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An experimental study to evaluate scour mitigation options for pipe-clamping mattresses

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ABSTRACT: Pipe clamping mattresses (PCMs) are a relatively new solution to anchor pipelines against axial walking. They comprise a hinged concrete structure that clamps onto a section of the installed pipeline, with concrete ballast logs then placed on top to secure the clamping action – and with 100% of the submerged weight of the PCM contributing to enhanced axial friction, they represent a highly efficient solution. However, questions remain over how suitable they are when installed on an erodible seabed – with scour potentially leaving long sections of pipe at the PCM location unsupported. Assessing this issue is the subject of the current paper, in which experiments undertaken in the Large O-Tube at The University of Western Australia were performed to first understand the risk, and then develop an effective mitigation solution. Testing was undertaken in three phases (i) an investigation into if/how scour resulted around PCMs when subjected to ambient current and storm conditions without any scour protection; (ii) experiments to evaluate the performance of various 'full protection' systems placed around the PCMs; and (iii) further study of a 'falling apron' type rock berm solution that allows an acceptable (and predictable) level of scour to develop. This paper presents a selection of the results from each phase of testing and summarises key observations / conclusions for application to future PCM installations.

Keywords: Pipe clamping mattress, subsea pipeline, scour protection, rock berm, concrete mattress

1 INTRODUCTION

Subsea structures placed onto a mobile seabed will often be subject to scour, which in the extreme can impact their functionality. Mitigating scour, where necessary, can be both complex and expensive. This paper presents select results from an experimental study undertaken first to address the risk of scour, and then to identify options to address its impact.

1.1 What is a pipe clamping mattress?

Pipelines used to transport hydrocarbons can experience 'walking' over their operating life, whereby thermal transients (cycles of heating and cooling associated with startup / shut down of the subsea system) lead to progressive movement of the pipeline in one direction. One innovative solution used to arrest this movement is the pipe clamping mattress (PCM) illustrated in Fig. 1, which was developed and initially deployed by Shell (Frankenmolen et al, 2017).

Comprising two parts, the 'clamp' is first lowered onto the pipeline, before the log mat is positioned on top – with the weight of the mat forcing the clamp to grip the pipeline. The primary advantage of this system is that all of the deployed weight is carried by the pipeline, leading to an increase in axial friction to reduce the risk of walking. Typically installed in multiple units, more details are provided in O'Beirne et al (2021), which describes a testing campaign investigating the geotechnical performance of PCMs.

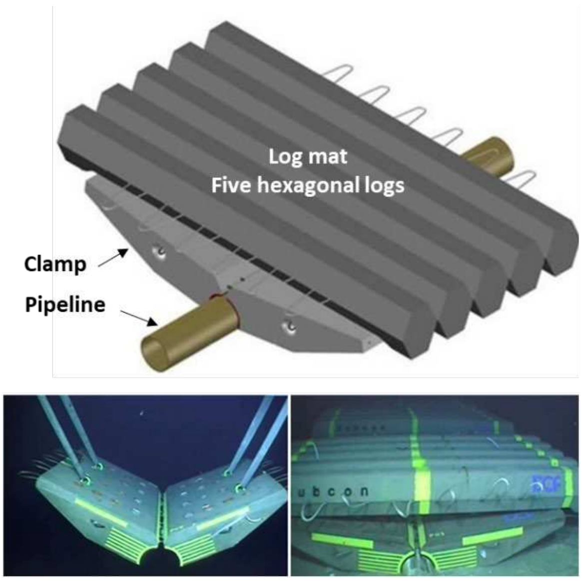

Figure 1. Illustration of pipe clamping mattress, including as installed (after O'Beirne et al, 2021)

1.2 What risks are associated with scour around PCMs?

Installing a PCM on a pipeline will lead to local amplification of near bed current. If the current is sufficient to mobilise the local seabed, then this may lead to scour around the PCMs and/or tunnel scour (or undermining) of the supporting pipeline, resulting in the development of a free span. In this case, the full weight of the PCM could end up resting on an unsupported section of pipeline – and depending on its structural capacity and the free span length, this could lead to overstress (failure) of the pipe section and/or lowering of the pipeline into the scour hole. The latter could cause the extremities of the PCM to contact the seabed, with a subsequent risk of 'de-clamping' – thereby leaving the pipeline free to move axially.

