ABSTRACT

After an extensive selection process in 2004 Boskalis Australia Pty Ltd was selected by the Port of Melbourne Corporation to execute the Melbourne Channel Deepening Project. The aim of the project was to make the Port of Melbourne accessible for 14-metre draught vessels at all tidal conditions. One of the most challenging parts of the project was the deepening of the Entrance to Port Phillip Bay, which is located in an environment characterised by a rock bottom, strong tidal currents, a persistent and long swell, regular shipping traffic and a National Marine Park abundant in deep reef fauna nearby. The metocean conditions prohibited the deployment of a cutter suction dredger and the use of drilling and blasting. The latter method was also not preferred for social and environmental reasons. Seeing the metocean constraints, a trailing suction hopper dredger remained the preferred equipment for the project. However, the layered, cemented limestone was too strong to be dredged with conventional dragheads. This article describes the development of a ripper draghead, capable of dredging rock.

Several parts of the dredging process were objects of research. Literature and former tests were analysed to derive the forces required for cutting the rock. A model was made to predict the cutting capabilities of ripper dragheads. Several types of pickpoints and cutting geometries were investigated during cutting tests with a test-cart equipped with measuring and logging instruments in a quarry. The ripper draghead was engineered and constructed after having determined the optimal teeth configuration with respect to forces and dimensions of the cut rock. In addition, vessel motion and vessel maneuvering studies were undertaken to investigate the operational limits of the dredger. The vessel crew was trained on a dredging vessel simulator whereby the actual currents and the predicted cutting forces were used as inputs.

A full-scale trial dredging campaign was undertaken with a trailing suction hopper dredger, the Queen of the Netherlands in 2005. The trial demonstrated that the rock at the Entrance could be dredged with the ripper draghead. Extensive video monitoring showed that the dredging process had to be optimised with respect to the loose material left behind after dredging. Additional laboratory tests with a scale model of the ripper draghead were performed at the Delft Hydraulics Laboratory. The tests focused on the optimisation of the suction process by investigating the effectiveness of the draghead’s water jets and the influence of different draghead geometries. Based on the laboratory results, the existing ripper dragheads were modified and the work method was amended. This article originally was presented at CEDA Dredging Days 2009 and is published here in a slightly revised version with permission.

INTRODUCTION

The size of trailing suction hopper dredgers (TSHD) has been significantly enlarged over the last decennia. Starting with the first jumbo dredger Pearl River, built in 1994, the hopper volumes have increased from 17,000 m³ up to 35,500 m³ nowadays, such as the Queen of the Netherlands. Currently, TSHDs are being built with a hopper volume of approximately 46,000 m³. Obviously, the total installed power, the propulsion power, the dimensions
Of the suction tubes, and the size and weight of the dragheads have also increased. As a result of these developments harder soils and even rock, which are normally dredged with a cutter suction dredger (CSD), can now also be dredged with a TSHD.

But why deploy a TSHD in harder materials if CSDs are already capable of dredging rock? A significant difference between the TSHD and the CSD is the workability. Large CSDs cannot work in wave heights exceeding 1 m, but TSHDs are capable of dredging in waves up to 3 m. For a CSD, strong currents prevent the use of a floating discharge line, whereas the maneuvering of a TSHD will be slightly affected only. In addition, jumbo trailing suction hopper dredgers can dredge significantly deeper than CSDs and they are much more flexible in relation to shipping traffic. In general the costs of mobilising a CSD are higher than for a TSHD.

For the Melbourne Channel Deepening project, workability and shipping traffic were the drivers to explore the dredging of rock with a TSHD further.

PLANNING THE PROJECT
For deepening the Entrance to Port Phillip Bay to -17.3 metre, a thickness of approximately 3 metre of rock had to be dredged at Nepean Bank and Rip Bank. The Entrance is a channel of 235 m wide with regular shipping traffic. Severe metocean conditions (strong currents and high swell) excluded dredging by a CSD. In addition to metocean constraints, also environmental and social constraints prohibited the use of drilling and blasting of the rock. However, vessel motion and vessel maneuvering studies showed that the workability for a jumbo trailing suction hopper dredger was good.

