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OPTIMIZATION OF ROCK BERMS FOR PIPELINE STABILIZATION SUBJECT TO INTENSE HYDRODYNAMIC FORCING

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ABSTRACT

This article describes a comprehensive study in which 2D and 3D physical modelling at 1:40 scale was used to optimize the design and validate the performance of dynamically stable rock berms to be used for stabilizing several large pipelines traversing water depths from 5m to 65m and potentially exposed to large waves and strong currents generated by intense tropical cyclones. For added realism, all of the model rock berms were constructed using a scaled simulation of rock installation by fall pipe vessel to be used in the field. Special attention was also given to simulating the self-stability of the model pipeline segments, including special end constraints designed to mimic the behaviour of a continuous pipeline. A large data set concerning the behaviour of dynamically re-shaping rock berms in a range of water depths under intense hydrodynamic forcing due to three-dimensional waves and currents was produced and used to develop efficient and cost-effective rock berm designs for all depth zones.

INTRODUCTION

Pipelines resting on the seabed can be displaced whenever the hydrodynamic forces due to the prevailing waves and currents exceed the gravitational and frictional forces between the pipeline and the seabed. Catastrophic failures may occur if the pipeline movements become excessive. Two general approaches are available for preventing pipeline movements due to hydrodynamic forcing, known as primary and secondary stabilization. Primary stabilization involves increasing the submerged weight of the pipeline, typically accomplished by encasing the pipeline in concrete; while secondary stabilization methods shelter the pipeline from some or all of the hydrodynamic forcing. These methods include installing a protective cover of rock materials over the pipeline (Figure 1), burying the pipeline within a trench and stabilization using gravity anchors. Secondary stabilization methods are generally expensive to implement, and can be an extremely important design consideration for pipelines traversing shallow and moderate water depths exposed to severe storms.

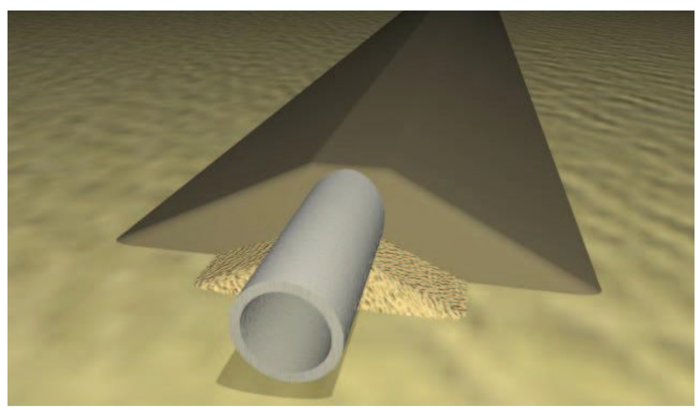

FIGURE 1. ROCK BERM CONCEPT

This paper describes a comprehensive study in which 2D and 3D physical modelling at 1:40 scale was used to optimize the design and validate the performance of rock berms to be used for stabilizing several pipelines traversing the northwest shelf of Australia. An earlier study in which several different secondary stabilization methods, including rock berms, were modelled and assessed is reported in [1]. The design metocean conditions varied along the route due to the local water depth and other factors, but included significant wave heights greater than 16 m and peak periods greater than 15 s, combined with steady near-bottom currents up to 2 m/s. The environmental conditions were simulated using short-crested waves combined with collinear and non-collinear currents. The rock berm design for each water depth zone was optimized to minimize both the rock volume and the rock size, since these were the main cost drivers. The goal was to develop dynamically stable rock berm designs for each depth zone that could be constructed using relatively small sized rock that could be placed efficiently through a fall pipe with minimal waste (Figure 2). Some re-shaping and loss of material from the rock berms was tolerated during exposure to severe hydrodynamic conditions, provided that sufficient rock material remained to ensure the pipeline remained immobile. For added realism, all of the model rock berms were constructed by placing material under water using a model scale fall pipe. Special attention was also given to simulating the self-stability of the model pipeline segments, including special end constraints designed to simulate the behaviour of a continuous pipeline.

