ABSTRACT
The shallow waters of the Manifa Oil Field make it impossible to use common offshore oil drilling platforms. For that reason Saudi Aramco opted for the construction of 25 oil drilling islands covering the entire Manifa Oil Field. The scope of the Project comprised the design and construction of some 41 kilometres of main causeway and associated lateral (secondary) causeways that provide vehicle and service access to the production islands and two water injection islands.

The article describes the large number of physical model tests conducted which permitted optimising the rock revetment design. It also deals with the practical management of a large scale quality control programme for the rocks. Specifically it describes some aspects of the extensive follow-up on rock quality parameters that varied with the rock source. It examines the comparison and design evaluation of the different rock properties encountered at the different quarries. The initial costs and efforts for setting up a well-functioning Quality Management System (QMS) are substantial but are easily recovered in the long run during the project.

INTRODUCTION
The Manifa Field Causeway and Island Construction Project is by far one of the most prestigious projects ever realised in the Kingdom of Saudi Arabia. The Manifa Oil Field is one of the Kingdom’s most important crude oil fields. The field can deliver 900,000 barrels of heavy crude oil per day when fully operational. It is the largest single offshore development ever undertaken by Saudi Aramco since the company’s establishment. The Jan De Nul (JDN) Group engineered, procured and constructed the Manifa Oil Field Causeway and Islands Project as Main Contractor. The combined value of the contracts for the Jan De Nul Group makes it one of the largest dredging contracts in recent years – worth 1.2 billion dollars. The Project is located on the east coast of Saudi Arabia, in the Arabian Gulf about 250 kilometres south of Kuwait. The site of the Manifa Causeway Project covers an area comparable to the size of Manhattan (Figure 1).

INNOVATIVE APPROACH
This article deals with the practical management of a large scale quality control programme for the rocks. Specifically it will describe some aspects of the extensive follow-up on rock quality parameters that varied with source; and the comparison and design evaluation of the different rock properties encountered at the different quarries (Figure 2).

Also the organisation of the test results obtained from a large number of physical model tests, performed to complement the design work for this massive project, is discussed in detail. This data included determining the damage criteria, based on testing classical overtopping discharge and armour layer movement.

The implementation of such a large scale quality programme in combination with a large number of model testing supported the engineering and essentially allowed the optimisation of the design to a large extent, therefore resulting in an economical and efficient design and construction.

LOCATION AND CONSTRUCTION
The location is critically complex. The shallow waters over the Manifa Oil Field, with a
Over a period of 3 years, 27 islands each with 10 well locations, as well as causeways with a total length of 41 kilometres, including 14 bridges – of which the longest is 2.4 kilometres – and 3 berthing areas with 2 roll-on /roll-off facilities for supply vessels, were designed and built (Figures 4 and 5). This included road surfacing and pipeline and cable trays for the export lines and the SCADA system. Several shore approaches for pipelines and cables had to be dredged and abandoned pipelines had to be removed. The causeways and islands essentially consist of hydraulically created sand cores, finished with a slope protection of armour and/or underlayer rock installed on a heavy duty geotextile (Figure 6). Several innovative installation techniques for the geotextile have been used. Rock has then been installed from the land side as well as from the waterside,
again with a variety of techniques. The enormous rock volumes necessitated the provision from different sources with very different properties. A large amount of rock quality data was obtained from the monitoring programme set up for the project. After the reclamation was completed, each island was compacted and finished with a marl layer to receive the drilling equipment (Figure 7). Finally, asphalt roads were constructed on the causeways and the bridges (Figure 8).

To preserve the existing marine fauna and flora, as well as the livelihood of the local fishing community, bridges – instead of dikes – were chosen for connecting islands, in order to allow the continued flow of the tides in and out of the bay and thus preserve the original water quality (Figure 9).

**CHALLENGES**

The Project was characterised by significant technical and logistical challenges. For instance, because work was done in shallow waters, only vessels with limited draught could be deployed for the construction of the Manifa oilfield.

