Hydraulic Cable Protection System Stability on Concrete and Rock Armour in Lateral Flow

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ABSTRACT

This paper describes the results of large-scale laboratory flume experiments on the stability of submarine cable-Cable Protection Systems. The data was collected in a 1.6 m wide flume channel with flow velocities ranging from as low as 0.1 m/s up to as fast as 1.9 m/s. The cable-CPS was installed in the test section and the flow velocity was increased in a controlled fashion to remove the effects of acceleration. Results were obtained for the onset of motion of two different CPS systems. The results reveal the added stability against movement arising from increased cable-CPS mass and differences in CPS external shape, and the enhanced stability when the CPS is placed on a layer of typical scour protection rock.

INTRODUCTION

Submarine high voltage cables used in offshore renewable energy generation projects transmit electricity between the generation location and substation. To provide protection against mechanical and hydraulic loads from current and wave loading the cable is often installed with an external layer of protection. The generic use of CPS (Cable Protection Systems) of various profiles and properties is ubiquitous in offshore wind energy projects. In the transition zone between the wind turbine foundation and cable which is often buried below the seabed away from the foundation itself the cable and CPS is in catenary and touches down on the seabed before the burial point. This touchdown point may be on the local seabed soil or on the top of a scour protection layer placed to resist scouring of the foundation.

The stability of the CPS-cable at and beyond touchdown is governed primarily by the balance between loading applied by hydraulic forces and the restoring force from the bottom contact. A cable catenary with fixity at the foundation and fixity in burial will experience partial fixity through interface friction when the cable is in contact with the bed (Figure 1). When lateral shear flow is applied to the catenary it will be stable when the horizontal load is less than the resisting force and move when the load exceeds the resistance. Whilst there may be some tendency for the cable profile to roll initially, further movement may actually take place through a mixture of rolling and sliding.

A set of experiments was devised to investigate the onset of movement of a segment of CPS-cable where it is initially in contact with the seabed. Two bottom boundary conditions were tested, firstly a concrete bed to provide an idealized set of results without the complicating effects of mobile sediment and partial burial due to scour/settlement, and secondly on a layer of rocks placed on top of the concrete bed to simulate the roughness associated with scour protection around the foundation.

