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FTA and Safety Monitoring Priorities for Third-Party Damage to Natural Gas Pipelines

Juan Xiong[1]*, Jia Jiang[2], Xingsi Cheng[1], Xiaobo Wu[1], Zongbao Xie[1], Jian Li[3]

[1]Pipeline Administration Department, PetroChina Southwest Oil & Gasfield Company, Chengdu, China
[2]Cost Control Center, PetroChina Southwest Oil & Gasfield Company, Chengdu, China
[3]General Natural Gas Purification Plant, PetroChina Southwest Oil & Gasfield Company, Chongqing, China
Email: *xiongjuan@petrochina.com.cn

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Abstract

With the continuous expansion of natural gas pipeline networks, operational experience identifies third-party damage as the leading external cause of pipeline failure. To identify initial risks and clarify the accident causal chain, a Fault Tree Analysis (FTA) model for third-party damage is constructed, encompassing 22 basic events that systematically represent three risk categories: unsafe human acts, unsafe equipment conditions, and management deficiencies. Boolean algebra simplification yields 19 minimal cut sets and 2 minimal path sets. Structural importance ranking identifies 12 first-order cut sets as single-point failure risks requiring "zero tolerance" control; 6 second-order cut set events require paired failures to constitute risk, suggesting a dual-control mechanism integrating inspection and rectification; 4 fourth-order cut set events require quadruple factor combination to trigger accidents, manageable through integrated preventive measures. Based on these analytical results, a three-tier progressive prevention and control strategy is proposed—event logic bottlenecks, work management modes, and on-site treatment measures—providing scientific basis for precise safety monitoring, differentiated resource allocation, and emergency planning. This approach facilitates systematic reduction of third-party damage risks in natural gas pipelines, preventing catastrophic accidents.

Keywords

Natural Gas Pipeline, FTA (Fault Tree Analysis) Method, Third-Party Damage, Minimal Cut Set, Minimal Path Set, Risk Prevention and Control

1. Introduction

Driven by the "Dual Carbon" goals, China's energy transition has accelerated, with natural gas, as a clean and low-carbon transitional energy source, experiencing a continuous expansion in its utilization scale. Serving as critical infrastructure to ensure national energy security and connect resources with markets, natural gas pipelines have seen significant development achievements in recent years. According to data from the National Bureau of Statistics, by the end of 2024, China had constructed 128,000 kilometers of long-distance natural gas pipelines, with an annual transmission capacity exceeding 400 billion cubic meters [1]. This has formed a nationwide, integrated network spanning east to west and north to south, covering the entire country and extending international connections, providing robust support for socioeconomic development and the realization of the "Dual Carbon" targets.

However, as the natural gas pipeline network rapidly expands, secondary disasters caused by pipeline safety incidents have become increasingly prominent. Among these, third-party damage has emerged as the primary external factor leading to pipeline failures [2]. The National Gas Accident Analysis Report (Q3 2024) indicates that, among 51 pipeline accidents with identified causes, 42 were attributed to third-party damage, accounting for 82.4%—significantly higher than other factors such as corrosion and material defects [3]. Frequent incidents involving mechanical excavation and illegal encroachment not only result in substantial economic losses and casualties but also threaten public safety and social stability, posing a significant constraint on the high-quality development of the natural gas industry.

To prevent catastrophic consequences caused by third-party damage, it is essential to conduct in-depth analysis of the initial causes of accidents, clarify the contribution of various factors, and prioritize risk control measures for targeted interventions. In systematic risk analysis, the FTA method offers advantages such as simplicity, flexibility, and visual clarity. Even in the absence of probabilistic data, it enables quantitative assessment of the importance of basic events through topological structures, providing a scientific basis for risk classification and resource allocation [4]. Therefore, this study employs the FTA method to systematically identify risks associated with third-party damage to natural gas pipelines, trace the initial factors that may lead to accidents, and reveal inherent or potential risks by illustrating logical relationships among these factors. This approach aids in identifying vulnerabilities and provides decision support for natural gas pipeline enterprises in developing differentiated, cost-effective, and efficient monitoring strategies, thereby helping to reduce the occurrence and severity of both major and minor accidents.

