

Article

Systemic Control Failures on Offshore Installations: A STAMP-Based Analysis of the Penglai 19-3 Accidents and Comparison with Deepwater Horizon

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Abstract

The 2011 Penglai (PL) 19-3 oil spills in China's Bohai Sea, resulting from two subsea accidents within a month and contaminating 6200 km², represent the nation's worst offshore pollution disaster. Yet, systemic analysis of lessons learned remains notably limited. The April 2021 blowout and fire at the same field, resulting in three fatalities, highlights the continuing relevance of the PL 19-3 case and the need to re-examine the 2011 accidents in depth. This study therefore focuses on the 2011 case as a systematically investigated instance to identify control failures that may explain recurring major risks at the field. This study develops a Systems-Theoretic Accident Model and Processes (STAMP)-based approach to systematically deconstruct the PL 19-3 accidents and benchmark their root causes against those of the 2010 Deepwater Horizon (DWH) disaster. Blowouts and well control incidents in the Norwegian sector are also mentioned to illustrate the well control hazard. The analysis identifies systemic control failures at the regulatory, organizational, and operational levels, revealing that the majority of human and organizational root causes identified are common to both accidents. Based on these findings, an integrated reform framework is proposed, comprising co-regulation models adapted from Norwegian practices, a national major hazard risk indicator system, and mandatory barrier management. This study contributes a theoretically grounded accident analysis and provides empirically informed policy recommendations for controlling major hazard risks in offshore petroleum activities.

Keywords: major accident; STAMP; root cause analysis; offshore safety; risk governance; Penglai 19-3



Academic Editor: Atilla Incecik

Received: 4 June 2026

Revised: 25 June 2026

Accepted: 26 June 2026

Published: 30 June 2026

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1. Introduction

1.1. Background

The Penglai (PL) 19-3 oil field, the largest offshore petroleum field ever discovered in China, experienced the nation's worst offshore pollution disaster in 2011. Two successive subsea accidents within a month contaminated approximately 6200 km² of the Bohai Sea [1]. The timeline of the PL 19-3 oil spills is presented in Figure 1, and the contaminated areas are shown in Figure 2.

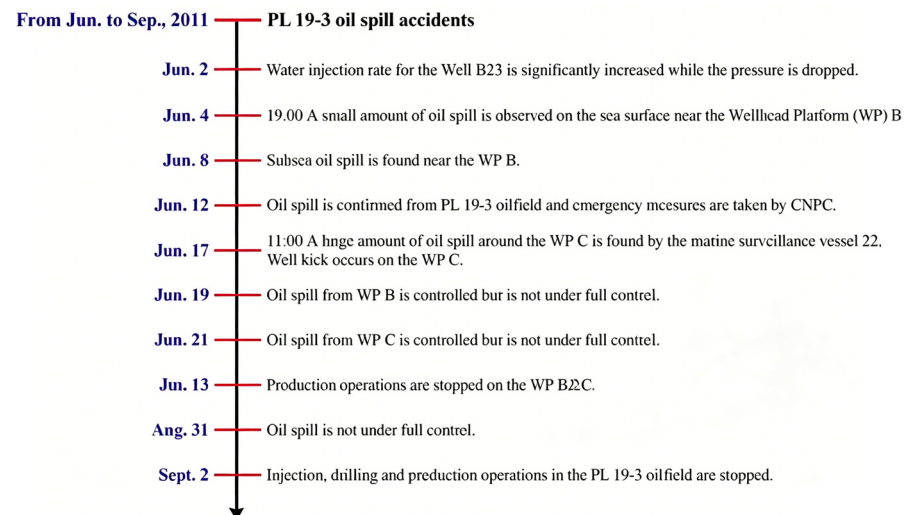


Figure 1. Timeline of the PL 19-3 oil spill accidents.

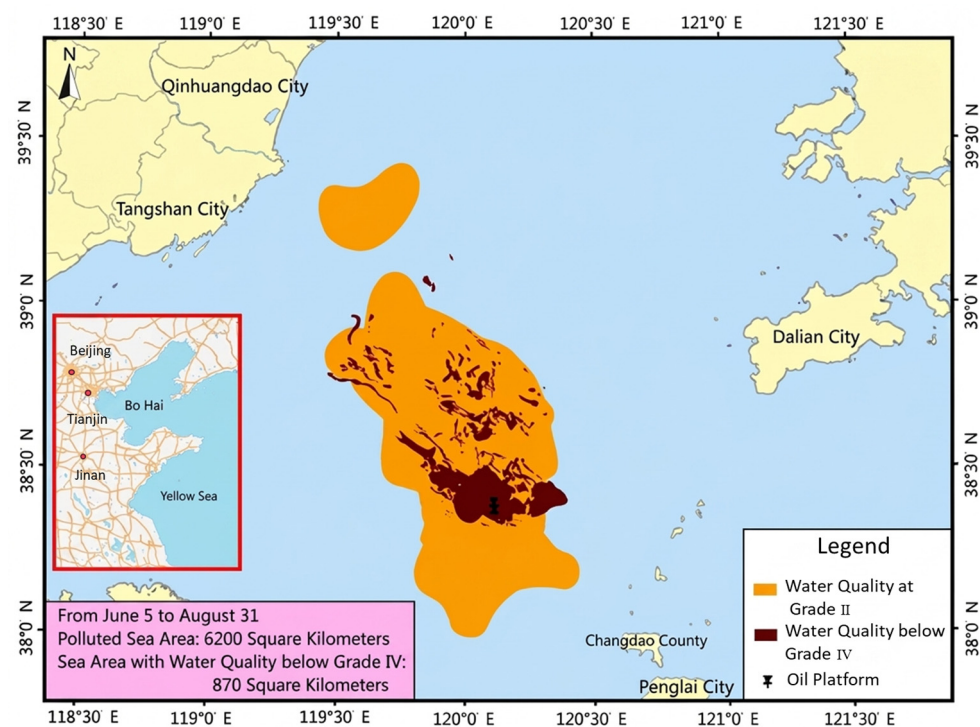


Figure 2. Polluted marine areas resulting from the PL 19-3 oil spill accidents. Note: China's seawater quality is classified into Grades I–IV according to the national standard GB 3097-1997 [2], with Grade I being the most stringent (suitable for fisheries and mariculture) and Grade IV being the least stringent (suitable for port and industrial waters).

