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# ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

# TECHNOLOGY OF PIPELINE INSTALLATION IN DEEPWATERS, ENHANCING OPERATIONAL RELIABILITY BY CONSIDERING EXTERNAL AND INTERNAL FACTORS

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| **Specialty:** | 3354.01 – "Construction and Operation of Oil and Gas Pipelines, Terminals, and Storage Facilities" |
| **Field of science:** | Technical sciences |
| | |
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## GENERAL CHARACTERİSTİCS OF THE RESEARCH

**Relevance of the topic and the degree of exploration:** The development of oil and gas fields in the Caspian Sea and other deepwater regions necessitates the implementation of new methods and technologies for the installation and operation of subsea pipelines as depths increase. It is well known that in the sectors of the Caspian Sea belonging to the littoral states, the collection of oil, gas, and other energy products from deeper fields and their transportation to shore is carried out through subsea pipelines stretching for hundreds of kilometers.

Since the initial operation of oil and gas fields in deep waters, and especially during and after the **"Contract of the Century"**, the intensification of oil and gas transportation in the Caspian Sea and other deepwater regions has led to significantly increased requirements for the safe execution of subsea pipeline installation technologies at depths ranging from 180 meters to 2000–3000 meters and beyond, where construction and installation works are conducted.

Research indicates that despite the application of various installation technologies as climatic variability, complexity, and depth increase, the calculation methods employed to prevent accidents resulting from deformations have not been entirely effective in mitigating this issue. This, in turn, leads to a reduction in pipeline reliability and potential structural failures during or after installation when subjected to even minor external influences.

Recent research findings highlight that internal factors have a significant impact on the operational reliability of subsea pipelines. One of the weakest and most vulnerable points of these pipelines is the risers, particularly the connections between the risers and the horizontal sections of the pipeline.

To enhance the operational reliability of subsea pipeline risers, it is crucial to conduct a fuzzy evaluation of the external factors affecting them, ensure in-pipeline separation at the seabed when transporting low-pressure gases, perform calculations of the hydrodynamic forces acting on subsea pipelines, and develop new diagnostic technologies to prevent leaks.

Investigating the existing challenges related to the operation and maintenance of subsea pipelines in deepwater basins, as well as examining the influence of hydrostatic pressure (an external factor) on pipeline wall thickness during J-lay installation, is of great importance.

As oil, gas, and other energy carriers—considered primary energy resources worldwide—are extracted from greater depths, the complexity of operations and associated challenges increase. Consequently, the development of innovative technologies and diagnostic methods, taking into account both internal and external factors, is of high relevance for improving operational reliability and efficiency.

**Object of the research:** Oil and gas pipelines in deepwater.

**Subject of the research:** The development of offshore oil and gas extraction, along with the development of fields in deeper waters, has significantly expanded the scope of hydrocarbon collection and transportation operations. Today, production has reached a depth of 3000 meters, and exploration activities are being carried out at even greater depths. The working environment at these depths introduces new technologies and imposes high demands on the integrity of pipelines throughout their operational lifespan.

Currently, during the construction of subsea pipelines in ultra-deepwater basins, the study of factors such as reliable and safe operation, hydrodynamic forces, and other load and load combinations that impact stability, as well as the development of risk factors and diagnostic methods to address safety and environmental issues, have become the main and current issues for selecting the dissertation topic.

**Purpose and objectives of the research:** The aim of the research is to contribute to the enhancement of the operational reliability of pipeline systems by examining surveying technologies in deep waters, utilizing computer software, laboratory analysis results, and real-practical data, while taking into account both external and internal factors.

**Research Objectives:**

1. Analysis of pipeline installation technologies for subsea pipelines.

2. Examination of the stability of subsea pipelines on the seabed, local buckling, and the propagation of buckling phenomena.

3. Investigation of fuzzy risk assessment methods for preventing accidents in subsea pipelines.

4. Development of an internal pipeline separation method for low-pressure gas transportation in deep waters.

5. Design of a new technology for the installation of vertical risers.

6. Analysis of hydrodynamic forces acting on subsea pipelines and vertical risers.

7. Assessment of the impact of hydrostatic pressure and bending moments on subsea pipelines in ultra-deepwater basins.

8. Development of a novel diagnostic method for detecting leakage points in subsea pipelines.

9. Evaluation of the operational efficiency of pipelines under multiphase flow conditions.

**Methodology of the research:** The methodological foundation of the research is based on theoretical and practical principles applied in the installation of subsea pipelines in the Caspian Sea and global practice. It encompasses the formulation and analysis of problems, the study of challenges encountered during the installation of pipelines in deep waters, and the system of theoretical provisions aimed at enhancing the operational reliability of subsea pipelines.

**Research Methods.** The issues raised in the research have been addressed through both theoretical and practical approaches. The solutions were derived based on the analysis of data from the installation and operational experience of subsea pipelines, utilizing standard laboratory equipment, computer modeling, and software tools.

**Principal Propositions for Defense:**

1. The influence of hydrostatic pressure and bending moments on the stress distribution in subsea pipelines within ultra-deepwater environments.

2. Development of an internal pipeline separation methodology for the transportation of low-pressure gases in deepwater conditions.

3. An algorithmic model for fuzzy risk assessment in subsea pipeline systems.

4. A novel diagnostic approach for the detection and localization of oil leakages in subsea pipelines.

**Scientific Novelty of the Research**

1. The impact of hydrostatic pressure and bending moments on stress distribution in subsea pipelines within ultra-deepwater environments has been assessed.

2. An internal pipeline separation method for the transportation of low-pressure gases in deepwater conditions has been developed.

3. An algorithmic model for fuzzy assessment of technological risks in subsea pipelines has been proposed.

4. A diagnostic method for detecting and identifying oil leakages in subsea pipelines has been developed.

**Theoretical and Practical Significance of the Research**

1. The proposed empirical method for identifying the location of oil leaks in pipelines has been modeled in the Delphi program and enables the determination of leak locations at various depths without additional resources or technological equipment.

2. The proposed constructive equipment for subsea separation during the transportation of low-pressure gas facilitates the separation of gas from mechanical particles.

3. The method proposed for determining the bending moment at the seabed when laying pipelines at ultra-deepwater depths using the J-method prevents the occurrence of local buckling in the pipes.

4. The proposed method for assessing risk factors during leak incidents in subsea pipelines, based on expert opinions and fuzzy logic theory, allows for the prevention of environmental pollution.

5. The proposed algorithmic sequence based on the fuzzy analytical triangle hierarchy method used to assess pipeline accidents in subsea pipelines enables the calculation of the weighting of risk factors.