2. Construction of a Fault Tree for Third-Party Damage to Natural Gas Pipelines

2.1. Data Preprocessing

Risk assessment methods for third-party damage to natural gas pipelines are primarily divided into qualitative and quantitative categories. Qualitative risk assessment mainly relies on expert experience, analyzing accident causes and consequences and classifying risk levels based on their understanding of incident patterns. While straightforward, this approach is relatively subjective. Quantitative risk assessment, in contrast, uses mathematical models to analyze statistical data based on failure databases and pipeline material mechanical parameters, yielding more objective results but requiring higher data completeness [5]. Currently, China's in-service natural gas pipeline network is extensive, with complex laying environments, and samples of third-party damage incidents are relatively sparse, making a fully quantitative analysis challenging. Therefore, semi-quantitative methods—such as safety checklists, preliminary hazard analysis, fault tree analysis (FTA), and event tree analysis—are commonly adopted in practice to balance evaluation efficiency with economic costs. Accordingly, based on the current state of China's natural gas pipeline infrastructure, specific national conditions, and data availability, this study employs the FTA method to systematically identify the root causes of third-party damage and clarify key safety monitoring points, thereby providing targeted support for risk prevention and control.

2.2. Fault Tree for Third-Party Damage

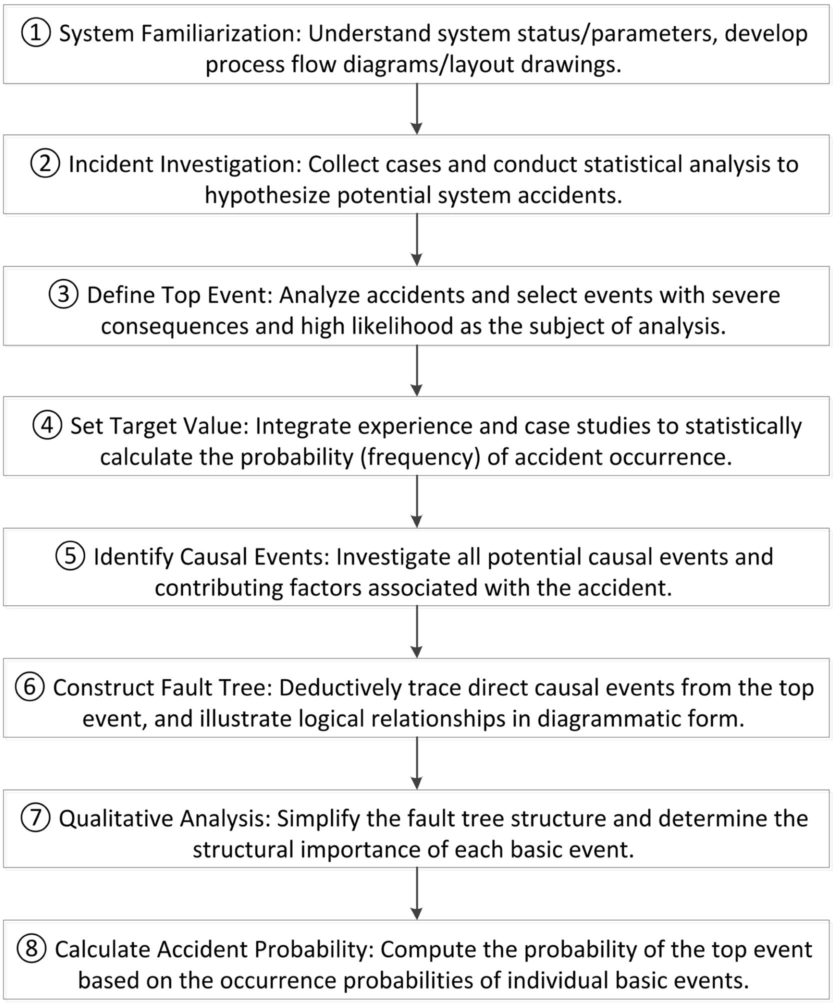
2.2.1. FTA Procedure

Fault Tree Analysis (FTA), first proposed by H. A. Watson at Bell Telephone Laboratories in 1961, is a logical diagramming method that works deductively from system failure to underlying causes [6]. This method starts with the "top event"—the most undesirable system accident—and traces all direct and indirect factors that may lead to it, using standard logic gates (such as AND and OR gates) to describe causal relationships, until reaching "basic events" that require no further decomposition. The entire analysis follows a progressive sequence of "preparation → investigation → core identification → analysis → calculation," with each step providing the foundation for subsequent stages. The basic procedure is illustrated in **Figure 1**.