FIGURE 2. FALL PIPE VESSEL AND ILLUSTRATION OF ROCK PLACEMENT

Previous experimental investigations dealing with the performance of rock berms used for pipeline secondary stabilization subject to hydrodynamic forcing by waves and/or currents are reported in [1,3,4,5,6,7,8,10,11,12]. Most previous experimental research has been undertaken in 2D flumes, with some studies only considering the effect of regular waves, and many excluding the effect of currents. In many studies, pipeline models are only oriented perpendicular to the flume, and relatively small scale models are used. Nearly all previous research considers rock berms where static stability (very little stone movement) was intended.

Compared with previous work, the present study features several unique and original aspects:

- fully three-dimensional simulations of extreme waves and currents, featuring wave and current direction offsets ranging from 0 to 90 degrees;
- a broad range of pipeline orientations, relative to the wave and current directions;
- water depths ranging from 5 m to 63 m
- focus on the performance of dynamically re-shaping rock berms, comprised of relatively small rock that becomes mobile under design conditions;
- model construction by means of a simulated fall-piping operation;
- realistic simulation of pipeline self-stability, including compliant end constraints for model pipeline segments.

PROJECT AND SITE DESCRIPTION

The overall goal of the study described in this article was to help optimize the design and validate the performance of rock berms to be used for stabilizing several pipelines traversing the northwest shelf of Australia. The design wave conditions for these waters are generated by intense tropical cyclones passing through or near to the area. Extreme seastates generated by intense local cyclones generally feature very steep waves and a moderate to high degree of directional spreading. The design wave conditions associated with a particular return period vary somewhat over the project area, depending on the local water depth and other factors, but include significant wave heights in excess of 16 m and peak periods above 15 s.

The extreme steady currents along the pipeline route (due to wind and tide) generally vary over the range of 0.7 – 2.3 m/s, depending on location, water depth, and return period. Significant near-bed velocities (due to the combined effect of significant waves plus wind plus tide) in excess of ~5 m/s are expected. The most critical zones, where the highest near-bottom velocities are expected, featured depths from ~25m to ~50m.

Various alternative secondary stabilization methods, including gravity anchors, trenching, statically stable rock berms and dynamically re-shaping rock berms were considered and assessed as part the pipeline design process. The relative suitability of these methods varied along the pipeline route depending on the local hydrodynamic forcing and the bottom conditions. An initial campaign of 3D physical modelling undertaken to help assess the technical performance of these alternatives is reported in [1].

Dynamically reshaping rock berms emerged as an attractive alternative for much of the pipeline route through the critical water depth zones. The re-shaping rock berm option was most attractive under the condition that the berms could be constructed by means of a fall pipe operation, since this construction method would greatly reduce waste compared with side-dumping, therefore greatly reducing the required volume of rock material. In order to facilitate efficient placement by fall-pipe, the full scale rock material was limited to a maximum size (D_{100}) less than 400 mm to prevent clogging of the pipe. Economic considerations emphasized the importance of minimizing rock volumes and rock sizes as much as possible. The viability of the dynamic rock-berm concept rested on developing suitable berm designs and verifying their stability and performance as secondary stabilization under the extreme hydrodynamic conditions forecast along the pipeline route. Hence, the main objective of the applied research described in this article was to help support the development of efficient rock berm designs and verify their performance as secondary stabilization in extreme metocean conditions.

PHYSICAL MODELLING

The physical modelling was conducted at a geometric scale of 1:40 in two experimental facilities at the National Research Council, Ottawa, Canada. Testing with non-collinear waves and currents was conducted in a 36m by 30m rectangular wave basin equipped with a powerful 60-segment directional wave generator, a current generation system, and a set of highly-effective passive wave absorbers (Figure 3). Testing with waves and collinear currents was conducted in a 97m long by 2m wide by 2.5m deep wave flume equipped with a powerful wave machine, a bi-directional current generation system, and a high-performance wave absorbing spending beach (Figure 4). Short-crested reproductions of the design wave conditions were generated in the wave basin, whereas long-crested waves were generated in the flume. Different water depths were simulated by varying the water level in both facilities.

