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Risk Management in Gas Flare Pipeline Construction Projects: A Case Study of Kimia Pars Middle East Petrochemical Complex

Reza Dehghani Bidokhti; Mohammad Reza Shokouhi *

Department of Oil & Gas Contracts and Management, Tehran Faculty of Petroleum, Petroleum University of Technology (PUT), Abadan, Iran.

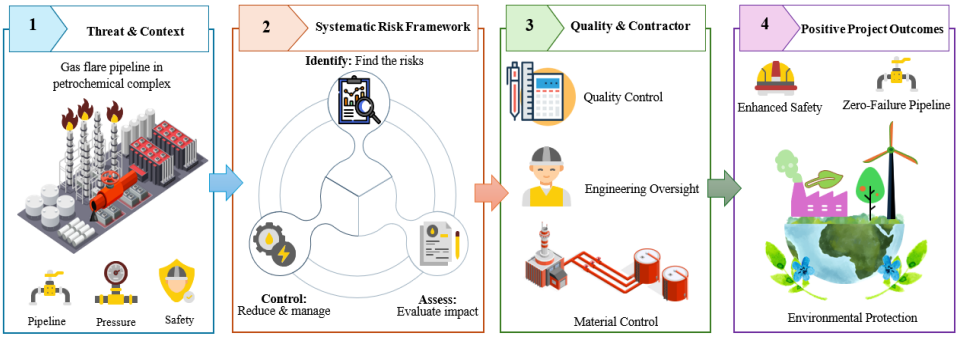
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A B S T R A C T

Failure of high-pressure gas flare pipelines can pose severe threats to human safety, civil infrastructures, and the environment. Therefore, implementing effective risk management strategies is essential to reduce the probability and impact of such undesirable events. This study focuses on risk management in the construction of gas flare transmission pipelines, where various critical risk factors may emerge throughout different stages of the construction process. A systematic risk management approach is applied to identify, assess, and control potential risks associated with pipeline construction activities. Quality control practices are considered as one of the fundamental tools for risk mitigation, enabling independent evaluation of construction processes, compliance with technical requirements, and verification of planned quality standards. The contractor plays a key role in ensuring the proper application of construction technologies and the quality of materials throughout the project lifecycle while assuming responsibility for preventing potential failures in execution and implementation. The findings highlight the importance of proactive risk identification and management in gas flare pipeline construction projects. Effective risk management practices can significantly improve project safety, enhance construction quality, reduce the likelihood of operational failures, and minimize environmental and social consequences. The proposed approach provides valuable insights for project managers and contractors involved in complex petrochemical infrastructure projects.



1. Introduction

The oil and gas industry is recognized as one of the most critical and strategic sectors worldwide due to its significant contribution to energy supply, economic development, and industrial growth. Oil and gas projects are generally characterized by high levels of complexity, large-scale investments, long execution periods, and exposure to various technical, environmental, financial, and safety-related uncertainties. Among these projects, pipeline construction projects represent one of the most sensitive infrastructures because any failure during construction or operation may result in severe consequences, including human casualties, economic losses, environmental degradation, and prolonged interruptions in industrial activities [1,2].

Project risk management has become an essential component of modern project management practices, particularly in complex engineering and construction projects. Effective risk management enables project stakeholders to identify potential uncertainties, evaluate their consequences, develop appropriate response strategies, and improve decision-making processes throughout the project lifecycle [3]. According to the Project Management Institute (PMI), risk management is a systematic process consisting of risk identification, qualitative and quantitative risk analysis, risk response planning, and risk monitoring and control [4]. Despite its importance, risk management practices in many developing countries, including Iran, have not been sufficiently integrated into

* Corresponding Author: Mohammad Reza Shokouhi
E-mail address: shokouhi@put.ac.ir
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industrial projects, and many organizations still lack comprehensive frameworks for systematic risk identification and mitigation [5].

Gas flare systems are among the most important safety components in petrochemical and oil processing facilities. These systems are designed to safely collect and burn hazardous gases released from process units under abnormal operating conditions, such as excessive pressure, temperature variations, or emergency shutdown scenarios. The released gases and liquids cannot be directly discharged into the environment because of their toxic, flammable, or explosive characteristics; therefore, they are transferred through flare headers, separation units, and flare stacks for controlled combustion [6]. Although flare systems significantly reduce operational hazards, the construction and installation of flare pipelines involve numerous risks due to high-pressure conditions, complex process requirements, material specifications, and strict safety regulations.