2.2.2. Fault Tree Construction

Using "Third-party damage to natural gas pipelines" as the top event, the immediate consequence chain of "pipeline strength failure → natural gas leakage → fire and explosion" is set as the secondary top event. A layered analysis is then conducted across three dimensions: pipeline integrity, personnel behavior, and management mechanisms. The constructed fault tree for third-party damage to natural gas pipelines is shown in **Figure 2**. The top event in this fault tree analysis—"third-party damage to natural gas pipelines"—is defined as the full accident chain wherein external human activities (excluding the operator's own maintenance) directly or indirectly cause physical damage to the pipeline, leading to gas leakage and potentially culminating in fire or explosion.

The fault tree comprises 22 basic events, as detailed in **Table 1**. To ensure comprehensiveness and scientific validity, the selection of these events was determined based on the following four criteria: 1) Statistical analysis of historical accident cases to extract high-frequency causative factors—for instance, events X1, X5, and X11 were identified as direct causes in multiple typical vases including the Qingdao "11·22" oil pipeline leakage and explosion accident and the San Bruno pipeline explosion in the United States; 2) Regulatory and standard requirements from documents such as the Petroleum and Natural Gas Pipeline Protection Law, Safety Management Regulations for Hazardous Chemical Pipeline Transportation, GB 50251 Code for Design of Gas Transmission Pipeline Engineering, and SY/T 6620 Specifications for Inspection and Maintenance of Oil and Gas Pipelines—events X6, X7, and X15 directly correspond to mandatory management requirements in these regulations; 3) Field investigations at multiple pipeline operating enterprises, where events including X4, X14, and X20 emerged from expert assessments of current technological equipment shortcomings and management blind spots; 4) Reference to similar fault tree studies in the literature, where events X2, X3, and X13 have been repeatedly validated as significant basic events in risk analysis models published in core journals, demonstrating high universality and representativeness.



① System Familiarization: Understand system status/parameters, develop process flow diagrams/layout drawings.

② Incident Investigation: Collect cases and conduct statistical analysis to hypothesize potential system accidents.

③ Define Top Event: Analyze accidents and select events with severe consequences and high likelihood as the subject of analysis.

④ Set Target Value: Integrate experience and case studies to statistically calculate the probability (frequency) of accident occurrence.

⑤ Identify Causal Events: Investigate all potential causal events and contributing factors associated with the accident.

⑥ Construct Fault Tree: Deductively trace direct causal events from the top event, and illustrate logical relationships in diagrammatic form.

⑦ Qualitative Analysis: Simplify the fault tree structure and determine the structural importance of each basic event.

⑧ Calculate Accident Probability: Compute the probability of the top event based on the occurrence probabilities of individual basic events.

Figure 1. FTA development procedure.

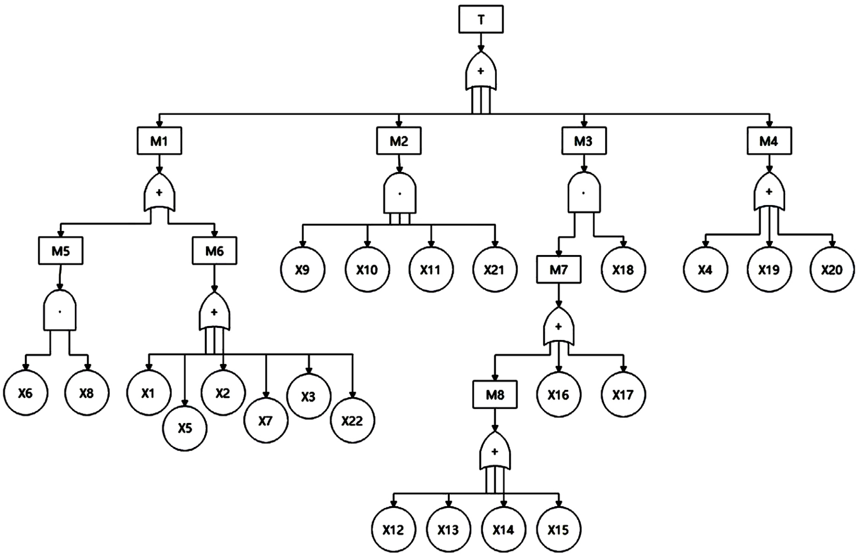


Figure 2. Fault tree for third-party damage to natural gas pipelines.

Table 1. List of basic events corresponding to the fault tree.