The construction and dredging fleet consisted of 11 dredging units, including cutter suction dredgers, trailing hopper dredgers and split hopper barges. About 50 auxiliary vessels such as tugboats, multicats, crew vessels, and fuel vessels were deployed, as were 40 barges and pontoons, including several heavy lift crane barges, positioning pontoons, floating workshops and a floating batching plant for offshore concrete (Figure 10). About 300 pieces of heavy equipment varying from extra-long reach excavators, dump trucks, wheel loaders, bulldozers, compactors, rollers and concrete mixers, were used (Figure 11).

The very large quantity of rocks required to be installed as rock protection on the islands were mainly purchased in the Kingdom of Saudi Arabia at a multitude of quarries, up to 600 kilometres inland from the worksite. Nevertheless, because of the high demand for rock on the worksite, rocks from quarries in Oman had to be transported to Manifa over

Figure 4. The RoRo facilities and Berth Area South at start of main bridge.  
Figure 5. A typical bridge abutment with increased rock revetment.

Figure 6. The causeways and islands consist of hydraulically created sand bunds, finished with a slope protection of armour and/or underlayer rock installed on a heavy duty geotextile.
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PHYSICAL MODEL TESTING
The rocks were treated as precious stones, and the consumption of these precious stones had to be kept to an absolute minimum. The design life of the project is 50 years. Several case studies were performed for many different locations in the work and for a storm with a return period of 100 years. The required different gradings for the rock revetment on different locations was obtained through detailed numerical wave modelling and then tested by physical modelling in wave flumes and wave basins (2D/3D) (Figure 15).

To optimise the design of the rock revetments, a large number of physical modelling tests have been done in a 2 dimensional wave at short notice and accommodating them in the empty desert required ingenuity. A camp in line with Saudi Aramco’s very high standards was constructed in the remote desert (Figure 14).

The main logistical challenge was to deliver and supply the equipment and the materials such as rocks, aggregates, containers, equipment, fuel, food, and so on, to such a remote working place where JDN was the first contractor to arrive. At peak periods a workforce of more than 3,000 workers from more than 40 different nationalities, were at work simultaneously. Sourcing this workforce
In particular shallow water conditions, where waves are depth-limited and empirical damage formulae fall outside of their applicable ranges. The amount of model test results made available in the project constitutes an important database that may well complement and expand the current state of the art.

In a 3-Dimensional wave basin at DHI in Denmark, the corner of the islands and bridge head sections have been tested, to check the stability of the gradings under a 3D wave attack. Again, armour damage has been investigated by expressing the number of displaced zones relative to the total amount of rock in a particular zone. In order to understand the particular 3D situation in combination with angled wave attack, due distinction was made between different areas on the slopes (hence the different colour bands in Figure 18). The approach allowed better localisation of problem areas and hence directing the efforts towards where they were needed. Starting from the extensive database of the physical model results, a final task then consisted in making sure that the design in the real world was consistent with the model. The numerically determined design wave conditions over the vast project area have been divided into areas of similar parameters (grouping), which could then be assimilated with one or more particular model test and type of revetment design.

The size of the armour has been determined in order to limit damage to allowable percentages. Damage was hereby expressed as the relative number of rocks that have been moved during a design storm out of their specific location on the revetment. Extensive use was made of coloured scale model armour in order to easily visualise the evolution of damage. An example of the way the armour damage could hence easily be observed is given in Figure 16.

The heights of the crests have been determined for an overtopping quantity of 2 l/m/sec. With respect to the overtopping phenomena, a number of important parameters have thoroughly been discussed during the design phase. These include the influence of the storm duration, the correlation between high water levels and design waves, the location where the overtopping volume is measured, the width of the crest, angled wave attack, the occurrence probability of the overtopping criterion, scale effects.

In particular cross sections, the breakwater was topped by a wave retaining wall (Figure 17). Apart from measuring the overtopping over the wall, the installation of pressure transducers on the model wall allowed for high frequency registration of wave induced pressures. These important pressures were compared to existing formulations available in literature and could then be used to further develop the strength design of the crest wall element.

Every grading and every slope angle has been tested. Also the toe stability has been optimised by physical modelling. Physical modelling proved to be helpful in some of the particular shallow water conditions, where waves are depth-limited and empirical damage formulae fall outside of their applicable ranges. The amount of model test results made available in the project constitutes an important database that may well complement and expand the current state of the art.