Failure of high-pressure flare pipelines can lead to catastrophic consequences, including explosions, fires, toxic emissions, structural damage, and environmental pollution. Previous studies have emphasized that pipeline failures are usually caused by a combination of technical, operational, managerial, and environmental factors rather than a single failure mechanism [7]. Therefore, identifying and evaluating critical risk factors during pipeline construction is necessary to prevent undesirable events and improve project performance.

Various methodologies have been developed for risk assessment in engineering and construction projects. Qualitative approaches, such as risk matrices and expert judgment methods, are widely used because of their simplicity and applicability in situations with limited data availability. However, these methods may suffer from subjectivity and uncertainty in risk evaluation [8]. On the other hand, quantitative methods provide more accurate estimations but often require extensive historical data, complex calculations, and significant time and financial resources [9]. Due to these limitations, integrated approaches combining qualitative and quantitative techniques have gained considerable attention in recent years.

Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and multi-criteria decision-making techniques are among the most commonly applied approaches for risk identification and prioritization in industrial projects. FTA, as a systematic deductive technique, enables analysts to investigate the logical relationships between basic events and undesirable top events, providing valuable information for accident prevention and reliability improvement [10]. Similarly, FMEA has been extensively applied in construction and industrial systems to identify potential failure modes and prioritize risks based on their severity, occurrence probability, and detectability [11].

However, risk assessment alone cannot provide a comprehensive risk management framework unless the relationships and interactions among identified risks are considered. In complex construction projects, risk factors are often interdependent, and the occurrence of one risk may influence the probability or severity of other risks. Therefore, approaches capable of modeling the relationships among risk factors, such as Interpretive Structural Modeling (ISM), have been increasingly applied to develop hierarchical risk models and support strategic decision-making [12].

Although previous studies have investigated risk assessment in oil and gas pipelines, most research has focused on operational failures, maintenance activities, or general pipeline safety issues. Limited studies have addressed the systematic identification, prioritization, and management of risks specifically associated with the construction phase of gas flare pipeline projects in petrochemical complexes. Moreover, the integration of risk identification techniques, risk prioritization methods, and response planning strategies remains insufficiently explored in this context.

Therefore, this study aims to develop an integrated risk management approach for gas flare pipeline construction projects by identifying critical risks, evaluating their importance, and proposing appropriate response strategies. A case study is conducted in the Kimia Pars Middle East Petrochemical Complex to demonstrate the applicability of the proposed approach. The findings of this research can contribute to improving construction safety, reducing project uncertainties, minimizing economic and environmental consequences, and supporting project managers in making more effective risk-based decisions.

1.1. Risk Management in Oil and Gas Construction Projects

Risk management has become an essential element of project management, particularly in large-scale oil and gas infrastructure projects where uncertainty, complexity, and potential consequences of failure are significant. Construction projects in the petroleum industry are exposed to various categories of risks, including technical, financial, environmental, safety, contractual, and operational risks. Effective risk management requires a systematic process for identifying, analyzing, prioritizing, and responding to risks throughout the project lifecycle [1].

1.2. Risk Assessment Methods in Pipeline Projects

Several approaches have been developed for risk assessment in oil and gas pipeline systems. These methods can generally be classified into qualitative, quantitative, and hybrid approaches. Qualitative methods mainly rely on expert judgment and experience, while quantitative approaches use statistical analysis and numerical modeling to estimate failure probabilities and consequences [9].

Although qualitative methods such as risk matrices are widely used because of their simplicity and applicability, they may suffer from subjectivity and uncertainty. Conversely, quantitative techniques require extensive historical data, which is often unavailable in developing countries or for unique industrial projects [8]. Therefore, hybrid approaches that combine expert knowledge with analytical techniques have gained increasing attention.

Failure Mode and Effects Analysis (FMEA) is one of the most frequently used techniques for identifying and prioritizing risks in engineering systems. The method evaluates potential failure modes based on severity, occurrence probability, and detectability criteria. Due to its systematic nature, FMEA has been extensively applied in pipeline safety assessment and industrial risk management [11].

Another important technique is Fault Tree Analysis (FTA), which is a deductive approach used to investigate the causes and logical relationships leading to a critical failure event. FTA allows researchers and engineers to identify basic events contributing to system failure and develop preventive strategies [10].

1.3. Previous Studies on Pipeline Risk Assessment

Previous studies have investigated different aspects of pipeline risk management. Jafari et al. developed a comprehensive risk assessment and management approach for communication pipelines by evaluating chemical exposure risks and modeling possible failure scenarios. Their study demonstrated the importance of combining failure probability analysis with consequence assessment for pipeline risk evaluation [13].

