Bert Van Es, Nöel Pille, Robert de Vlaming and Jan de Vries

Construction of Wellhead Protection Glory Holes for White Rose Project, Canada

Abstract

Icebergs, driven by the Labrador Current along the eastern coast of Canada, form a serious hazard for offshore installations. Gravity base platforms are designed to sustain the impact of icebergs; FPSOs are equipped with quick release systems; and offshore support vessels are used to deviate icebergs by towing or jetting with heavy firefighting systems. Normally wellheads and manifolds are installed on the seabed only protected by a steel structure against fishing activities. In an iceberg environment the only adequate protection is to lower the wellheads and manifolds into the seabed in so-called Glory Holes.

This article presents two unique methods which were used during the Canadian Oil Company Husky Energy's White Rose Project to excavate the Glory Holes. Tideway and Boskalis excavated two Glory Holes in 2002 and 2003 with a heavy grab deployed from the DP Fall Pipe Vessel *Seahorse* using an underwater grab and drag system. Then in late June 2003 Vasco S.A., a member of the Jan De Nul Group excavated a third glory Hole by using its trailing suction hopper dredger *Vasco da Gama*.

Introduction

Icebergs, driven by the Labrador Current along the eastern coast of Canada, form a serious hazard for offshore installations and have to be taken into account in the design of offshore oil and gas facilities. Gravity base platforms are designed to sustain the impact of icebergs; FPSOs are equipped with quick release systems; and offshore support vessels are used to

Figure 1. Location map of White Rose field, with Jeanne d'Arc Basin.

deviate icebergs by towing or jetting with heavy fire-fighting systems. Normally wellheads and manifolds are installed on the seabed only protected by a steel structure against fishing activities. In an iceberg environment the only adequate protection is to lower the wellheads and manifolds into the seabed in so-called Glory Holes.

Tideway and Boskalis began excavation in late August 2002 with a large, heavy grab deployed from the DP Fall Pipe Vessel *Seahorse* using an underwater grab and drag system. The *Seahorse* is usually used as a rock-discharging vessel for the protection of offshore pipelines and ballasting of platforms. In this case by using innovative engineering a Grab Excavation Method deployed from the *Seahorse* was designed. Two Glory Holes were completed in 2003.

In late June 2003, Vasco S.A., a member of the Jan De Nul Group, excavated a third Glory Hole, sending its trailing suction hopper dredger *Vasco da Gama* from Singapore. This vessel is the largest trailing hopper dredger in the world and was equipped with a deep dredging suction pipe with a 6,500 kW underwater pump, enabling dredging down to 135 m water depth. In a later phase, extension of the dredging depth to 165 m is possible.

The Jeanne d'Arc Basin

The Jeanne d'Arc Basin is located approximately 350 km east of the Province of Newfoundland and Labrador (Figure 1). There are two other fields in operation in this basin:
– The Hibernia Field with operation from a Gravity Base Platform
– The Terra Nova Field, which is a FPSO based development.

The seabed in the Jeanne d'Arc Basin consists in general of glacial till, which can be subdivided in several soil layers. These can be summarised as follows:
– the top layer is a loose to dense silty fine/medium sand (marine deposit)
– the intermediate layer is a dense to very dense gravelly sand/sandy gravel (moraine or peri-glacial deposit). It includes an inter-bedded overconsolidated sand/clay layer and random isolated boulders
– the bottom layer consists predominantly of stiff to very stiff clay with inter-bedded layers of very dense, clayey sand (glacial till/boulder clay).

The Glory Holes

The size of a Glory Hole depends on the equipment that is to be installed and this, in turn, depends on the number of wells that are to be completed within the

After graduating from Delft University, The Netherlands (Civil Engineering) in 1980, Bert Van Es worked as project engineer on various projects for the Offshore Industry. He was involved in the development and commissioning of a Fall Pipe Vessel for rock dumping operations in deep water. In 1993 he joined Tideway, where he is presently responsible for special projects as Engineering Manager.


Bert Van Es

After receiving his degree in Mechanical Engineering from the University of Ghent in 1975, Mr. Pille joined Jan De Nul N.V. in 1976 where he has fulfilled a wide variety of positions in the last 30 years. He has worked on port reclamation and deepening projects, beach replenishment, presweeping, trench dredging and back-filling projects in Belgium and abroad. In 1992 he joined the International Dredging Division, Acquisition and Production, where he is presently Manager of Offshore Works responsible for co-ordinating pipeline projects worldwide.


Noël Pille

After receiving a degree from the Technical University in Twente, The Netherlands, Robert de Vlaming began his career at Agency Ruys & Cie (Nedlloyd), Paris, then moved to the Olau Line. In 1976 he joined Smit International, working in many of their various companies. Since 1993 he has worked for the Royal Boskalis Westminister Group and is presently Area Manager for Boskalis Offshore BV.


