

Study On The Application Of The Articulated Concrete Block Mattresses Method As Subsea Pipeline Protection

Abstract

Submarine pipelines are laid on the seabed using a specialized anchoring mechanism to ensure their stability against oceanic wave action, tidal flows, and seabed shifts. These submerged conduits are crafted to contour to the relief of the ocean floor, extending over numerous kilometers, and are commonly utilized to convey feed intake and other processing substances. Therefore, the existence of these underwater pipelines is crucial. However, various challenges arise for these submerged lines, including damage from bending and kinking, collisions with ship anchors, and displacement due to anchorage, all of which can lead to deterioration and fractures. Such incidents have the ability to disrupt and suspend operational endeavors for enterprises. A thorough examination is necessary to identify the contributing elements and root causes of these complications to formulate effective solutions. Articulated Concrete Block Mattresses (ACBM) consist of rectangular concrete units that are systematically positioned over submerged pipelines (SPL) and interconnected by polypropylene cords. ACBM adapts its arrangement to match the structure and accommodate alterations in the riverbed or seabed, including changes resulting from scouring. Based on the research outcomes and discussions, several deductions can be made: The hydrodynamic coefficient of the ACBM can be determined using an experimental method known as the direct pull test, which yields coefficient values that must be validated by evaluating cell strength load and critical velocity, ensuring a maximum error margin of 8.3% over five distinct tests. Moreover, numerical evaluations were conducted to simulate pipes safeguarded by ACBM under two scenarios—regular waves in deep waters and breaking waves in shallow waters. Both investigations revealed that the drag and lift coefficients for pipes protected by ACBM were lower than those for unprotected pipes.

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1. Introduction

Subsea pipelines are installations designed to transport fluids (water, oil, gas) through piping systems situated on the sea floor (seabed). This underwater piping setup allows for the movement of fluids from one location to another, whether from a production unit to another, from a storage unit to a processing unit, or from a processing unit back to a storage unit. These subsea pipelines are essential transportation infrastructure for the offshore oil and gas sector and are regularly employed to deliver raw materials like crude oil from centralized storage facilities to distillation units. With the growing development of underwater pipeline networks and the establishment of coastal ports, it is common for the landfall sections of subsea pipelines to cross shipping lanes.

Subsea piping systems are positioned on the seabed using specific security measures to prevent the pipes from shifting their locations due to wave dynamics, tidal movements, and ground displacement. The underwater piping is installed in a manner that follows the natural contours of the seabed, often extending tens of kilometers, regularly transporting feed intake and other necessary materials. Therefore, the presence of these underwater pipelines is critical.

Challenges encountered by underwater pipelines include damage from shifting and kinking, collisions with ship anchors, and being dragged by anchors, which can lead to breaks and other damage. More than half of the global failures in subsea oil and gas pipelines result from external factors, with ship anchoring operations being a significant contributor. The risk posed to pipelines by falling anchors has been evaluated in the code DNVGL-RP-F107. Once an incident results in pipeline damage, the financial impact can be substantial, and the pollution of seawater can be severe. Such occurrences lead to interruptions and halts in company operations, especially with equipment that transports crude oil at high flow rates and pressures, which could cause the pipeline to shift and rise from the seabed. If the underwater pipeline is installed according to established standards and regulations, it should remain in place on the seabed. This issue necessitates further examination to identify the contributing factors and causes of such incidents to develop effective solutions.

2. Methodology

The approach taken for this study is library research, focusing on published library materials. The sources of literature include scientific journals, books, and articles. In this study, the researcher will analyze the comparison between the application of the Articulated Concrete Block mattress method in experimental tests and software simulations.

Articulated Concrete Block Mattresses (ACBM) are uniquely crafted concrete segments shaped like rectangular forms that are systematically arranged above submerged pipes (SPL), with each segment linked by polypropylene cords. ACBMs are frequently utilized for erosion defense in a variety of scenarios. The connecting cords between the segments establish a flexible framework that enables the ACBM to adapt to the contours of the underlying structure and adjust to the characteristics of the riverbed or seabed (for instance, in reaction to erosion). In the 19th century, ACBMs were initially conceived and employed to safeguard riverbanks from degradation caused by flooding. Moreover, ACBM is extensively applied in offshore engineering for erosion protection and acts as an additional method of stabilization. For all these diverse uses, it is essential that the mattress is designed to preserve stability and hydrodynamic effectiveness in line with specified design criteria, which necessitates an understanding of the hydrodynamic forces affecting the mattress.

