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SUBMARINE PIPELINE STABILITY ISSUES UNDER THE INFLUENCE OF WAVES AND CURRENTS

ПИТАННЯ СТІЙКОСТІ МОРСЬКОГО ТРУБОПРОВОДУ ПІД ВПЛИВОМ ХВИЛЬ І ТЕЧІЙ

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Abstract. *When designing and constructing submarine pipelines, special measures must be envisaged and implemented to ensure reliable, trouble-free operation for an extended period of time. The submarine pipelines lying loose on the bottom are subject to the influence of water flow both in the construction period (with different methods of laying) and in the period of operation. A submarine pipeline stability depends on the water flow force and the amount of negative buoyancy. An underwater pipeline will be stable against floating if its weight with the product is sufficiently higher than the ejective force of the water.*

The factors affecting pipeline stability must be considered when constructing submarine pipelines. The submarine pipeline must be stable under the influence of various loads tending to cause the pipeline to shift or float with inevitable damage.

Damage to submarine pipes caused by anchors, wave pressure, and bottom currents is quite a large percentage. Therefore, reasonable prevention efforts are needed so that leaks do not occur, negatively impacting the environment and economy.

To achieve stability, it is common practice to add weight coating to the outside surface of the pipeline. The pipelines are weighted with cast iron or reinforced concrete individual weights and in the form of a continuous concrete coating of the pipe. This complicates the work and creates additional difficulties when laying the pipeline. Solid concreting is associated with significant labour intensity of its application, and also leads to an increase in the rigidity of the pipeline.

The article discusses theoretical research results for assessing factors affecting submarine pipeline stability, such as wave, current, and geotechnical soil characteristics around the pipeline.

Keywords: *submarine pipeline, stability, surfacing/floating, weighting elements, concrete mattresses.*

Introduction.

The global demand for energy, particularly fossil fuels, continues to broaden the boundaries of offshore engineering. Using piping systems in the oil and gas industry to distribute oil and gas products is very effective and efficient, especially over long distances, compared to using land or air routes. Offshore structures in shallow water often subject to higher flow velocities caused by both currents and waves. Potential dangers and safety risks such as leaks, spills, explosions, and environmental pollution may occur. Submarine oil and gas pipeline leaks will cause pollution and threaten marine ecosystems. Therefore, reasonable prevention efforts are needed to prevent pipe leaks from occurring, which hurt the environment and the economy.

Key factors resulting in pipeline accidents include weld failures, corrosion, excavation damage, and outside force damage [1]. The study compares the databases of US PHMSA, Canada National Energy Board (NEB), and European Gas Pipeline Incident Data Group (EGIG) are shown in. Fig. 1.

In the picture (Fig. 1), it can be seen that damage to pipes caused by five leading causes of pipeline damage: corrosion, excavation damage, incorrect operation, equipment failure and natural force damage. According to EGIG data, 15 per cent of submarine pipeline failures are caused by natural factors (strong tidal currents, waves in shallow waters).

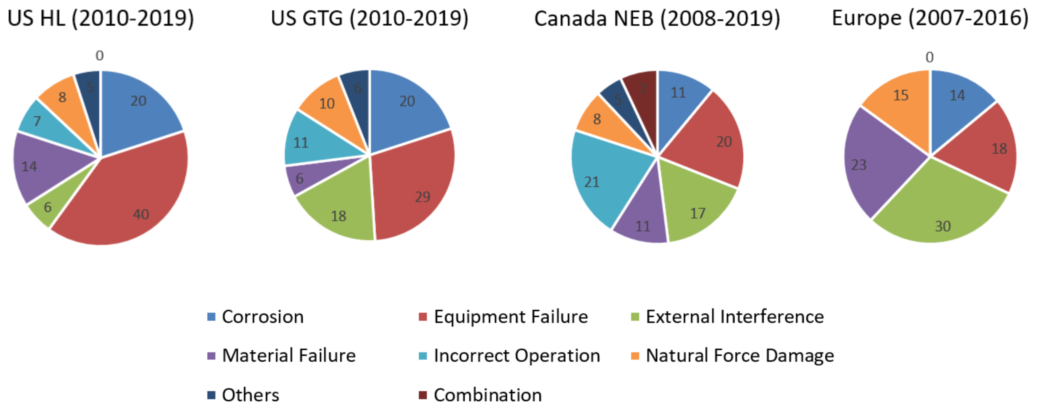

Figure 1 - Distribution of causal factors for PHMSA HL, PHMSA GTG, NEB and EGIG incident data