The Port of Melbourne Corporation conducted a soil investigation with a jack-up platform in the Entrance in 2003. This investigation took 8 weeks to complete and comprised 10 boreholes (see Figure 1), showing that the seabed is underlain by a layered sequence of “dune calcarenites”; siliceous calcarenite, calcareous sandstone and sand belonging to the Bridgewater Formation. Strength tests and seismic investigation indicate that for this type of rock a CSD would normally be deployed.
As a TSHD was the preferred dredger to be used, the focus was on the development of a draghead, capable of dredging the rock in the Entrance. This project was incorporated in the R&D programme of Boskalis and a project group was formed by the R&D Department, Technical Department and Dredging Department to integrate knowledge regarding the cutting process, production levels, soil characteristics and construction details.

The development process started with a desktop study. This study comprised an inventory of rock cutting theories, analysis of laboratory cutting tests and collecting knowledge on ripping by bulldozers in various rock types.

The desktop study led to relations between properties of the rock and the force levels required for cutting the rock. A model was set up for the cutting of rock with a TSHD equipped with a ripper draghead. This model predicts the maximum strength of rock that can be dredged, depending on characteristics like propulsion power, trailing speed, draghead weight and draghead layout. The cutting production, depending on the strength of the rock, is also predicted. Figure 2 shows a generic result of the model for a particular TSHD equipped with a ripper draghead with different numbers of teeth. The figure indicates that the teeth will not penetrate if the rock strength exceeds a certain limit. As a consequence, the production will be zero unless the number of teeth is reduced.

**CUTTING TRIALS IN THE QUARRY**

For the optimisation of the design of the draghead an experimental test programme in an Australian quarry was proposed. The general set up comprised a bulldozer pulling a test cart equipped with ripper teeth or pickpoints. The aim of the tests was to gain insight in the cutting forces, penetration forces and the size of the cut rock. The size of the cut rock is important because large rock lumps might block the draghead or even worse, block the dredging pump.

Several quarries in the vicinity of Melbourne were visited, and the geological setting and mechanical properties of the present rock were investigated. The quarry for the test programme was selected based on the good similarity with the rock properties in the Entrance. Seismic velocities measured in the quarry were approximately the same as those measured in the Entrance.

The conclusion from the study was that the rock in the quarry was representative of the rock in the Entrance, with respect to strength, layering and cementation. A test cart with ripping teeth was built, to be pulled by a bulldozer (Figure 3).

At the quarry two sites were selected for testing. The first site consisted of weakly cemented sands with densely cemented rock concretions and extensive rock ridges, representing the areas at the Entrance where caprock is present. The second site consisted of layered aeolianite rock that compared well with the rock encountered in the boreholes at the Entrance. During each test the cutting forces and penetration forces on the ripper...
teeth were derived from load pins. After removal of the cut rock in the track, the groove patterns were mapped. From these measurements the cutting production and the specific energy of the rock could be derived. The dimensions of the cut rock were measured after each test. Samples of the cut rock were collected for strength analysis.

The cart was constructed in such a way that the number of teeth, the type of teeth and the space in between the teeth could be varied. In addition, the cutting depth and cutting angle of each tooth could also be varied.

Although the cutting processes above and under water show many similarities, there are some differences: Cutting in dry rock is a drained process, while cutting under water in saturated rock might be an undrained process. To quantify the differences between the cutting process above and under water, a separate study was conducted by Delft Hydraulics in the Netherlands.

The results of this desktop study were used to translate the measured forces, breakout patterns and production levels in the quarry to the underwater situation.

Fifty tests were conducted to achieve an optimal layout of the cutting geometry with acceptable force levels and production levels. The size of the cut rock was sufficiently small to pass the suction mouth of the draghead and the pump, minimising the risk of blocking (Figure 4). Based on the quarry tests the basic design criteria for the ripper draghead were established, like the weight of the draghead and number and type of the pickpoints. Also the optimal cutting depth and the spacing between the pickpoints were derived from the quarry tests.

**DESIGN OF THE RIPPER DRAGHEAD**

The data of the cutting tests in the quarry and the results of the desk studies on the cutting and the breaking of rock were used as inputs for the design phase of the ripper draghead.

The first issue was to define the design criteria and the risks. The forces which could be expected during normal operation were known from the quarry tests. However, besides these normal cutting forces, the expected harsh operational conditions will cause external forces affecting the construction. The ripper draghead or suction pipe may hit the edge of the Rip Bank and additional vertical forces will be generated when the draghead lands on the rock bottom while the ship is rolling in 3-metre waves. The draghead may be subject to sideward movements when the motions of the ship and the suction pipe are influenced by the long waves and strong currents in the Entrance. All teeth may simultaneously hit a hard rock edge and cause extreme force levels.