The current study was undertaken in support of a planned deployment of multiple PCMs to an operational pipeline located offshore Australia, in greater than 100 m water depth. Given the potential for structural risk to the pipeline, and concerns over a PCM not fulfilling its long-term purpose, the study described in this paper aimed first to investigate risk (and extent) of scour, and then to identify potential mitigations solutions.

2 EXPERIMENTAL CAMPAIGN

The testing described in this paper was performed in three phases:

- Phase 1 investigated if/how scour would occur around a PCMs when subjected to both ambient current and storm conditions, and without any scour protection.
- Phase 2 investigated the performance of different types of scour protection, comprising combinations of rock berm and concrete mattresses.
- Phase 3 investigated the extent of scour when protection was limited to (only) rock placed on top of the pipeline at either side of the PCM.

Testing was performed in the Large O-Tube (LOT) facility at The University of Western Australia. Shown in Fig. 2, the LOT is a horizontal fully-enclosed circulating water channel, with a rectangular test section and an impeller-type pump driven by a motor that is capable of generating both steady current and wave velocities. The working section has a width of 1 m, height of 1 m and a length of around 17 m. An Acoustic Doppler Velocimeter (ADV) was used to measure the velocity profile in the flume, with video cameras and a 3D scanner used to capture the seabed profile during testing.

The scale adopted for modelling was 1:8.25, which was a compromise between (i) maximising the model size to minimise the influence of model scale effects such as bed ripples and (ii) ensuring that two PCMs could be placed within the O-Tube working section. An artificial, fine-grained sand with a narrow grading (D_{50} ~ 0.2 mm) was used in the tests; this ensured repeatable testing and produced results that could be extrapolated to different field conditions (or different laboratory sediments) after accounting for differences in the erosion properties of the test sand and the field sediment. For instance, with knowledge of the threshold shear stress of field sediment (obtained via an erosion test similar to that discussed in Mohr et al. 2021, for example), it is possible to determine what flow conditions will cause scour in the field based on observations of the required shear stress (relative to the free field shear stress) needed to cause scour in the laboratory. Furthermore, if additional testing is undertaken to correlate scour rates to erosion rates, then it is possible to quantitatively adjust the laboratory scour rates to account for different sediment properties. This latter approach, for example, has been adopted in Mohr et al. (2016) for pipelines and Yao et al. (2018) for a subsea structure. For the present paper, erosion testing results were not available for the field sediment at the time of the study, and so testing results in the laboratory sands were treated as an upper estimate of scour response (with field sediment expected to scour at a slower rate than a clean uniform sand).

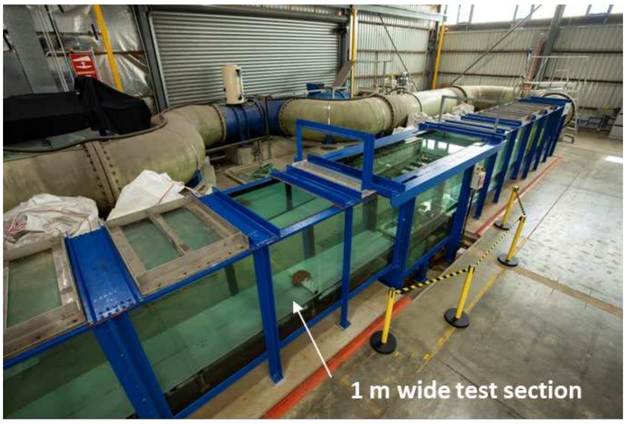

Figure 2. UWA Large O-Tube

Flow conditions explored in the project included the following cases:

- 'Ambient current' that is close to (but just below) the current needed to initiate live bed scour conditions. In this case, sediment far from the PCM is not mobile – but local scour is likely due to amplification around the structure. At model scale, a current of 0.3 m/s at 0.2 m above the sand was used.

- 'Design current' that is representative of a low (0.1%) exceedance event at the target location. At model scale, a current of 0.45 m/s at 0.2 m above the sand was used.
- A 'storm condition' that is representative of a 100-year storm event and comprises both current and wave (orbital) velocities. At model scale, this event coupled 0.28 m/s current with 0.1 m/s peak wave velocity (both at 0.2 m above the sand), with the latter applied at a period of 5 s.

Each of these flow conditions were modelled to act both perpendicular and parallel to the pipeline.