Code	Event Description	Code	Event Description
T	Third-Party Damage to Natural Gas Pipelines	M1	External Construction Damage
M2	Vehicle Impact Damage	M3	Unauthorized Encroachment
M4	Pipeline Damage Failure	M5	Accidental Damage
M6	Unauthorized Construction	M7	Delayed Detection and Response
M8	Routine Patrol Failure	X1	Mechanical Excavation Without Avoidance Above Pipeline
X2	Construction Personnel Lacking Pipeline Protection Skills	X3	Failure of Construction Machinery Positioning/Anti-Tip Devices
X4	Missing Accurate As-Built Pipeline Documentation on Site	X5	Reckless Construction
X6	Unauthorized Commencement Without Administrative Approval	X7	Failure to Implement Excavation Permit System
X8	Lack of On-site Government/Supervisory Oversight	X9	Increased Traffic Load After Road Modification
X10	Insufficient Pipeline Cover Depth Below Design Value	X11	Frequent Heavy Vehicle Traffic Over Pipeline Route
X12	Patrol Staff Failing to Perform Duties at Required Frequency	X13	Inadequate Hazard Identification Skills Among Patrol Personnel
X14	Absence of GPS Patrol Devices or Fiber Optic Monitoring Equipment	X15	No Established Daily Pipeline Inspection System
X16	No Established Procedure for Clearing Unauthorized Encroachments	X17	Insufficient Enforcement Against Existing Encroachments
X18	Long-term Storage of Overweight Materials Above Pipeline	X19	Buried Pipeline Sections Lacking Warning Tape/Tracer Wire
X20	Third-party Construction Data Not Integrated into Pipeline Company GIS Platform	X21	Missing or Insufficiently Buried Surface Marker Posts
X22	Poor Visibility During Nighttime/Adverse Weather Construction		

3. Fault Tree Analysis of Third-Party Damage to Natural Gas Pipelines

3.1. Basic Analysis

Based on the structural characteristics of the fault tree shown in Figure 2, the following analytical consensus is summarized:

1) Structural importance decreases as the path length increases. The shorter the path from the top event to a basic event, the higher the weight of that event in the structural importance ranking. Such events do not depend on complex preconditions; once they occur, they can directly propagate risk to higher system levels and should therefore be prioritized for monitoring. For instance, events X1 and X5 are located directly at the bottom of the M1 branch with shorter paths, exerting a more direct impact on the top event.

2) Logic gates control or amplify risk propagation. Input events connected by an AND gate are mutually necessary conditions, forming redundant barriers that reduce top event probability. For instance, M2 employs an AND gate requiring X9, X10, X11, and X21 to occur simultaneously for the intermediate event to hold, reflecting multi-factor coupling control. Conversely, input events connected by an OR gate are mutually sufficient conditions—any single path can trigger the output, producing a risk amplification effect. For example, M6 connects X1, X2, X3, X5, X7, and X22 via an OR gate—the occurrence of any single event can lead to construction damage. Consequently, branches with higher OR gate density typically correspond to lower-order minimal cut sets, making the top event probability more sensitive to changes in basic events.

3) The probability of intermediate events is determined by combinations of basic events, and they themselves possess no independent physical meaning. Intermediate events such as M1 through M8 are merely products of logical abstraction, not actual risk factors. All control measures must be implemented at the level of the 22 basic events, reducing system failure frequency by cutting off minimal cut sets.

4) It should be noted that the fault tree analysis conducted in this section focuses on qualitative structural analysis, aiming to reveal the logical relationships among basic events and their contribution paths to the top event, rather than performing probability-based quantitative calculations.

3.2. Determination of Minimal Cut Sets

A cut set refers to a collection of basic events whose occurrence can lead to the top event T. If no proper subset of a cut set can itself constitute a cut set, the set is defined as a Minimal Cut Set (MCS). The quantity and order (*i.e.*, the number of basic events contained) of MCSs jointly determine the risk level of the system. A greater number of MCSs indicates more potential failure paths, while higher-order cut sets exhibit exponentially decreasing sensitivity to changes in the probability of basic events. Consequently, lower-order cut sets—particularly first-order and second-order ones—constitute critical points for risk prevention and control.

Common methods for solving MCSs include Boolean algebra, the determinant method, and matrix approaches. Any fault tree can be described by a Boolean function, whose disjunctive normal form is expressed as [7]:

$$f = A_1 + A_2 + \cdots + A_n = \sum_{i=1}^{n} A_i \tag{1}$$

The conjunctive normal form is:

$$f = B_1 \times B_2 \cdots B_n = \prod_{i=1}^{n} B_i \tag{2}$$

where A_i and B_i represent the cut sets and path sets of the fault tree, respectively. If there is no inclusion relationship among the terms within A_i, then the disjunctive normal form is the simplest, and A_i constitutes the minimal cut sets of the structural function f.