Several researchers have focused on risk analysis in oil and gas EPC projects. These studies indicate that engineering risks, financial uncertainties, equipment failures, material-related problems, and external factors are among the most influential risk categories affecting project performance [5].

In another study, risk factors associated with gas refinery construction projects were evaluated using fuzzy Delphi and fault tree analysis methods. The results demonstrated that combining expert-based approaches with analytical methods can improve the accuracy of risk prioritization [14].

Furthermore, studies on gas transmission pipeline projects have applied integrated methods such as FMEA and AHP to evaluate environmental and safety-related risks. These approaches have shown that multi-criteria decision-making methods can improve risk ranking by considering different dimensions of project risk simultaneously.

Recent research has also investigated aging-related risks in oil and gas pipelines by integrating risk indices with fuzzy TOPSIS methods. These studies highlight the importance of combining risk indicators and decision-making models to support effective mitigation strategies.

Table 1. Summary of Previous Studies on Pipeline and Oil & Gas Risk Management

Study	Research Area	Risk Assessment Method	Main Contribution
Jafari et al. [13]	Pipeline risk assessment	Risk index + failure modeling	Development of comprehensive pipeline risk evaluation
EPC risk studies [5]	Oil and gas construction projects	Qualitative risk analysis	Identification of engineering and management risks
Gas refinery projects [14]	Refinery construction risks	Fuzzy Delphi + FTA	Prioritization of critical construction risks
Pipeline environmental risks [15]	Gas transmission pipelines	FMEA + AHP	Integration of safety and environmental risk assessment
Aging pipeline studies [16]	Oil and gas pipeline deterioration	Fuzzy TOPSIS	Risk ranking using combined indicators

1.4. Research Gap and Contribution of the Present Study

Although previous studies have significantly contributed to pipeline risk assessment, several limitations remain. First, most existing studies have focused on operational risks, maintenance activities, or general pipeline safety, while fewer studies have investigated risks associated with the construction phase of gas flare pipelines.

Second, previous research has commonly evaluated individual risk categories, whereas construction of flare pipelines involves interconnected risks originating from design, materials, equipment, workforce, financial issues, environmental conditions, and external factors.

Third, limited studies have integrated risk identification, risk prioritization, sensitivity analysis, and response planning into a unified framework for petrochemical flare pipeline construction projects.

Accordingly, the present study aims to address this gap by developing a comprehensive risk management framework for gas flare pipeline construction projects. The proposed approach combines expert-based risk identification, qualitative risk evaluation, prioritization techniques, and risk response planning to support decision-making in petrochemical projects.

2. Materials and Methods

2.1. Research Design and Approach

The present study employs an applied research design using a descriptive-survey approach to develop an integrated risk management framework for gas flare pipeline construction projects. Due to the complexity of petrochemical projects and the existence of multiple interacting risk factors, a single risk assessment technique may not provide sufficient information for effective decision-making. Therefore, this research applies a hybrid multi-method approach by integrating qualitative and quantitative techniques to identify, analyze, prioritize, and manage construction-related risks.

The research methodology was designed based on four consecutive phases. Initially, potential risk factors associated with the construction of gas flare pipelines were identified through an extensive review of previous studies, analysis of project documents, technical reports, and expert consultations. Since construction projects in the oil and gas industry involve technical, managerial, environmental, financial, and safety uncertainties, expert knowledge plays a critical role in recognizing project-specific risks. Subsequently, the identified risk factors were evaluated and screened using the Fuzzy Delphi Method to achieve expert consensus and eliminate insignificant factors.

Following the identification of the final risk factors, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique was applied to analyze the causal relationships and interdependencies among risks. Since risk factors in complex industrial projects are rarely independent, determining the influence and dependence relationships among them provides a more realistic understanding of the risk structure. After establishing the causal network, the Analytic Network Process (ANP) method was employed to calculate the relative weights of risk factors by considering the interrelationships among criteria. Finally, the Weighted Aggregated Sum Product Assessment (WASPAS) method was used to prioritize the identified risks and determine the most critical risks requiring mitigation actions.

The combination of these methods provides a comprehensive framework for risk management by integrating expert knowledge, uncertainty handling, causal analysis, and multi-criteria decision-making. The proposed methodology enables project managers and engineers to identify high-impact risks at early stages of construction and implement appropriate response strategies to reduce potential failures.