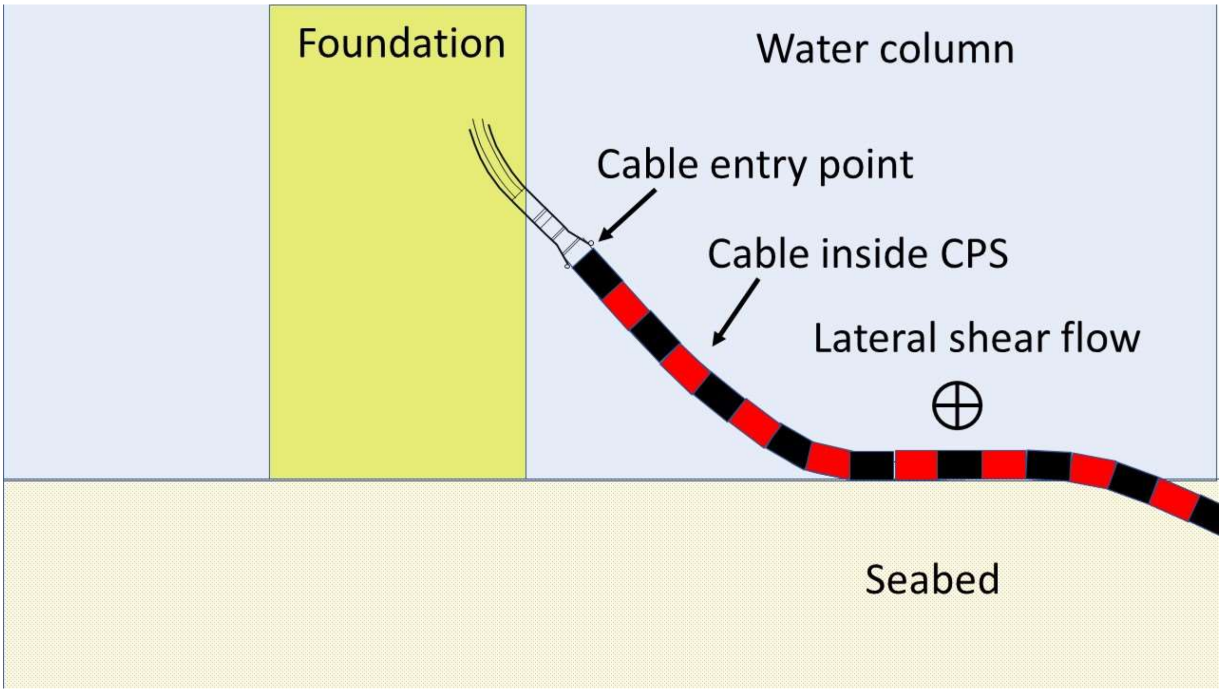

Figure 1. Schematic drawing of cable CPS profile between foundation and burial.

METHOD

Flume Channel. The experiments were carried out in the Fast Flow Facility (Whitehouse et al., 2014) with flow pumped around the flume channel and through a gradually (1:4) contracting section into a 1.6 m wide parallel sided channel in front of one of the main viewing windows of the flume. Fresh water of density 998 kg/m^3 was used in the tests.

The fixed bed of the channel was constructed from a layer of concrete poured over a ballast fill layer to raise the test section 0.5 m above the reinforced concrete slab of the flume. This enabled the tests to be observed from the viewing window.

For the bottom configuration with scour protection rocks, AIS specified that a rock layer similar to a standard scour protection rock (LMA5/40; CIRIA et al., 2017) should be used. This was to obtain an appropriate roughness interface between the CPS and the rock layer. Figure 2 shows the standard grading of the rocks. For logistical reasons of placing the rocks by hand in the test section, the lower half of the grading curve was adopted with rocks between 1-2 kg and 20 kg installed and packed together. This provided a 200 mm thick layer which was required both to seat the CPS but also to maintain operating freeboard for the water levels in the flume. The rock was sourced from a UK quarry in the Southwest of England and the standard limestone density of 2700 kg/m^3 was specified by the quarry.

As noted above, the lower half of this LMA5/40 grading was used to create the rock bed to an average thickness of 200 mm creating a uniform but irregular rock surface. A length of PVC fascia board with height 200 mm was placed at the flume window prior to rock placement to protect the window from damage. The natural variability in the scour protection rock surface at the location of the CPS created different responses, both in terms of the nature of the bottom contact between the CPS and the rock and also in terms of the local shear flow due to the bottom roughness. The placed rocks had nominal diameters of between about 0.23 m (20 kg) and 0.15 m (5 kg).