The accidents involved two independent events. In the B-Event (Wellhead Platform B on 4 June 2011), water injection into Well B23 deviated from the approved Overall Development Plan (ODP) by using commingled injection without separate layer control. When the injection rate increased while pressure simultaneously decreased, a recognized precursor of formation fracturing, operations were not suspended for further investigation. As a result, Fault No. 502 was eventually reactivated, allowing crude oil to migrate through the fault and seep onto the seabed. In the C-Event (Wellhead Platform C on 17 June 2011), the cuttings reinjection layer was repeatedly adjusted upward without authorization, creating an overpressured zone. When Well C20 drilled into this zone, a kick occurred. Essential emergency measures, such as setting intermediate casing, were not

implemented, and the surface casing depth failed to meet environmental impact assessment (EIA) requirements [1], leading to subsurface leakage. A total of approximately 723 barrels of oil and 2620 barrels of mineral oil-based mud (MOBM) seeped into the Bohai Sea [3]. The Bohai Sea is characterized by its semi-enclosed nature and weak self-purification capacity. Tar balls and polycyclic aromatic hydrocarbons have continued to be detected in the Bohai Sea more than a decade after the spill [4–6].

Critically, on 5 April 2021, a blowout and fire occurred on Platform V at the same PL 19-3 oil field, resulting in three fatalities. To date, no official investigation report has been released, leaving the systemic causes of this recent accident largely unknown. This recurrence, a decade after the 2011 spills, highlights the continued relevance of the PL 19-3 case and raises the question of whether the systemic deficiencies identified in the 2011 investigation persist, and whether critical lessons have been learned.

If the scope is extended to worldwide drilling operations, several well-known blowouts have occurred: for instance, the Montara blowout in 2009 [7] and the Deepwater Horizon (DWH) blowout in 2010 [8]. By contrast, the last blowout in the Norwegian sector was the Snorre A subsea gas blowout in 2004 [9], which was stopped after some 15 h without fatalities. There have been several serious well control incidents in the Norwegian sector during the last 20 years: for instance, the most recent Deepsea Bollsta well control incident in 2025 [10]. Three serious well control incidents have occurred in 2010, 2016 and 2025, but the blowout preventer (BOP) closed in these incidents and loss of control was averted.

1.2. Relevant Research Works and Motivation

A literature review of studies related to PL 19-3 oil spills has been performed. These studies can be grouped into three main categories, covering safety management, consequence assessment and accident liability.

Chen and Liu [11] summarized their own revelations on PL 19-3 oil spills, emphasizing the evolution of the accident, the urgent demand for advanced offshore oil-spill treatment technologies, and lessons from international oilfield cooperation. Wu et al. [12] examined the accident from the perspective of ocean management and highlighted the importance of timely intervention, improved marine environmental legislation, and effective compensation mechanisms. Similarly, Liu et al. [13] discussed regulatory responsibilities, partner selection, and emergency-response capabilities within China's offshore petroleum cooperation framework. He et al. [14] presented and discussed the lessons learned from the perspective of emergency responses, identifying deficiencies in the emergency management system, information communication, and inter-agency coordination. On this basis, they recommended strengthening national emergency planning, improving monitoring and communication mechanisms, and establishing an independent emergency-response administration. Likewise, Li [15] put forward principles and countermeasures for improving offshore oil-spill emergency response mechanisms, including prevention planning, early-warning systems, institutional coordination, resource allocation, and emergency rescue capabilities. Yue et al. [16] further emphasized the need to strengthen environmental protection and adopt a more cautious approach to resource development in environmentally sensitive areas of the Bohai Sea.

In parallel, a number of studies investigated the environmental and economic consequences of the accident. Wei et al. [17] developed an assessment model of oil-spill damage in combination with historical databases and satellite remote-sensing information, while Yang et al. [18] conducted a long-term hindcast simulation and estimated a contaminated area of approximately 7800 km² and 160 km of polluted coastline (the full simulated contamination extent including seawater and sediment, compared with the SOA-reported 6200

km² confirmed contaminated sea area). More recently, Qin et al. [19] demonstrated that earlier cleanup intervention could have substantially reduced the extent of contamination, with a one-day improvement in response time reducing the final polluted area by nearly 48%. Wang et al. [20] developed a monitoring program to assess the environmental impact and restoration of the Bohai Sea, concluding that chronic contamination remained problematic several years after the spill. Oil-spill trajectory models developed by Liu et al. [21] and Li et al. [22] successfully reproduced the observed transport pathways and identified potentially affected sea areas. From an economic perspective, Pan et al. [23] estimated the total losses to fisheries and aquaculture at approximately CNY 12.56 billion.

The deficiencies of legal liabilities in China's marine environmental protection law were revealed by the PL 19-3 oil spill accidents. Hence, some researchers [24–27] examined the PL 19-3 oil spill accidents extensively from the perspectives of civil liability, administrative liability and criminal liability, so as to construct an effective responsibility assigning mechanism. These research works are not in the domain of engineering science, but in the category of legal system. Nonetheless, it should be noted that assigning blame is not necessary to learn from past major accidents and prevent the recurrence of similar accidents. Leveson [28,29] argues that blame is the enemy of safety and focus should not be placed on who or what to blame.

Although the PL 19-3 accidents generated substantial public concern in China, systemic academic analysis remains limited. Existing studies exhibit three critical shortcomings. First, most research is descriptive rather than analytical, lacking structured theoretical frameworks for accident investigation [11,12]. Second, studies remain predominantly China-centric, failing to engage with international advances in offshore risk governance, human and organizational error modeling, or comparative petroleum safety systems [28,30]. Third, existing recommendations are largely reactive, emphasizing emergency response improvements rather than proactive major accident prevention [14,15].

In our previous work, Zhen et al. [31] proposed a conceptual framework of major-accident risk indicators for offshore petroleum activities. However, the underlying organizational mechanisms represented by these indicators have not been systematically validated through empirical accident investigations. In particular, the role of feedback deficiencies as a potential systemic contributor to major offshore accidents remains insufficiently understood.