When constructing submarine pipelines, it is necessary to consider the factors affecting the stability of the pipeline laid on the seabed. The stability of the pipelines in the coastal zone depends on the depth of installation, bottom topography, wave and bottom current parameters, and the location of the pipelines on the seabed. In the deep-water zone, the bottom topography does not affect the main characteristics of waves. In contrast, in the shallow-water zone, the bottom topography significantly influences the development of waves and their main characteristics. In the surf zone, the flow from broken waves periodically rolls onto the shore. For each of these zones, the pipeline stability calculation has its specifics.

The above-mentioned information shows that adequate measures must be taken to ensure the sustainability of submarine pipelines and prevent damage to the pipes, which can be detrimental to the environment and the economy. Leaks from oil and gas pipelines underwater will cause pollution and jeopardise marine ecosystems.

Statement of the problem. The construction of pipelines on the seabed requires the consideration of many external factors affecting the submarine pipelines, which influence their stability, strength and reliability. In deep water, the primary influence that affects the stability of the pipeline is the Archimedes force. Loss of pipeline stability in shallow seas is expressed by its floating. In their article [2], Ian Nash and Mark Haine have noticed that a submarine pipeline has to be stable under wave and current actions. One of the methods used to protect on-bottom submarine pipelines from damage and to ensure their stability when creating additional weight may be the use of modern weight coats.

Analysis of research and publications. A brief review of the materials of various studies related to the problem of floating submarine pipelines is carried out, which showed that constructing pipelines on the seabed requires accurate consideration of external factors such as waves and currents affecting submarine pipelines, which affect their stability.

The problem of stability (floatation) of the submarine pipeline on sandy seabed sediments has been investigated experimentally (small-scale modelling) and theoretically by scientists such as W. Magda, S. Maeno et al. [3]. The authors of paper concluded that the resulting hydrodynamic vertical force arises from changes in pore pressure and has an oscillatory character. The longer the time of action and amplitude of hydrodynamic vertical force, the shorter the time of pipeline surfacing.

F. Van den Abeele., J. Vande Voorde [4], D. Suresh Kumar, D. Achani et al. [5] have noted that the coastal zone is characterized by the mobility of bottom soils under wave action. It has been observed that during the formation of the sediment load, the soils partially lose cohesion and become suspended. This changes the density of the liquid in which the pipeline is located, leading to a change in the Archimedes force and consequently to the floating of the pipeline. The ballasting method is actively used to solve this problem.

Fuad Mahfud Assidiq, Risal Risal [6] hade monstrated those concrete mattresses are cost-effective and may be readily deployed using standard handling systems.

A literature review has shown that, to date, the exact cause of submarine pipeline surfacing has not been established. Some researchers suggest that wave, seismic and bottom current effects may be the causes, but there is no definite answer. Additional experiments and studies are required to resolve this issue. Currently, the over-ballasting method is used, increasing the pipelines' cost. The task in this area should be to identify the most dangerous external influences affecting the stability of pipelines and to develop the most cost-effective solutions to ensure pipeline stability.

The purpose of the research. To carry out computational and theoretical studies to assess the stability of an offshore submarine pipeline against surfacing and shear under the influence of waves and currents. The tasks of the research are as follows:

- to calculate the main loads acting on pipelines of different diameters and wall thicknesses laid on the seabed and the horizontal force of hydrodynamic water pressure acting on an unprotected pipeline;
- to assess the effectiveness of modern Concrete mattresses in protecting submarine pipelines from damage and ensuring their resistance to surfacing and shear when additional weight is applied.

The results of the research. The stability of the pipeline section against floating should be checked in accordance with the current SNiP 2.05.06-85 [7]. Obviously, the stability of the position of submarine pipelines should be checked for individual sections depending on the specific conditions of construction and operation. Depending on the nature of wave effects, the route of the submarine pipeline should be divided into the following sections: deep-water (relative depth $H/\lambda > 0.5$), shallow ($H_{kr} < H \leq 0.5\,\lambda$) and coastal ($H \leq H_{kr}$). For each of these sections, the stability of the pipeline is calculated.