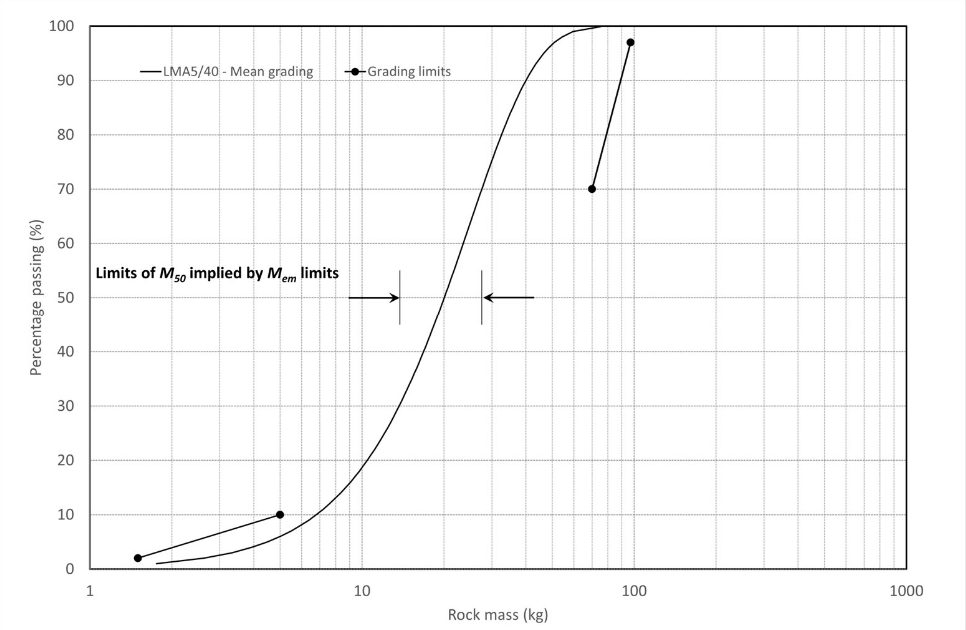

Figure 2. LMA5/40 grading curve showing limits for the upper, lower and median mass M_{50} based on the effective mean mass M_{em}.

The rock bed extended about 10 m upstream from the test location and a scan of the rock bed is shown in Figure 3. The test section was located at the left-hand end of the 19 vertical markers painted on the wall, each about 100 mm wide and spaced with a gap of about 100 mm. The markers were used to check the position within the test section and as a reference for CPS movement.

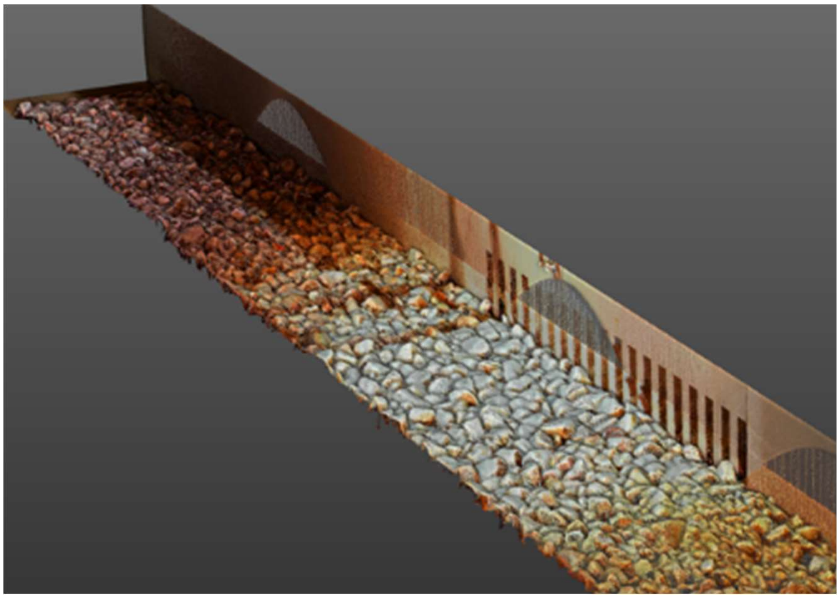

Figure 3. Terrestrial laser scan of the rock bed. The test section is located at the vertical markers on the wall and flow direction is from top left to bottom right.

CPS and Cable. The products being tested were provided by AIS from their proprietary product range. One was a standard circular section CPS and the second was a circular ballasted (i.e. heavier) section CPS with small feet moulded into the profile to provide added resistance to rolling. The two lengths of 130 mm diameter submarine power cable were 3-core copper power conductors with an external single layer of cable armour and waterproof exterior sheath (Figure 4). The cable and CPS were combined for testing with the cable installed in the 200 mm diameter internal duct (Figure 4). They were placed in the test section perpendicular to the flow direction with a small initial gap of 50 mm at each end so as to ensure free movement.

The details of the CPS system are proprietary but basic information is provided to allow intercomparison of the two systems. The CPS outside diameter was 380 mm and the mass underwater for the combined cable and traditional CPS was about 29 kg/m and combined cable and ballast CPS was about 140 kg/m.