The 2021 blowout provides additional motivation to re-examine the 2011 PL 19-3 accidents, but its causes cannot be assessed here due to the lack of an official investigation report. To address these gaps, the present study develops the Systems-Theoretic Accident Model and Processes (STAMP) framework, a structured methodology for analyzing complex socio-technical systems. Specifically, the study aims to systematically investigate the PL 19-3 accidents, to compare findings with the DWH disaster, and to develop theoretically grounded and practically implementable recommendations for controlling major accident risks in Chinese offshore petroleum activities.

1.3. Structure of the Paper

Section 2 describes the STAMP methodology and data sources used in this study. Section 3 presents the STAMP-based analysis of the PL 19-3 accidents, including the safety control structure, unsafe control actions (UCAs), and control deficiencies. Section 4 compares the root causes between PL 19-3 and DWH, and discusses lessons to be learned from the PL 19-3 oil spill. Conclusions and recommendations are presented in Section 5.

2. Methodology

2.1. The STAMP Framework

Traditional accident analysis methods, such as fault tree analysis, event tree analysis, and the Swiss cheese model, are fundamentally linear and assume that accidents result from a chain of component failures or human errors [32]. These approaches treat technical, human, and organizational factors as independent elements, thereby failing to capture the nonlinear interactions, feedback loops, and emergent properties inherent in complex socio-technical systems such as offshore well control systems. Consequently, they often attribute accidents to proximate causes while overlooking systemic control deficiencies embedded in regulatory, organizational, and operational levels.

The STAMP framework addresses these limitations by reconceptualizing safety as a control problem rather than a reliability problem. Accidents are understood to result from inadequate enforcement of safety constraints across hierarchical control structures, including defective control actions, insufficient feedback, and flawed process models [28]. This systemic perspective is particularly suitable for analyzing major offshore accidents, which typically involve multi-level interactions, long latency periods, and complex human–organizational–technical couplings. In the present study, STAMP serves as the underlying theoretical foundation, while System-Theoretic Process Analysis (STPA) is employed as the analytical procedure to identify control deficiencies and feedback failures within the safety control structure.

STAMP rests on three constructs: safety constraints, hierarchical control structures, and process models [32]. Safety constraints define the conditions necessary to prevent hazards. The hierarchical control structure imposes constraints downward and receives feedback upward via control and communication channels. Process models are internal representations held by each controller and should accurately reflect the actual system state because mismatches lead to flawed control actions [28]. The interactions among these constructs can be represented by the basic control loop structure illustrated in Figure 3.

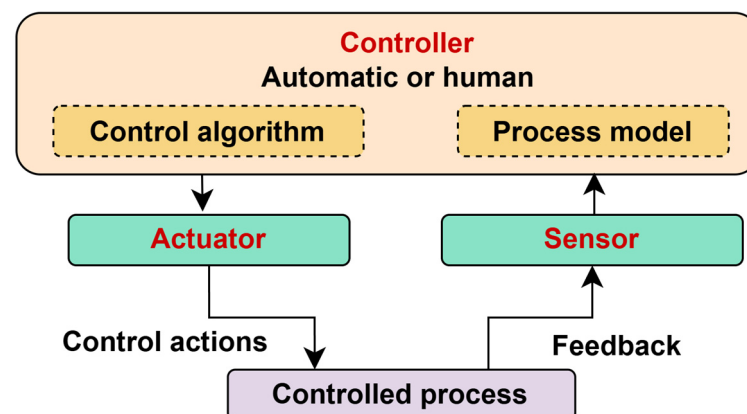


Figure 3. Basic control and feedback loop of STAMP.

2.2. Data Sources

Three primary data sources are analyzed. The State Oceanic Administration (SOA) investigation report [1], the only publicly available official document, is systematically reviewed and supplemented by ConocoPhillips China (COPC) operational reports [3]. A structured literature search was conducted across Web of Science, Scopus, and CNKI databases covering the period from 2011 to 2025, using the keyword combinations: (“Penglai 19-3” OR “PL 19-3”) AND (“oil spill” OR “offshore accident” OR “well control” OR “safety management”). The initial search yielded 38 records after duplicate removal. Following title and abstract screening, 16 records were excluded because they

were not directly relevant to the objectives of this study. The remaining 22 records were retained and cited in the present work. Among these, 15 publications directly related to accident causation, safety management, consequence assessment, or liability analysis were included in the detailed literature review. Thematic grouping of literature identified through systematic search is presented in Table 1. For comparative analysis, the DWH investigation reports [33,34] and subsequent academic analyses [30,35] are also drawn upon.

Table 1. Thematic grouping of literature identified through systemic search.

Theme	Number of Records	Representative References
• Accident investigation and root cause analysis	5	SOA [1]; Chen & Liu [11]; Wu et al. [12]; Liu et al. [13]
• Emergency response and management	4	He et al. [14]; Li [15]; Yue et al. [16]; Qin et al. [19];
• EIA and monitoring	8	Wei et al. [17]; Yang et al. [18]; Wang et al. [20]; Liu et al. [21]; Li et al. [22]; Zhang et al. [5]; Zhang et al. [6]; Wang et al. [4]
• Fishery and economic damage estimation	1	Pan et al. [23]
• Legal liability and regulatory framework	4	Wu [24]; Song [25]; Chu [26]; Zhai [27]
Total	22	

2.3. Analytical Procedure

The analysis began with reconstruction of the accident timeline and identification of critical events and decisions. The STAMP framework was then applied to map the offshore petroleum safety control structure in China, identifying actors, responsibilities, control actions and feedback mechanisms at each hierarchical level. Control failures were identified by tracing backward from the accidents to inadequate constraints, control actions or feedback at each level. A cross-case comparison with the DWH accident was conducted to identify common patterns and China-specific factors. The coding of human and organizational root causes was performed independently by the first and third authors using a taxonomy derived from the STAMP framework. Disagreements were resolved through cross-referencing multiple data sources and discussion to reach consensus, and the second author reviewed the final coding for consistency.

3. STAMP-Based Causal Analysis of the PL 19-3 Accidents

3.1. Identification of Systemic Hazards and Constraints in Offshore Well Control Systems

Following the STAMP framework, accident analysis begins with the identification of the losses and hazards. Safety constraints are then derived to prevent the system from entering or remaining in these hazardous states. For offshore well control systems, the accident process can be viewed as a progressive loss of pressure containment and barrier integrity, ultimately resulting in environmental, economic, and human consequences.

