leak tightness. Also, additional guidance will be provided for checking against implosion, and reinforcement requirements across construction joints. Lastly, a detailed discussion of geotechnical soil investigations will be added, along with information on soil drains, skirt piles, and soil reactions for shallow foundations.

Technical Session on Offshore and Marine Structures

A two-part technical session titled “Offshore and Marine Concrete Structures: Past, Present, and Future” will be held at The ACI Concrete Convention and Exposition – Spring 2019, March 24-28, in Québec City, QC, Canada. This session is sponsored by ACI Committee 357, and it will highlight research that will result in more cost-effective offshore concrete GBS construction. The session will provide an overview of offshore and marine concrete structures, landmark projects, and recent advancements in design and construction practices, including materials technology. The presented papers will be published in an ACI Special Publication (SP).

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Selected for reader interest by the editors.

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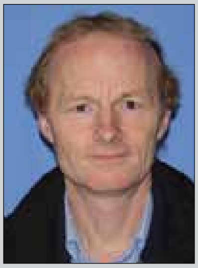

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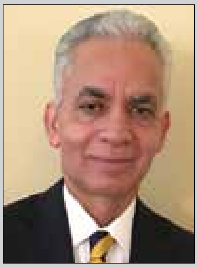

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