FIGURE 3. 3D TESTING IN A 36M X 30M MULTIDIRECTIONAL WAVE BASIN

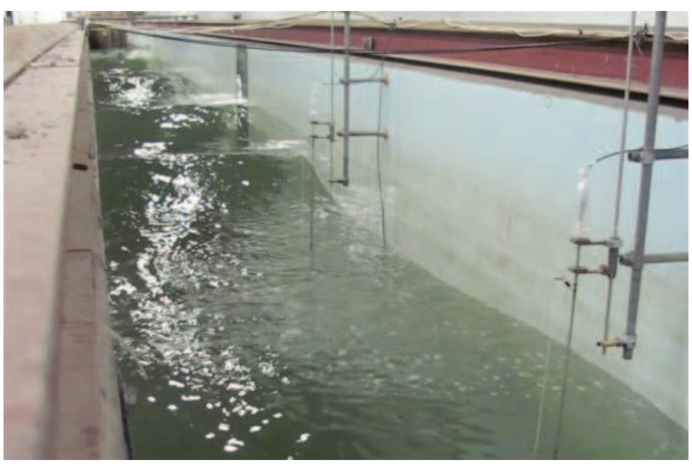

FIGURE 4. 2D TESTING IN A 97M X 2M WAVE FLUME.

Scaling Considerations

In fluid mechanics, the well-known Froude number (Fr) represents the relative magnitude of gravitational and inertial forces, while the Reynolds number (Re) represents the balance between inertial and viscous forces. Together these dimensionless quantities determine the behaviour of fluids and the interaction between fluids and objects, including pipelines and rock berms lying on the seabed. In an ideal physical model, both the Froude number and Reynolds number would be preserved in the model as in the prototype situation. Unfortunately, in most practical situations it is very difficult, if not impossible to preserve both the Reynolds number and the Froude number in a physical model. However, since wave motion and wave-structure interactions are primarily governed by the balance between gravitational and inertial forces acting on water particles, similitude of the Froude number, together with geometric similitude, ensures that the model provides a good simulation of these processes. With this approach, modelling laws derived from Froude scaling can then be used to relate conditions in the model to those at full scale. For free-surface flows, the best practical approach in most cases is to preserve the Froude number and minimize the distortion in Reynolds number as much as possible. This is normally accomplished by making the model as large as the facility and equipment will allow. Everything else being equal, larger models generally yield more accurate and more reliable results and are therefore recommended whenever feasible.

All dimensions in both physical models were forty times smaller than the corresponding dimensions in nature, and scaling relationships based on similitude of the Froude number in the models and in nature were used to infer real world behaviour from the behaviour observed in the models. Velocities were 6.3 times smaller in the model, while time passed 6.3 times faster in the model than in nature. Weights and forces in the model were reduced by a factor of ~64,000. Freshwater was used in the model to represent seawater; and the weight of the pipelines and rock materials was adjusted to preserve submerged stability, accounting for the density difference between the model and prototype fluid. Since Reynolds numbers were ~250 times smaller in the model than desired, the effects of viscosity were smaller in the model than they should have been. In these studies, the seabed was modelled as a hard impermeable concrete surface, so potential interactions with in-situ seabed sediments were not included. These factors introduce some uncertainty into the study results, which may be non-conservative. Hence, a suitable safety factor should be applied when extrapolating the model results to prototype conditions.

Metocean Conditions

In the wave basin, short-crested reproductions of the cyclonic wave conditions forecast at various zones along the pipeline route were synthesized and generated using the methods described in [2]. A 10m by 6m rectangular test site was established near the center of the basin, and all the different wave conditions for each water depth were generated, measured, and revised as necessary to ensure that the measured wave conditions, averaged across the test site, were in good agreement with specified design conditions. Nine capacitance-type wave gauges were deployed at the test site to measure the wave conditions. The directional properties of the wave field were measured using a wave gauge co-located with a 2-axis current meter, and resolved using the maximum entropy method (MEM) of directional wave analysis as described in [9]. The waves were first pre-calibrated without currents, and later generated in tandem with various current fields. In most cases, the wave conditions measured across the test site were reasonably homogeneous and in good agreement with specified design conditions. As expected, the waves at the test site were modified when generated in combination with a current. The nature of the modification depended on various factors, including the water depth, the current speed, the wave properties, and the relative direction between the waves and current.