The greatest risk is damage to the suction pipe and to the connection of the suction pipe with the ship’s hull. Several measures were designed to protect the construction against these peak loads and to avoid damage of the construction.

To determine the force levels for the design of these safety measures vessel motions, vessel maneuverability and the structural integrity of the suction pipe and the vessel were analysed in great detail. An extensive study was started...
to find out which limit should be observed to minimise the risk of incurred delays caused by damage.

Based on the results of the quarry tests and risk analysis the design criteria could be translated into the design of the ripper draghead and the protection of the pipe construction. The draghead consists of a helmet and a visor. The helmet is the base construction, including the suction mouth, which has to collect the ripped rock. The function of the visor is to cut the rock with its teeth. A safety break pin construction was designed in the connection of the visor with the helmet. This construction was based on a pre-stressed pin, which should break before the construction is overstressed. If an overload occurs because forces on the teeth are too high, the pin will break and the visor can swing away to the back and the teeth will lose contact with the rock.

The sensitivity for fatigue is a weak point of a normal break pin construction, and because of that, the lifetime of the pin material is affected. If this were to cause a break, instead of an overload, it would result in an unnecessary delay of the ship.

The lower part of the suction pipe is exposed to bending by its own weight and the forces generated by the ripper draghead. Besides that, a typical risk at the Melbourne project concerns the collision of the pipe with the sharp edges of protruding rock ridges and with the edge of the canyon, a geological erosion feature in the Entrance. This will cause buckling and bending of the pipe, followed by breaking. To guarantee the integrity, a protection unit was constructed and installed at the lower side of the suction pipe. Impact by collisions is damped in this way. During the project this has proven to be effective.

For picking up the rock, a minimum speed of the water flow is required. Proper matching of the dredge pump capacity and the suction inlet of the helmet is very important to avoid blockage and spillage behind the draghead. The photos and films which were made of the quarry tests were very helpful to examine how the rock was cut by the teeth and what would be the best design in which the water flow would pick up as much rock as possible.

Another point of attention was the wear of the draghead. The dragging of the heavy draghead on the rock bottom and the hydraulic transport of the stones with high suction speed causes enormous wear of the construction. To combat the wear, wear-resistant material was added on several critical locations in the design.

The design of the draghead was optimised by means of FEM calculations. All expected load cases were considered in these calculations.

During the final design phase a selection procedure for a manufacturer of the dragheads was started. Criteria for the selection were:
- quality of steelwork and welding,
- references of similar jobs,
- organisation of the orders,
- capacity,
- price and
- delivery time.

After the selection three ripper dragheads were built in Australia according to high quality standards. The construction was observed and checked by a superintendent every day.

**FULL-SCALE TRIAL AT ENTRANCE OF PORT PHILLIP BAY**

To determine the environmental effects of dredging in general and to see whether the TSHD was able to dredge the rock at the Entrance of Port Phillip Bay, a full-scale dredging trial was conducted in 2005. Part of the Entrance to Port Phillip Bay was designated as trial area. In August, the TSHD *Queen of the Netherlands* dredged for two weeks to demonstrate that the ripper draghead technology (Figure 5) was capable of dredging the rock at the Entrance.

An extensive follow-up programme of the trial was set up. Amongst other attention points it comprised the measurement of production, vessel motions and stresses and loads in the suction tubes. Also the properties of the dredged material were analysed in detail.

A wave buoy located nearby was used for real time monitoring the wave height and direction. Also two ADCP profilers were installed on the bottom near the trial area to obtain current and wave spectrum information. Every day the survey vessel performed a survey at the trial area to gain insight in the progress and in the development of the bottom roughness.

The forces in the suction tubes were measured by load pins in the hinges. No stress limits were exceeded, the theoretical models were confirmed and the integrity of the suction pipe and hull connection could be guaranteed. The cutting forces were roughly comparable with the forces measured during the tests at the quarry. Minor damage to the draghead was encountered, probably caused by collisions with seabed ridges. To reduce the bottom roughness, the dredging method
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initially aimed at high spots in order to flatten the sea bottom. The survey after the trial showed a significantly smoother sea bottom than before starting the operations (Figure 6).