Based on the method described above, Boolean simplification was applied to the fault tree for third-party damage to natural gas pipelines shown in **Figure 1**. A total of 19 minimal cut sets were derived, as summarized in **Table 2**. The analysis reveals that the system possesses 19 distinct failure modes capable of leading to the top event. Among these, the minimal cut sets {X5} (Reckless Construction) and {X18} (Long-term Storage of Overweight Materials Above Pipeline) represent single-point failure events with the highest structural importance and should be prioritized as key targets within the risk prevention and control framework.

Table 2. Minimal cut sets for third-party damage incidents in natural gas pipelines.

No.	Order	Minimal Cut Set	No.	Order	Minimal Cut Set
1	1	{X1}	2	1	{X2}
3	1	{X3}	4	1	{X4}
5	1	{X5}	6	1	{X6}
7	1	{X7}	8	1	{X8}
9	1	{X18}	10	1	{X19}
11	1	{X20}	12	1	{X22}
13	2	{X12, X18}	14	2	{X13, X18}
15	2	{X14, X18}	16	2	{X15, X18}
17	2	{X16, X18}	17	2	{X17, X18}
19	4	{X9, X10, X11, X21}			

3.3. Determination of Minimal Path Sets

In a fault tree, a set of basic events whose non-occurrence guarantees the prevention of the top event is termed a path set. If the set cannot be further reduced, it is defined as a minimal path set (MPS). Each MPS represents an independent pathway for preventing the top event. A larger number of MPSs indicates greater flexibility in selecting strategies to block accidents. This study employs the dual tree method to obtain MPSs. First, the fault tree is transformed into its dual success tree by interchanging all logic gates (OR gates become AND gates, AND gates become OR gates) and complementing all events. The minimal cut sets of the success tree then correspond to the MPSs of the original fault tree. Each MPS identifies a combination of basic events that must all be prevented to avoid the top event, representing the minimal necessary configuration for accident prevention.

The analysis shows that the fault tree for third-party damage to natural gas pipelines contains two MPSs, as presented in **Table 3**. Both sets are of high order, indicating low system redundancy and underscoring the need for simultaneous control across multiple elements to effectively prevent accidents.

Table 3. Minimal path sets for third-party damage incidents in natural gas pipelines.

No.	Order	Minimal Path Set
1	21	{X1, X2, X3, X4, X5, X6, X7, X8, X9, X10, X11, X12, X13, X14, X15, X16, X17, X19, X20, X21, X22}
2	16	{X1, X2, X3, X4, X5, X6, X7, X8, X9, X10, X11, X18, X19, X20, X21, X22}

3.4. Structural Importance Ranking

In the absence of occurrence probability data for basic events, the structural importance coefficient $I_S(i)$ can be used to quantitatively evaluate the influence of each basic event on the top event based on the system's topological structure [8]. This provides a logical-structure-based ranking for risk classification, resource allocation, and prevention strategy development. By mapping the 22 basic events to their corresponding cut sets and calculating the structural importance, the ranking of the basic events for third-party damage to natural gas pipelines is obtained as follows:

X1 = X4 = X5 = X6 = X8 = X18 = X22 > X12 = X13 = X14 = X15 = X16 = X17 > X9 = X10 = X11 = X21 > X2, X3, X7, X19, X20

1) X1, X2, X3, X4, X5, X6, X7, X8, X18, X19, X20, and X22 are first-order minimal cut sets—any single event can independently trigger the top event, constituting "single-point failure" risks. With the highest structural importance, these events require "zero tolerance" control. Priority deployment of mandatory protective measures is recommended, including intelligent excavation alarm systems, construction permit linkage mechanisms, removal of illegal encroachments, enhanced warning signage, and meteorological early warning systems.

2) X12, X13, X14, X15, X16, and X17 are second-order minimal cut sets. These events cannot independently trigger accidents, but as components of second-order cut sets, their structural importance is secondary to first-order events. It is recommended to establish a closed-loop "inspection-rectification" management mechanism to ensure these two types of events do not fail simultaneously, thereby effectively mitigating risks.

3) X9, X10, X11, and X21 are fourth-order minimal cut sets—requiring all four factors to pose a threat. Structurally, these events contribute to the top event only

through multi-factor coupling; individually they pose no threat, thus their importance is relatively lowest. Combined engineering measures such as "protective casing installation during road reconstruction + load limit management + densified marker posts" are recommended to achieve one-time risk elimination.