For calculating submarine pipelines' stability, it is essential to accurately determine the forces acting underwater. The following forces act on a pipeline laid on the bottom without deepening: weight of 1 m of pipe length (weight of the pipeline without insulation, insulation weight, concrete coating weight); weight of the product filling a 1 m long pipe; a force equal to the weight of the water it displaces; dynamic loads (horizontal force of hydrodynamic pressure and vertical lifting force).

Vertical lifting force results from the asymmetrical flow of water around the pipeline and, therefore, only occurs when the pipeline is located on the seabed. When calculating the stability of submarine pipelines laid on the seabed, the effect of the weight of the soil on them is not considered.

Let's consider the stability of a submarine pipeline against surfacing, laid in a straight line along the seabed. In this case, the pipeline will be subject to only vertical forces directed from top to bottom: the weight of the pipeline with insulation and concrete coating *G*, the weight of the ballast *Gb* and the product in the pipeline *Gnp*. The Archimedean pushing force *Pa* and the vertical lifting force *Pв* act from bottom to top. For pipelines laid in deep water, wave action can be disregarded. The stability of the pipeline will be ensured if its lowest weight is selected in accordance with the following condition:

$$K\text{в} = \frac{G + G_{б} + G_{np}}{Pa + P\text{в}} \qquad (1)$$

The surfacing safety factor *Kв* varies between 1.15 and 1.20 depending on the hydrometeorological conditions along the pipeline route. The submarine pipeline will be resistant to surfacing if *Kв* ≥ 1.15. In this case, the pipeline will have negative buoyancy.

Thus, since the repulsive force of water increases in proportion to the square of the pipeline diameter, and its weight is proportional to the diameter in the first power, the weight of the ballast increases sharply with the increase in the pipeline diameter and for large diameter pipelines can be several times higher than the weight of the pipe itself. For example, Table 1 shows the calculated values of the leading forces acting on hollow metal pipelines of various diameters and wall thicknesses laid without insulation and concreting on the bottom.

As we can see from Table 1, to create negative buoyancy for a pipeline with a surfacing safety factor of *K=1.15*, a rather large weight of ballast is required, exceeding the weight of the pipeline itself. This complicates the work, increases the cost, reduces the reliability of the work and creates additional difficulties when laying the pipeline.

Table 1 - Estimated loads acting on 1 linear meter of pipeline laid on the seabed

Outer diameter of pipe, *Dн*, mm	Pipe wall thickness *δ*, mm	Weight of 1 m of empty pipe *Gmp*, kN/m	Archimedean force *Pa*, kN/m	Lifting force *Pв*, kN/m	Required ballast weight, *Gб*, kN/m at Кв=1,15
529	10 11 12	1,24 1,42 1,56	2,42	0,65	1,90 1,78 1,71
630	10 11 12	1,50 1,65 1,74	3,18	0,68	2,68 2,64 2,60
720	10 11 12	1,65 1,96 2,18	3,68	0,72	3,77 3,46 3,12
820	10 11 12	1,88 2,34 2,73	4,8	0,82	5,02 4,66 4,28
1020	10 11 12	2,34 2,80 3,20	7,7	0,90	8,07 7,68 7,14
1220	11 12 14	3,80 5,12 4,60	11,4	1,34	15,6 14,9 14,4
1420	11 12 14	5,26 7,38 7,86	14,8	1,42	17,8 18,9 19,6

For a straight pipeline laid on the seabed, the normal pressure force will be determined by the weight of the pipeline G, including insulation and concreting, the weight of the product that fills the pipe G_{np}, the Archimedean repulsive force P_a, the lift force $P_в$ and the weight of the ballast $G_б$:

$$N = G + G_{np} - P_a - P_в + G_б \tag{2}$$

In this case, the condition for the pipeline's shear stability is written as

$$P_г \cdot K_c = f_T (G + G_{np} - P_a - P_в + G_б) \tag{3}$$

where Kc is the shear stability factor, Kc=1,15÷1,25. The coefficient of friction of the pipeline on the ground is taken for fine-grained soils equal to $tg\varphi$. Here is the angle of internal friction of the soil. For sandy soil of medium grain size f_T it is assumed to be 0.55. The results of calculating the horizontal force of hydrodynamic water pressure acting on an unprotected pipeline at different values of the outer diameter of the pipeline and the speed of its flow by the water flow are given in Table 2.