3.1.1. Identification of Systemic Losses and Hazards

The losses considered in this study are defined as follows:

- L1: Loss of human life or injury to personnel.
- L2: Environmental damage to the Bohai Sea ecosystem.
- L3: Economic losses to fisheries, aquaculture, and coastal communities.

Based on the accident evolution process, the following systemic hazards were identified:

- H1 (Kick): Pressure barrier breached—formation fluids enter the wellbore or injection overpressure fractures the formation.
- H2 (Blowout): Hydrocarbons escape from the wellbore or injection zone into the surrounding subsurface formations.
- H3 (Spill): Escaped hydrocarbons migrate via geological faults and discharge onto the seabed.

3.1.2. Identification of Systemic Constraints

To prevent the identified hazards and associated losses, a set of hierarchical safety constraints was established at the regulatory, organizational, and operational levels.

- C1: Regulations must mandate risk reduction to ALARP with independent third-party design verification, rather than relying solely on prescriptive compliance with submitted ODP and EIA documents.
- C2: Regulatory agencies must conduct risk-based audits and independent on-site verification, and maintain a direct feedback channel from the Joint Management Committee (JMC) that is independent of the operator.
- C3: A formal Management of Change (MOC) process must be enforced for all operational or design changes affecting wellbore pressure or barrier integrity, including mandatory cross-team communication, risk assessment, and documented approval.
- C4: Management must establish validated emergency well control procedures for all foreseeable abnormal conditions, supported by scenario-based drills and verified crew competence.
- C5: Wellbore pressure must be maintained within the safe window between pore pressure and fracture pressure at all times and formation integrity must be preserved during all water injection and cuttings reinjection operations.
- C6: The three-tier technical barriers must remain functional and available at all times: (i) mud column and managed pressure drilling (MPD), (ii) BOP, choke, and kill system, and (iii) spill response system.
- C7: Early warning parameters must be continuously monitored with defined alert thresholds and any anomalies must trigger immediate procedural responses without operator discretion.

The relationships among the identified hazards, losses, and safety constraints are summarized in Table 2. The table illustrates how specific constraints are intended to prevent hazardous states from developing into unacceptable losses, thereby forming the foundation of the system safety control structure.

Table 2. Relationships among systemic hazards, losses, and safety constraints of the offshore well control system.

Systemic Hazard	Relevant Losses	Relevant Safety Constraints
H1	L1, L2, L3	C1, C2, C3, C5, C6, C7
H2	L1, L2, L3	C1, C2, C4, C5, C6, C7
H3	L2, L3	C1, C2, C4, C6, C7

3.2. Safety Control Structure of Offshore Well Control Systems

Figure 4 illustrates the hierarchical offshore safety control structure in China based on STAMP. Downward arrows denote control actions and upward arrows denote feedback. Effective well control relies on maintaining hydrostatic pressure and early kick suppression.

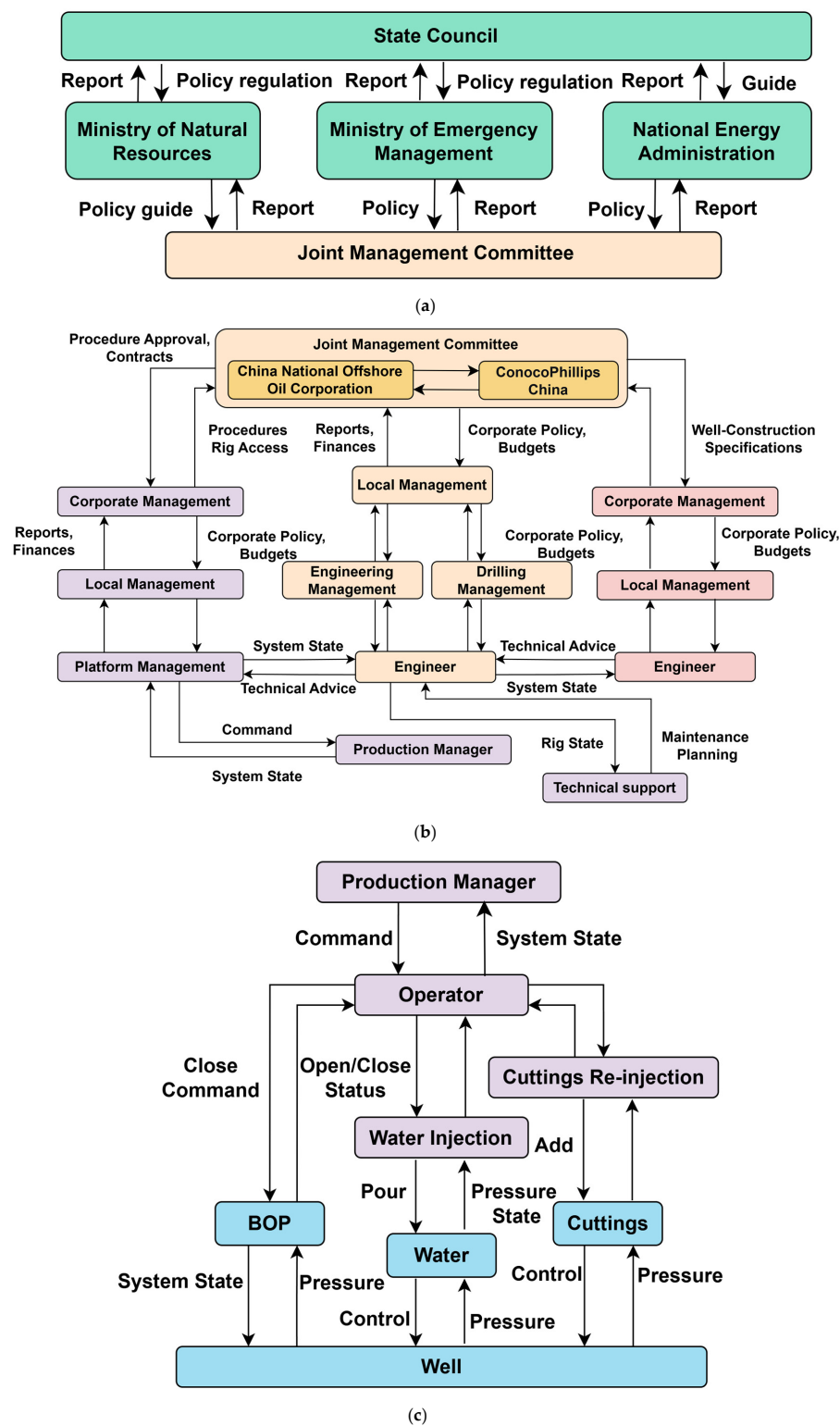


Figure 4. Hierarchical control structure of Chinese offshore petroleum safety based on STAMP analysis: (a) Regulatory Level, (b) Organizational Level, and (c) Operational Level.