Currents were generated in the basin by using variable-speed thrusters to force water to flow through a series of 20 m long tunnels installed below the basin floor. The tunnel entrances and exits were located on opposite sides of the rectangular test site. The thrusters forced a turbulent return-flow within the basin across the test site that could be reversed and adjusted by regulating the direction and speed (rpm) of the thrusters. The tunnels were oriented diagonally across the rectangular wave basin, so that a range of non-collinear wave and current flows could be generated. Undisturbed current tests were performed to determine rating curves describing the relationship between the thruster setting and the resulting near-bottom current velocity at the test site for each water depth, without waves. The rating curves were then used to determine the thruster setting required to generate a particular near-bottom current at the test site. The resulting current field was neither perfectly steady nor perfectly uniform, since natural turbulent fluctuations and unsteady eddies were observed whenever the current system was running. However, the time-averaged near-bottom velocities were in good agreement with specifications.

Similar methods were used in the flume to pre-calibrate the wave and current flows for each water depth in that facility. As in the basin, the waves and currents were first generated and calibrated on their own, then later generated in combination.

Fixed and Compliant Pipeline models

Two different pipeline diameters were simulated in these studies. Several lengths of pipe, each roughly 2.4 m long (at model scale) and having the correct outer diameter, were ballasted to achieve the correct submerged weight and then sealed to prevent water ingress. Fine silica sand with a particle diameter of ~0.2 mm was applied to the surface of the model pipeline segments in order to simulate marine growth on the external concrete coating. Since freshwater was used in this study to represent seawater, the model pipelines were designed and fabricated to have the same submerged stability in freshwater as the prototype units would have in typical seawater. This was accomplished by decreasing the density of the model pipelines to compensate for the difference in water density.

Even though the submerged weight of the pipeline was well simulated, most of the rock berm modelling was performed with the model rock berms constructed on top of model pipeline segments that were fixed to the concrete basin floor. This approach was taken because previous experience showed that not fixing the model pipeline segments often led to premature failure of the pipeline – rock berm system. However, at the same time it was recognized that this approach could be non-conservative, since the fixed model pipeline segments could not move, even when the hydrodynamic forces acting on them exceeded the restoring forces.

In order to investigate the impact that fixing the model pipeline segments to the floor had on the performance of the pipeline – rock berm system, a more sophisticated and realistic simulation of pipeline behaviour was also implemented. The goal was to simulate the mobility and flexibility of a near infinitely long prototype pipeline using a model pipeline segment with a finite length. In this more sophisticated approach, the model pipeline segments were 2.5 times longer (6 m model scale), the flexural stiffness of the prototype pipeline was modelled (along with the diameter, surface roughness and submerged weight), and compliant end constraints were introduced to simulate the presence of adjacent lengths of pipeline. Using this approach, the true combined stability of the pipeline – rock berm system could be more accurately replicated and more reliably assessed in the physical model.

A means of applying end constraints was developed to replicate, at model scale, the constraints felt by an equivalent segment of prototype pipeline. The purpose of the end constraints was to simulate in the model the influence of the continuous pipeline at either end of the tested pipeline section. In nature, very long pipeline segments will be exposed to hydrodynamic loading at the same time and may move together as a single unit. Therefore, in the physical model it was assumed that the ends of the modelled pipeline segment should be free to move in the horizontal and vertical directions, but restrained in the axial direction. The end condition simulators were designed to prevented surge and roll motions (displacements along the pipeline axis and rotations about the pipeline axis) without restricting pipeline movement in sway (side to side), heave (vertical), pitch or yaw. The pipeline end condition simulator consisted of two main components: an L-shaped bracket that was securely fastened to the basin floor approximately 2 meters beyond the end of the pipe model; and a rigid plate that could slide (on ball casters) horizontally or vertically across the upright portion of the bracket (Figure 5). Adjustments were made to stiffen the entire assembly and ensure the system was free to move as intended. An aluminium shield was developed to enclose the device so that hydrodynamic forcing could not move the slider unintentionally. Steel wire was used to connect each end of the pipe model to the sliding part of an end condition simulator. The wire ran from the end of the pipeline model, first to a waterproof axial load cell, then to a turnbuckle, and finally to the slider. The turnbuckle was used to tension the steel wire and the load cell was used to record the initial tension and any changes in axial tension caused by pipeline movement during testing. At the beginning of each test, before constructing the rock berm models, the turnbuckles were used to pre-tension the wire to a constant force of ~6,300 kN (~10 kg model scale) and then released to ~950 kN (~1.5 kg model scale) pre-tension. This pre-loading was applied to overcome the bottom friction, remove the effects of hysteresis, and to remove any slack from the pipe model and the steel wire. The load cell outputs were monitored continuously during testing with waves and currents in order to detect whenever the hydrodynamic forcing was able to de-stabilize the model pipeline.