**Approval and Application of the Work:** The main results of the dissertation were presented at several international conferences, including: the 11th International Conference on "Intelligent Systems for Industrial Automation" (WCIS-2020) held in Tashkent, Uzbekistan; the online scientific conference dedicated to the 98th anniversary of the birth of the National Leader Heydar Aliyev on May 21, 2021 (Baku 2021); the SPE Annual Caspian Technical Conference held on October 5-7, 2021 (OnePetro 2021); the scientific-practical conference "Innovative Technologies in the Oil and Gas Industry: Implementation Experience and Development Prospects" held in Aktau on November 19, 2021; the "2nd International Science and Engineering" conference held at Baku Engineering University on November 26-27, 2021; the VI International Scientific Research Conference held on December 17, 2021; the International Scientific and Practical Conference "The Sustainable Development of Economy and Administration: Problems and Perspectives" held at Baku Engineering University on December 24-25, 2021; the "III International Scientific Conference of Students and Young Researchers," dedicated to the 99th anniversary of the birth of the National Leader Heydar Aliyev, held at the Baku Higher Oil School on April 18-29, 2022; the "VI International Scientific Conference of Young Researchers," held at Baku Engineering University on April 28-29, 2022, dedicated to the 99th anniversary of the birth of the National Leader Heydar Aliyev; the 15th International Scientific Conference "Applications of Fuzzy Systems, Soft Computing and Artificial Intelligence Tools" (ICAFS-2022) held in Budva, Montenegro on August 26-27, 2022; the "Fourth Eurasian Conference Innovations in Minimization of Natural and Technological Risks: Satellite Symposium on Technological, Environmental, and Economic Risks of the Oil and Gas Sector," held on October 11-13, 2022; the Caspian Oil and Gas 2022 International Scientific-Practical Conference; the International Scientific Conference "Innovations in Minimization of Natural and Technological Risks," dedicated to the 100th anniversary of the birth of National Leader Heydar Aliyev, held in November 2023; and the 2nd International Seminar on "Dynamic Oil Spill Localization in the Caspian and Global Aquatories" held on December 19, 2023.

**The results of the dissertation have been applied in the following areas:**

1. The proposed design for subsea separation can enable the cleaning of low-pressure gas before it reaches the technological equipment and is transported.

2. The proposed computational methodology for fuzzy risk assessment of subsea pipelines can be applied to calculate the distance between the vectors of the highest risk values of individual expert's vectors (in other words, the "very high" risk factor) for subsea pipeline risk factors.

3. The method proposed for determining the bending moment of a pipe on the seabed can be applied during J-configuration laying operations.

4. The proposed evaluation method for identifying leakage locations in subsea pipelines can be applied in the industry without incurring additional costs.

**Personal Contributions of the Author:** The author's personal contribution lies in the selection of the research objective and direction. Furthermore, all the results obtained and the coordination of the research methods are attributed to the author. It should also be noted that the research work will play an exceptional role in the improvement of the **"Technology of pipeline installation in deep waters, enhancing operational reliability by considering external and internal factors"** as well as in the development of the theoretical and practical foundation in the investigation of the key issues highlighted in the dissertation.

**Publications:** The main results of the dissertation have been reflected in 21 scientific works, of which 5 are single-authored, including 4 articles published in scientific journals indexed in international abstracting and indexing systems. Additionally, 15 papers have been published based on the results of scientific events at the national and international level, 7 of which were presented at conferences held abroad.

**Structure and Scope of the Dissertation** have been determined by the logical progression of the research and the sequence of tasks set forth. The dissertation consists of an introduction (~27923 characters), four chapters (Chapter I ~20269, Chapter II ~54806, Chapter III

~16917, Chapter IV ~44855), conclusions, and a list of 130 references. The total volume of the dissertation is 189 pages (~167333 characters).

## MAIN CONTENT OF THE DISSERTATION

In the introduction of the dissertation, the relevance of the work is substantiated, the objectives and the main issues addressed are outlined, the scientific novelty, practical significance, and defended propositions are presented, and a brief overview of the content of the dissertation is provided.

The first chapter of the dissertation, titled **"Technologies for Laying Pipelines in Ultra-Deep Waters and Analysis of Reaction Forces During Installation"**, consists of five sub-chapters.

In the first sub-chapter, the requirements for underwater pipeline laying operations, the criteria for construction and installation, the key parameters for maintaining the integrity and stability of the pipe during underwater installation, and the methods used in global practices for laying underwater pipelines are discussed.

The second sub-chapter covers the technologies for laying underwater pipelines using the S-method, the use of stingers to reduce tension during installation, their specific functions, the role of special bending devices in mitigating the tension caused by pipe bending on the seabed, the advantages and disadvantages of the S-method, and the calculation of the pipe's angle of travel on various pipe-laying vessels during underwater pipeline installation.

The third sub-chapter analyzes the installation of underwater pipelines using the J-method, explaining its advantages over the S-method for deeper waters, and the absence of the need for a stinger in this case.

The fourth sub-chapter focuses on the analysis of the reel method for laying subsea pipelines, discussing the graphical dependency of the bending moment generated during installation.

In the fifth sub-chapter, the analysis of reaction forces in the stinger and the pipe during underwater installation is presented, including the support reactions on the stinger, the bending moment, and the maximum support reaction at the suspension support of the stinger.

As a result, the simulation of the dependence of the reaction force generated at the roller during installation and the length of the freely suspended pipe on the bending radius of the stinger using MATLAB software is presented (Figure 1).

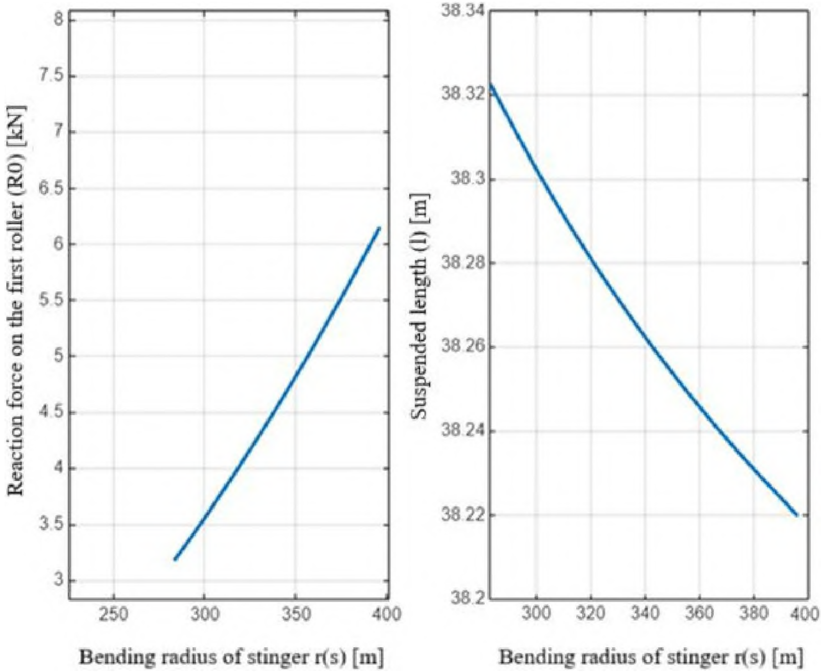


**Figure 1. Simulation of the dependence of the reaction force generated at the drum during installation and the length of the freely suspended pipe on the bending radius of the stinger using MATLAB software**

The second chapter of the dissertation, titled "Determination of Hydrodynamic Forces, Local Buckling, and Tensions During Pipeline Laying in Ultra-Deep Waters, and the Development of a New Method to Prevent Local Bends", consists of 12 sub-chapters.