Offshore well control systems are modeled as a three-level control system. The regulatory level (top) imposes constraints via legislation, licensing, and enforcement. The organizational level (middle) applies control through management systems. The operational level (bottom) consists of personnel and control systems. Actuators include the choke and kill manifold, choke valves, rotating control device (RCD), and BOP.

At the regulatory level, responsibilities are distributed among the Ministry of Natural Resources (environmental oversight), the Ministry of Emergency Management (safety regulation), and the National Energy Administration (policy and planning). At the organizational level, China National Offshore Oil Corporation (CNOOC) and COPC share governance via a joint committee. At the operational level, personnel evaluate real-time pressure data against risk thresholds and issue control actions.

During production, Permanent Downhole Gauges monitor reservoir pressure and voidage replacement ratio for reservoir stability. Upon identifying pressure depletion, Water Injection Operators initiate high-pressure injection to supplement formation energy. To ensure formation integrity, choke manifolds are adjusted to maintain bottomhole flowing pressure within the safe window between pore pressure and fracture pressure. Meanwhile, cuttings re-injection (CRI) operators perform CRI, disposing of drilling waste into designated formations through a dedicated injection loop, ensuring environmental compliance while maintaining the geomechanical balance of the field.

3.3. Identification of UCAs

In the preceding section, the controller functions, control actions, and controlled process of the offshore well control system were defined and analyzed. As illustrated in Figure 5, this section examines four categories of UCAs. Well control safety requires that both system states and formation pressure remain predictable, observable, and controllable. All system components must be considered in the UCA identification, including controllers, actuators, sensors, and the controlled process. Based on the safety control structure established above, the UCAs associated with the PL 19-3 incident are identified and summarized in Table 3.

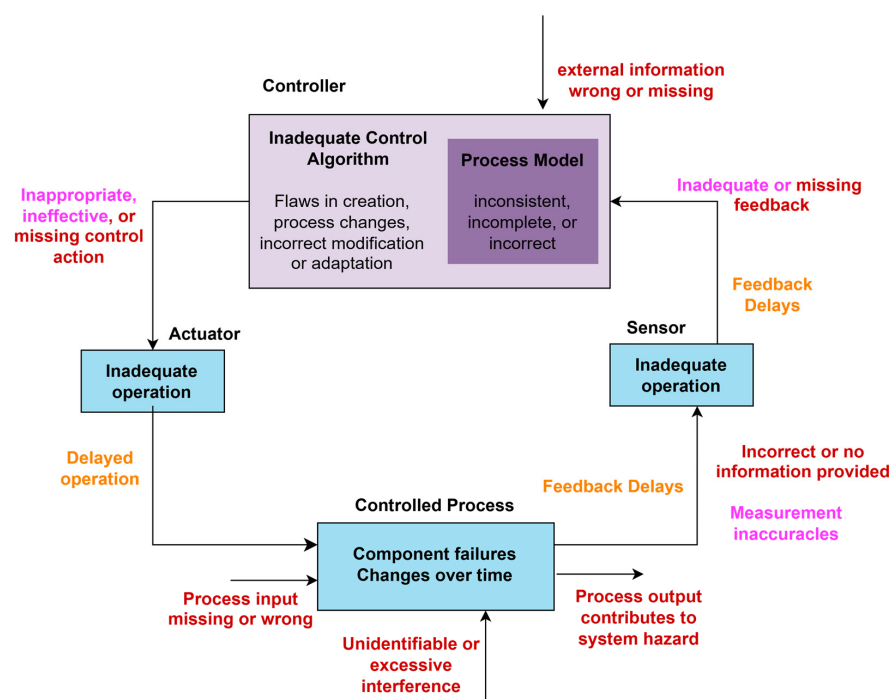


Figure 5. General safety control structure based on STAMP.

Table 3. The UCAs associated with the PL 19-3 incident.

Classification	UCAs	Evidence Source
Failure to provide safety control measures	COPC injected water into Well B23 without implementing stratified control measures [1,13,15].	SOA report, academic literature
	The JMC failed to exercise effective oversight over COPC.	STAMP-based inference
	Operational personnel failed to set intermediate casing after drilling into over-pressured formations in Event C [1,13,15].	SOA report, academic literature
	COPC failed to establish a quantified pressure upper limit for B23 water injection wellhead [1].	SOA report
	COPC failed to conduct numerical analysis to quantify bearing capacity or rupture limit of Fault No. 502 [1].	SOA report
	The adjustment plan for the clastic reinjection layer in Well C25 was not communicated to the drilling team of Well C20 [1].	SOA report
Providing erroneous or unsafe control behaviors	Operational personnel failed to stop injection in Event B when pressure dropped and rate increased [1].	SOA report
	Regulatory agencies conducted mandatory compliance audits rather than risk-based performance audits.	STAMP-based inference
	COPC made unauthorised upward adjustments to C25 reinjection layer near the reservoir [1,13].	SOA report, academic literature
Safety control behaviors are provided too late	The surface casing depth of Well C20 failed to meet the EIA standards [1,13].	SOA report, academic literature
	Regulatory agencies ordered stop injection, stop drilling, stop production approximately three months after first spill (4 June) [1,11,13,14].	SOA report, academic literature
Premature termination of safety control behaviors	Regulatory agencies ceased continuous monitoring and supervision after ODP/EIA approval.	STAMP-based inference

To distinguish between documented evidence and STAMP-based interpretation, each UCA is assigned an evidence source. Sources include explicit documentation from the SOA investigation report, peer-reviewed academic literature, and analytical conclusions inferred from the recorded facts through the STAMP control-theoretic perspective.