4. Identification of Key Prevention and Control Priorities for Third-Party Damage to Natural Gas Pipelines

Based on the fault tree analysis results for third-party damage to natural gas pipelines, and by integrating the structural importance of basic events with the characteristics of minimal cut sets and path sets, this paper proposes the establishment of a three-tiered prevention and control framework structured around "event logic bottlenecks—work management models—on-site response measures." This approach ensures that critical resources are precisely allocated to the basic events exerting the greatest influence on system risk, thereby achieving effective risk reduction.

1) The first level involves "zero tolerance" control for first-order cut-set events. In terms of work management mode, the "Law of the People's Republic of China on the Protection of Oil and Natural Gas Pipelines" is strictly enforced, with pipeline safety protection plans being made a prerequisite for construction permit review. An administrative law enforcement linkage mechanism is established, and behaviors such as concealment and forced construction are severely punished according to the law. The responsibility for inspection is assigned to individuals, sections, and construction sites to ensure that the system is implemented without any loopholes. In terms of on-site disposal measures, intelligent sensing technologies such as fiber optic vibration monitoring, Beidou positioning, and video AI recognition are introduced, and manual and intelligent dual-track inspections are carried out within a 5-kilometer range of high-consequence areas. Ground warning signs are improved to ensure that warning tapes, tracer lines, and marker posts are set up in accordance with specifications. A construction control plan under adverse weather conditions is established to eliminate additional risks caused by poor visibility.

2) A dual control mechanism for second-order cut-set-related events at the second level. In terms of work management mode, a closed-loop management mechanism of "inspection-rectification" is established to ensure that inspection performance, hazard identification, technical means, and system implementation work together with occupation control; a dynamic ledger for occupation hazards is established, forming a closed-loop process of "discovery-filing-removal-closure"; pipeline units such as communication, electricity, and water supply and drainage are jointly established to establish a cross-industry pipeline protection linkage platform, achieving information exchange, measure linkage, and shared responsibility. In terms of on-site disposal measures, the discovered occupation points are to be removed within a specified time limit, and special rectification is carried out in historical occupation concentrated areas; the "pipeline map" is promoted and applied, with relevant data synchronized and collected into the pipeline com-

prehensive management information system. Before the location of pipelines is confirmed, no excavation work is allowed, eliminating excavation accidents caused by missing information or poor communication from the source.

3) The third level involves combined governance for fourth-order cut-set events. In terms of work management mode, construction is strictly carried out according to the design drawings to ensure that the burial depth of pipelines meets standards, and that the as-built drawings are fully consistent with the actual situation on site. A consultation mechanism for road reconstruction projects is established to grasp traffic planning change information in advance and predict load change risks. In terms of on-site disposal measures, engineering measures such as installing steel casings or load limit plates are taken for sections with insufficient burial depth to fundamentally block the damage path caused by traffic loads. Ground signs and load limit signs are improved, and height and load limit facilities are set up at key road sections. Special assessments are conducted for newly added heavy vehicle traffic routes after road reconstruction, and pipe positions are adjusted or protective structures are added when necessary.

5. Conclusions

1) A fault tree model for third-party damage to natural gas pipelines was constructed using FTA methodology, encompassing 22 basic events that systematically identify three risk source categories-unsafe human acts, unsafe equipment conditions, and management deficiencies-along with their logical propagation paths. Boolean algebra simplification yielded 19 minimal cut sets and 2 minimal path sets, providing a quantitative foundation for risk analysis.

2) Based on minimal cut set order characteristics, the 22 basic events were classified into three risk tiers: Tier 1 comprises 12 first-order cut set events constituting single-point failure risks requiring “zero tolerance” control; Tier 2 comprises 6 second-order cut set associated events requiring paired failures to constitute risk, suggesting a dual “inspection-rectification” control mechanism; Tier 3 comprises 4 fourth-order cut set events requiring multi-factor combination to trigger accidents, manageable through integrated preventive measures. This tiered classification enables clear mapping from FTA results to differentiated prevention strategies.

3) Based on risk tier classification, a three-tier progressive prevention system-“event logic bottlenecks-work management modes-on-site treatment measures”-was proposed. This system formulates differentiated management strategies and technical measures targeting the logical characteristics of each tier, guiding pipeline enterprises to precisely allocate resources and systematically prevent pipeline failures, providing scientific basis and practical pathways for systematic reduction of third-party damage risks to natural gas pipelines.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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