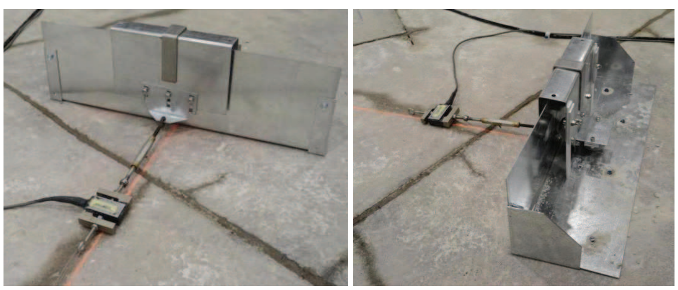

FIGURE 5. END CONDITION SIMULATORS FOR COMPLIANT PIPELINE MODELS

Rock Berms

Numerous rock berm designs involving rock materials with different densities, different sizes, and different gradations were modelled and assessed in order to investigate the influence of the many parameters that can affect the stability, performance, and cost of this type of secondary stabilization:

- Size of rock, denoted by the median diameter D_{50};
- Density of rock, ρ_r;
- Gradation of the rock material, denoted by the ratio D_{85}/D_{15};
- Diameter or size of the pipeline;
- Density of the pipeline;
- Nominal width of the berm crest, W;
- Nominal height of the berm, h;
- Volume (V), or weight of rock material per meter;
- Symmetry and uniformity of rock material placement;
- Orientation of the pipeline relative to the waves, and
- Orientation of the pipeline relative to the current.

Rock materials with densities of 2.49, 2.65 and 3.01 g/cm^3 were used in the study. Numerous gradations of each rock type were prepared to replicate the behaviour of the prototype materials under consideration for use in prototype construction. The raw materials were sieved and the particles retained on each screen were stored in separate stockpiles. The specific rock gradations to be used in constructing the model structures were prepared by blending together pre-calculated quantities (by weight) from each pre-sorted stockpile. Bulk density checks were performed on several occasions, and the measured bulk densities were used as a basis to calculate the weight of material required to construct each model rock berm.

All of the model rock berms were constructed around either a fixed or compliant pipeline model, using a method that simulated prototype construction via fall pipe (Figure 6). A simple human powered model fall pipe vessel was developed and used. Two operators were involved in the material placement: one guided the fall pipe vessel from above water; while the other gradually fed material into the funnel. The volume of rock material required to build each model structure was pre-determined (by weight) and set aside in multiple containers. The rock was placed in several passes in order to achieve a nearly uniform distribution of rock material. This method of placement produced rock berms which had slightly irregular cross-sections that were generally wider and had shallower side slopes than comparable rock berm structures constructed by hand in the dry. The model rock berm structures were considered to be quite representative of real-world conditions.

FIGURE 6. SIMULATION OF ROCK BERM CONSTRUCTION BY FALL PIPE

The volume of rock to be placed on the upstream and downstream sides of each structure was pre-computed based on nominal design sections, like those shown in Figure 7. The minimum design section featured a berm height and crest width equal to the pipe diameter, and 1:3 side slopes. Many other nominal design sections with wider crests, asymmetric profiles and greater rock volumes were also modelled whenever the minimum design section did not offer adequate performance. However, for all of the berms considered in this study, the height of the nominal design section remained equal to the pipe diameter. Since the structures were constructed underwater using a fall pipe, the as-built berm profiles approximated the nominal design sections, but were certainly not identical (Figure 8). An 33% over-dump allowance was added to the rock volume used to build each structure to account for material misplaced during construction.