The choice to implement ACBM came after a series of steps in identifying solutions, which involved analyzing the types and weights of vessels anticipated to travel through the SPL area, examining the anchor weights utilized, assessing the level of damage to the SPL, suggesting appropriate protective measures to avert future problems, calculating the distance from the anchors to the SPL, and pinpointing the critical locations and areas that required protection with ACBM.

3. Literature Review

In order to assess the hydrodynamic force coefficients acting on the ACBM, An, H. (2022) conducted five tests. These tests included: 1) tensile testing the ACBM to find the lift coefficient and hydrodynamic friction force; 2) predicting the cell strength load and critical sliding speed under various conditions and then comparing these predictions with experimental data to validate the derived force coefficients from the ACBM; and 3) testing the edge lift force to find the front row lift force coefficient.

The findings from Gabriella (2013) demonstrate that when the interplay between waves and the protection offered to pipes lying on the seabed was examined, it was found that the pipes were horizontal and watertight. The model demonstrated a strong agreement with values found in the literature and validated its applicability to unprotected pipes. The hydrodynamic forces acting on pipes under two hydraulic scenarios regular waves in deep water and breaking waves in shallow water as well as the effects of concrete block beds on flow and vortex patterns were examined. Particularly through the gaps between the pipe and the mattress blocks, this study demonstrated the formation of a complicated recirculating flow structure. It was discovered that the lift, drag, and additional mass coefficients were less than those determined for the exposed pipe.

The impact of falling anchors on underwater pipes buried beneath ACBMs composed of four different protective materials stone, concrete mattresses with stone, concrete mattresses with a rubber layer on top of the concrete, and a flexible compound pad with rock was examined experimentally in the study by Zhang, C. (2022). According to the experimental findings, the pipe experiences its greatest strain at the point of impact before reducing in length. When examining the highest stress measured at the middle of the pipe, the impact of the dropped anchor can extend up to 30 to 40 times the pipe's diameter.

A. Hydrodynamic Force Coefficient On ACBM

This method enables calculating the total force coefficient without needing to measure forces on individual concrete blocks, which can be complex when multiple blocks form a mattress. This innovative technology will be integrated with approaches using numerical simulations and load cell measurements.

When placed on flat surfaces and exposed to waves or currents, ACMs can become unstable due to multiple failure types. The first occurs when water flow lifts the front row of mattresses, leading to instability in ACM rolls - commonly known as edge lift failure [8]. The second type is shear failure, where the mattress shifts because drag force exceeds sliding frictional resistance.

The proposed approach centers on the shear failure mode since it's comparatively easier to assess. In practice, floors with low friction coefficients can be used to control the sliding failure mode, simplifying the testing process described. However, the force coefficients obtained through this method are also applicable to ACMs on surfaces with varying friction coefficients. The testing utilizes an ACM model, winch, water flume, and one-dimensional load cell. Figure 1 illustrates the model setup. The testing methodology consists of three main steps that will be explained.

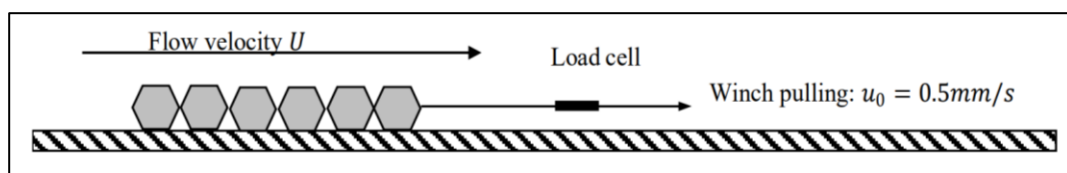


Figure 1. Drawdown testing plan

To calculate the hydrodynamic force coefficients and demonstrate the suggested testing