During the two-week trial in the Entrance about 30,000 m$^3$ were dredged, which was well in agreement with the production levels estimated from the quarry tests. At hard spots the production was lower, sometimes significantly, but the trial showed that all rock could be dredged.

Rock samples were collected from the draghead and from the hopper. Geotechnical analysis by the University of Melbourne showed that UCS values generally varied between 1-30 MPa. The strength of two very dense samples was respectively 71 and 112 MPa.

During the trial the work method was evaluated and optimised. At the time the crew got used to the complex currents, the sailing patterns were adjusted. The setting of the swell compensator, determining the effective weight of the draghead, was optimised and two pickpoint types were tested. Eventually an optimal balance was derived between effective draghead weight, forces in the pipe and production.

Several photo and video inspections were made by divers and a comparison was made between the actual dredging test and the ripping tests in the quarry. Both situations are shown in Figure 7.

However, the inspections also showed that the amount of stones remaining on the seabed after dredging should be reduced. These stones were not stable under the present currents and waves and could potentially be relocated to other areas, which was not acceptable.

**LABORATORY RESEARCH**

The full-scale trial showed that the cutting process of the ripper draghead was well in line with the expectations, but additional research was necessary to improve the suction characteristics of the draghead, aiming at minimisation of the amount of stones left behind on the sea bottom. Experiments with a scale model draghead appeared the best way to visualise and analyse the suction process. Because of their experience and their suitable laboratory facilities Delft Hydraulics was engaged for the test programme. A scale model of the ripper draghead was constructed and the sea bottom was simulated by preparing a layer of cemented gravel in the dredging flume. A test comprised a passage of the draghead through the prepared bed over several metres. The passage was monitored through a glass wall. Underwater video cameras were used for registration and sensors were installed for measuring operational parameters.

The test programme focused on the variation of relevant parameters like suction flow, jet flow, geometry of the draghead and suction mouth. Operational parameters were scaled in accordance with Froude's law. Because a flat sea bottom does not represent reality, also the influence of the topography of the sea bottom was investigated.

The material left behind after passage of the draghead was measured by a laser survey system (Figure 8) and checked by simple weight measurements of the loose material. The test programme was arranged into resemblance tests, insight tests and optimisation tests.

The resemblance tests, in which the model draghead and operational parameters were equal to the draghead used at the full-scale trials in Melbourne, showed that not all cut material was removed. Then the influence of the jet flow, suction flow, geometry of the draghead and suction mouth was investigated and adjusted during insight tests. The final layout of the draghead was established in the optimisation tests. Compared with the original layout, a significant improvement in suction characteristics was achieved, as can be seen in Figure 9.

In accordance with the results of the laboratory tests the ripper dragheads in Australia were modified and tested further on the Salalah project in Oman where approximately 1,000,000 m$^3$ were dredged. The dredging of the Entrance of the Melbourne Channel Deepening project could start with fully developed and well-tested ripper dragheads in the beginning of April 2008.

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Figure 8. Measuring bottom topography with laser (left) and result of laser measurement before and after the passage of the draghead (right).
A total of 140,000 m$^3$ of rock had to be dredged at the Nepean Bank and 135,000 m$^3$ at the Rip Bank. The borehole data suggests that a Holocene aged layer of gravelly sand and blocks of cemented carbonate overlies in patches a Bridgewater Formation siliceous calcarenite, calcareous sandstone and sand (Figures 10 and 11). Petrological analysis (Holdgate and Wallace, 2004) indicates that in some cases, additional cementation has taken place near the seabed surface, probably adding to the strength near the seabed surface. This additional cementation is of marine origin (i.e. calcite precipitated directly from sea water). Marine cements are also present in the gravel fragments overlying the Bridgewater Formation. This is contrary to the older calcite cement of the rock, which is of fresh water origin (cement precipitated from meteoric water when the dune deposits were above sea level).

Based on the available soil information, an estimate was made that a small amount of the total volume could not be dredged directly by the ripper dragheads. As contingency, a dedicated hydraulic hammer system was designed which could be positioned using a dynamically positioned vessel and swell compensated arm, to pre-treat this harder rock.

With 80% of the time waves having a significant height (Hs) larger than 1.0 metre (Figure 12) and currents up to 3.5 m/s, and approximately every hour a vessel passing by, conditions were more suitable for a jumbo trailer suction hopper dredger than any other type of dredger.