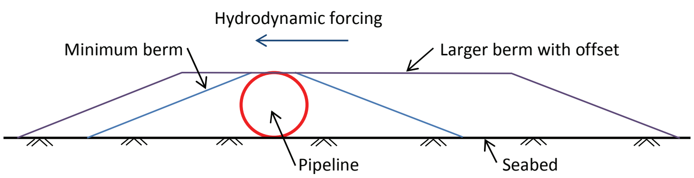

FIGURE 7. NOMINAL ROCK BERM CROSS-SECTIONS

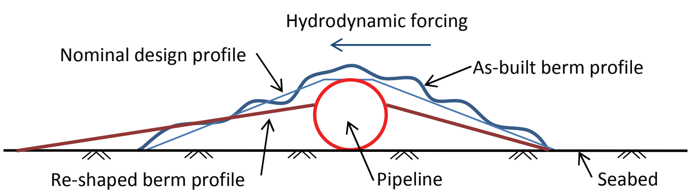

FIGURE 8. NOMINAL, AS-BUILT AND RESHAPED BERM PROFILES

Testing procedure

Multiple (up to 12) different rock berm models were constructed and tested at the same time. Each model structure represented a particular secondary stabilization alternative, constructed at a particular orientation relative to the wave and current forcing. The various models were distributed across the rectangular test site to minimize interference as much as possible. This approach was adopted as it greatly increased the number of alternative rock berm designs that could be tested in a given period of time; however, it also introduced some uncertainty into the results, related to the fact that the flow conditions across the test site were not perfectly uniform.

Tests were conducted wherein a cluster of model structures was exposed to a sequence of metocean conditions that became progressively more severe over time. The water depth typically was held constant while the waves and currents were varied at three hour intervals (prototype time). In most cases, the model rock berms were exposed to a shakedown event followed by a single 3-hour long 100 yr design event followed by a single 3-hour long 1,000 yr design event. Rock berm performance in the 10,000 yr design event was also tested in some cases. Virtually all tests involved waves and currents interacting and acting together. Underwater video surveys were conducted to document the state of each model structure after each stage. The response of the model structures to the wave and current forcing was also carefully observed in the dry after draining the basin at the end of each test series. Rock samples were also collected and analyzed to determine the mass of rock remaining on each structure following exposure to extreme hydrodynamic conditions.

Assessment of performance

No well-established criteria were available for assessing the performance of the dynamically re-shaping rock berms examined in this study. Therefore, a new classification system was developed and applied to assess rock berm performance. A re-shaping rock berm can provide adequate secondary stabilization under design conditions, even though individual stones become mobile and the overall berm profile gradually re-shapes from its initial condition towards a more stable equilibrium profile (Figure 8). In certain conditions, adequate secondary stabilization can still be achieved, even when a significant fraction of the initial rock material is removed and swept downstream by the hydrodynamic forcing. The assessment and classification of rock berm performance was also complicated by the fact that the pipeline models and hydrodynamic forcing were three dimensional, and there was often some variability in the amount of re-shaping that occurred along the model length.

The assessment/classification system that was eventually developed and applied in the study is summarized in Table 1. The rock berms were considered to be dynamically stable whenever at least 1/2 (preferably 3/5) of the pipeline height remained continuously embedded in rock at the end of testing (a three hour exposure to the design condition). The crown of the pipeline could be exposed, but it was necessary to have continuous wedges of rock on both sides of the pipeline and for the height of both rock wedges to be at least 1/2 (preferably 3/5) of the pipe diameter. The rock berm was considered to no longer provide adequate secondary stabilization whenever the height of the rock berm on either side of the pipeline was at any point less than 1/2 the pipe diameter. For a rock berm design to be considered acceptable, it was necessary to retain dynamic stability after a 3-hour long exposure to the 1,000-year design event.

TABLE 1. PERFORMANCE CLASSIFICATION SYSTEM FOR ROCK BERMS.

Classification	Definition
Dynamically stable	Some rock movement and loss of material allowed, however berm remains “intact” and at least 1/2 (preferably 3/5) of the pipeline height remains embedded.
Unstable	Extensive damage to the berm such that the berm is no longer continuous or less than ½ of the pipeline height remains embedded.

The quantity (weight) of rock material remaining on the upstream side of each model after testing was also adopted as a quantitative indicator of the performance of each structure. Minimum rock volumes (weight per meter) corresponding to the threshold between unstable and dynamically stable performance were established for each pipeline size.

Rock berm designs that were found to be overly stable were typically optimized to reduce rock size, rock density, and/or initial rock volume. Similarly, under-performing rock berm designs were revised to increase stability by increasing rock size, rock density, or rock volume.

RESULTS AND DISCUSSION

Efficient rock berm designs that were judged to be dynamically stable after exposure to 1,000-year design conditions were successfully developed and verified for all critical portions of the pipeline route. All of the structures were reshaped by the hydrodynamic forcing into more streamlined profiles that comprised less rock than was placed initially, yet were dynamically stable and provided adequate stabilization for the pipelines.