Measurement Equipment: Measurements and observations were made in the test section as follows. The water velocity was measured with a 2MHz Nortek Aquadopp HR profiler operating in downwards looking mode upstream of the test section. The Aquadopp measured the vertical profile through the water column from 0.1 m away from the instrument face to a depth of 1 meter. At speeds in excess of 1 m/s the range was reduced to avoid wrapping of the signal. Data recorded was processed to produce average current speed profiles. This allowed the cable-CPS behaviour to be correlated with specific measured velocities.

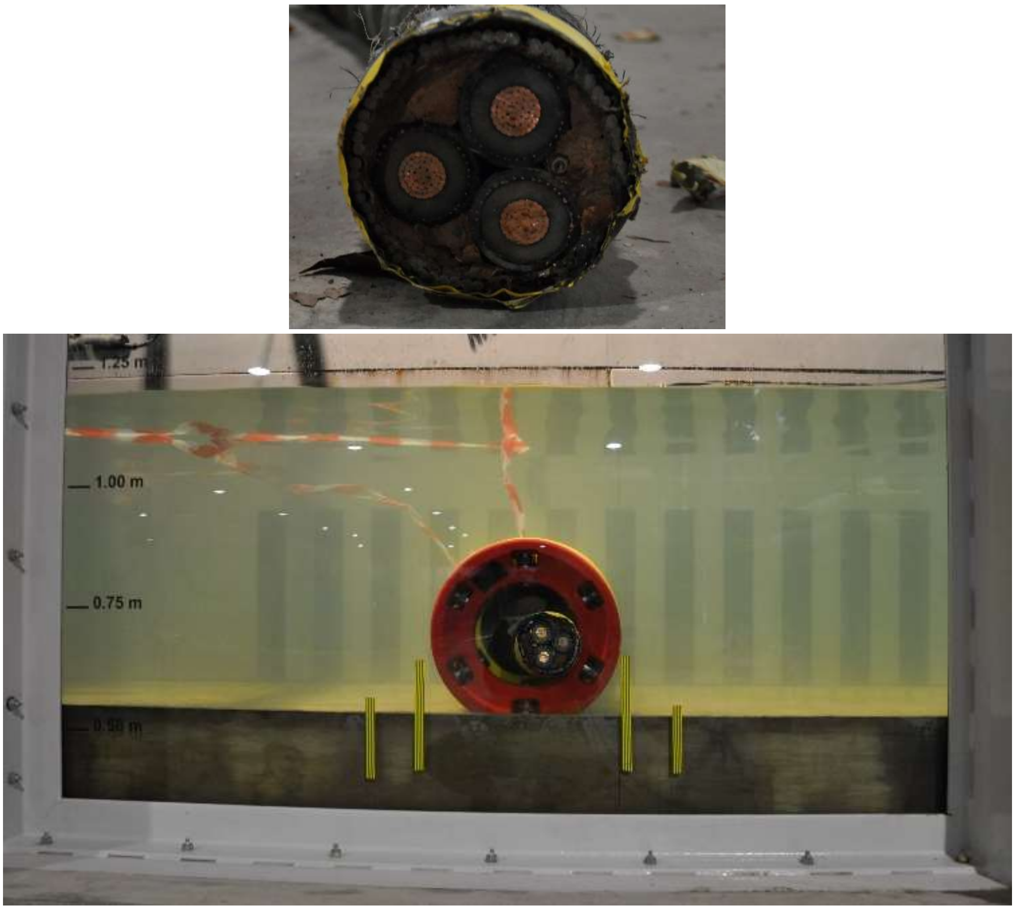

Figure 4. End view of cable and combined cable-CPS set up in the test section prior to commencement of flow.

Observations were made in the test section whilst the flow was being increased, and neutrally buoyant marker tape (visible in Figure 4) was used to visualize flow patterns. The movement of the cable-CPS was observed at the test window (Figure 4) and gauged against the vertical markers underwater on the wall and with taped lines on the window. An underwater camera fixed to the inner wall directly above the CPS and external camera directly opposite the CPS opening were recorded for post-test analysis of movement.