In the first sub-chapter, the issues related to the determination and analysis of the pipe geometry during the laying process are addressed.

Finally, the horizontal, vertical, and total tensions of the pipe are determined based on its suspended length and the depth of the sea.

In the second sub-chapter of Chapter II, the static analysis of the loads on subsea pipelines at various depths in the Caspian Sea is examined. The simulation, using MATLAB software, includes the dependence of pipe tension on water depth, the dependence of the pipe's diameter on tension and deformation, the variation of hydrostatic pressure with depth, and the dependence of axial deformation on tension.

Figure 2 shows the dependence of the length of the freely suspended section of the pipe on depth, tension, and the weight of the pipe for installation depths ranging from [500-2000 m].

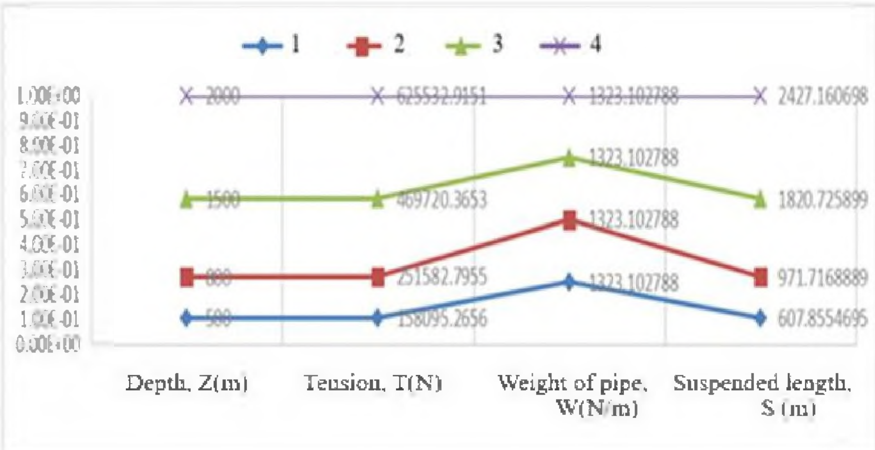


**Figure 2. Dependence relationships of the length of the freely suspended section, the weight of the submerged pipe, and the tension of underwater pipelines varying in the installation depth interval of [500-2000] m**

In the third sub-chapter of Chapter II, issues related to the checking and analysis of the stability of underwater pipelines on the seabed are examined. The calculation of the vertical stability of the underwater pipeline is performed, and the validity of the calculation is confirmed based on international standards.

The fourth sub-chapter of Chapter II discusses short-term wave conditions and the JONSWAP spectrum during the installation and operation of underwater pipelines.

In the fifth sub-chapter of Chapter II, environmental data and the pipe-soil interaction are discussed. Several assumptions for calculations in this section are provided, including:

1. Only one-year periodic waves and currents are considered during the installation phase of the pipeline;
2. The direction of waves and currents acts perpendicular to the pipeline;
3. The density of seawater is $\rho water = 1016\text{-}1025\ kg/m^3$;
4. The seabed is assumed to have a flat, infinite surface;
5. A general penetration depth of 0.2D is accepted;
6. After initial penetration, the seabed is considered impermeable;
7. During installation, trenching and penetration are considered due to the dynamics and movement of the pipes;
8. The general size of the sand particles on the seabed ranges between 0.5-2 mm;
9. For the Caspian Sea, a characteristic propagation parameter (s) of 4 is accepted, while a range of 6-8 can be used for the North Sea.

In the sixth sub-chapter of Chapter II, issues related to the calculation of flow velocity are considered. Based on the comparison between theoretical and measured spectral dependencies using the Wake model, the time-dependent variations in velocity, the time-dependent variations in free-stream velocity, the time-dependent variations in the Wake model, the time-dependent variations in effective velocity, time-dependent variations in horizontal forces, time-dependent variations in vertical forces, and time-dependent variations in soil resistance are modeled. The simulation for depths of 300 m and greater, considering seabed roughness, is implemented using MATLAB software.

In the seventh sub-chapter of Chapter II, the hydrodynamic forces acting on vertical pipes at a depth of 300 m in the Caspian Sea are calculated using the SACS software.

The following initial parameters have been taken for the report:

H = 300 m sea depth;

A vertical pipe with a diameter of D = 323.8 mm according to the ASME 36.10[1] standard;

The wall thickness of the pipe has been accepted as 10.31 mm, 11.13 mm, and 12.70 mm according to the ASME 36.101 standard.

The results of the calculations and simulations are presented for three variants.

Variant 1: Non-passable case – the pipe fails and undesirable conditions occur (Figure 3).

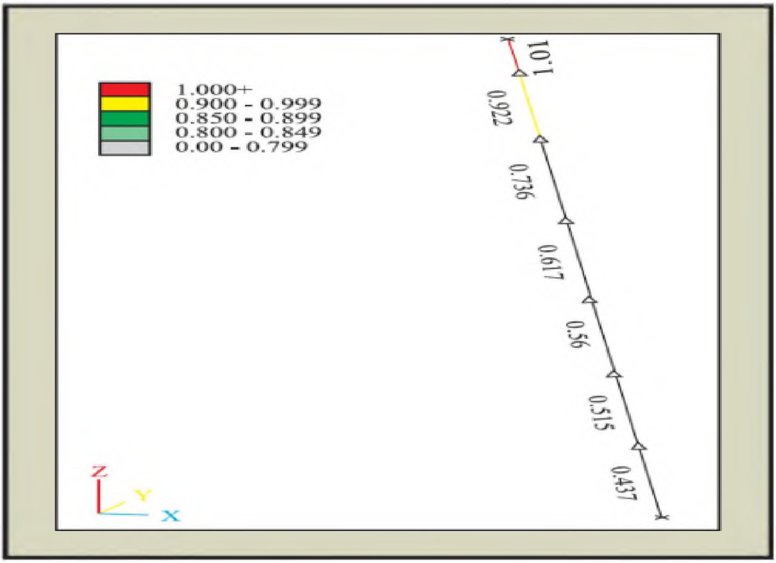


**Figure 3. Load combination effect profile for Case 1 (Variant 1)**

[1]ASME B36.10M "Welded and Seamless Wrought Steel Pipe" // Adopted in 2023. – New York: American Society of Mechanical Engineers (ASME), – 2023, – 29 p

Variant 2: Critical case – that is, the vertical pipe can be operated, but it is constantly on the verge of failure due to unexpected hydrodynamic impacts.

Variant 3: Passable case – that is, the vertical pipe can be operated completely safely at a depth of 300 m in the Caspian Sea with these dimensions.

In the eighth sub-chapter of Chapter II, issues related to the selection of materials for underwater pipelines and the analysis of their characteristic properties are discussed. Except for large-diameter pipes (greater than 30 inches), high-pressure pipelines or those in deep waters typically use material grades such as X-60 or X-65. In special cases, higher grades may be selected. Lower grades such as X-42, X-52, or X-56 may be used for shallow waters, large-diameter pipelines aimed at reducing material costs, or where higher elasticity is required for improved impact resistance.