Robert de Vlaming

Jan de Vries has worked on pipeline engineering since the early days of North Sea offshore oil and gas production, first with RJ Brown and Associates, later with John Brown-Zeetech. He was involved with new techniques, such as the first ploughs for trenching, bottom-tow installations and installation under the ice in the Canadian Arctic. In the Dutch Sector of the North Sea, he was project manager responsible for the design and engineering of Amoco's P15 oil pipeline and the offshore part of the NOGAT Gas Transportation System. He joined Tideway in 1995, where he works on special projects.

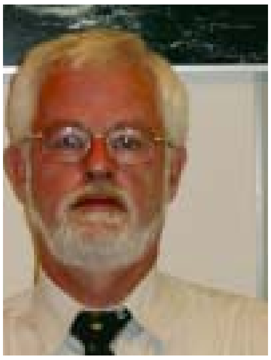

Jan de Vries

Figure 2. Offshore facilities – floating production storage and offloading system – at the Glory Hole, with cutaway showing manifold.

Glory Hole. The depth of the Glory Hole is usually 9 m, which is related to the minimum height of the well-heads above the seabed with a margin of several metres to allow for iceberg scour (Figure 3).
At one side a gradual slope between the bottom of the Glory Holes and the surrounding seabed had to be excavated to facilitate the installation of flowlines and umbilicals.

Description of the Grab Excavation Method

The Grab Excavation method utilised bij Tideway and Boskalis consists of two main elements:
- excavation of the seabed with a grab and
- lateral transport of the material between the excavation location and the discharge site.

The grab is in fact an assembly of a clamshell bucket and an ROV. The ROV has four powerful thrusters with the main function to maintain position and orientation of the clamshell above the point of excavation, i.e., for small movements in the horizontal plane. The grab is hanging on two main hoist wires, one forward and one at the aft of the vessel. These hoisting wires are to lift the grab and to drag it horizontally between the excavation location and the discharge site (Figure 3).

A separate umbilical provides the necessary power to the grab and exchange of all signals for operation, control and monitoring of the system.

When sailing to the dredging location, the grab is stored under the A-frame of the aft lifting point.
After arrival at the dredging location it is lifted off the deck and placed overboard. The excavation consists of the following main steps:
- When dredging starts, the grab is lowered to the seabed from the aft hang-off point. The winches are heave compensated, so that the movements of the vessel do not affect the vertical position of the grab.
- Once the grab has landed on the seabed, hydraulic cylinders are activated to open and close the two halves of the clamshell.
- After closing of the blades, the grab is lifted from the seabed.
- The forward hoist wire is hauled in, while the aft hoist wire is slowly veered resulting in the horizontal movement of the grab from under the hang off point to under the forward lifting point.
- The clamshell is opened and the excavated material is released at the discharge location.
- Once discharge is completed, the grab is returned to the excavation location.

Some features of the system are worth emphasising:
- By keeping the grab assembly close to the seabed, the cycle time can be kept as short as possible by avoiding travel time and time for lifting and lowering.
- The distance between forward and aft hoist wires is sufficient to manoeuvre the grab between the dredging and the dumping sites, while the vessel is in a fixed position. When also the sequence of excavation is carefully planned, taking into account