2.1 Research Population and Sampling Procedure

The research population consists of experts, managers, consultants, and technical specialists involved in the construction activities of gas flare pipelines at Kimia Pars Middle East Petrochemical Complex. Due to the specialized nature of the research topic, selecting knowledgeable respondents with sufficient experience in petrochemical construction projects was essential to ensure the reliability of collected data. Therefore, participants were selected based on their professional background, technical expertise, and direct involvement in pipeline construction activities.

The required sample size was determined using Cochran's sampling formula, which is widely applied in survey-based research to estimate an appropriate sample size from a finite population [17]. The mathematical expression of Cochran's formula is presented as follows:

where represents the required sample size, denotes the population size, indicates the standard normal value corresponding to the confidence level, represents the estimated proportion of the population possessing the required characteristics, is equal to , and represents the acceptable sampling error.

Considering a population size of 137 individuals, confidence level of 95%, maximum variability assumption, and a 5% acceptable error level, the calculated sample size was approximately 100 respondents. Accordingly, 150 questionnaires were distributed among experts, and 100 valid questionnaires were collected and used for further analysis.

Table 2. Research Design and Methodological Characteristics

Item	Description
Research approach	Applied
Research method	Descriptive-survey
Research domain	Risk management in petrochemical construction projects
Case study	Kimia Pars Middle East Petrochemical Complex
Target respondents	Managers, engineers, consultants, and technical experts
Data collection tool	Expert questionnaire
Sample size	100 valid responses
Analysis methods	Fuzzy Delphi, DEMATEL, ANP, WASPAS

2.2 Application of the Fuzzy Delphi Method

The Delphi technique is a structured decision-making approach that aims to achieve consensus among experts through iterative evaluation processes. However, conventional Delphi methods may not adequately handle uncertainty and ambiguity inherent in human judgments. To overcome this limitation, the Fuzzy Delphi Method combines traditional Delphi procedures with fuzzy set theory, allowing experts' subjective opinions to be expressed through linguistic variables and fuzzy numbers [18].

In this study, the Fuzzy Delphi Method was employed to evaluate the initial list of identified risks and determine the most significant risk factors affecting gas flare pipeline construction. Experts were asked to evaluate the importance of each risk factor using linguistic terms. These linguistic assessments were converted into triangular fuzzy numbers to mathematically represent uncertainty in expert judgments.

A triangular fuzzy number is represented as:

where, and indicate the lower, middle, and upper values of the fuzzy number, respectively. The aggregated fuzzy importance value of each risk factor was calculated based on experts' opinions, and the final crisp value was obtained through the defuzzification process:

Risk factors with values higher than the predefined acceptance threshold were retained for subsequent analysis, while factors with lower values were excluded from the final model.

Table 3. Linguistic Variables Used in the Fuzzy Delphi Method

Linguistic Evaluation	Triangular Fuzzy Number
Very Low	(1,1,3)
Low	(1,3,5)
Medium	(3,5,7)
High	(5,7,9)
Very High	(7,9,9)

3. Results and Discussion

3.1. Respondent Characteristics

A total of 100 valid questionnaires were analyzed. Table 4 summarizes the demographic characteristics of the respondents.

Table 4. Demographic characteristics of respondents (n = 100)

Variable	Category	Frequency	Percentage (%)
Gender	Male	61	61.0
	Female	39	39.0
Age	≤25 years	14	14.0
	25–30 years	14	14.0
	30–35 years	23	23.0
	35–40 years	26	26.0
	>40 years	23	23.0
Education	Associate degree	23	23.0
	Bachelor's degree	28	28.0
	Master's degree	27	27.0
	Doctorate	22	22.0

The respondents represented a relatively balanced distribution in terms of age and educational background, while male participants constituted the majority (61%). Most respondents possessed at least a bachelor's degree, indicating that the collected opinions were obtained from technically qualified personnel involved in gas flare pipeline construction projects.

3.2. Weighting of Evaluation Criteria

Expert judgments were collected using linguistic variables to evaluate the relative importance of four project objectives including schedule, cost, quality, and safety. Linguistic assessments were converted into fuzzy numerical values before aggregation.

The resulting normalized weights of the four evaluation criteria are presented in Table 5.

Table 5. Final weights of project evaluation criteria

Criterion	Weight
Quality (Q2)	0.92
Safety (Q4)	0.68
Cost (Q3)	0.79
Time (Q1)	0.61

The results indicate that quality received the highest importance among the four project objectives, followed by cost, safety, and schedule.