In the ninth sub-chapter of Chapter II, the issue of ovalization occurring during the installation of underwater pipelines is addressed. Flattening or ovalization resulting from bending should not exceed 3%. Significant ovalization will result in a reduction of the structural strength of the pipeline. Ovalization refers to a situation where the cross-sectional shape of the pipeline is not a perfect circle but has become somewhat flattened.

Ovalization issues can be reduced by increasing the wall thickness of the pipeline.

In the tenth sub-chapter of Chapter II, the analysis of local buckling and its propagation during the laying of underwater pipelines is presented. The sequence of the ovalization or buckling propagation process occurring in underwater pipelines is shown. The graphical results of moment-curvature and ovalization-curvature dependencies, representing the effects on pipes subjected to pure bending and bending under external pressure, are provided. Additionally, the process of underwater pipeline failure by a third-party (agent) is illustrated.

In the eleventh sub-chapter of Chapter II, the impact of stresses induced by hydrostatic pressure and bending moments on underwater pipelines at ultra-deep depths is analyzed. Given that the "J" method is commonly applied in deeper water environments, this section investigates the effect of hydrostatic pressure on the structural integrity of the pipeline during installation, particularly in extreme depth conditions.

For the case of an underwater pipeline at a depth of H = 500 m (Figure 4)[2], considering the allowable yield strength limit of $\left[\sigma_{yield}^{strength}\right]$=4000kgf/cm², the analysis of the stress-strain state of the pipeline according to the "J" lay method reveals that the hydrostatic pressure-induced stress, $\sigma_{hid}$ = -391kgf/cm², and the compressive stress, $\sigma_{total}$ = -4129kgf/cm², result in $\sigma_{total} > \left[\sigma_{yield}^{strength}\right]$. This indicates that bending is inevitable on the pipeline's wall.

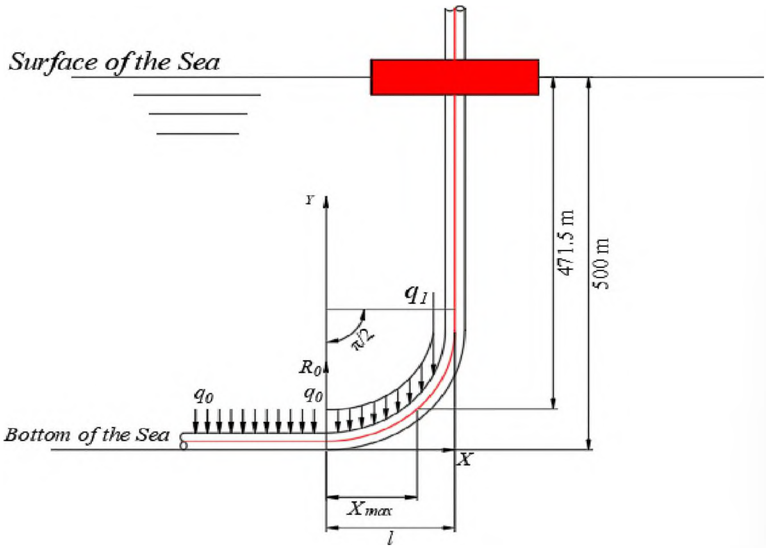


**Figure 4. Scheme of load distribution on the pipeline wall**

[2] İsmayılov, Q.Q., Şahlarlı, M.E. Super dərinliklərdə hidrostatik təzyiqdən və əyici momentdən yaranan gərginliklərin sualtı boru kəmərlərinə təsiri // – Bakı: PAHTEİ, – 2024. 36(05), №01, – s. 437–443.

This section also provides an overview of pipe arrestors and their respective types for preventing buckling. The proposed alternative approach for pipe design to safeguard against collapse pressure is categorized, taking into account various depths and economic efficiency.

The problem of calculating the buckling propagation criterion for pipes with differing diameters during installation at various depths in the Caspian Sea has been addressed. A MATLAB-based model has been developed to simulate the propagation of local buckling and external pressure, with dependencies on pipe diameter and water depth during the installation of subsea pipelines.

The assessment of local buckling propagation for subsea pipelines at varying depths was conducted using Excel, and a graph illustrating the variation of material grade with respect to the buckling propagation pressure has been presented.

Chapter III of the dissertation, titled "Fuzzy Assessment of Accident Risks and Diagnostics of Operational Challenges in Subsea Pipelines", consists of four subchapters.

The first subchapter of Chapter III addresses the development of a new algorithm for fuzzy risk assessment of accidents in subsea pipelines. The steps for conducting the fuzzy analytic hierarchy process based on the triangular method have been provided, and the weight values of risk factors have been determined within the [0-1] range (Figure 5)[3].

The second subchapter of Chapter III discusses the fuzzy risk assessment of technological risks in subsea oil pipelines.

The prediction of accident spill frequencies from oil pipelines is generally categorized, with the combined influence of factors presented.

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[3] Ismayilova, H.G., Shahlarli, M.E., Ismayilova, F. Investigation of submarine pipeline failure accidents in deepwater based on the fuzzy analytical hierarchy process // 15th International Conference on Applications of Fuzzy Systems, Soft Computing and Artificial Intelligence Tools (ICAFS-2022), – Budva: Springer Cham, – 26-27 August, – 2023, – p. 391-398.

The relative impact degree, expressed as the weight coefficient (share of the factors' group), of each group of factors on the variation intensity of accident occurrences in the considered pipeline is demonstrated.

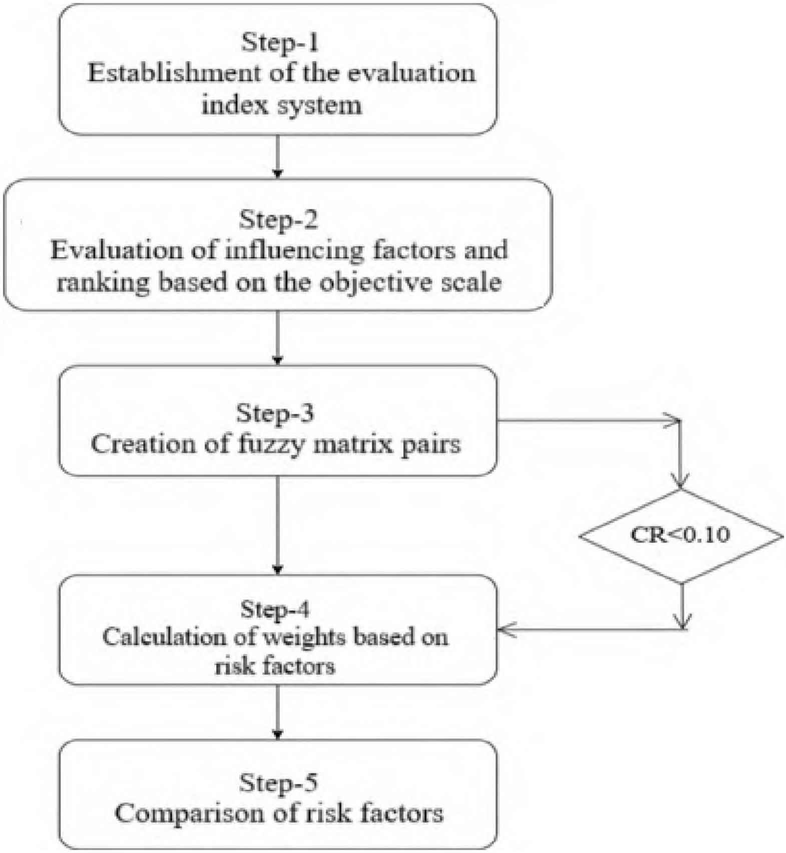


**Figure 5. Algorithm Developed for the Investigation of Accident Occurrences in Subsea Pipelines**

Based on the accepted weight coefficients, an assessment of the influencing factors was carried out using a 5-point scale for ranking, and the aggregation of expert opinions on the identified factors for oil spills was conducted.