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quarry is located some 600 km inland from the coast, the closest 50 km. A traffic management plan was set up in coordination with the Client and the Saudi Authorities to safely guide the trailers to the site. Rocks from Oman quarries were transported to Manifa over water. Some 12 million tonnes of rock of 6 different gradings were transported to the site. Daily 400 trucks and trailers were received and offloaded on the stockpile areas (see Figure 19) and the rock loading jetties.

QUALITY MANAGEMENT SYSTEM
To guarantee the quality of the materials used in the work, as well as the construction itself, an extensive Quality Management System (QMS), based on internationally accepted ISO standards, was introduced, in close coordination with Client and Suppliers. The QMS has been set up in line with the JDN Group Corporate Quality Management System based on ISO 9001. A team of more than 30 quality inspectors was responsible for the implementation, follow-up and constant improvement of this QMS. An important part of the QMS is internal audits, of which 13 have been executed, and these internal audits are an indispensable tool to continuously correct the quality system where necessary.

Besides Method Statements and Procedures, the QMS requires working with materials with confirmed quality complying with the project specifications. Quality control on the construction materials is an important part of the daily site activities. Project specific tests and inspections were identified and were performed on sand materials, aggregate materials, rock materials, geotextile, cement and concrete, base course materials, marl, asphalt aggregates, steel rebars, tubular steel piles, fibre glass products, coating and welding (Figure 20).

Three fully equipped site laboratories were constructed to be able to follow and perform the considerable amount of tests. About 7,000 individual lab tests were concluded during the execution period of the project. Given the remote location of the project and the necessity to be able to correct and interfere immediately in case of negative trends in the test results, the installation and operation of the site laboratories proved to be a cost-effective approach.

ROCK REVETMENT
The entire work area covered not less than 80 km². The logistical co-ordination and transport over land and over water of construction materials and equipment was one of the biggest challenges of the project. In total 121 km of rock revetment was installed. This whole project was about rock and its logistical arrangements to get the required quantity of rock within the required quality, timely on the stockpiles and on the different worksites.

Six quarries were used, spread out over the desert in eastern Saudi Arabia. The furthest

Figure 12. Top to bottom: Rock arriving by sea, being transported by dump trucks and being transferred from a barge to shore.

Figure 13. Successive drop test simulation tests were performed at the stockyard.

Figure 14. A camp in the remote desert was constructed for more than 2,000 workers.
needed in order to decide which combination of batches is going to be needed to result in a good moving average of the W50 for each particular constructed area on site. It appeared that due distinction was necessary between the different rock suppliers, different laboratories and the different origin and nature of the rock. A similar procedure was set up for the sand borrow areas and reclamation areas, and use of geotextile.

Operations
In operational phase, the quality management programme was essentially built around the acceptance of batches of 10,000 tonnes of rock, as described in reference literature. The Rock Manual (1st and 2nd editions) was one of the main references adopted. Acceptance of batches is therefore based on a combination of laboratory tests for the intrinsic properties of the rock (density, water absorption, …) and on site tests for the properties of the individual armour stones location and finally the location where the rock was used. A good stockpile management and traceability from quarry up to installation was implemented and maintained. Based on the W50 of the batches in the quarry a good stockpile management and traceability was

Traceability of materials is obviously required. Near the stockpile area 3 weigh bridges were operational, registering every incoming rock load. An extensive document control allowed tracing each batch of rock, based on the quarry source, supplier, grading, stockpiling location and finally the location where the rock was used. A good stockpile management and traceability from quarry up to installation was implemented and maintained. Based on the W50 of the batches in the quarry a good stockpile management and traceability was
and the properties of the rock as a granular material (e.g., grading, see Figure 21).

The challenge was to produce representative sampling for every batch (laboratory and field tests) subject to the inspection process. Since the time required to produce a laboratory result sometimes took more than the time schedule for the job could allow, an early attempt was made to examine if reliable relationships could be established between the fast tests (or tests that produce a nearly immediate result) and the so-called slow tests.

It appeared that due distinction was necessary between the different rock suppliers and the different origin and nature of the rock. An example of such a relationship for a particular type of rock from one area in a certain quarry is given in Figure 21. Based on these kinds of relationships it was possible to establish safe working limits. Careful continued observation of the evolution of these relationships with time was necessary however in order to continue to produce conclusions with confidence.