methods, four different ACM models were created. For a single block, the height is 0.05 m, the top and lower surfaces are $0.026 \text{ m} \times 0.026 \text{ m}$, and the central dimensions are $0.05 \text{ m} \times 0.05 \text{ m}$. The ACM is set up in the typical offshore engineering arrangement of $n \times m = 5 \times 6$. $L = 0.3 \text{ m}$, $W = 0.25 \text{ m}$, $H = 0.05 \text{ m}$, $H_e = 0.0338 \text{ m}$, and $L_1 = 0.05 \text{ m}$ at the model size are the parameters in this arrangement. Comparing this model to the full-size ACM, the approximate scale ratio is 1:10. [5].

1. ACM Sliding Behavior

Pull-out tests were performed to assess the shear characteristics of the ACM. The data presented in the image indicates that the highest tensile load signifies the maximum static friction between the floor and the ACM. This data will be utilized to calculate the hydrodynamic force coefficients in the subsequent section.

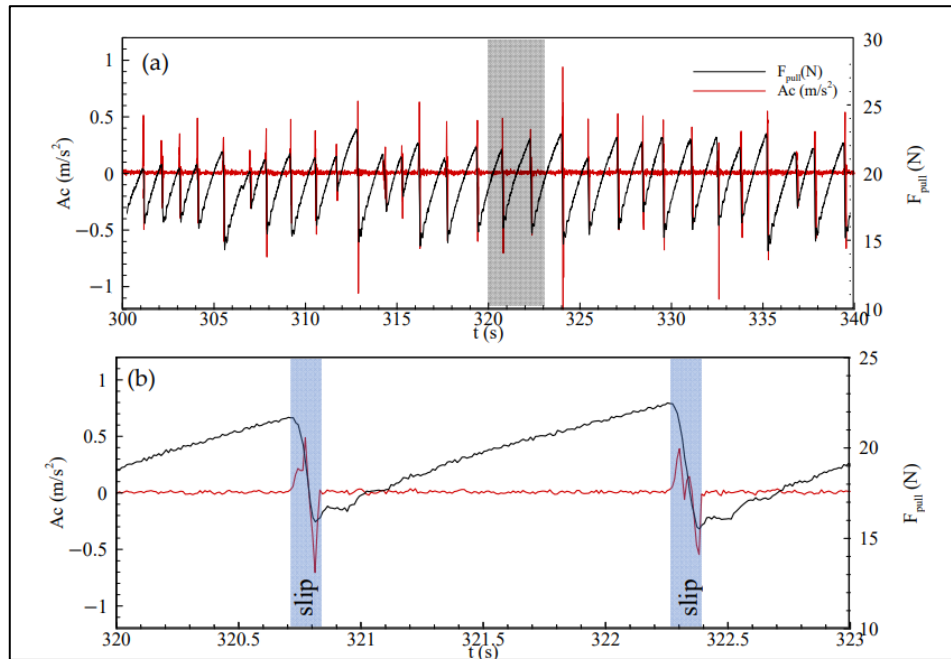


Figure 2. Load and acceleration data from the ACM pull test ($sg = 3.23$, air test). (a) captured duration of 40 seconds. The shaded region indicates the area that has been magnified. (b) magnified view for 3 seconds. The shaded region in (b) highlights two slips of ACM.

2. Sliding Mode of Failure

The test results from the three-step procedure outlined in Section 2 demonstrate how the ACM's force coefficient was determined under steady current conditions. The testing sequence began with moving the ACM at 0.5 mm/s in stationary water to determine the friction factor. Following this, the second phase involved pulling the ACM in alignment with the flow direction at a velocity of 1.0 m/s . The final phase successfully tested the ACM by pulling it upstream against a current with a velocity of -1.0 m/s . Table 1 provides a comprehensive overview of both the force coefficient calculations and tensile test measurement results.