When choosing the velocities quoted above, Froude scaling was adopted to ensure that the onset of scour beneath the pipeline due to piping was correctly reproduced (or not) at model scale – see (for example) Sumer and Fredsøe (2002) for details of the mechanisms causing onset of scour. Shields scaling was not adopted directly, although the Froude scaled velocities (listed above) coincided with live bed conditions (or very close to live bed conditions) taking account of the sediment type at the planned location of the PCMs. In live bed conditions the extent of scour – which was the focus of this test program more so than the rate of scour development – is not as sensitive to Shields parameter (e.g. see Figure 1.3 in Sumer and Fredsøe, 2002).

A range of physical models were developed for this project, as illustrated in Fig. 3. These include fabrication of two model PCMs, which allowed (a) testing together, to explore the effect of PCMs interacting with each other; and (b) testing in isolation, such as might be expected at the edge of a series of installed structures. Additional models included the concrete mattresses and rock used for creating the berms.

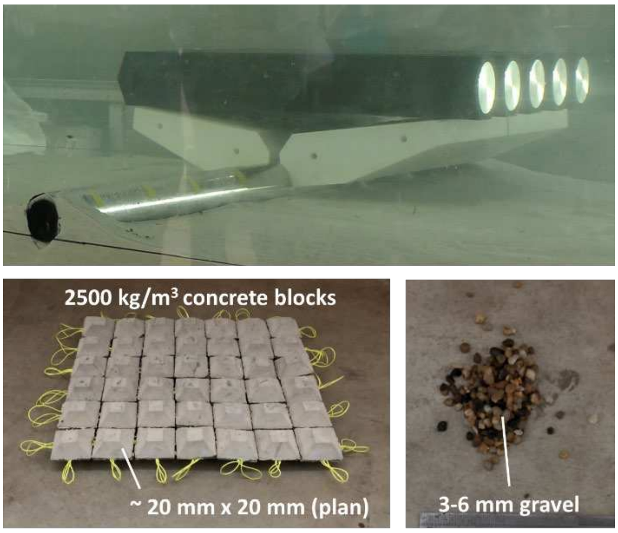

Figure 3. Models used in experiments – PCM (top), concrete mattress (bottom left) and rock (bottom right)

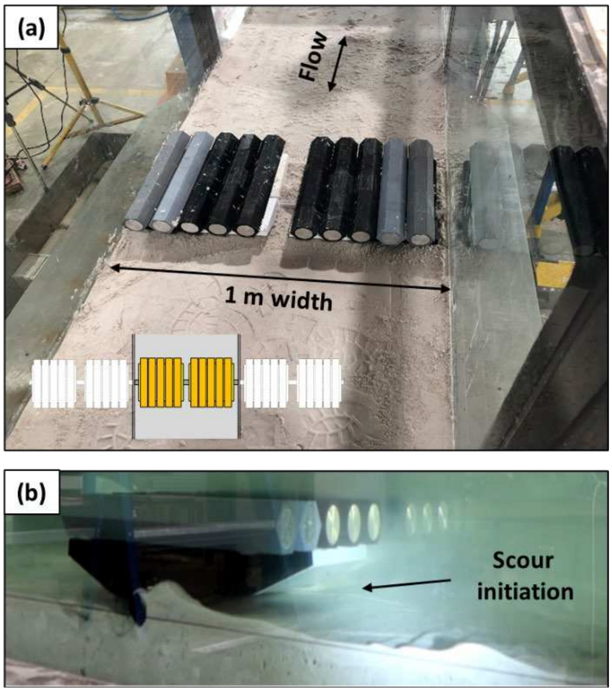

Figure 4. Modelling a series of PCMs (no protection)

3 PHASE 1 TESTING

The first phase of testing investigated whether scour would occur under a PCM without any protection, and if so, to what extent. Fig.4a shows the setup across the LOT channel in which two PCMs were placed side by side; while a test exploring scour around an end PCM is shown in Fig. 5a. Tests were performed with different pipeline embedment – ranging from 5% to 20% of the pipe diameter (D), and with the sand surface initially flattened around the pipe.

Key observations include:

- For perpendicular flow, scour initiated below the pipeline at a number of locations (beneath the PCMs) in both ambient and storm conditions when the pipeline was embedded to only 0.05D. For deeper embedment (0.2D), scour did not initiate for ambient current, but did initiate under the pipeline at the gap between PCMs in design current and storm conditions (Fig. 4b). Similar results are seen for the end PCM, with scour as shown in Fig. 5b and Fig. 5c.