Run Sequence. A standard approach was used to control the pump discharge time series. The flow was ramped up slowly so as to avoid any acceleration effects in the test section. The starting time of the flow sequence and camera observations were synchronized to allow post processing of the data for the onset of motion. After some initial trials, a flow sequence for the tests was established to allow intercomparison of results.

RESULTS

Results were obtained for three runs, i.e., including repeats, for each of the cable-CPS sections on the concrete bed and on the scour protection rock bed. The current speed for initiation of movement was recorded and for the product to move 1 CPS diameter downstream. An example of the data for one of the tests is shown in Figure 5. The pump discharge is calibrated to give a velocity which shows as the yellow time series. In this test the data were interpreted to show the start of cable-CPS movement at 0.27 m/s and 1 CPS diameter at 0.36 m/s.

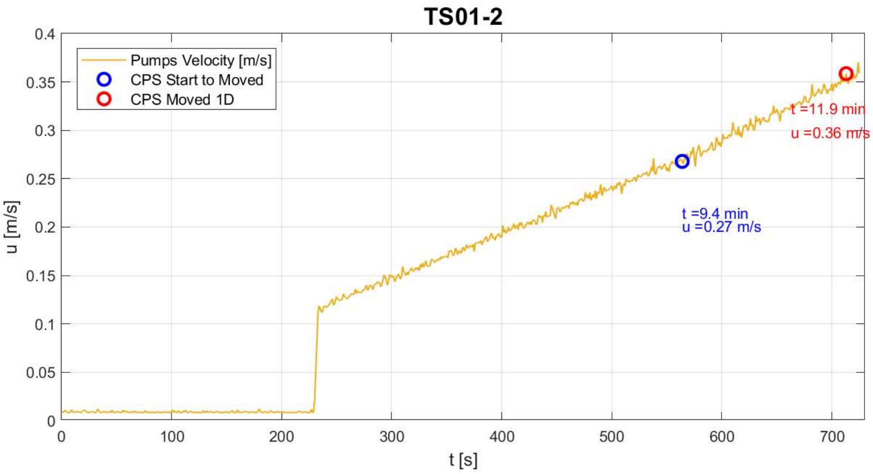

Figure 5. Example of test result for cable-CPS.

Concrete bed. The two different CPS products being tested yielded a range of results (Table 1) in terms of the velocity required to initiate movement on the concrete bed.

As expected, the velocity to initiate movement of the traditional cable-CPS was lower in each test than that required to move the cable-CPS. The movement of the traditional CPS took place through rolling with the current direction. As the CPS rolled the cable adjusted position within the central duct of the CPS creating a periodic anchoring effect or added moment to rolling if it was elevated above the invert of the duct in the center of the CPS. The first two test results gave similar results for the start of movement, whereas the third test yielded a smaller speed which may have been due to a slightly different subjective criterion for the initiation of movement, or the initial condition of the cable inside the CPS being slightly different. The average flow velocity for start of movement was 0.25 m/s.

The movement of the ballast CPS was through sliding rather than rolling, as the feet of the product in contact with the concrete floor prevented rolling. The velocity required to initiate sliding and the velocity required to move the ballast CPS one diameter were very similar as the initial force required for movement was large, and once in motion the product slid at a fairly uniform rate. The average velocity for the start of movement was 1.3 m/s.

Overall the results showed the velocity required to move the ballast CPS-cable combination was about 5 times larger than the traditional CPS on a solid concrete bed.

Table 1. Results with concrete bed for the two different CPS products.

Test name	**Product type**	**Bed type**	**Movement Start u [m/s]**	**Moved 1D u [m/s]**
TS01_1	Traditional	Concrete	0.29	0.46*
TS01_2	Traditional	Concrete	0.27	0.36
TS01_3	Traditional	Concrete	0.18	0.32

*The result for this test was influenced by the CPS temporarily becoming snagged at one end which increased the resistance to movement by about 0.1 m/s

Test name	**Product type**	**Bed type**	**Movement Start u [m/s]**	**Moved 1D u [m/s]**
TS04_1	Ballast	Concrete	1.33	1.33
TS04_2	Ballast	Concrete	1.27	1.28
TS04_3	Ballast	Concrete	1.29	1.33

Rock layer. The results with the rock layer are summarized in Table 2. The roughness of the rock layer influenced the results as follows.