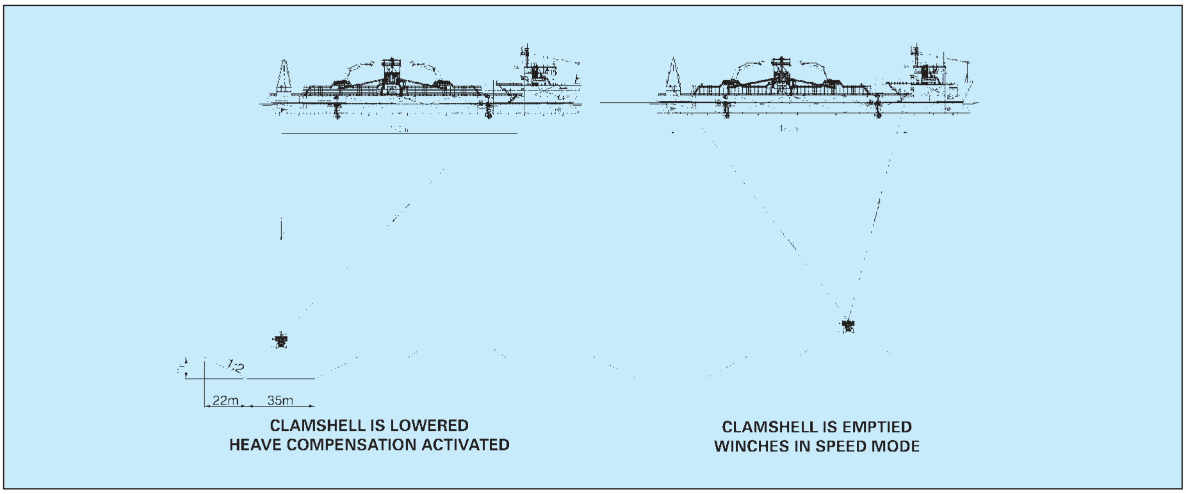


Figure 3. Underwater Grab Excavation System.

the vessel position with respect to the incoming waves, vessel movements between the dredging cycles can be kept to a minimum.

The engineering on the grab system started May 2001, followed by fabrication and construction during the first half of 2002. During early summer 2002 the system was commissioned and tested and the operations on site started in August 2002. The operations were suspended when weather conditions on site deteriorated in early October to return to site in April 2003. Spring that year brought exceptionally heavy ice conditions and bad weather. Nevertheless the first hole was completed in July 2003 and the second hole in August 2003.

The Grab

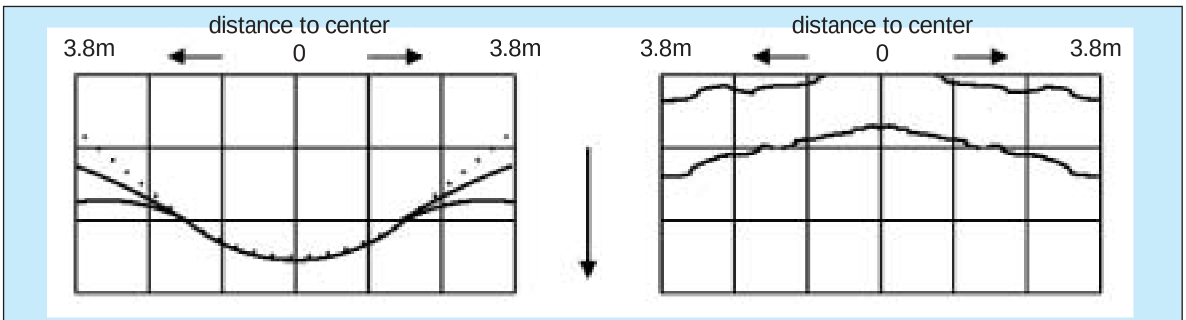
The filling rate of the clamshell is a function of the shape and the weight of the grab and the soil properties. These factors determine the initial penetration and the path the cutting edges will follow through the seabed when the clamshell is closed. The initial penetration of the clamshell in the seabed depends on the weight of the whole structure. This weight is particularly important in clayey materials, where the initial penetration determines the production. The production of sand is less influenced by the initial penetration, as is illustrated by the two sketches below (Figure 4). The curves show the path of the cutting edges of the clamshell when the two halves are closed. The area above the curves is an indication of the production. The width of the opened clamshell, when it is set on the seabed, is 7.6 m.

In view of the seabed soils, the weight of the grab was a crucial item for a good production and the following properties were selected:

– dry weight is 700 kN
– water volume is 16 m^3
– a width of 6.6 m when closed and 7.6 m when opened
– a breadth of 3.3 m.

The clamshell halves have been fitted with special cutting blades to maximise the initial penetration and the production (Figure 5).

Figure 4. Production as function of penetration in sand and clay.



Digging planes in sand with three different dead weights: initial penetration (with grab open at position 3.8m) may be different, the final penetration in the center (after closing of grab) is about similar for all cases.

Digging planes in clay with different dead weights: when initial penetration (with grab open at position 3.8m) is different, also the final penetration in the center (after closing of grab) will be different.

Figure 5. Cutting blades of hardened steel.

The emptying of the clamshell is also an important factor, particularly with sticky clays that can remain behind in the clamshell. The better the clamshell bucket is emptied during discharge, the better the efficiency of the next loading will be. Giving the bucket blades a certain rounded shape, which differs slightly from the shape of the excavated soil body, avoids to some degree that the clay remains behind.

Bleijenberg BV of The Netherlands, one of the world's major grab builders manufactured the clamshell bucket. Design and construction took 18 weeks including factory testing.

The Remote Operated Vehicle (ROV)

Since the grab takes considerably deep bites in the ground, excavation with the grab can result in an uneven bottom with numerous ridges and depressions.

Figure 6. ROV with protective frame before assembly with clamshell.