For a given water depth zone, rock size, and rock density, the volume of rock material used to build the model structure typically was adjusted until the berm that remained after testing was classified as dynamically stable. Multiple versions of each structure featuring different nominal berm designs were often modelled and assessed at the same time. Sensitivities to changes in pipeline orientation with respect to the wave and current directions were also confirmed. In many cases, adequate performance could be achieved without increasing the overall rock volume by offsetting the rock berm centerline with respect to the pipeline; i.e. by placing more of the rock material on the upstream side of the pipeline and less on the downstream side.

Underwater video cameras were positioned to observe the rock movement during testing. Individual stones on the surface of the rock berm were generally mobilized by the peak orbital velocities under the larger waves, and slowly transported in the across pipe or along pipe directions, steered by the quasi-steady current. For a given hydrodynamic condition, the number of stones that were mobilized tended to decrease over time as the berm was smoothed and reshaped into a more stable and more streamlined equilibrium profile that was generally lower and had milder side slopes (see Figure 9).

Figure 10 shows the range of reshaping that occurred in these tests. For the model structure shown in Figure 10a, only a minimal amount of reshaping occurred such that the crown of pipeline remained covered by rock material. For the structure shown in Figure 10b, most of the rock material was retained even though the crown of the pipeline was exposed, and the berms on either side of the pipeline were smoothed. For the structure shown in Figure 10c, which was initially constructed with an equal volume of rock on the upstream and downstream sides, a substantial volume of material was transported from the upstream side to the downstream side, and some material was also removed and swept downstream. However, a sufficiently large and uniform wedge of rock remains on both sides such that the pipeline remains well embedded and well protected against removal. For the structure shown in Figure 10d, extensive re-shaping and rock loss has occurred, such that the pipeline is no longer embedded or protected. Finally, for the structure shown in Figure 10e, all of the rock was removed from both sides of the pipeline, leaving the pipeline fully exposed to the hydrodynamic forcing. The structures shown in Figure 10a-c were classified as dynamically stable, whereas the structures shown in Figure 10d,e were classified as unstable.

a)
b)


**FIGURE 9. ROCK BERM DYNAMIC RESHAPING:
A) INITIAL CONDITION; B) RESHAPED CONDITION**

It was concluded that roughly 80% of the rock contained in each side of the minimum nominal design section shown in Figure 7 and Figure 8 must remain on the upstream side for the berm to be classified as dynamically stable.

On several occasions, identical rock berm models were constructed and tested on top of pipeline models that were both fixed to the basin floor and restrained only by the special end condition simulators shown in Figure 5. Testing with the compliant pipeline models highlighted several possible modes of failure that were not evident from similar testing with fixed pipeline models. Most importantly, results from the compliant pipeline models were critical in establishing reliable thresholds for acceptable amounts of berm reshaping and rock loss (see Table 1). Whenever the compliant pipelines were displaced by the hydrodynamic forcing, it was clear that the amount of berm reshaping and rock loss had become excessive.