3.4. Root Cause Analysis: Control Deficiencies

3.4.1. Inadequate Safety Constraints

In the PL 19-3 accidents, safety constraints were either absent or poorly specified. At the regulatory level, the Chinese petroleum safety framework relies on prescriptive rules that specify how operations must be conducted, rather than functional performance standards that define what level of safety must be achieved. Consequently, no explicit constraint required operators to conduct quantitative risk assessment for geological faults such as Fault 502, or to establish pressure-bearing capacity limits for water injection wells. The lack of risk-based performance standards meant that even when COPC deviated from the approved ODP and EIA requirements, no regulatory constraint was violated in a manner that triggered corrective action.

At the organizational level, the JMC was structurally designed as a co-venturer oversight body, but it lacked a clear safety constraint mandating independent technical review of operational changes. The MOC failure, where the cuttings reinjection layer adjustment in Well C25 was never communicated to the C20 drilling team, directly resulted from the absence of a binding constraint that required formal cross-team notification and risk assessment before design changes.

3.4.2. Insufficient Execution of Control Actions

At the organizational level, COPC's management issued procedures for pressure monitoring and well control, but these were not effectively implemented. In the B-Event, despite recognizing the connection between Fault 502 and multiple oil layers, management did not execute the control action of requiring numerical analysis or installing upper safety limits for injection wellhead pressure. The control command "monitor injection pressure" was executed only as routine data logging, without real-time alert thresholds or automatic shut-in triggers.

At the operational level, crews failed to execute critical control actions when precursors appeared. During the B-Event, when water injection rate increased sharply while pressure dropped, a classic signature of formation fracture, the required control action was to stop injection and investigate. Instead, operations continued. During the C-Event, when overpressured layers were encountered, the prescribed emergency measures (e.g., setting intermediate casing) were not executed. These execution failures reflect inadequate training, ambiguous responsibility assignment, and a safety culture that implicitly prioritized production over hazard mitigation.

3.4.3. Defective or Missing Feedback Mechanisms

At the regulatory level, feedback relied almost exclusively on operator self-reporting. The SOA did not conduct independent on-site verification of compliance with ODP or EIA conditions. As a result, deviations such as the B23 water injection without separate layer control and the C20 surface casing depth violation were never fed back into the regulatory oversight loop. This one-way, trust-based feedback structure made the regulator effectively blind to accumulating risks.

At the organizational level, the JMC was supposed to provide a feedback channel from the COPC to the CNOOC. However, the committee lacked technical staff and independent auditing capacity. Critical information such as the unrecognized risk of Fault 502 pressurization or the unreinforced MOC for Well C25 never reached CNOOC's decision-makers in a usable form. In addition, internal feedback between drilling teams was broken. The C25 design change was known to one team but not communicated to the C20 team, exemplifying information compartmentalization.

At the operational level, sensor feedback was available but was either ignored or not escalated. In the B-Event, pressure and rate data showed clear anomalies, but no alarm logic or procedural requirement forced the driller to report these as potential precursors. In the C-Event, logging-while-drilling data indicating overpressured zones were not transmitted in real time to onshore technical support, delaying any corrective response.

4. Comparative Analysis and Systemic Lessons: Insights from the PL 19-3 and DWH

4.1. Comparative Root Cause Analysis: PL 19-3 Versus DWH

On 20 April 2010, approximately one year before the PL 19-3 oil spills, the largest oil spill in the history of offshore drilling operations resulted from the DWH drilling platform. A total of four million barrels of petroleum flowed from the damaged Macondo well to the Gulf of Mexico over an 87-day period. The mechanism of the DWH accident has been thoroughly investigated and discussed by a number of researchers, including the author [30]. In this section, the similarity and differences in root causes between PL 19-3 and DWH oil spill accidents are addressed and discussed [3,33,34]. Given that operational and technical root causes are incident-specific, the comparison is restricted to the human and organizational domain, as is presented in Table 4.

Table 4. Comparison of the human and organizational root causes between PL 19-3 and DWH oil spill accidents.

Common Causes	Specific to DWH	Specific to PL 19-3
• Ineffective leadership	• Inadequate use of technology/instrumentation	• Weakness in design not identified
• Compartmentalization of information and deficient communication	• Regulatory capture and outdated safety standards	• Lack of compliance
• Failure to provide timely procedures • Poor training and supervision of employees • Ineffective management and oversight of contractors • Failure to analyze and evaluate risk appropriately • Focus on time and costs rather than control of major accident risks • Weakness in MOC	• Failure to recertify critical safety equipment (BOP, diverter)	

To ensure comparability, root causes were identified from official investigation reports [3,33,34] and relevant academic analyses [36,37], and subsequently classified using established human and organizational factor categories. Table 4 groups the identified causes into three classes, namely common causes observed in both accidents, causes specific to DWH, and causes specific to PL 19-3. In total, thirteen human and organizational root causes were identified, of which eight were common to both accidents, three were unique to DWH, and two were unique to PL 19-3. The predominance of common causes suggests that the comparison provides a sufficiently robust basis for identifying systemic characteristics that extend beyond a single accident case.

A closer examination of the common causes reveals that they are not distributed randomly, but tend to cluster around several recurring themes, including oversight and accountability, risk assessment and change management, communication and feedback, and the balancing of production and safety objectives. These themes span multiple levels of the safety control structure and indicate that accident causation cannot be adequately explained by isolated technical failures alone. Instead, they point to broader interactions among regulatory arrangements, organizational processes, and operational decisions.

4.2. Systemic Lessons Derived from the Comparative Analysis

4.2.1. Regulatory Constraints and Independent Oversight

The comparison presented in Table 4 shows that several of the common root causes are associated with deficiencies in regulatory oversight, including ineffective leadership, failure to analyze and evaluate risk appropriately, and ineffective oversight of contractors and employees. These recurring deficiencies suggest that major accident prevention depends not only on technical controls but also on how safety constraints are established and enforced at the regulatory level.