To avoid this required that dredging be done in a pre-defined pattern. To uncouple the orientations of vessel and grab, the latter is provided with an ROV with four powerful thrusters, each with a diameter of 1.3 m (Figure 6).

The direction between discharging and dredging is a function of the heading of the vessel, as the grab shuttles between forward and aft winch positions. Discharging is allowed anywhere around the Glory Hole, except for the circle segment, where flowlines and umbilical will be installed. To increase the freedom of discharging, also when the vessel is heading towards the closed segment, the suspension system allows excavation as well as discharging below forward and aft winches. The grab movements are, thus, allowed in forward or backward direction relative to the vessel.

The ROV was designed and built by Seatools BV of Numansdorp in The Netherlands. Seatools also developed the software to control and monitor the grab. ROV-operators were extensively trained to operate the system. Design and construction of the ROV took 35 weeks. The power requirement of the Grab Excavation Method is 600 kW. Power is supplied via a separate umbilical. This umbilical is kept tight and free from the lifting wires by a constant tension winch on board of the *Seahorse*.

Figure 7. Assembly of clamshell and ROV suspended from A-frame.

Figure 7 shows the clamshell and ROV assembly. It has an overall height of 9.3 m in the closed position and 7.0 m in the open position.

Grab hoisting arrangement

For manoeuvring the grab between the dredging and discharge site, the grab is suspended from two points of the vessel: at a forward position just behind the bridge and near the stern (Figure 8).

The aft lifting arrangement contains two hoist winches, both equipped with a constant tension system plus active heave compensation mode. One hoist wire is guided via outriggers to the front end lifting point near the bow of the vessel. The aft arrangement is capable of launching and recovering the grab-ROV assembly by lifting and lowering via the A-frame. Either one of the two lifting arrangements can be used to pull the grab sideways from the dredging point to the discharge site, which enhances the operational flexibility.

Extensive analysis has been carried out to study the influence of dynamic effects of vessel and grab on the tension in the lifting wires. The selected 80 mm suspension wires have a breaking strength of 5,100 kN.

Because of the continuously changing loading conditions, the following procedure was developed to control the tension in the cables:

- When the grab is lowered and hanging overboard, the heave compensation is activated.
- The grab is lowered to the seabed in a controlled way with the heave compensation.
- The heave compensation is automatically switched off to a constant tension mode the moment that the grab is placed on the seabed.
- The grab penetrates into the seabed by its own weight where after the clamshell closes.
- The tension in the main hoist wire is gradually increased until the grab with the excavated material is pulled free from the seabed. The control automatically changes back to heave compensated control.
- The grab is transferred horizontally by paying out the aft hoist wire and hauling in the forward hoist wire at high speed.
- Once over the discharge site, the clamshell is opened and the material discharged on the seabed.
- The grab is transferred back to the aft lifting point ready so start a new cycle.
- The heave compensation remains active during lateral transport between dredging and discharge sites, continuing through discharge of the excavated material.

Huisman-Itrec of Schiedam in The Netherlands designed and built the entire grab hoisting equipment, inclusive of the hydraulic drive and control systems, all foundations and, also, the umbilical winch. All systems, i.e., hoisting, grab and ROV, were installed on the

Figure 8. Grab hoisting system with A-frame for launching and recovery of grab.

Seahorse in Huisman-Itrec's quayside, commissioned and dry-tested. Design, construction of the hoisting equipment took about 36 weeks. Assembly of all elements and on-board installation followed by commissioning and testing took another 4 weeks.

Control and monitoring of the excavation operations

On-line vessel and grab positions

The position of the grab has to be continuously known during all dredging and discharge operations. Hereto, motion control of the system during travelling through the water is supplied by accurate and regular position updates at an update rate of 60 Hz. Survey equipment is used to determine on-line the position of the grab, including:

- Vessel positioning by Differential GPS (DGPS)
- Grab position relative to the vessel by an acoustic Ultra Short Baseline System (USBL) with a transducer on the vessel and a responder on the grab
- Transducer position on the vessel by the vessel's gyro compass and the Motion Reference Unit (MRU)
- The relative position of the grab system by a motion sensor on the ROV providing the high update rate that is required for motion control
- Additional information by a depth sensor on the ROV.

All data are used as input for the on-line positioning survey software on board of the vessel as well as input for the motion control of the system.

Most of the equipment is standard used on board of the vessel and therefore survey operations are not different from position control of the fall-pipe ROV when the *Seahorse* is in the Rock Discharging Mode.

Grab handling

A software programme has been developed to link all elements involved in grab handling. The programme takes automatically into account such factors as heave compensation, winch load and/or speed settings, cable catenaries and such, which have an influence on the behaviour of the grab. Simultaneously, the programme

Figure 9. Radar image of ice in White Rose Area.