Table 1. Evaluated tensile forces and computed force coefficients. (ACM $sg = 3.23$, $\mu = 0.25$)

Trial	U (m/s)	(F _{pull,1}) (N)	(F _{pull,2}) (N)	(C _f) (0,65)	(C _f) (0,15)
(1)	($\pm 1,0$)	(8,6)	(14,1)	(0,65)	(0,17)
(2)	($\pm 1,0$)	(8,4)	(13,9)	(0,65)	(0,18)
(3)	($\pm 0,8$)	(10,2)	(13,3)	(0,60)	(0,167)

Trial	U (m/s)	(F _{pull,1}) (N)	(F _{pull,2}) (N)	(C _f) (0,65)	(C _f) (0,15)
Average	-	(9,07)	(13,77)	(0,633)	(0,172)

Trial	U (m/s)	(F _{pull,1}) (N)	(F _{pull,2}) (N)	(C _f) (0,65)	(C _f) (0,15)
(1)	(±1,0)	8,6	14,1	0,65	0,17
(2)	(±1,0)	8,4	13,9	0,65	0,18
(3)	(± 0,8)	10,2	13,3	0,60	0,167
Average	-	9,07	13,77	0,633	0,172

These force coefficients were verified using two distinct methods. First, the constants $CD = 0.633$ and $CL = 0.167$ were used to calculate the required tensile force on the load cell at different flow velocities. The results of two tensile tests, which were conducted at $U = -1.20$ m/s and -1.38 m/s (referred to as T4 and T5), are summarized in Table 2. The projected values (derived from Equation (9)) and the actual measurements deviate by 8.3% and 1.9%, respectively.

Table 2. Validation tests for hydrodynamic force coefficients (performed at different flow speeds using ACM with $sg = 3.23$)

Trial	U(m/s)	$F_{pull,2}$ (N) Quantified	$F_{pull,2}$ (N) Anticipated	Error
(4)	(-1.20)	(15.6)	(14.3)	(-8.3%)
(5)	(-1.38)	(15.8)	(15.5)	(-1.9%)

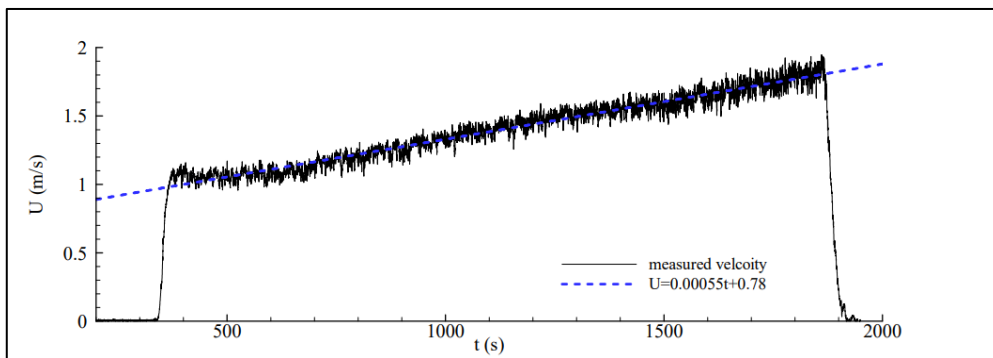


Figure 3. Speed in Test 6 ($sg = 3.23$, $\mu = 0.25$). The critical shear failure speed is 1.8 m/s.

Table 3. An overview of the assessed and anticipated significant failure rates.

Trial	sg	U_{cr} (m/s)							
		(Measured)	(Measured)	(Measured)	(Measured)	(Avegare)	(Predicted)	(error)	
(6)	(3.23)	(1.80)	(1.75)	(1.76)	(1.75)	(1.76)	(1.76)	(1.81)	(2.5%)
(7)	(2.69)	(1.61)	(1.62)	(1.60)	(1.55)	(1.55)	(1.59)	(1.57)	(-1.0%)
(8)	(2.21)	(1.37)	(1.38)	(1.34)	(1.42)	(1.42)	(1.38)	(1.33)	(-4.0%)