3.3. Positive Ideal Solution

Following normalization of the decision matrix, the positive ideal solution (PIS) was determined for each project objective. The resulting benchmark values are presented in Table 6.

Table 6. Positive ideal solution

Objective	Positive Ideal Value
Time	0.79
Cost	0.61
Quality	0.92
Safety	0.60

These values served as reference points for evaluating the relative significance of identified project risks.

3.4. Probability of Risk Occurrence

Fifty-three potential risks associated with gas flare pipeline construction were evaluated by project experts. The estimated occurrence probabilities ranged from 46.6% to 64.1%. The highest occurrence probabilities were observed for:

Table 7. Risks with the highest occurrence probabilities

Rank	Risk Factor	Probability (%)
1	Insufficient worker safety awareness and inadequate safety training	64.1
2	Poor availability or quality of construction materials	61.6
3	Failure to apply value engineering during design	60.3
4	Management pressure to shorten the design phase	59.7
5	Inappropriate employee incentive and disciplinary systems	59.1
6	Poor coordination among project stakeholders	58.4
7	Failure to employ modern construction methods	57.8
8	Lack of systemic thinking among project departments	56.6
9	Compressed project schedule imposed by the client	56.6
10	Improper allocation of manpower and equipment	55.9

Overall, organizational deficiencies, contractor capabilities, workforce management, and supply chain issues exhibited relatively high probabilities of occurrence.

3.5. Risk Impact on Project Schedule

The combined effect of occurrence probability and impact severity was calculated to prioritize schedule-related risks.
Table 8 presents the ten highest-ranked schedule risks.

Table 8. Top schedule-related risks

Rank	Risk	Risk Index
1	Cash flow shortages and delayed contractor payments	0.53
2	Errors in project scheduling and activity sequencing	0.52
3	Insufficient contractor financial capability	0.51
4	Incorrect cost estimation during bidding	0.49
5	Sanctions and war	0.49
6	Equipment manufacturing delays	0.47
7	Poor contractor management and coordination	0.44
8	Replacement of key personnel	0.38
9	Improper allocation of manpower and equipment	0.35
10	Equipment transportation delays	0.33

Financial constraints and contractor management issues were identified as the dominant threats to project schedule performance.

3.6. Risk Impact on Project Quality

Quality-related risks demonstrated a different prioritization pattern. Table 9 summarizes the highest-ranked risks.

Table 9. Top quality-related risks

Rank	Risk	Risk Index
1	Poor quality control during equipment manufacturing	0.41
2	Compressed project schedule imposed on the contractor	0.40
3	Poor availability or quality of materials	0.38
4	Replacement of key personnel	0.34
5	Insufficient supervision of construction quality	0.28
6	Inefficient contractor evaluation system	0.28
7	Sanctions and war	0.28
8	Delayed contractor payments	0.28
9	Poor workshop equipment	0.28
10	Insufficient contractor financial capability	0.28

The findings suggest that supplier quality management, contractor capability, and client-imposed schedule pressure are the primary determinants of project quality.

3.7. Risk Impact on Project Cost

Cost-related risks were dominated by planning inaccuracies and contractor financial performance.

Table 10. Top cost-related risks

Rank	Risk	Risk Index
1	Errors in project scheduling and sequencing	0.38
2	Insufficient contractor financial capability	0.30
3	Delayed contractor payments	0.29
4	Sanctions and war	0.28
5	Incorrect bid estimation	0.27
6	Exchange rate fluctuations	0.26
7	Compressed project schedule	0.25
8	Improper resource allocation	0.20
9	Incomplete feasibility studies	0.19
10	Inefficient contractor evaluation	0.18

The results indicate that financial uncertainty and inadequate project planning are the principal drivers of cost overruns.

3.8. Risk Impact on Project Safety

Safety analysis revealed a different hierarchy of influential risks.

Table 11. Top safety-related risks

Rank	Risk	Risk Index
1	Insufficient worker safety awareness and inadequate safety training	0.49
2	Delayed contractor payments	0.30
3	Compressed project schedule	0.29
4	Poor workshop equipment	0.28
5	Poor contractor management and coordination	0.28
6	Insufficient contractor financial capability	0.28
7	Poor stakeholder coordination	0.28
8	Inefficient contractor evaluation	0.28
9	Low workforce productivity	0.27
10	Inappropriate design standards	0.27

Safety performance was primarily affected by workforce competence, contractor management practices, and organizational coordination.