Figure 10. One of the icebergs crossing the work area.

calculates velocities, cable loads, winch speed and loading and so on and checks them against allowable limits. If these limits are exceeded, alarms are activated, followed by automatic corrections and, if needed, with manual override control.

The output is projected on various screens, showing items as grab position in a local system and the real path of grab versus a planned path in X- and Z-direction, so that the path can be adjusted, actual tensions in the both cables and winches, status of cylinders, and so on.

Operations

Production

Various factors determine the production per unit of time, such as:
Cycle-time: each cycle consists of a series of steps, as described before. The average cycle time was 273 seconds (4.6 minutes), consisting of:

- Excavation: 35 sec
- Hoisting and lateral transport: 114 sec
- Discharging: 12 sec
- Return to excavation point: 62 sec
- Positioning of grab: 50 sec

The soil characteristics: for the first hole the seabed proved to be in accordance with what could have been expected in the worst case scenario:

- Stiff clay with kPa values of up to 750 for isolated cases
- Clay layers already present in upper regions
- Boulders with sizes up to 1m
- Hard pan layer

The soil in the second hole was significantly less challenging. Excluding downtime, a production of 100-150 in-situ cubic metres per hour was realised. This was in line with expectations.

Execution

The net excavation time for the first Glory Hole amounted to 6 weeks and for the second Glory Hole only 2 weeks. The levelling requirement of the bottom of the Glory Hole was defined when it was close to completion. This was dictated by the installation tolerances of the templates later to be placed in the Glory Holes. Locally the tolerances had to be as narrow as +/- 0.05 m. It was decided in consultation with Client to use a rock bedding layer on top of the stiff irregular clay bottom to enable such levelling without spending a lot of costly vessel time and avoiding modifications to the subsea equipment. With all rock discharging installations still intact, this levelling was nothing more than a routine operation for the *Seahorse*.

The minimum bottom dimensions of the first Glory Hole were increased locally when it was close to completion. This proved to be possible because of the flexibility of the system: adjustments were relatively easy to implement.

As previously mentioned, the adverse weather conditions negatively affected the operations. The wave climate on the Grand Banks can be very unstable and therefore there is often not an optimum vessel heading to minimise the vessel motions. Also there were in spring 2003 extensive ice fields and pack-ice on site (Figures 9 and 10).

Mechanical downtime was mainly experienced as a result of the failure of the mechanical strength of the clamshells' cutting blades. These were therefore re-designed and used successfully thereafter.

Results of the Grab Excavation Method

The Grab Excavation method has proved to be able to successfully construct the Glory Holes and cope with challenging soil conditions. Actually the flexibility of the system ensures that soil excavation can be undertaken in a range of soil characteristics and in water depths up to 1,000 m. The graphic results of the first Glory Hole are presented in Figures 11 and 12 with an intermediate survey and a bird's eye view of the final product.

The adjustments made for the Grab Excavation Method did not interfere with the installed rock-discharging equipment so that the exchange of functions can be accomplished quickly. The innovative method of grabbing and dragging included high tech solutions such as a powerful ROV on top of the clamshells for precision positioning and heave compensated support of the grab during the various phases of the excavation cycle.

Excavation with a grab system means that the slopes of the Glory Holes can be kept to their natural angle of repose, which results in the quantities excavated and the effects to the environment being kept to a minimum.

Description of the TSHD *Vasco da Gama* Method

In late June 2003, Vasco S.A., a member of the Jan De Nul Group, was engaged by the Canadian Oil Company Husky Energy to excavate another Glory Hole on the White Rose Project, approximately 200 nautical miles southeast of Newfoundland on the Grand Banks in the Atlantic Ocean. Jan De Nul immediately sent its trailing suction hopper dredger *Vasco da Gama* from Singapore. This vessel is the largest trailing hopper dredger in the world and was equipped with a deep dredging suction pipe with a 6,500 kW underwater pump, enabling dredging down to 135 m water depth. In a later phase, extension of the dredging depth to 165 m is possible (Figure 13).

With 9 m depth and bottom dimensions of 50 x 60 m, the central Glory Hole was the largest in size of the three to be excavated. The TSHD *Vasco da Gama* rushed through the excavation in a record time of just over one month. Despite the presence of a boulder field containing rocks weighting up to 4.8 tonnes and stiff clay to be dredged, a remarkably flat level floor of the Glory Hole was achieved with an accuracy of 25 cm. This was the result of trailing the 8 m wide and 50 tonne draghead as a sweepbeam over the seabed, which proved to be an extremely effective method both timewise and costwise.

During the dredging operations a number of specific environmental precautions were taken into account, including the presence of whales. Furthermore two members of the crew had been trained as ornithological observers to monitor sea birds.