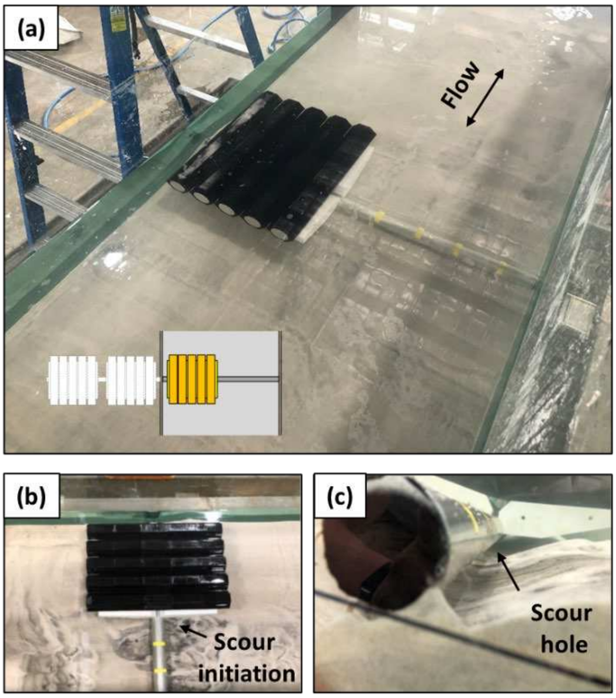

Figure 5. Modelling the end PCM (no protection)

- The observation of scour are consistent with general expectations based on existing literature for scour under an isolated pipeline (see Sumer and Fresdøe, 2002) provided an allowance is made for the increase in flow velocity around the PCM and through the gap between two PCMs. For instance, the critical upstream velocity for onset of scour beneath an isolated pipe presented in Sumer and Fresdøe (2002) explains that scour results from the development of a pressure gradient across the pipe-soil interface, which causes local piping failure of the sediment immediately downstream of the pipe. This same mechanism was apparent in the present testing, but the critical upstream velocity was lower than that for an isolated pipe because of amplification associated with the PCM causing increased flow velocity around and through the gap between PCMs.
- Once scour initiation occurred, the scour hole quickly grew in depth and extent along the pipeline. Sagging or sinking of the pipeline was not modelled in the present testing campaign (as the pipeline was rigid and supported), although the presence of extensive scour suggests that pipeline lowering would be inevitable following scour initiation if no scour protection is adopted.

Although not shown, scour also occurred for flow acting parallel to the pipeline, in each case undermining the pipeline towards the upstream end of the PCM. In the event of a change in flow direction, this scour could act as an initiation point for scour under the PCM.

Overall, the Phase 1 testing clearly demonstrated the risk posted by scour to the performance of the pipeline-PCM system.

4 PHASE 2 TESTING

A number of scour protection configurations, using combinations of concrete mattresses and rock berms, were tested in Phase 2. In all cases, an initial pipeline embedment of 0.05D was adopted – since the Phase 1 testing clearly showed this to be the more onerous condition for tunnel scour.

Initial Phase 2 testing focused on scour protection options that provide only partial protection, such as through the placement of (limited) rock along the pipeline on either side of the PCM, and with the addition of one concrete mattress adjacent to the PCM. However, the arrangements tested did not prevent scour under the pipeline when the system was orientated either parallel or perpendicular to the flow direction (even for the least onerous flow conditions). Based on this, an option for more extensive scour protection was devised – which is described below.

Fig. 6 shows the scour protection scheme devised in an attempt to provide ‘complete’ protection of the pipeline and PCM – comprising rock plus multiple concrete mattresses. This arrangement largely suppressed scour when the pipeline was orientated parallel to the incident flow direction, with only minor scour observed under the concrete mattresses following testing (Fig. 7). In contrast, when orientated perpendicular to the flow direction scour was observed under the pipeline after a combination of ambient current, design current and storm conditions.

While the mechanisms leading to scour under the pipeline could not be observed directly, it was evident following testing that sediment had been transported by flow passing through the concrete mattresses. This implies that unless full protection can be assured – which is likely difficult given installation tolerances in the field – then scour can still occur around the pipeline, even with such extensive protection.

A secondary concern with this ‘complete’ protection scheme is the restriction it placed on subsea inspection requirements. Observations of scour were only possible at the end of testing – this is consistent with what would happen in the field, where observation would be difficult and may not allow early identification (and intervention) in the case of unplanned scour.