Following the 2011 PL 19-3 accident, the Chinese petroleum regulatory framework underwent only limited revisions in 2013 and 2015 and continues to rely predominantly on prescriptive compliance-based supervision, without adopting functional regulation. Similarly, despite regulatory reforms following the DWH accident, Chinese petroleum sector has not fully incorporated lessons from either event.

In contrast, following the Alexander L. Kielland disaster (1980, 123 fatalities), Norway transitioned from prescriptive regulation to a goal-based, system-oriented regulatory regime, centered on tripartite cooperation among regulators, industry and employee representatives. Since 1985, no major process-safety accident of the Alexander L. Kielland/Piper Alpha scale with fatalities has occurred on offshore installations on the Norwegian Continental Shelf (NCS), suggesting the effectiveness of this approach.

As illustrated in Figure 6, which compares the Norwegian functional co-regulation framework with China's prescriptive regulatory approach, there is a clear imperative to reconsider and redesign the Chinese petroleum regulatory framework. Such reform is essential to bridge the persistent gaps in major accident risk governance.

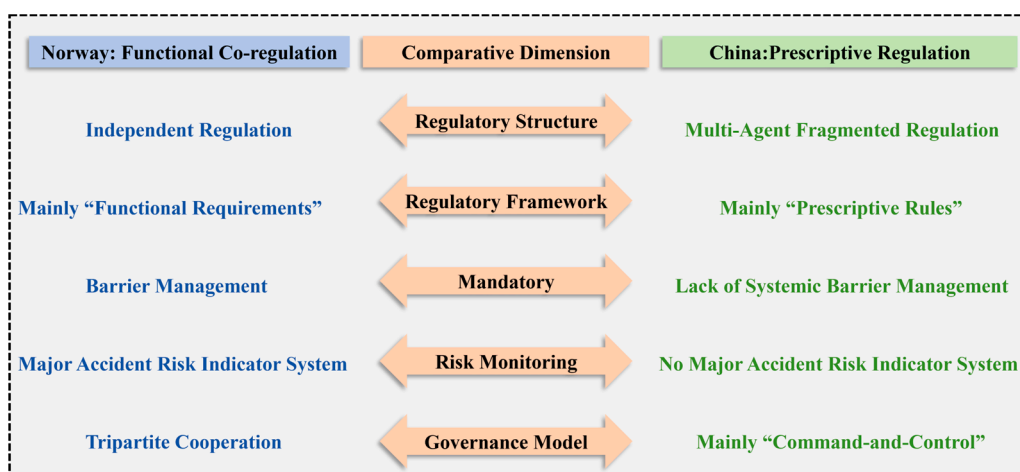


Figure 6. Comparative regulatory frameworks: Norway petroleum functional co-regulation versus Chinese petroleum prescriptive regulation.

4.2.2. Organizational Control and Barrier Integrity

Comprehensive accident investigations consistently show that non-technical failures are persistent root contributors to major accidents. As shown in Table 4, the majority of com-

mon root causes are associated with organizational processes, including communication, contractor management, and MOC.

In the PL 19-3 case, the absence of key organizational controls directly led to Events B and C, such as no defined injection pressure limit, no risk assessment for Fault No. 502, and no structured MOC communication mechanism. A comparison with the DWH accident reveals highly consistent human and organizational root causes, suggesting that such deficiencies are systemic and largely independent of geographical and temporal contexts. Notably, a similar incident occurred at the Frade field five months after PL 19-3 [38].

The recurrence of these deficiencies across different accidents suggests that major accident prevention depends not only on the reliability of technical safeguards, but also on the effectiveness of the organizational and operational barriers that support them.

Drawing on the Norwegian Performance Standards for Safety Barriers [39], Figure 7 illustrates how technical, organizational, and operational barriers interact with performance requirements and influencing factors to ensure barrier integrity. Norwegian offshore practice demonstrates that this barrier-based approach is effective in preventing major offshore accidents.

OVERARCHING BARRIER FUNCTION FRAMEWORK			
TECHNICAL:	BARRIER ELEMENTS Which equipment and systems are included?	PERFORMANCE REQUIREMENTS What requirements must be defined for equipment and systems?	PERFORMANCE-INFLUENCING FACTORS What affects the performance of the various technical barrier elements?
ORGANISATIONAL:	Which personnel have defined roles, functions and specific competences?	What requirements must be defined for specific competence, availability, safety drills and co-training?	What affects the performance of personnel?
OPERATIONAL:	Which safety-critical tasks must be performed?	What requirements must be defined for execution of the tasks?	What affects the potential for performing the tasks correctly and on time?

Figure 7. The interaction between the technical, organizational and operational barrier elements.

4.2.3. Feedback Deficiencies and Major Accident Risk Monitoring

In addition to deficiencies in regulatory constraints and organizational controls, both accidents reveal weaknesses in the collection, interpretation, and utilization of safety-related feedback information.

In practice, COPC relied heavily on conventional safety indicators, while failing to recognize precursors specific to major accidents, such as abnormal formation overpressure and loss of well integrity. Similarly, the DWH accident showed that BP did not effectively assess major accident risk based on occupational safety statistics [40]. The comparison indicates that traditional occupational safety indicators alone provide limited information regarding the degradation of barriers associated with low-frequency, high-consequence events.

Based on extensive field experience, Zhen et al. [31] proposed a set of performance standards, defined as key risk factors influencing the occurrence and consequences of major offshore accidents (see Table 5). However, no practical or simple method currently exists to quantitatively assess these standards, indicating that non-technical barrier management will remain challenging in the foreseeable future.

Table 5. Overview of performance standards [31].

PS NO.	PS Description
PS01	Work practice
PS02	Competence
PS03	Procedure and documentation
PS04	Communication
PS05	Work load
PS06	Physical environment
PS07	Task supervision
PS08	Risk awareness
PS09	Management
PS10	Management of change
PS11	Work schedule aspects

4.3. Institutional Context and Feasibility Analysis

The comparative analysis indicates that the PL 19-3 and DWH accidents share common deficiencies in three areas, namely regulatory constraints, organizational control, and feedback mechanisms. Notably, these areas correspond closely to the core elements of the Norwegian major accident prevention framework, namely co-regulation model, systemic barrier management, and the Trends in Risk Level (RNNP) project. The relevance of the Norwegian experience therefore arises not from institutional similarity, but from its alignment with the systemic weaknesses identified in both accidents.