The TSHD *Vasco da Gama* completed its work within the anticipated working days and with no weather standby costs, which ultimately resulted in a lower final cost than was originally anticipated by the Operator.

Glory Hole excavation works
The work comprised the excavation of the central White Rose Glory Hole, with following requirements for the floor, ramp and stable slope angles:

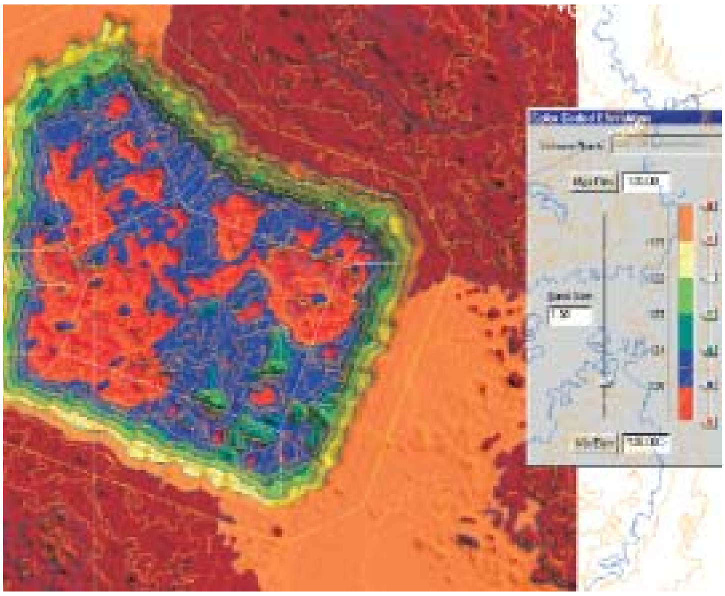


Figure 11. Intermediate survey.

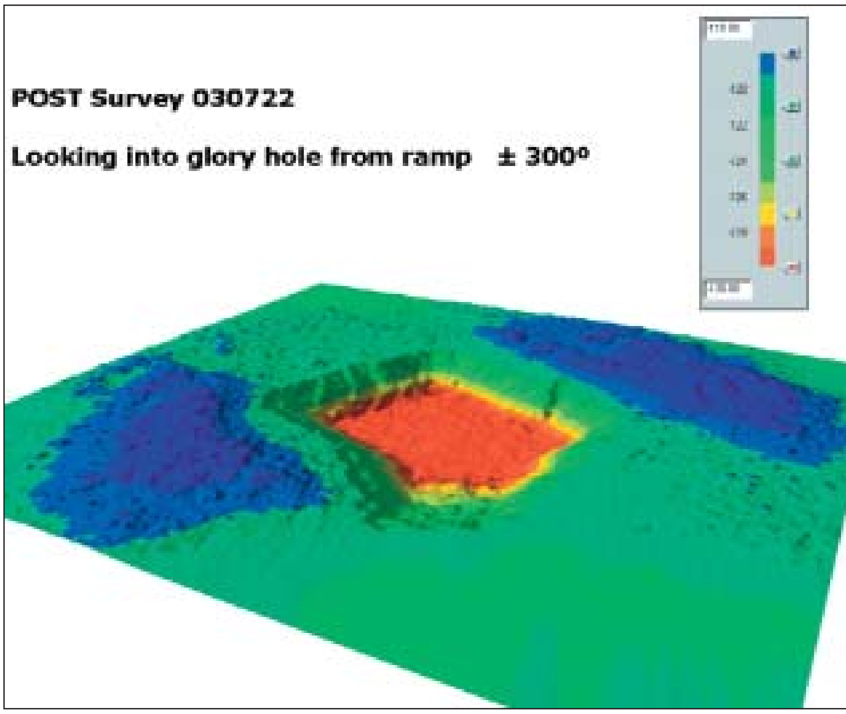


Figure 12. Post survey 030722: looking into the Glory Hole from ramp ± 300°.

- Width 45.7 m, length 58.3 m.
- Sidewalls had to be stable under all environmental conditions.
- White Rose Glory Hole bottom had to be at least 9 metres below the original surrounding seabed.
- The flowline exit corridor had to be on a 5 horizontal to 1 vertical slope.
- The corridor base could not have rocks or sharp protuberances likely to cause damage or wear to any flexible flowline or umbilical.
- Bottom floor tolerances had to be to the requirements of the subsea production system including

Figure 13. TSHD Vasco da Gama entering the narrows at the port of St. John's, Newfoundland, Canada.

smoothing the hole base and flowline access corridors; bridging of flowline spans and backfilling the hole and flowline access corridors with rock as necessary.