Table 2 - Estimated value of the horizontal force of hydrodynamic water pressure per 1 m of unprotected pipeline (*Pг*, kN/m)

υ, м/с	Calculated value of the horizontal force of hydrodynamic water pressure at some external pipe diameters Dн, mm						
	529	630	720	820	1020	1220	1420
0,5	0,068	0,076	0,088	0,098	0,12	0,16	0,18
1,0	0,27	0,32	0,38	0,42	0,52	0,63	0,72
2,0	1,12	1,28	1,48	1,74	2,16	2,50	3,12
3,0	2,51	3,12	3,43	3,91	4,84	5,80	6,74
4,0	4,36	5,28	6,08	6,88	8,62	9,87	11,86

In the calculations, the drag coefficient was assumed to be Cx = 1.12.

As we can see from the table, the horizontal component of the hydrodynamic water pressure force on the unprotected pipeline is significant, going up with the increase in the pipeline diameter and with the increase in the water flow rate.

To ensure the pipeline's shear stability, it is necessary to load it with additional ballast, a separate cast iron or reinforced concrete weight. The required weight of the ballast can be determined for an unprotected empty pipeline in water using the following formula:

$$G_б = \frac{P_г K_c}{f_T} + P_a + P_в + G_{тр} \qquad (4)$$

For example, Table 3 shows the calculated values of the required ballast weight in water for loading a submarine gas pipeline at a water flow rate of υ = 2 m/s and a shear safety factor of K = 1.15.

As we can see from Table 3, a significant weight of ballast is required to provide the necessary shear stability of the pipeline, which is several times the weight of the pipe itself. A comparison of Tables 1 and 3 also shows that the required ballast weight for shear stability of the pipeline is higher than the ballast weight for floating stability.

Table 3 - Estimated loads acting on 1 linear metre of unprotected pipeline laid on the seabed at a flow velocity of υ = 2 m/s and the required ballast weight

Outer diameter of pipe, *Dн*, mm	Pipe wall thickness *δ*, mm	Horisontal force *Pг*, kN/m	Weight of 1 m of empty pipe *Gтр*, kN/m	Archimedean force *Pa*, kN/m	Lifting force сила *Pв*, kN/m	Required ballast weight, *Gб*, kN/m at Кв=1,15
529	10	1,12	1,20	1,88	0,487	3,21
630	10	1,28	1,48	2,88	0,584	4,12
720	10	1,48	1,67	3,76	0,680	5,87
820	10	1,74	1,84	4,97	0,796	7,12
1020	10	2,16	2,12	7,82	0,947	9,56
1220	11	2,50	2,76	10,86	0,996	16,24
1420	11	3,12	3,78	14,74	1,180	21,12

Modern protective Concrete mattresses have been developed to protect bare or insufficiently buried submarine pipelines from mechanical damage, prevent current seabed scouring, and load submarine pipelines with positive buoyancy.

Concrete mattresses provide a recognized engineering solution for several of the challenges faced in submarine pipeline construction. Typically, concrete mattresses may be used to provide:

- Protection from dropped objects
- Added weight and stabilization
- Scour prevention

The concrete Fleximats mattress is shown in Fig. 3. It provides a high degree of lateral and longitudinal flexibility, allowing it to follow the contours of the pipeline and seabed closely. It is constructed using high-strength concrete blocks and U.V. stabilised polypropylene rope. Once installed, the fleximat may scour into the seabed to increase stability.

Wedged (Tapered) Fleximats. Extreme seabed, current and wave conditions may determine that additional stability is required beyond that provided by the standard fleximat. In this case, fleximats with enlarged tapered (wedged) edge elements.

The Concrete Logmat mattress is shown in Fig. 4. The logmat is flexible in only one plane. This provides an engineering solution of challenge - load bearing where soft soil conditions exist.