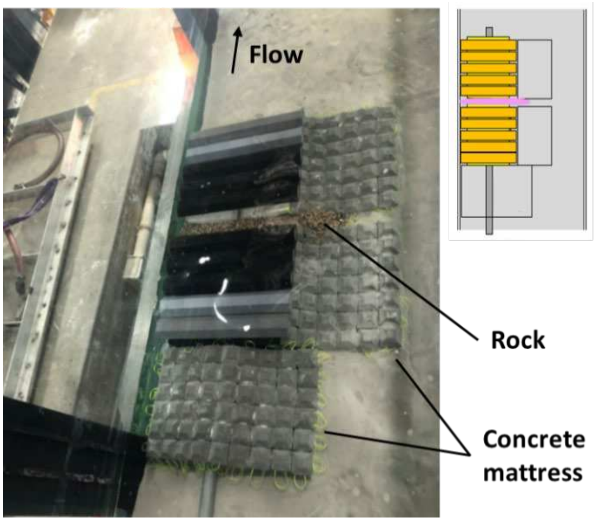

Figure 6. Composite scour protection comprising concrete mattresses and rock berm – model setup for parallel flow

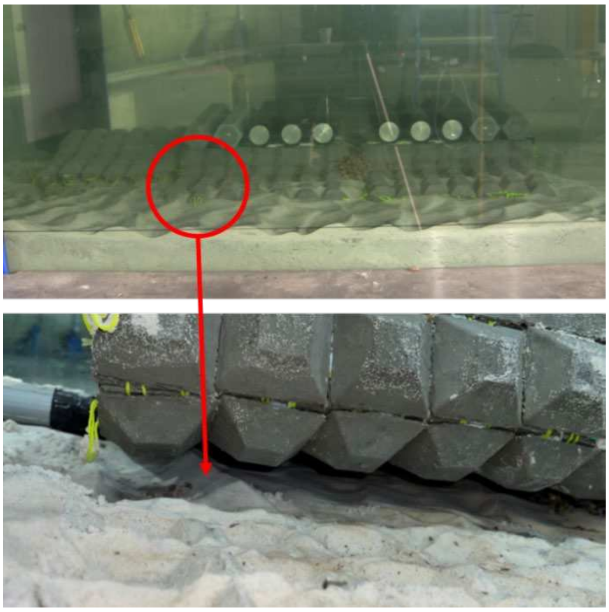

Figure 7. Limited scour observed under mattress

5 PHASE 3

Given the conclusion from Phase 2, i.e. that it was not possible to fully ensure no scour under the pipeline, the motivation for Phase 3 was to see if the use of (only) rock berms either side of the PCMs would serve to limit the horizontal extent of scour beneath the pipeline to just the length of the PCMs. Provided the pipeline could be shown to be able (structurally) to support the weight of an isolated PCM, then this may provide a more robust solution overall. The arrangement adopted is shown in Fig.8a for a single PCM located in the centre of the LOT channel.

Testing for this arrangement was undertaken for perpendicular ambient current and storm conditions until equilibrium scour was observed. It was evident during testing that the adjacent rock entered into the scour hole due to avalanching as the scour hole developed, as is shown in Fig. 8b. This rock acts to armour the hole, limiting the scour depth and the scour extent to just the length of the PCM.

This was further investigated by placing a half model of the PCM against the wall of the LOT channel and observing rock avalanching with time. Fig 9. shows the gradual progression of scour, ultimately leading to a stable condition – whereby the hole did not grow further or extend under the adjacent pipe.

Further testing would be required to confirm these findings for all flow conditions, but the results suggest that a ‘falling apron’ rock berm solution such as this may be an effective means of limiting scour and pipeline lowering, allowing the use of PCMs on mobile seabed.