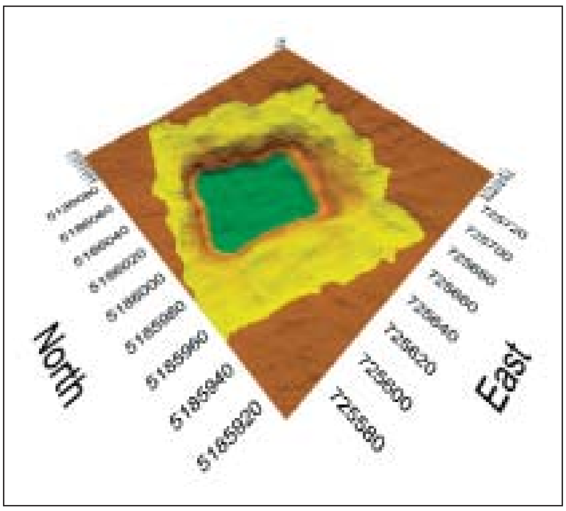
- The Contractor had to ensure that all White Rose Glory Hole survey dimensions were accurate to within one percent and White Rose Glory Hole base centres were located to within one metre of the exact co-ordinates specified by the Operator.
- Dredged material had to be disposed at a location as approved and stated in the Ocean Dumping Permit.

Surveys

Surveys and reporting of the "as excavated" White Rose Glory Hole had to include both the raw data taken from the multi-beam device installed in the moonpool of the TSHD *Vasco da Gama* and the preparation of an AutoCad 3D model (Figure 14).

The Contractor also provided a flying eyeball camera ROV onboard of the TSHD *Vaso da Gama*. The ROV was used for inspection of the completed Glory Hole and to confirm the condition of the hole visually with respect to flatness and the presence of boulders.

Figure 14. White Rose Central Glory Hole 3D survey as excavated.



Working conditions

In view of the dredging depth at up to 128 m, the harsh sea-state conditions and the challenging soil conditions, the works were executed by means of the very large TSHD *Vasco da Gama*. Figure 15 shows the distribution of the wave directions from June to October. It also indicates that the prevailing wave direction during the summer and the beginning of autumn is about 210 degrees (wind coming from the SE). A substantial percentage of the waves also have a NW direction. This sailing direction was adopted for excavating the flowline ramps. At the Glory Hole excavation sites, the swell consists of a primary swell component, a secondary swell component (bi-directional waves) and a wind-sea component.

Weather sensitivity

Because of the large size of the vessel (200 m long and 36 m wide), operational environmental conditions up to 8 sec waves and 2.5 m significant wave height were possible. A significant wave height of 2.5 m corresponds with maximum waves of approximately 5 m in accordance with a Jonswap wave distribution spectrum, which provides a sufficient safety margin at

Figure 15. Wave directional distribution at White Rose, exavation site.

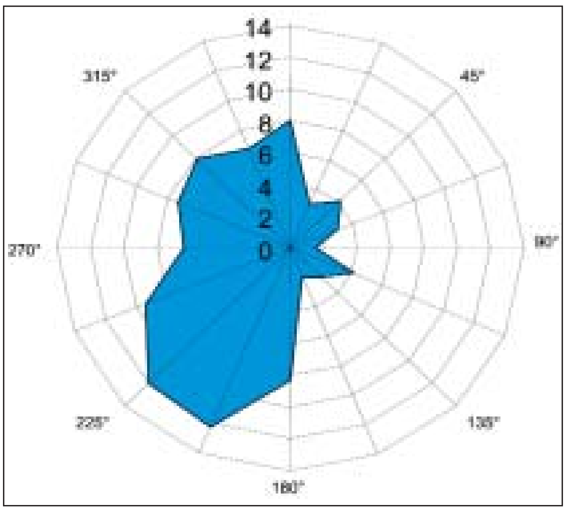


Figure 16. Boulders of considerable size were encountered.

Figure 17. Draghead with boulders.

both ends of the 8 m stroke of the swell compensator device installed on the deep dredging installation. Although statistically there is a 10% exceedance of these working conditions in August, the *Vasco da Gama* completed the work without any weather standby time.

Soil conditions

The soil conditions at the White Rose Glory Hole can be summarised as follows:

- Scattered hard layers over the total excavation depth with characteristics comparable to caprock.
- The sandy/gravely layers contained clay and numerous boulders with a very high density of 2.8 tonne/m^3 and dimensions up to 1.4 m long, 1.2 m wide and 1.1 m high and a total weight of 4.8 tonnes. This boulder field was present between 3 m and 7 m excavation depth (Figures 16 and 17).
- The clay layer was very stiff to hard with a shear strength of 250 to 300 kPa .