Finally, considering the opinions of individual experts and the expert group, an evaluation was made to determine the percentage distance from the "very high" risk indicator, and the final assessment was conducted based on the calculated final vector.

The third subchapter of Chapter III addresses the development of diagnostic methods for oil spills from subsea pipelines, considering water depth. Based on the results of the conducted calculations, the dependencies between the spill location ($X_{SL}$), the oil discharge after the spill ($Q_1$), and the ratio of the pressure at the pipeline's starting point to the hydrostatic pressure ($P_1/P_{hid}$) were graphically illustrated in a three-dimensional space using a specialized software developed for the Windows system within the Delphi environment. These dependencies were depicted graphically in the $X_{SL}$ - Q - $P_1/P_{hid}$ coordinate system for spill cases with q = 1, 3, and 7%. It was established that, based on a highly significant correlation coefficient ($R^2 = 0.999$), the spill location can be determined indirectly with up to 1% accuracy, using the following regression equation-empirical [4] expression, which depends on the parameters $Q_1$ and $P_1/P_{hid}$.

$$X_{SL} = a + \frac{b}{Q_1} + c\frac{P_1}{P_{hid}} + \frac{d}{Q_1^2} + e\left(\frac{P_1}{P_{hid}}\right)^2 + f\frac{P_1}{Q_1 P_{hid}} + \frac{g}{Q_1^3} + \\ + h\left(\frac{P_1}{P_{hid}}\right)^3 + \frac{i}{Q_1}\left(\frac{P_1}{P_{hid}}\right)^2 + \frac{j}{Q_1^2}\left(\frac{P_1}{P_{hid}}\right)$$

In the fourth paragraph, the focus is on the diagnostics of oil leakages based on the relative changes in flow rate and pressure. Given that piston pumps are rarely used in practice, the study investigates the impact of oil leakages on the operation of a pumping station equipped with centrifugal pumps, connected to a pipeline with diameter D and length l. For this purpose, the pipeline and pump station characteristics (the relationship between pressure and flow rate) before and after the leakage event are analyzed. Consequently, it is determined that, based

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[4] İsmayılov, Q.Q., İsmayılova, H.Q., Şahlarlı, M.E. Sualtı boru kəmərlərlərindən neft sızmalarının diaqnostika üsullarının işlənməsi // – Bakı: Fövqəladə Hallar Nazirliyinin Akademiyasının Elmi Xəbərləri, – 2023. №2, – s. 70–76.

on the relative changes in flow rate and pressure (head), the location and severity of the leakage can be identified through the established relationships. Here: a, b,..., j are coefficients and their values are given in the table 1 depending on the depth of the sea.

**Table1**

| For different leakage condition | | | | | | |
|---|---|---|---|---|---|---|
| | **Hd = 150 m** | | | **Hd = 200 m** | | |
| | **1** | **3** | **7** | **1** | **3** | **7** |
| a | -0,204 | -1,006 | -4,821 | -0,060 | -0,927 | -4,0362 |
| b | -0,302 | -0,191 | 0,198 | -0,438 | -0,312 | 0,170 |
| c | -0,396 | -0,210 | 0,733 | -0,650 | -0,398 | -0,797 |
| d | -0,1399 | -0,1434 | -0,1623 | -0,1836 | -0,1874 | -0,2007 |
| e | 0,1166 | 0,1124 | -0,1068 | 0,2833 | 0,2828 | 0,8646 |
| f | 0,4274 | 0,3838 | 0,3302 | 0,5300 | 0,4672 | 0,2932 |
| g | 0,0001 | 0,0001 | 0,0003 | 0,0001 | 0,0001 | 0,0002 |
| h | -0,0427 | -0,0467 | -0,0223 | -0,1011 | -0,1107 | -0,2291 |
| i | 0,0441 | 0,0490 | 0,0432 | 0,0785 | 0,0872 | 0,1130 |
| j | 0,1311 | 0,1318 | 0,1357 | 0,1748 | 0,1758 | 0,1773 |
| | **$H_d$ = 350 m** | | | **$H_d$ = 500 m** | | |
| **a** | 0,096 | -0,813 | -3,789 | 0.311 | -0.655 | -3.399 |
| **b** | -0,563 | -0,421 | 0,106 | -0.679 | -0.519 | 0.0543 |
| **c** | -0,981 | -0,698 | -1,158 | -1.463 | -1.139 | -2.754 |
| **d** | -0,2274 | -0,2314 | -0,2451 | -0.2711 | -0.2754 | -0.2898 |
| **e** | 0,5465 | 0,5717 | 1,6199 | 0.9543 | 10.101 | 27.221 |
| **f** | 0,6116 | 0,5283 | 0,2941 | 0.6736 | 0.5667 | 0.2675 |
| **g** | 0,0001 | 0,0001 | 0,0002 | 0.0001 | 0.0001 | 0.0002 |
| **H** | -0,1952 | -0,2163 | -0,4475 | -0.3371 | -0.3737 | -0.7732 |
| **i** | 0,1230 | 0,1364 | 0,1768 | 0.1772 | 0.1966 | 0.2546 |
| **j** | 0,2185 | 0,2198 | 0,2217 | 0.2622 | 0.2638 | 0.2660 |

Chapter IV of the dissertation is entitled "Methods for Enhancing the Operational Reliability of Multiphase Subsea Pipelines (Risers)" and comprises eight subsections.

The first subsection of Chapter IV is dedicated to the factors influencing the operational reliability of subsea pipelines under multiphase flow conditions. It presents the structural flow patterns in horizontal and vertical pipelines, detailing the distribution of liquid and gas phases in annular-slug and mist flow regimes for multiphase upward vertical flows.

The second subsection provides structural regime maps for multiphase flows, as illustrated in Figure 6[5].