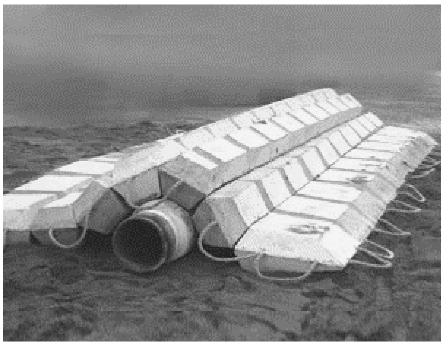

Figure 3 - Concrete Fleximats

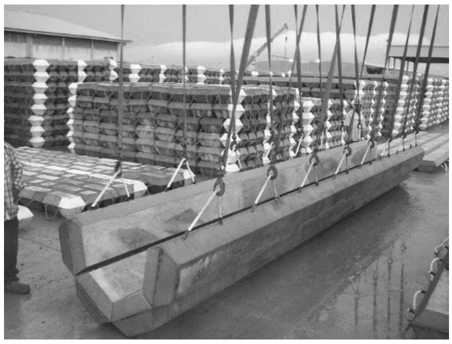

Figure 4 - Concrete Logmat

D. O'Brien et al. [8] have presented the outcomes from two programs of physical model testing of mattresses to improve understanding of mattress stability under hydrodynamic loading. They have shown that mattresses can provide to prevent flowline lateral movement when both the mattress and flowline are under hydrodynamic loading. The authors noted that the Concrete mattress protection significantly reduces the horizontal drag force of the pipeline and eliminates the vertical lifting force.

Conclusions. The analysis of the results of the calculation and theoretical studies allows us to draw the following conclusions:

1. The results of the calculations showed that with an increase in the diameter of the pipeline and the speed of its flow by the water flow, the horizontal component of the hydrodynamic water pressure force, the pushing force and the weight of the ballast cargo increase significantly. This indicates that, when assessing the stability of submarine pipelines laid on the seabed, it is of particular importance to accurately determine the force impact of the water flow associated with the destruction of sections of submarine pipelines.

2. To ensure the required shear stability of the pipeline, a significant ballast weight is required, several times the pipe's weight. The required weight of ballast to ensure the pipeline's shear stability exceeds the weight of ballast to ensure its floatation stability.

3. A review of research results of some authors has shown the effectiveness of Concrete mattresses in shallow seas. The use of Concrete mattresses, in contrast to a solid concrete coating of the pipeline, does not increase its rigidity and, consequently, does not increase the minimum radius of curvature when laying it while also eliminating the considerable labour intensity of applying a solid ballast coating.

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Анотація. *При проєктуванні та будівництві морських трубопроводів повинні бути передбачені та виконані спеціальні заходи, які б забезпечили надійну, безаварійну його експлуатацію протягом тривалого часу. Морські трубопроводи, що вільно лежать на дні, піддаються впливу потоку води як у будівельний період так і в період експлуатації. При будівництві морських трубопроводів необхідно враховувати чинники, що впливають на стійке положення трубопроводу. Пошкодження підводних труб, які викликані хвильовим тиском і придонними течіями, має досить великий відсоток, тому необхідні хороші заходи профілактики, щоб не виникало витікав, які негативно впливають на навколишнє середовище. Для досягнення стійкості загальноприйнятою практикою є додавання ваги у вигляді обтяжувального покриття, до зовнішньої сторони трубопроводу. Обтяження трубопроводів виконують чавунними або залізобетонними окремими вантажами та у вигляді суцільних покриттів труби бетоном. Це ускладнює виконання робіт і створює додаткові труднощі під час протягування трубопроводу. У статті розглядаються результати теоретичних досліджень для оцінки факторів, що впливають на стійкість морського трубопроводу, таких як хвилі, течії, геотехнічні характеристики ґрунту навколо трубопроводу. Розглянуто ефективність застосування сучасних бетонних матраців для захисту морських трубопроводів від пошкоджень, а також для забезпечення їх стійкості на спливання та зсув при створенні додаткової ваги.*

Ключові слова: *морський трубопровід, стійкість, спливання, обтяжувальні елементи, бетонні матраци.*

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