For the traditional cable-CPS combination the velocity required to move it 1 CPS diameter was larger than the velocity to start movement. This is as expected as movement can be initiated locally within the roughness layer which is estimated to be about 1/3rd of the CPS diameter. Therefore, the initial position of the CPS may be located with respect to rocks which promote the initial movement or resist it, for example if there is a rock peak adjacent to the CPS on the downstream side. Once movement had been initiated the CPS was able to roll over rock pinnacles (Figure 5). The average velocity required to initiate movement was about 0.66 m/s, and 0.72 m/s to move the CPS by 1 diameter. These are very similar, and a value of 0.7 m/s is probably appropriate considering experimental uncertainty.

For the ballast cable-CPS combination the velocity required for the onset of movement was also influenced by the initial position of the CPS with respect to the rock layer. For the two, out of five, tests conducted where the CPS was able to be moved by the flow, movement commenced at an average flow velocity of 1.44 m/s and an average velocity of 1.7 m/s was required to move the CPS by 1 diameter. Differences in the speed for onset of movement is likely controlled by the interface between the underside of the ballast CPS and the rock bed. The movement by 1 diameter, where it occurred in two out of the five tests, was characterised by a sudden rotation downstream.

The lack of movement of the CPS in Test TS03-03 at a speed that exceeded the movement threshold in Tests TS03-01 and TS03-02 was due to the natural support from rocks under the CPS feet on the downstream side preventing rotation of the product.

Table 2. Results with rock layer for the two different CPS products.

Test name	Product type	Bed type	Movement Start u [m/s]	Moved 1D u [m/s]
TS02_1	Traditional	Rock	0.57	0.70
TS02_2_D	Traditional	Rock	0.83	0.86
TS02_3	Traditional	Rock	0.59	0.61

Test name	Product type	Bed type	Movement Start u [m/s]	Moved 1D u [m/s]
TS03_1	Ballast	Rock	1.55	1.76
TS03_2	Ballast	Rock	1.33	1.70
TS03_3	Ballast	Rock	N.M.	N.M.
TS03_4_D	Ballast	Rock	N.M.	N.M.
TS03_5_D	Ballast	Rock	N.M.	N.M.

* N.M: No Movement at peak speeds of 1.95 m/s, 1.5 m/s and 1.6 m/s, respectively.

Figure 5. Standard cable-CPS product rolling over a rock pinnacle.

DISCUSSION

The results provide useful comparative data for the stability of cable-CPS systems under lateral shear flow on rigid beds and scour protection rock. The minimum velocity causing a movement of one CPS diameter was 0.3 m/s for the traditional CPS on concrete. The introduction of scour protection rocks as the bottom layer increased the resistance to movement by a factor of two due to the irregular nature of the contact roughness with the underside of the CPS.

The maximum flow velocity reached after which movement occurred of the ballast CPS product on the scour protection rock was 1.70 m/s and 1.76 m/s. The maximum flow velocity reached without any movement of position of the ballast CPS was 1.9 m/s which shows additional capacity can be obtained from the natural positioning of the CPS within the surface layer of rocks and the resistance this provides to resist CPS rotation.

The most consistent set of results were from tests performed on concrete due to the evenness of the bed. In the tests with rock, the variation in the bottom contact with the ballast CPS and the in-test displacement and transport of some rocks, provided a random bed condition which resulted in different positions of the contacts for each test and hence, more variability in test results. On the concrete bed the uniformity of test results yielded a velocity of about 1.3 m/s for movement of the ballast product.

To evaluate the enhanced stability of the ballast CPS for 1D movement an evaluation was made on the basis of ratio of forces applied by the flow. From the results obtained, the traditional CPS with cable on the scour protection rock moved at a flow velocity of about 0.7 m/s and the ballast CPS with cable on the rock moved at a flow velocity of about 1.7 m/s. Since the force applied to the CPS by the flow is related to flow velocity squared, the ballast CPS was shown to be approximately 1.72/0.7 or about 6 times more stable than the traditional CPS.