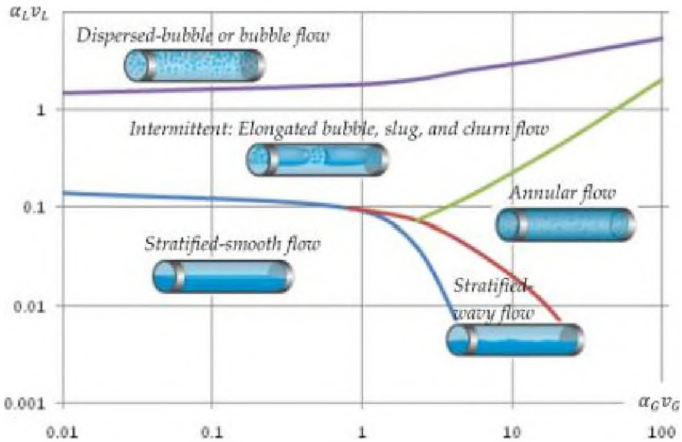


**Figure 6. Example of a Flow Regime Map for Two-Phase Gas-Liquid Flow in a Horizontal Pipeline**

The classification of flow regime structures is based on visual observations of phenomena occurring in experimental pipelines. However, in engineering applications, direct visual observation is not always feasible, necessitating the development of simplified methodologies to predict flow regimes within pipelines based on given flow parameters.

Consequently, flow regime maps must be constructed either from experimental data or mechanistic models to determine transitions between different flow structures. Nevertheless, these flow maps are

[5]Bratland, O. Pipe Flow 2: Multi-phase Flow Assurance / O. Bartland. – Trondheim: drbratland.com, – 2010. – 379p.

constrained by the predetermined properties of the working fluids and the geometrical configuration of the pipeline, thereby limiting their applicability. Moreover, they offer restricted utility in cases involving flows with more than two phases.

For horizontal gas-liquid flows, the most widely used flow regime map was developed by Taitel and Dukler (1976).

The third subsection of Chapter IV presents the simulation of a technological scheme to mitigate slug formation in risers. Due to the bending of the riser near the seabed, particularly at the transition from the seabed to the platform, the likelihood of slug formation increases.

The formation of slugs in vertical pipelines occurs through the following four-stage mechanism:

1. Liquid accumulation;
2. Slug initiation;
3. Bubble formation;
4. Gas eruption and liquid displacement.

The study examines multiphase flow-related challenges arising from the topographical variations of the seabed and the configuration of vertical pipelines. The research identifies desirable and undesirable conditions encountered in bends and elbows of risers, specifically at the junction between the seabed and a stationary offshore platform. Furthermore, a mathematical formulation is provided to describe the unfavorable phenomena occurring at the elbow sections of risers where they transition toward the platform.

Considering the topographical irregularities of the seabed and their impact on subsea flow behavior, the accumulation of solid particulates in depressed sections of subsea pipelines—whether between offshore platforms or along the pipeline route to shore—can lead to localized corrosion, structural perforation, and environmental contamination due to leakage. To mitigate such risks, the final section of this study proposes a technological scheme to prevent these adverse occurrences.

A simulation of the proposed technological scheme was conducted using Aspen HYSYS, calibrated with laboratory analysis results. The study provides graphical and simulation-based correlations for various thermodynamic and physical parameters (Figure 7)[6].

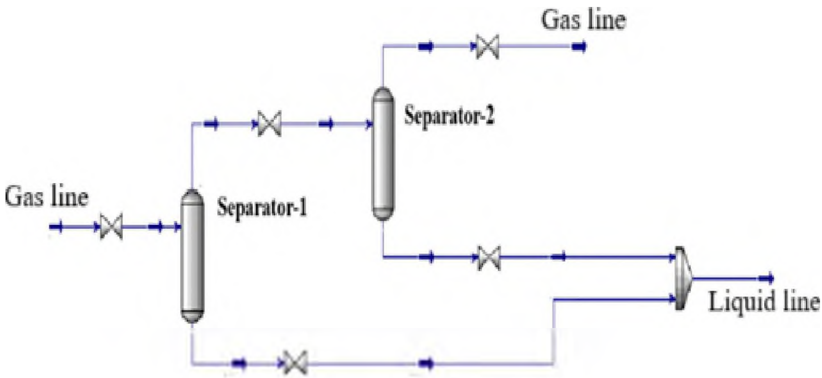


**Figure 7. Development of the Technological Scheme in the Aspen HYSYS**

The fourth subsection of Chapter IV examines technological approaches for mitigating slug flow formation. Based on experimental, theoretical, and field studies, several advanced slug control techniques have been proposed. This section provides a comprehensive analysis of their operating principles, along with an evaluation of their advantages and limitations.

The fifth subsection of Chapter IV introduces a novel in-line separation equipment for low-pressure gas transportation in subsea pipelines (Figure 8)[7], followed by its mathematical analysis based on d'Alembert's principle.

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[6] İsmayılov, Q.Q., Şahlarlı, M.E., İsmayılov, Ş.Z. Multifazalı sualtı boru kəmərlərinin istismar səmərəliliyinin artırılmasının bəzi məsələləri // – Bakı: Azərbaycan Mühəndislik Akademiyasının Xəbərləri, – 2022. Cild 14, №2, – s.75-80.

[7] Shahlarli, M.E. To Increase the Efficiency of Low-Pressure Gas Transportation in the Gunashli Energy Sector // SPE Annual Caspian Technical Conference, – Baku: OnePetro, –5-7 october, – 2021, – p. 1-5.

This method employs subsea separation systems to segregate multiphase flow into its liquid and gas components, thereby necessitating the use of two separate pipelines for gas and liquid transportation. A submersible pump is required to ensure adequate pressure for liquid delivery to the platform.

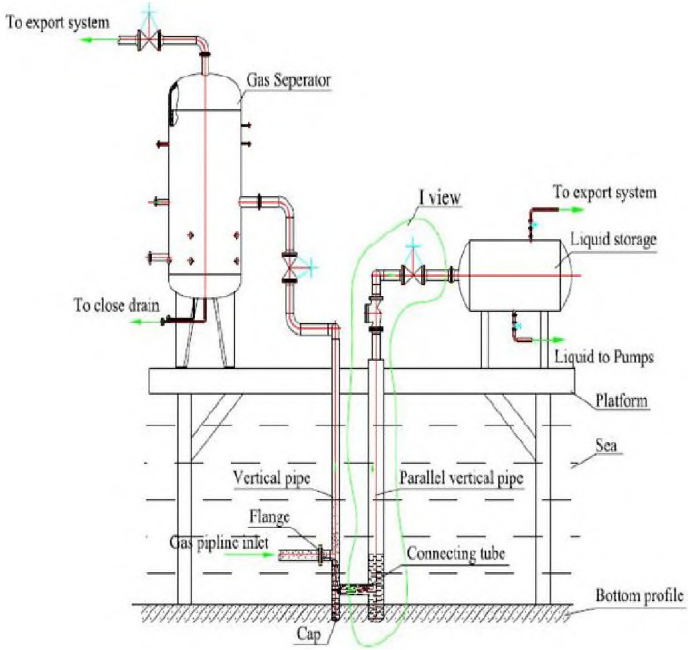


**Figure 8. Principal diagram of the proposed construction**

As a result, this approach effectively prevents multiphase flow instabilities and mitigates the formation of severe slugging.