3. Edge Lifting Test

A series of edge lifting tests utilized ACM with a specific gravity of 1.72, following testing protocols identical to those employed in the T6-T8 studies. It's important to note that the ACM configuration in this test differs from McLaren's 2019 research. A key testing requirement involves elevating the block above the ground to accommodate load cell measurements. This creates

minute gaps between the joists and ground surface that prove difficult to eliminate. While these gaps significantly impact the lift coefficient, their effect on drag force is minimal. To illustrate this impact: when a cube is raised by just 8% of its edge length above the ground, the lift coefficient shows a dramatic decrease from 0.6 to -0.1. [9]

B. Drag And Lift Coefficient On ACBM

Pipeline stability at deeper depths can be effectively enhanced by using mattresses or debris layers as covering. For critical deep-water pipelines, asphalt mattresses are commonly utilized (as shown in figure 4, left), while articulated concrete blocks often serve as a more economical alternative (illustrated in figure 4, right). This study specifically focuses on the latter protection method. The installation process typically involves divers placing the mattress on a pipeline, supported by steel cables near the installation location. Once in place, the mattress forms an "omega" configuration. This shape proves advantageous as it creates a more hydrodynamic form for both the mattress and pipeline system, thereby reducing wave load impacts. The additional mass also increases the system's overall inertia.

In the numerical simulation, waves are generated from the left boundary, producing surface elevation and velocity profiles that align with linear wave theory. The right boundary maintains free flow conditions, while no-slip and Neumann boundary conditions are applied to the bottom and obstruction surface. This modeling approach enables detailed collection of data regarding surrounding velocity, pressure, and turbulence fields. The hydrodynamic forces affecting both the pipe and mattress are calculated by integrating the pressure distribution across all exposed areas of the barrier cell. [6]

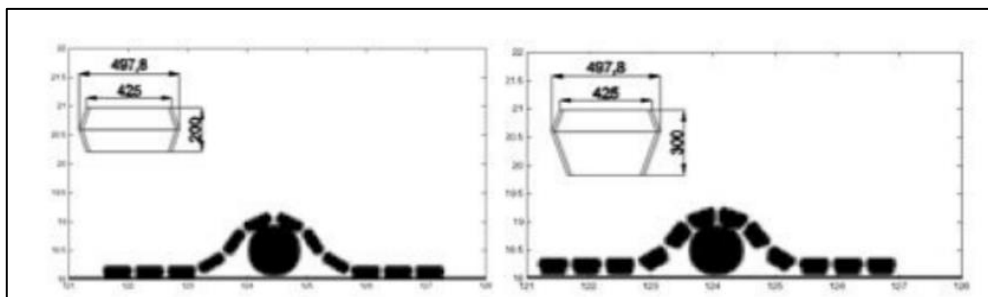


Figure 4. Numerical discretization of the studied articulated concrete block mattress: block thickness of 20 cm (on the left) and 30 cm (on the right).

As shown in Figure 2, right, the mattress under examination is made up of a concrete blanket made up of twelve interconnecting hexagonal blocks that are connected in two directions by a system of cables. This arrangement produces a flexible mattress that offers stability and protection with excellent resistance. In order to maintain a consistent pipe diameter of 90 cm, simulations were conducted on mattresses with two different block thicknesses: 20 cm (s20) and 30 cm (s30). The simulations' analysis includes:

- Regular waves propagating in deep water, with $H=8$ m, $T=12$ s, $d=24$ m, and $KC= 25$ (Uji A);
- A solitary wave traveling in shallow water, with $H=5$ m and $d=8$ m (Test B).