In tests at high flow velocity with the ballast CPS, rocks were observed to vibrate and move out of the layer under and just downstream of the CPS. A selection of three rocks that moved are shown in Figure 6. This changed the local bottom configuration under the CPS allowing localized adjustment of the CPS profile, in this case increasing the stability. The larger rocks in the grading did not move, and if larger than M_{50} sized rocks had been installed this would have increased the local elevation and provided randomly occurring pinnacles of rock to resist movement of CPS.

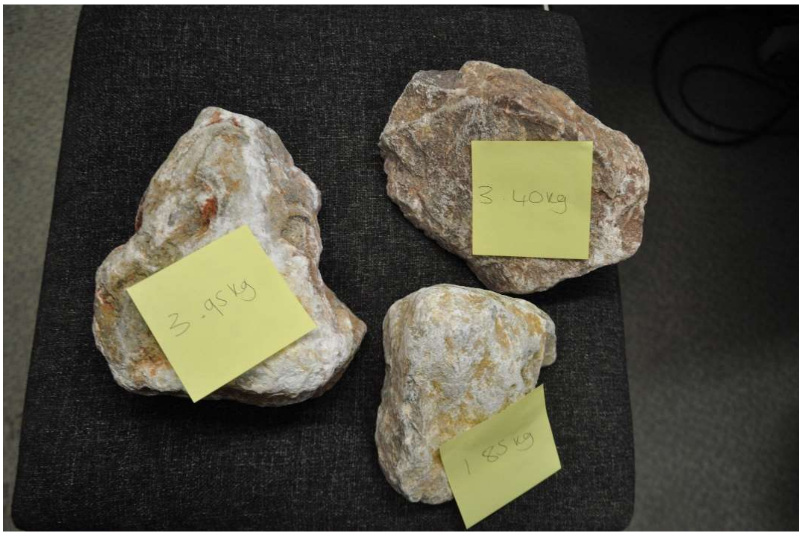

Figure 6. Three rocks displaced from the scour protection layer at a flow speed of 1.9 m/s.

CONCLUSION

A range of laboratory tests were completed with sections of armoured submarine high voltage cable installed within two different specifications of Cable Protection System. The cable-CPS combination was exposed to lateral shear flow in large scale laboratory tests and the onset of movement was recorded.

A standard round section CPS was tested which was able to be moved by a current velocity of 0.25 to 0.3 m/s on a rigid concrete bed. When the same CPS was installed on a layer of scour protection rocks, as would be used for foundation scour protection, the velocity required for movement was increased to about 0.7 m/s. This increase by about a factor of two was due to the additional bottom roughness on which the CPS was initially placed.

A heavier, ballasted, CPS was tested and was found to be more stable on the concrete bed partly due to its weight but also due to the inclusion of supporting feet which prevented rolling from occurring. This CPS was able to be moved by sliding at a current velocity of about 1.3 m/s. The outcome of tests on the scour protection rock were more variable and illustrate the importance of the local bottom contact configuration. On average the ballast CPS was able to be moved at a current velocity of about 1.4 m/s, causing local readjustment of position in the rock surface, whereas failure by rotation was not created until the flow velocity reached 1.7 m/s. However, in some tests the CPS was able to resist a flow velocity of 1.9 m/s due to the nature of the bottom contact, and at these very high velocities smaller rocks in the scour protection layer were mobilized locally to the CPS without any motion of the CPS itself.

Whilst it does not affect the relative conclusions, we note if the results are applied to seawater the density is about 2 or 3 % higher than the freshwater used in the laboratory tests. This will have a small effect on the submerged masses quoted and the force applied to the CPS at a given flow velocity.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the HR Wallingford laboratory and IT support team for construction, lifting, camera and instrumentation support in the execution of the experiments. Funding for the work was provided by AIS Ltd with matching funds from HR Wallingford's strategic research programme.

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