3.9. Overall Project Risk Prioritization

To identify the most critical risks affecting overall project performance, the integrated risk index was calculated by combining occurrence probability and impact severity across all project objectives.

Table 12 presents the highest-ranked project risks.

Table 12. Overall project risk ranking

Rank	Risk	Category	Risk Index
1	Cash flow shortages and delayed contractor payments	Client	0.38
2	Insufficient contractor financial capability	Contractor	0.30
3	Compressed project schedule imposed by client	Client	0.29
4	Sanctions and war	Political	0.28
5	Errors in scheduling and activity sequencing	Contractor	0.28
6	Incorrect bid estimation	Contractor	0.28
7	Poor contractor management and coordination	Contractor	0.28
8	Improper allocation of manpower and equipment	Contractor	0.27
9	Inefficient contractor evaluation system	Client	0.27
10	Poor coordination among project stakeholders	Client	0.27

The findings demonstrate that contractor-related risks constitute the largest proportion of high-priority risks, followed by client-related risks. Financial management deficiencies, inadequate planning, poor contractor capability, and organizational coordination were identified as the most influential factors affecting the successful construction of gas flare transmission pipelines.
Overall, the analysis indicates that proactive financial management, improved contractor selection, effective project planning, enhanced quality assurance, and stronger stakeholder coordination should be prioritized to improve the performance of gas flare pipeline construction projects.

4. Conclusions

4.1. Summary and Practical Implications

The construction of gas flare transmission infrastructure is a high-cost, multi-stage process that serves as a strategic component of national energy security. Ensuring the reliability and uninterrupted performance of these systems is critical for both industrial production and environmental safety. This research, conducted at the Kimia Pars Middle East Petrochemical Complex, underscores that every project participant—investor, designer, and contractor—must

maintain strict adherence to construction laws and quality standards to mitigate risks effectively.

The findings reveal that quality control serves as the primary risk management tool in this industry. A systematic approach to quality assurance allows for independent evaluation of construction progress, ensuring that the final facility meets the investor's requirements and legal regulations. In complex projects such as those studied here, contractors are encouraged to utilize sub-contractor expertise and maintain a highly qualified quality control staff. The implementation of an in-process control system, where subsequent project phases do not commence until previous stages are verified, is strongly recommended to prevent the propagation of defects.

4.2. Proposed Risk Mitigation Framework: The Four-Level Early Warning System

Based on the analysis of historical data and expert feedback, this study proposes a comprehensive risk management and real-time monitoring system specifically designed for gas flare pipeline slope hazards. Unlike traditional "black-box" models that rely on rigid critical thresholds—often leading to false alarms—the proposed system utilizes real-time numerical simulations.

By integrating data from onsite monitoring equipment (e.g., rainfall, water infiltration, and slope displacement), the system provides a quantitative risk estimation. The proposed four-level warning hierarchy is summarized in Table 13.

Table 13. Proposed Four-Level Early Warning Framework for Pipeline Hazards

Warning Level	Risk Condition	Trigger/Indicator	Required Action
Level IV (Blue)	Potential Risk	Heavy rainfall or minor soil saturation.	Increased frequency of monitoring.
Level III (Yellow)	Moderate Risk	Measurable slope displacement within safe limits.	Technical inspection and preliminary stabilization.
Level II (Orange)	High Risk	Displacement approaching critical simulation thresholds.	Immediate maintenance and site evacuation.
Level I (Red)	Imminent Hazard	Significant pipeline stress/deformation detected.	Shutdown of gas transmission and emergency repairs.

This procedure allows for targeted monitoring, reduces false alarms, and provides a clear roadmap for rapid prevention and control measures.

4.3. Research Limitations and Future Directions

Despite its contributions, this study acknowledges certain limitations:

1. Data Subjectivity: The reliance on questionnaires as the primary data collection tool may introduce respondent bias, potentially affecting the precision of the results.
2. Contextual Specificity: The findings regarding production and control strategies—developed using the Weighted Aggregated Sum Product Assessment (WASPAS) approach—are specific to the organizational culture and operational environment of the Kimia Pars Middle East Petrochemical Complex and may not be directly generalizable to other firms.
3. Spatial Scale: The current study focuses on project-wide risks. Future research should expand the scope to include localized micro-risks that emerge during the operational life cycle of the pipeline.

Author Contributions

All authors contributed equally to the conception, preparation and writing of this manuscript.

Conflict of Interest

The authors, while observing publication ethics in the referencing, declare the absence of interest of conflict.

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AI Used Statment

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