To enhance the operational reliability of subsea pipelines, a new transportation methodology has been developed. This technology is designed to implement in-line separation at the seabed level. Initially, based on d'Alembert's principle, the forces acting on liquid and solid particulates within a vertical pipeline were analyzed. Subsequently, a novel structural design was proposed for gas purification and transfer to the separator at the seabed level.

To prevent the accumulation of liquid and mechanical impurities at the riser entry points during low-pressure gas transportation, a modification to the riser design has been proposed. A secondary pipeline is installed parallel to the riser and connected to it at the lower section. The length of this parallel pipe exceeds that of the riser, and it is anchored several meters into the seabed sediment.

A flange connection is mounted on the riser above the junction with the parallel pipeline, allowing the subsea pipeline to be connected to the flange assembly. A submersible pump is deployed inside the parallel pipeline at the end of a pump-compressor pipeline. According to the principle of communicating vessels, the separated liquid and mechanical impurities in the riser are diverted through the pipeline junction into the lower section of the parallel pipe. The accumulated liquid in the parallel pipe is subsequently transported to the processing unit via the submersible pump.

The sixth subsection of Chapter IV investigates the impact of gravitational losses in risers on the flow rate characteristics of subsea pipelines (Figure 9)[8].

In downward-directed flows, the stratified flow regime is predominant, and the increase in the potential energy of the flow is determined by the weight of the gas column.

As the velocity of the multiphase mixture increases, the length of the stratified zone in free-flow regions initially decreases and then gradually transitions into a slug flow regime. Consequently, with increasing velocity, the density difference between the phases in both upward and downward flows progressively diminishes. This, in turn, leads to a reduction in gravitational pressure losses (Δpgr), asymptotically approaching the value $\rho_{mix} \cdot g\Delta z$. It is well known that, in oil and gas reservoirs, the accumulation and transportation of well fluids are typically designed based on single-phase oil or gas flow assumptions.

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[8]İsmayılova, F.B., Şahlarlı, M.E., İsmayılov, Ş.Z. Multifazalı axınlarda struktur formaları və qravitasiya itkiləri // II Beynəlxalq Elm və Mühəndislik Konfransı, – Bakı: Bakı Mühəndislik Universiteti, – 26-27 Noyabr 2021, – s. 312–315.

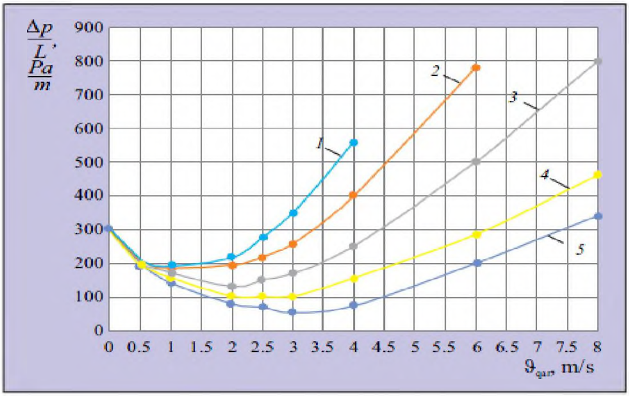


**Figure 9. Flow Rate Characteristics of a Multiphase Production Pipeline**
**β = 1-0.2; 2-0.3; 3-0.4; 4-0.5; 5-0.6**

However, during actual field operations, the real costs often deviate significantly from the projected costs, primarily due to the failure to account for multiphase flow dynamics and the simultaneous transportation of liquid and gaseous hydrocarbons through pipelines.

As observed in the graph, an increase in β corresponds to a higher velocity value at which minimum pressure loss occurs. For lower values of β, where the density difference between the phases in rising and falling flows is negligible, the pressure loss curve does not exhibit a distinct minimum ($\Delta p_{min}$) within the pipeline.

In Section 7 of Chapter IV, the structural loads and forces acting on vertical pipes during operation have been assessed, and the time-dependent effects of structural loads have been computed.

The passage of slag-containing flows through subsea pipeline–vertical pipe systems induce significant variations in structural loads over time, which substantially influence component design. Operational experience with subsea pipelines indicates that the highest incidence of damage occurs at the curvature of vertical pipes, specifically at the junction where the vertical pipe connects to the linear segment of the pipeline. This critical transition region, where the pipeline rises from the seabed toward the foundation, is particularly susceptible to structural stress accumulation and failure.

In Section 8 of Chapter IV, the technologies employed for the installation of vertical pipes are discussed.

Walker and Davies, in their research, have extensively elucidated the mechanics of pulling vertical pipes using J-type conduit systems. They identified three distinct stages in the deployment of vertical pipes[9]:

1. Initial Contact and Deflection: The vertical pipe initially encounters the inner walls of the curved section of the J-type conduit and must undergo bending to proceed further.

2. Conformational Adaptation: The inner vertical pipe progressively conforms to the curvature of the J-type pull conduit, altering its shape along the bending trajectory.

3. Residual Curvature Formation: Upon entry into the straight section of the J-type pull conduit, the vertical pipe exhibits residual curvature due to plastic deformation. This results in persistent bending effects, causing the pulling head to ultimately remain in contact with the inner surface of the conduit.

When the subsea pipeline–vertical pipe system reaches the entrance of the J-shaped vertical conduit (i.e., the bellmouth) the pulling head experiences a force slightly exceeding the tensile stress at the rear section of the pipeline.

A counteracting stress develops along the lower side of the pipeline, which faces the seabed. This phenomenon arises due to the opposing movement of the pipe-laying vessel relative to the direction of pipe deployment, as well as the frictional interaction between the pipeline and the seabed.

The force exerted on the pulling head originates from the winch system fixed on the foundation, which induces tensile stress in the pulling cable. The force required to pull the subsea pipeline–vertical pipe system through the interior of the J-shaped conduit can be determined using the law of energy conservation.

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[9] Qiu W., Chang S.-H.M., Liu X., King J. "Advanced Pipeline Riser Pull-In Analysis for a Fixed Offshore Production Platform" // Offshore Technology Conference. – Houston: Texas, USA, – 4 may, – 2009, – p. 1-10.

The analytical approach at specific contact points during the pulling process follows the methodologies outlined in Analytical Approaches 1 and 2 within the dissertation and is analogous to those approaches. It is critical to acknowledge that as the subsea pipeline–vertical pipe system enters and exits the curved section of the J-shaped conduit, maximum stress is expected to develop along the upper surface of the J-conduit. If this stress distribution is not adequately accounted for, the outer vertical pipe's wall may undergo structural deformation.

Based on extensive theoretical and practical calculations, the frictional force between the vertical pipe and the J-conduit can be determined using Coulomb's and Amontons' friction laws.

The sequential mechanism for the installation of vertical pipes using J-type conduits is demonstrated in three steps (Figure 10). The approximate locations of contact loads at various points have been identified, and MATLAB-based modeling has been performed at each step to analyze the dependence of pulling loads on the distance between contact points.

Computational results indicate that, depending on the obtained findings, it would be highly advisable to establish a dedicated international standard for J-shaped conduits, considering geographical variability and climatic complexity. These conduits should be classified based on water depth, as they are particularly sensitive to hydrodynamic and other loading conditions, and subsequently implemented accordingly.