From a STAMP perspective, these Norwegian practices can be interpreted as mechanisms for strengthening safety constraints at different levels of the control structure. Co-regulation model reinforces regulatory oversight and accountability. On this basis, barrier management supports the integrity of technical, organizational, and operational controls, and RNNP enhances feedback quality through systemic monitoring of leading indicators. Collectively, these mechanisms address the same categories of control deficiencies revealed by the comparative analysis.

However, the effectiveness of such approaches depends on the institutional environment in which they are implemented. Compared with Norway, the Chinese offshore petroleum sector is characterized by a stronger concentration of operational and governance responsibilities, a predominantly compliance-oriented regulatory tradition, and limited experience with independent third-party verification. These factors do not invalidate the relevance of the Norwegian approaches, but they may affect the pace and manner of implementation.

Accordingly, the transferability challenge is better understood as one of institutional adaptation rather than direct transplantation. A phased implementation pathway may therefore provide a practical means of incorporating proven elements of the Norwegian system while accommodating the characteristics of the Chinese offshore petroleum sector. In the short term (1–2 years), efforts could focus on strengthening independent technical review within the existing regulatory framework and piloting voluntary reporting of major accident precursor indicators. In the medium term (3–5 years), performance-based requirements and independent third-party verification could be progressively integrated into critical design reviews, barrier management, and MOC processes. In the longer term (5–10 years), subject to the development of regulatory capacity and industry experience, selected elements of co-regulation and a similar RNNP project could be implemented as part of a more comprehensive major accident risk governance framework.

5. Conclusions and Recommendations

By comparing offshore oil spill cases using the STAMP model, this study demonstrates that accidents result from systemic failures in multi-level control-feedback loops rather than isolated errors. Consequently, this section presents a “Regulatory Failure and Reform Framework”, which maps fragmented supervision and organizational gaps to optimized pathways involving risk indicators and integrated control structures.

5.1. Conclusions

Based on the STAMP analysis, comparison with the DWH accident, and lessons from the PL 19-3 incident, three key conclusions are drawn:

- (1) Inadequate regulatory constraints are the fundamental precondition. The Chinese petroleum safety regime relies heavily on prescriptive compliance, lacking risk-based performance standards and independent verification, which allowed violations in development plans and EIAs to persist undetected.
- (2) Insufficient enforcement of organizational controls is the direct trigger. In PL 19-3, the absence of injection pressure limits, lack of fault risk assessment, and missing formal MOC processes directly led to Events B and C. Similarly, MOC failure was a primary contributor in DWH. Norwegian practice shows that clear operator accountability and barrier management systems are effective in preventing major accidents.
- (3) Deficient feedback and delayed response at the operational level are consequence amplifiers. Ignored pressure precursors, delayed casing decisions, and prolonged leakage (>3 months) reflect a safety culture prioritizing production over risk response. Both accidents highlight the critical impact of feedback failure. Establishing a national risk indicator monitoring system, analogous to Norway’s RNNP framework, offers an effective pathway to strengthen feedback and early warning capabilities.

5.2. Recommendations

Based on these findings, three integrated recommendations with specific implementation guidance are proposed.

- (1) Transition toward a co-regulation model. The experience of the NCS suggests that a co-regulation framework, which balances prescriptive requirements with functional performance standards, can be effective in managing major accident risks. A practical step in this direction would be strengthening coordination among existing regulatory bodies while progressively enhancing the independence of offshore safety oversight functions. Functional regulations that specify safety goals, rather than detailed means of compliance, could be developed to permit industry flexibility in achieving desired safety outcomes, drawing on the principles of the Norwegian Internal Control Regulation.
- (2) Adopt systemic barrier management. The barrier management approach developed by the Petroleum Safety Authority Norway [39] provides a useful reference for regulatory practice. When applied in the Chinese offshore petroleum sector, the approach could be integrated into existing regulatory requirements and organizational structures while progressively expanding the use of independent verification mechanisms. It typically involves three core elements. First, operators should identify technical, organizational, and operational barriers for each major hazard and define performance requirements for each barrier element. Second, leading and lagging indicators should be established to monitor barrier performance over time. Third, independent verification of barrier integrity and effectiveness can provide an additional layer of assurance.

- (3) Establish a national major accident risk monitoring system. Inspired by the Norwegian Trends in RNNP project [41], a national system for monitoring major accident risk level in offshore petroleum activities may be considered. Given differences in data availability, reporting practices, and institutional capacity, implementation could begin with a phased programme focused on the gradual standardization and collection of risk indicator data. Such a system could ultimately cover all offshore installations and involve annual collection of standardized risk indicator data to support national-level risk trend analysis. The indicator set should include both technical and organizational measures to capture hardware integrity, management system effectiveness, and organizational learning.

Author Contributions: Conceptualization, X.Z. and J.-E.V.; writing—original draft preparation, X.Z. and Y.C.; writing—review and editing, J.-E.V. All authors have read and agreed to the published version of the manuscript.

Funding: The research received no funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The opportunity to guest-edit the Special Issue on Risk Assessment and Mitigation Strategies in Offshore Petroleum prompted the authors to investigate systemic control failures on offshore installations. It is hoped that these insights will draw practitioners' attention and stimulate critical self-examination, thereby enhancing the industry's capacity to prevent, control, and mitigate major accident risks across all phases of offshore petroleum activities.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ALARP	As Low As Reasonably Practicable
BOP	Blowout Preventer
CNOOC	China National Offshore Oil Corporation
COPC	ConocoPhillips China
CRI	Cuttings Re-injection
DWH	Deepwater Horizon
EIA	Environmental Impact Assessment
JMC	Joint Management Committee
MOBM	Mineral Oil-Based Mud
MOC	Management Of Change
MPD	Managed Pressure Drilling
NCS	Norwegian Continental Shelf
ODP	Overall Development Plan
PL	Penglai
RCD	Rotating Control Device
RNNP	Trends in Risk Level
SOA	State Oceanic Administration
STAMP	Systems-Theoretic Accident Model and Processes
UCAs	Unsafe Control Actions

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