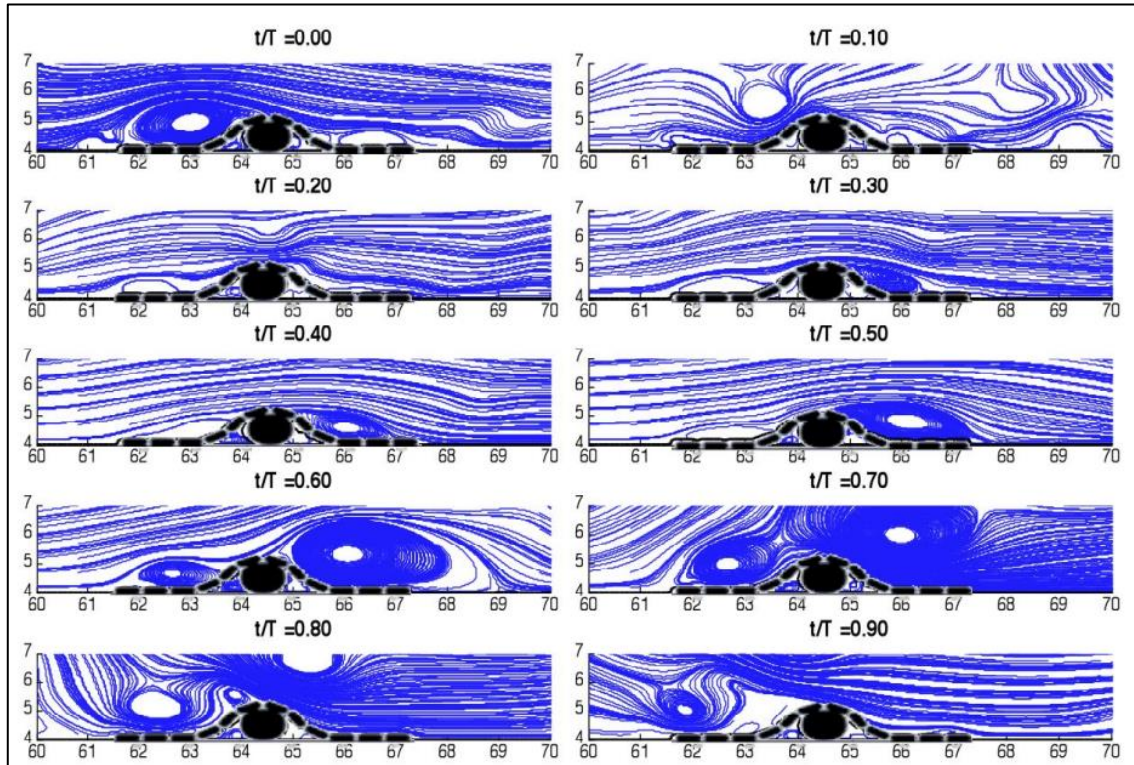


Figure 5. The streamlines around the mattress (Test As20) evolve when a continuous wave travels in deep water from left to right.