The trailing suction hopper dredger successfully dredged these soils, and the bottom of the Glory Hole was levelled in hard clay within a bottom tolerance of 25 cm (Figure 18).

TSHD *Vasco da Gama*

As a result of the sea state conditions, types of soil and large water depths, the TSHD *Vasco da Gama* was equipped with a deep dredging suction pipe with underwater pump for a dredging depth of 135 m. The deep dredging suction pipe carried an 8 m wide and 50 ton heavy draghead in order to limit the number of runs and to obtain a smooth bottom profile.

Operations

For excavation of the Glory Holes up to 9 m below seabed, the dredger sailed parallel lines at approximately 2 knots speed and 5 m distance in order to take into account some overlapping in order to deal with the horizontal positioning and tracking tolerances. The layer thickness removed by the draghead during each track varied between 15 cm for loose granular sand, to less than 5 cm for stiff clay. Slopes of around 1 to 5 in the upper layers and 1 to 2 below were achieved by defining consecutive boxcuts in the dredge computers for each layer thickness to be removed (Figures 19 and 20).

For safety reasons, the dredger traversed around the Glory Hole during the dredging cycle instead of moving backwards to reach the start point of the next dredging cycle. Approximately two vessel lengths were needed for the approach. The suction pipe was raised to at least 15 m above the seabed when sailing away from the Glory Hole.

Figure 18. Cross section at central White Rose Glory Hole (as dredged).

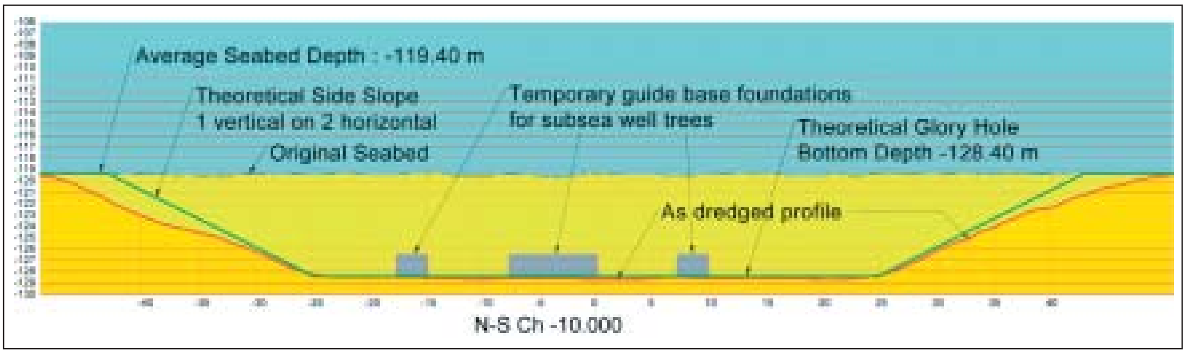


Figure 19. TSHD Vasco da Gama during crew change in St. John's, Newfoundland.

The dredged materials were loaded into the hopper and discharged by opening the bottom doors at the agreed location. In order to limit the disturbance of the seabed, all the loads were discharged at the same location.

Monitoring

During the process of the Glory Hole excavation, progress was monitored on board the dredger by means of the dredging control systems, more particularly by the suction tube monitoring system. The actual draghead depth and the target depth per layer were compared online and any differences displayed.
The position of the draghead was visualised on screen on a background of bathymetric data by means of a plan view with a differential colour chart showing the amount still to be dredged together with a longitudinal and cross profile of the Glory Hole, marking seabed level and target level.

At regular intervals, progress was checked by a multi-beam bathymetric survey system installed in the moon pool of the dredger which avoided the use of a separate survey vessel. The system provided immediate on-line seabed information for the project team on board and was interlinked with the dredge computers in order to continuously update the dredge level achieved.

Conclusions

Two innovative methods were successfully used during the White Rose Project to excavate Glory Holes. The Grab Excavation Method coped very well with challenging soil conditions, and the flexibility of the system ensured that soil excavation could be undertaken in a range of soil characteristics and in water depths up to 1,000 m. The rock-discharge vessel *Seahorse* was easily adapted to its grab and drag function, and effects to the environment were kept to a minimum.

The Trailing Suction Hopper Dredger Method utilising the *Vasco da Gama* achieved a remarkably levelled floor in the Glory Hole, despite the presence of a boulder field containing rocks weighing up to 4.8 tonnes and very stiff to hard clay. Dredging was done with tolerances of 25 cm as a result of trailing the 8 m wide and 50 tonne draghead as a sweepbeam over the seabed.

Figure 20. Box cut design for the Glory Hole excavation, cross view and longitudinal view.