The design of the rock revetment is based on average values of the main rock parameters characterising the rock in its performance in accordance with the Rock Manual (The use of rock in hydraulic engineering, CIRIA, 2007). It is therefore inherently recognised that these parameters are varying over the revetment with areas of slightly lesser performance balanced by areas with higher performance. As a result, the quality programme had to monitor the average values. However, in a project of this size over such a large area, variances could not be allowed to err on the lower side for too long even though the overall average was respected. This could have resulted in non-acceptable large areas of lower performance. To avoid this, the following approach was developed at quality management level.

A first criterion was established whereby rock properties were only averaged over a limited period of time and were compared to the average design standards. Secondly, an absolute lower limit for judging each individual batch remained in place. Such a combined approach can be found in the Rock Manual for the assessment of the acceptance of a batch parameter based on multiple tests from the same batch, but has been in an innovative way extended to the evaluation of the evolution of the characteristics of the rock (such as W50) in time. Constant production at the lower limit.

Wmin does evidently not yield an average W50 guarantee at the end of the job. A sample chart of the evolution of the W50 of the rock in time can for a particular quarry be found in Figure 23. Such figures could be used to steer the rock suppliers.

It was finally also established that due care was necessary when taking a representative sample. From an analysis of the data of the weigh bridge at the site entrance, together with the results of a rock counting campaign, reliable values for the mean mass Mem for a given batch could be determined. The ratio Mem/M50 was found to be systematically higher than unity for some of the quarries and some of the gradings. It appeared that this could be directly associated with the way in which the rock and the grading were mined.

Some of the gradings at particular quarries were typically mined as a by-product for...
another quarry activity; other gradings were clearly the main purpose of the quarry activity. It appeared to affect to an important extent the way a representative sample was taken in the quarry. An idea of quarry mining activity is given in Figure 24.

**Rock degradation**

The lifetime of the structure being well specified, a systematic approach was adopted with respect to possible causes of degradation of the rock with time. Probably for the first time, the provisions for reduction of the W50 during the lifetime as detailed in the Rock Manual version 2007 were applied on such a big scale. The design gradings of the job were upgraded in order to cope with the natural degradation of the rock once it is installed on the slopes.

Before installation on the slope, rock typically underwent a considerable amount of manipulations. Mining at the quarry, transport to site, delivery on site, transfer to an island, offloading … may all be sources of successive minor and major breakage of rock. In order to quantify the weight loss caused by an important amount of manipulations, a series of successive drop tests was organised. This allowed having a good idea on the weight loss as a function of the number of manipulations.

**CONCLUSIONS**

Several challenges presented themselves in the execution of this major project in the Kingdom of Saudi Arabia. First of all, the location is critically complex. The shallow waters of the Manifa Oil Field made it impossible to use common offshore oil drilling platforms and an innovative solution of building oil drilling islands connected by causeways was designed. Shallow waters however demand ships with a limited draught.

Rock was obviously the key player in the success of this project: Although rocks were mainly purchased in the Kingdom of Saudi Arabia at several quarries, up to 600 kilometres inland from the worksite, more was needed. The high demand for rock on the worksite meant that rocks from quarries in Oman were transported to Manifa by sea. This demanded that a practical and well thought-out Quality Management System be set up in time and in close cooperation with all parties involved, i.e., the design and engineering team, the construction team, the QAQC department, and the Client. The initial costs and efforts for setting up a well-functioning QMS are substantial but are easily recovered in the long run during the project.

A large number of physical model tests were conducted and this permitted optimising the rock revetment design to a large extent – which was critical. In an innovative way, a relation between specific rock parameters was identified. This was helpful in early acceptance of the materials before arrival on site.

In addition, a big logistical challenge was to deliver and supply the equipment and the materials such as rocks, aggregates, containers, equipment, fuel, food, and so on, to such a remote working place. A workforce of – at peak periods – more than 3,000 workers from more than 40 different nationalities, had to be sourced in a short notice and had to be accommodated.

All in all, an end product of good quality was the result of the intentional effort, intelligent guidance and skilful execution by the entire workforce – the design and engineering team, construction team, QAQC department and the Client.