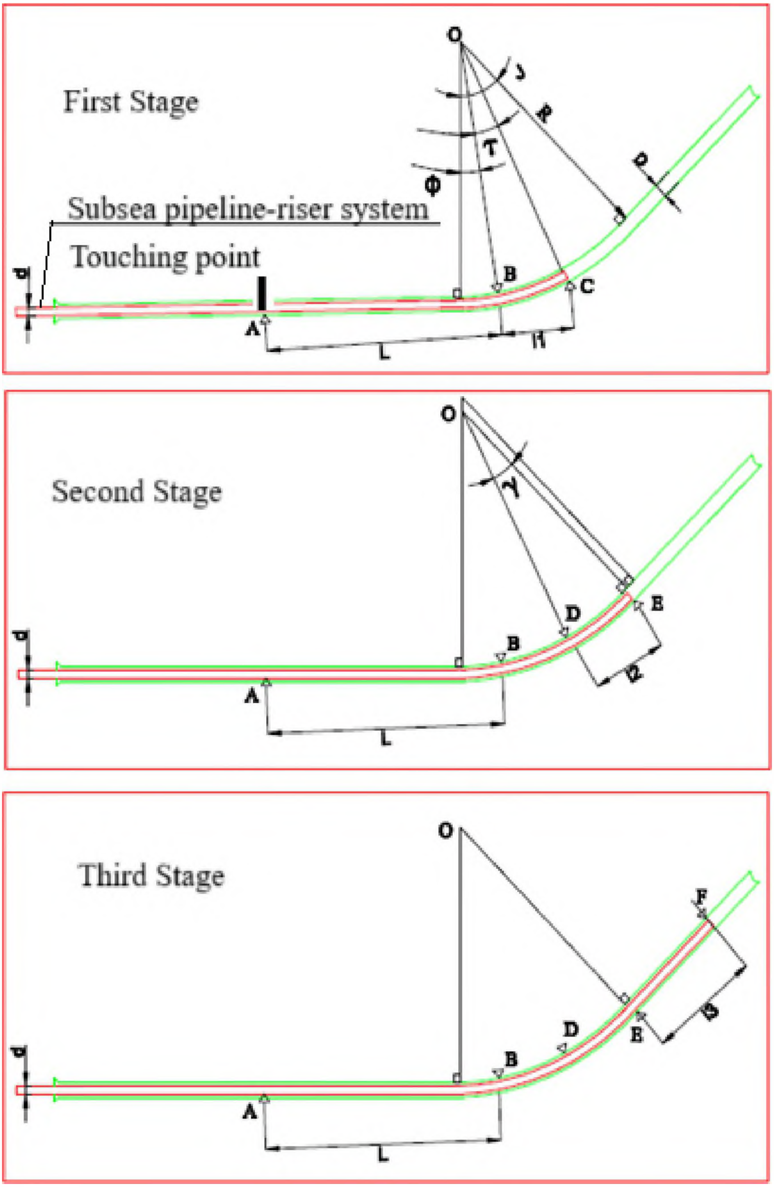


**Figure 10. Sequence of Riser Pulling Using a J-Shaped Tube a) First Stage, b) Second Stage, c) Third Stage**

## CONCLUSIONS

1. The technologies for super depths water pipeline installation were analyzed, with a comparative analysis of these technologies, including their advantages and disadvantages. The reaction forces during installation were analyzed and simulated using MATLAB software [8].

2. A new method was developed for super depths water pipeline installation using the J-method, and arrestors were proposed to prevent local buckling at the seabed [2, 20, 21].

3. In ultra-deep waters, where the external hydrostatic pressure exceeds the allowable limit, the potential for pipeline compression and the rapid propagation of this compression along the pipeline's length was demonstrated.

4. For underwater pipelines at a depth of H=500 m, considering the allowable strength limit of the pipeline material ($\left[\sigma_{\text{yield}}^{strength}\right]$=4000 kgf/cm²), the stress-deformation state of the pipeline was analyzed in accordance with the "J" installation method. The hydrostatic pressure-induced stress and compression stresses were determined to be $\sigma$hid = -391 kgf/cm² and $\sigma$total = -4129 kgf/cm², respectively.

5. Since $\sigma$total > $\left[\sigma_{\text{yield}}^{strength}\right]$, it was concluded that bending in the pipeline wall is inevitable [20, 21].

6. A new method for diagnosing oil leaks in underwater pipelines in ultra-deep waters was developed, with simulations performed in Delphi software, taking into account water depth [19].

7. An algorithm was developed for evaluating risk factors associated with accidents in underwater pipelines, using the fuzzy analytical triangle method [17].

8. Risk evaluation of technological risks in underwater pipelines was conducted based on expert opinions, and a new method was developed to determine the distance from the highest risk area [7, 15, 16].

9. A new subsea separation system was proposed for the separation of low-pressure gas in underwater pipelines [3].

10. The installation technologies for vertical pipes were analyzed, and the stresses and frictional forces generated during installation were examined.

11. Factors influencing the operational reliability of underwater pipelines, including vertical pipes, in deep-water reservoirs were analyzed. The importance of considering gravitational flow regimes and pressure losses caused by gravity in the flow characteristics was emphasized [6].

12. For the stability analysis of non-metallic pipes in underwater pipelines, a MATLAB-based model was developed, and simulations were conducted.

13. Hydrodynamic forces acting on vertical pipes at a depth of 300 meters in the Caspian Sea were analyzed, and simulations were conducted using SACS software [17].

14. The operational efficiency of multi-phase flow in underwater pipelines and vertical pipes during cross-platform flow was investigated. Based on laboratory test results, the technological scheme for the retention of mechanical particles was calculated using Aspen HYSYS software [4, 5, 11].

**The main findings and content of the dissertation have been published in the following works:**

1. Həsənov, F.Q., Bayramov, S.B., Şahlarlı, M.E., Əhmədzadə, F.N. Magistral kəmərlə qazın nəqli // – Bakı: ANT, – 2019. №5, – s. 30–32.

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3. Shahlarli, M.E. To Increase the Efficiency of Low Pressure Gas Transportation in the Gunashli Energy Sector // SPE Annual Caspian Technical Conference, – Baku: OnePetro, – 5-7 October, – 2021, – p. 1-5.

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12. Shahlarli, M.E. "Analysis of Application of Fuzzy Analytic Hierarchy Process to Determine Risk Factor Weights in Deepwater Pipeline" // The Third International Student Research and Science Conferences Dedicated to the 99th Anniversary of the National Leader of Azerbaijan Heydar Aliyev, Baku: Baku Higher Oil School, – 18-29 april, – 2022, – p. 87-89.

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**The claimant's individual contributions within co-authored studies are categorized as follows:**

[2,3,12,13,14] – Research works independently developed by the claimant.

[1,4,5,6,7,8,9,10,11,15,16,17,18,19,20,21] – In these studies, the claimant was responsible for formulating the problem statement, proposing the methodological approach for its resolution, and participating in the verification of the accuracy and validity of the obtained results.

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