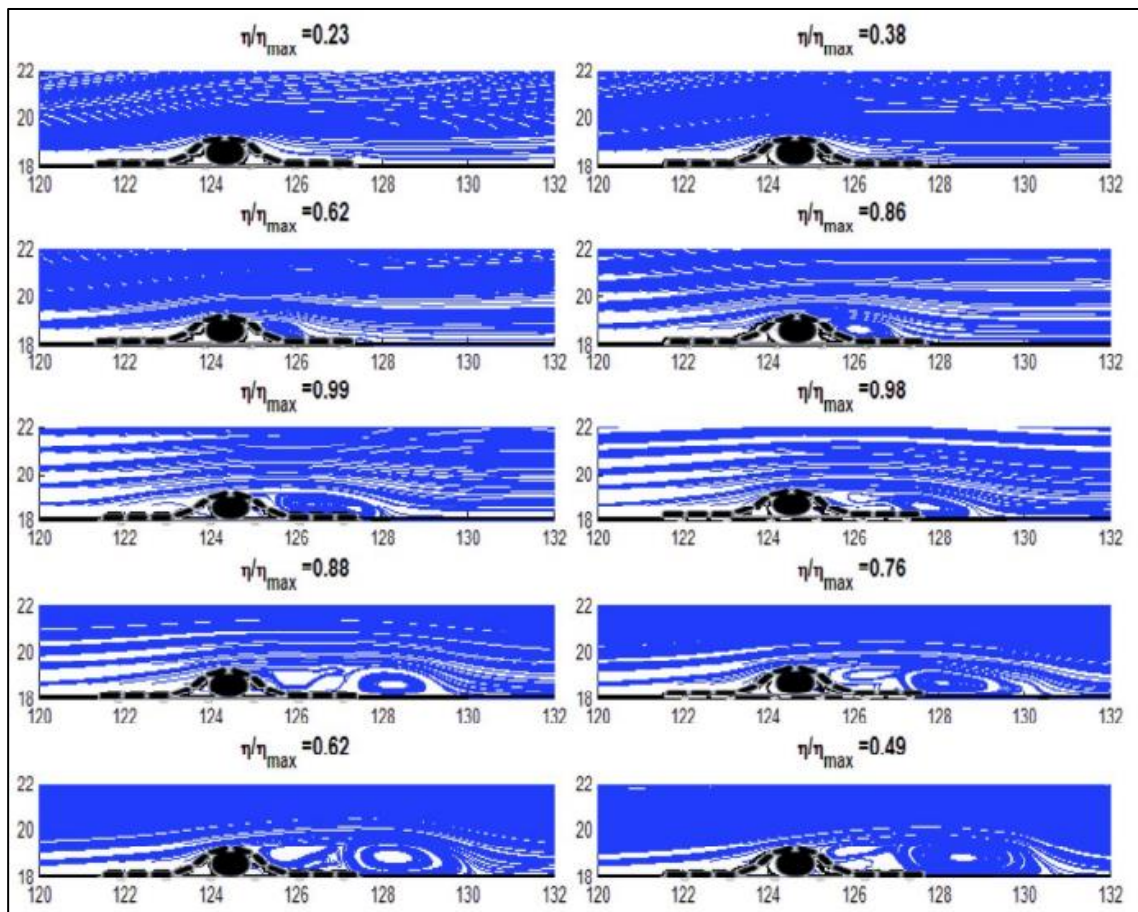


Figure 6. Flow dynamics surrounding the mattress (Test Bs20): in shallow water, a single wave moves from left to right.

Figure 5 depicts the streamline progression during wave propagation (Test As20) over a mattress pipe structure, captured at ten different time points. A notable clockwise vortex formation on the mattress's leeward side is clearly visible in Figure 6. As wave movement continues, this vortex expands and travels further inland compared to earlier observations. While thicker concrete blocks don't significantly alter the flow pattern around the protected pipe, they do enhance pipe stability through their increased mass. The stability of block edges is influenced by both block size and geometry, highlighting the need for more precise laboratory studies using dynamic foundations.

The drag and lift forces generated by oscillatory flow in the mattress pipe system are evaluated by integrating the calculated dynamic pressures along both the block contours and pipe diameter. Figure 8 illustrates the temporal pressure variations at three critical pipe locations during Test As20. The comparative results are summarized in Table 3, where the impact of mattress installation is demonstrated through three key ratios when comparing Tests A and B against an unprotected pipe: reduced drag ratio (C_D/C_{D0}), increased mass ratio (C_M/C_{M0}), and lift coefficient ratio (C_L/C_{L0}).

Table 4. The shielded pipe's lift coefficient C_L , added mass C_M , and drag coefficient C_D .

	C_D	C_M	C_L
A	(0.50) C_{D0}	(0.25) C_{M0}	(0.50) C_{L0}
B	(0.85) C_{D0}	(0.25) C_{M0}	(0.85) C_{L0}

The turbulence created by the waves' interaction with the mattress disrupts the formation of vortices and the incoming forces that impact the structure when waves are continuously acting on deep water. By contrast, the effect of isolated waves moving into shallow water is less noticeable.

4. Conclusion

The research findings yield several significant conclusions. The direct pull test emerges as an effective experimental method for determining ACBM's hydrodynamic coefficient. The validity of these coefficient values is confirmed through cell strength load and crisis speed estimations, maintaining a maximum error margin of 8.3% across five distinct tests. Numerical modeling was conducted for ACBM-protected pipes under two scenarios: shallow water with breaking waves and deep-sea conditions with normal waves. Both analytical scenarios consistently demonstrated that ACBM-protected pipes exhibit lower lift and drag coefficients compared to unprotected pipes.

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