To protect the Port Phillip Heads Marine National Park close to Nepean Bank, a ridge of at least 5 m wide along the north-west edge of the Nepean Bank had to be left in place, until the remaining area was dredged.
to the required design depth. Strict environmentally enforced control was set to prevent loose material falling into the adjacent deep, locally known as the canyon.

In addition, dredging of the canyon edges (North edge of the Rip Bank and all edges of the Nepean Bank) was conducted from the canyon towards the plateau. When dredging towards the canyon, the dragheads were lifted so that no rock was removed within 5 m of the edge (Figure 13).

Regular clean up of the dredged area was required to avoid accumulation of loose material on the sea bottom. Special teeth were fitted on the ripper dragheads and the swell compensator pressure was set on a high level to avoid that new material was cut during clean up. A dedicated software application was used to register the area covered during the clean up operation.

During the dredging works, dragheads were inspected on a regular basis. During these inspections, rock samples were collected. All samples were selected on having only fresh cut sides, so it can be assumed they were ripped from the bed by the dragheads and not already present as loose stones beforehand. Only larger rock lumps with a certain minimum strength got stuck in the draghead (Figure 14). In the hopper the very weakly cemented part of the volume was found as sand or as coin-sized fragments.

With all available soil information, together with production figures and survey progress, it could be confirmed that the initial estimated amount of hard rock (UCS=15-30 MPa for a few percent of the total volume), was approximately correct. It was possible to remove all material with the ripper dragheads. Mobilisation of the contingency equipment such as the underwater hammer system was not necessary.

The mechanical, operational and monitoring measures that were taken to manage and control damage to the pipes and the dragheads, were effective. The mechanical measures included a fender attached to the lower suction pipe, a breaking bolt between helmet and visor as described before. In addition, special care was taken for the “streamlining” of the dragheads.

Figure 12. Workability graph

Figure 13. The NW Ridge of the Nepean Bank was left in place until the remaining area was dredged to design. Left: insurvey, Right: survey before start of removal of the NW Ridge.

Figure 14. Typical samples of rock that are removed from the draghead.
At the start of the works, dredging focused on the shallowest parts first. This reduced the bottom roughness and thus the risk of rock ridges impacting the dredge pipe. Figure 15 shows a distribution of the measured sea bottom depth before and after the dredging.

Software was developed to help the operator to lift the pipe in time. In addition to the standard instrumentation load pins were installed in the cardan between upper and lower suction pipe to monitor the level and fluctuations of forces in the suction pipes.

A semi-quantitative approach was chosen to investigate and classify the rock spill. Towed video surveys were conducted 4 weeks after technical completion. A total of 35 km of video transects were sailed resulting in 33 hours of video footage. Then, from the video footage, 1280 pictures were captured and selected, which evenly covered both the Nepean and Rip Bank dredged areas. All pictures were independently reviewed by 5 persons and visually divided into 5 classes, based on a percentage of the area covered by loose material (4 classes are shown in Figure 16).

Based on this classification procedure it could be derived that about 12% of Nepean Bank and about 20% of Rip Bank was covered with rock spill. This was well within the predictions of the Supplementary Environmental Effects Statement (SEES).

REFERENCES


CONCLUSIONS

This article describes the successful development of a ripper draghead, capable of dredging rock with a Trailing Suction Hopper Dredger. The cutting forces were determined by cutting tests in a quarry and the suction characteristics were optimised by scale model tests in the laboratory. This research resulted in the construction of a ripper draghead that has proven to be very effective at the Channel Deepening Project in Melbourne. The ripper draghead was sufficiently strong to withstand all occurring forces and the protection measures of the suction pipe were appropriate. The dredging of the Entrance of Port Phillip Bay was executed well within time from April to September 2008. As a result of the optimised draghead design and the well-prepared work method, the amount of spill was minimal.

The realised productions accorded with the estimated productions and video surveys proved that the quantity of loose material left behind was well within expectations. The work benefited from the continuous interest and support of our Alliance partner, the Port of Melbourne. Besides the authors the following persons have made significant contributions to the project in their specific field of knowledge: G.J. Grundlehner who supervised the workability studies, R.J.M. van Maastrigt who conducted the production calculations, W.F. Rosenbrand as manager of the R&D department of Boskalis, F. Uelman as the engineering manager of the Channel Deepening Project, P.N.W. Verhoef who did the engineering geological investigation and last but not least the crew of the Queen of the Netherlands.