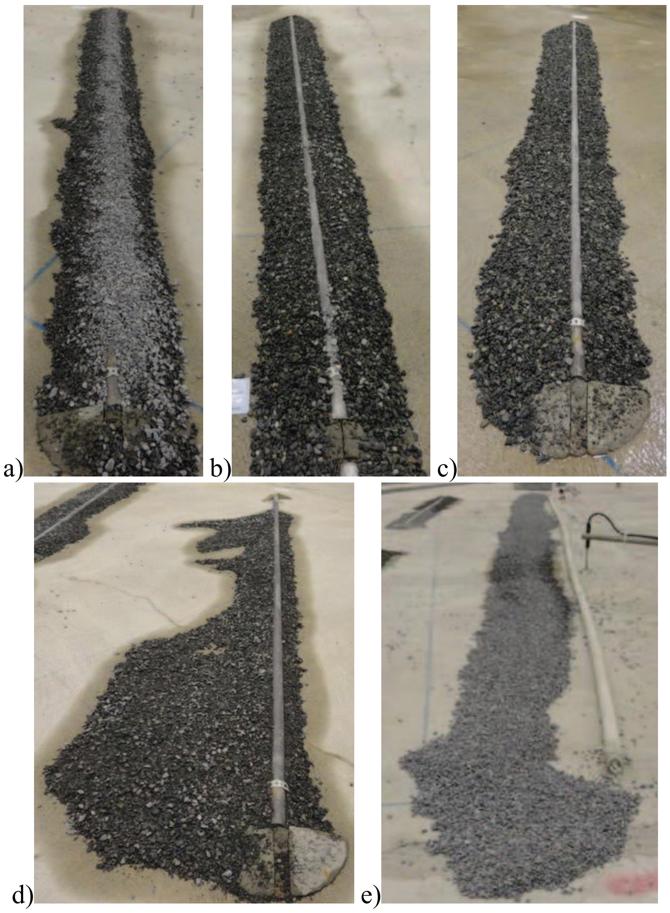

FIGURE 10. ROCK BERM RESPONSE TO HYDRODYNAMIC FORCING

Testing with the compliant pipeline models also revealed that the stability of the pipeline – rock berm system was sensitive to the quality of the rock berm construction. Berms that contained weak sections or gaps in the construction, over even short spans, were prone to failure during the most severe storm conditions. In general, when the rock berms around the compliant pipeline models were well built, their stability was similar to the performance of identical rock berms built around fixed pipeline models under the same conditions. However, when the rock berms were poorly built (thin sections or gaps in the rock berm) the compliant pipeline models tended to fail prematurely.

Results from testing with high density (SG 3.0) rock clearly showed that the denser rock was more stable than the normal density (SG 2.65) rock, as expected. Thus, when high density rock was used instead of normal density rock, the same performance could be achieved by using either slightly smaller rock sizes, or slightly smaller initial rock volumes. In general, the high density rock provided a benefit to the overall stability, and in some cases allowed for a reduction in rock volume or rock size.

Dynamically stable rock berm solutions that employed rock material (with 200 mm D_{50}) that could be installed by fall pipe were developed for the larger pipeline in all water depths. However, the nominal berm width and hence initial volume of rock material per meter of pipeline varied with the intensity of the near-bottom kinematics. For the smaller diameter pipeline, slightly larger rock material and wider nominal berm widths were required to ensure adequate stability in some water depths. The rock sizes and rock volumes could be reduced in deeper water as expected.

SUMMARY

2D and 3D physical modelling at 1:40 scale has been used to optimize the design and validate the performance of dynamically stable rock berms to be used for stabilizing several large pipelines traversing water depths from 5m to 65m, and potentially exposed to large waves and strong currents generated by intense tropical cyclones. The modelling was conducted in a manner such that the real-world behavior of the stabilization measures could be extrapolated from their behavior in the physical model with as little uncertainty as possible. For added realism, all of the model rock berms were constructed using a scaled simulation of the fall-piping operation to be used in the field. Special attention was also given to simulating the self-stability of the model pipeline segments, including special end constraints designed to mimic the behaviour of a continuous pipeline. A large data set concerning the behaviour of dynamically re-shaping rock berms in a range of water depths under intense hydrodynamic forcing due to three-dimensional waves and currents was produced and used to develop efficient and cost-effective rock berm designs for all depth zones.

Several innovative methods to accurately model and assess the performance of dynamically stable rock berms for pipeline secondary stabilization were developed and demonstrated in the course of conducting this unique study. The instrumentation setup allowed for the reliable and accurate measurement of wave and current forcing with minimal interference. The use of real-time underwater video monitoring provided valuable insight into the movement of rock material, rock berm re-shaping, and pipeline lift-out. The practice of constructing all model structures underwater using a model fall pipe produced highly realistic structures and allowed for more reliable assessments of their performance. A new classification system was developed to categorize and help assess the performance of dynamically re-shaping rock berms. A method of realistically simulating the behaviour of a continuous prototype pipeline using a model pipeline with finite length was also developed and successfully demonstrated. Results from the compliant pipeline models were critical in establishing reliable thresholds for acceptable amounts of berm reshaping and rock loss. They also revealed that the performance of the rock berm – pipeline system was sensitive to the quality and uniformity of the rock berm construction.

The study described in this article generated a large amount of data and new information concerning the behaviour and performance of dynamically stable rock berms, comprised of relatively small rock sizes, used for pipeline secondary stabilization in shallow and intermediate water depths under intense hydrodynamic forcing due to extreme short-crested waves and currents.

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