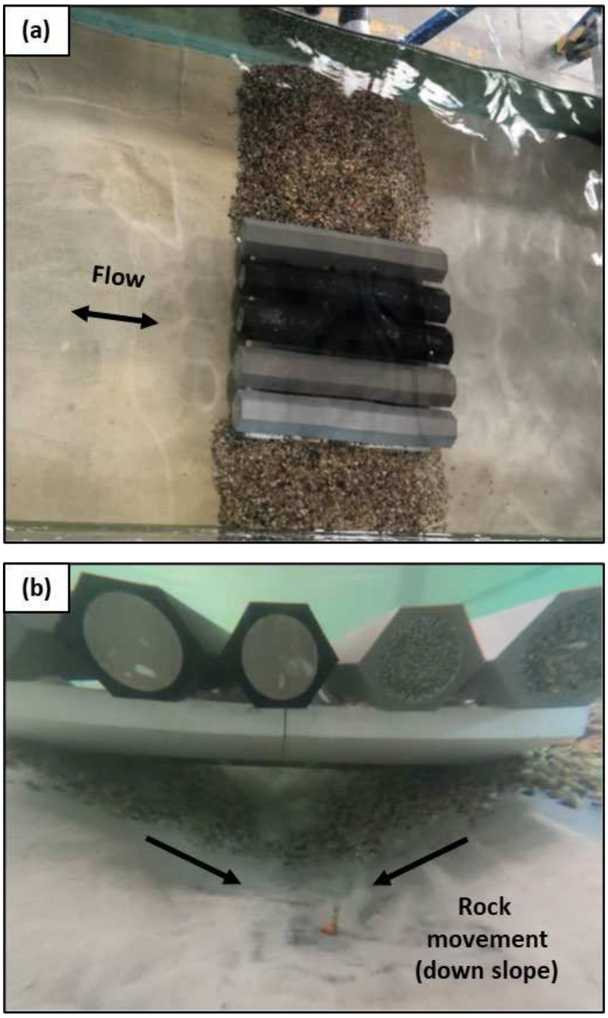

Figure 8. Use of rock berms either side of PCM

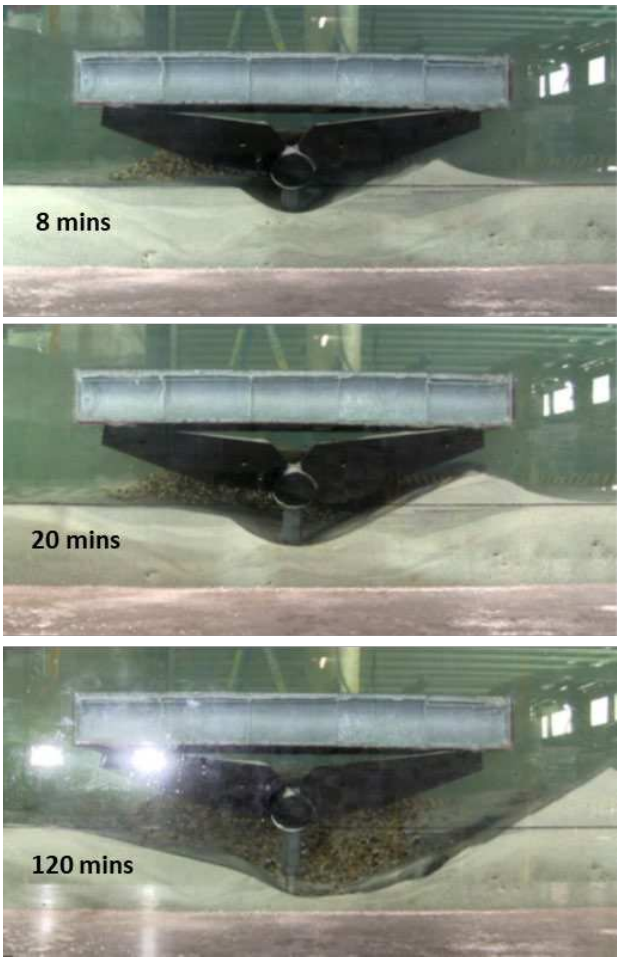

Figure 9. Use of rock berms either side of PCM

6 CONCLUDING REMARKS

The impact of scour in the marine environment is challenging and can be the cause for extensive operational expenditure. Based on the planned deployment of PCMS to a location offshore Australia, the test program outlined in this paper motivates further research to explore scour around such subsea structures, including to (i) develop guidelines to predict when scour will develop; (ii) better quantify the extent of scour beneath PCMs, including for hybrid scour protection solutions; and (iii) better quantify the effectiveness of scour protection solutions across a full range of design conditions.

AUTHOR CONTRIBUTION STATEMENT

All Authors contributed to the planning, supervision and interpretation of experiments. **The corresponding author** prepared the first draft of this manuscript, which was reviewed by all authors.

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