Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

doi: 10.3850/978-981-18-8071-1_P028-cd

A study on safety analysis during the construction period of oil and gas reservoir-type storage based on STAMP-STPA

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In order to improve the safety level of the construction period of oil and gas reservoir-type gas storage and to address the shortcomings of the traditional safety analysis method that cannot comprehensively consider the interaction between components in a complex non-linear system, the safety analysis of the construction period of gas storage is carried out from three perspectives: control, feedback, and coordination, based on the STAMP-STPA method. Based on the STAMP model to establish a control and feedback model for construction operations and the STPA method to analyze unsafe control behaviors, the analysis obtained vital risk factors, including defects in the compressor installation, poor casing gas tightness, damage to reservoir cavity stability, errors in capping reservoir special play operations and inadequate technical handover, taking underground drilling operations and surface facility installation operations as examples. By comparing the results with the accident tree method and HAZOP method for safety analysis of drilling construction, the STAMP-STPA method has improved the risk identification capability by 38.5%, and the analysis results are more comprehensive in terms of information transfer and personnel psychology. The results show that the STAMP-STPA safety analysis method fits well with the construction period of oil and gas reservoir-type gas storage, effectively solving the problem of risk identification caused by the non-linear and non-stationary characteristics of the system during the construction period of gas storage and providing strong support for risk management.

Keywords: oil and gas reservoir-type gas storage; Systems theory accident process model(STAMP); Systems theory process analysis(STPA); construction period; Risk identification; Drilling.

1. Introduction

With the rapid development of the natural gas industry, the transportation and storage of natural gas have become an important issue, and the importance of gas storage as a tool for natural gas storage and peaking has been increasing day by day. Underground gas storage has the characteristics of safety and large storage capacity. Nowadays, countries with suitable geological conditions have adopted underground reservoirs in large numbers as energy reserves, which can be built in depleted oil and gas reservoirs, salt rocks, or aquifers (API. 2018). Among them, oil and gas reservoir-type gas storage with abundant geological information, large storage capacity and low cost (Wang et al. 2019) is the most widely used at home and abroad.

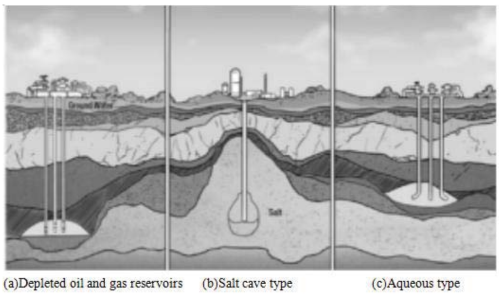

Fig. 1. Types of underground gas storage(API. 2018)

Gas storage production is characterized by strong injection and alternating loads, involving underground, wellbore, and surface engineering, etc. The technology to be implemented is complex, with high environmental, safety and quality requirements (Niu et al. 2016). In case studies of reservoir-type gas storage accidents, damage to injection and extraction wells or casing, gas-tightness damage to gas reservoirs, and failure of surface facilities are the main causes of accidents (Yang et al. 2011), involving the whole life cycle of design, construction, and operation risks. Among them, the quality of construction determines whether the operation period can be operated safely. In order to guarantee the safe operation of underground gas storage, it is necessary to comprehensively understand and regulate the risks during the construction period of underground gas storage. Traditional safety analysis methods mostly describe the linear relationship between risks within the system, and the analysis ability of inter-system interaction is weak. The construction period of gas storage reservoirs contains both technical and personnel and management levels, which is a non-linear complex system, and the traditional methods cannot fit the safety analysis of the construction period of gas storage reservoirs well.

Regarding the safety analysis methods for complex systems, Leveson (Nancy G. Leveson. 2004) formally proposed the System-Theoretic Accident Model and Processes (STAMP) model and the System-Theoretic Process Analysis (STPA) method based on STAMP for the first time in 2004. The STAMP-STPA method considers the nonlinear relationship between components from the system perspective. The STAMP model is constructed to divide the system into different levels of control structures, and the STPA method is used for risk analysis to identify unsafe control behaviors and the causes of control defect accidents (Liao et al. 2023), which has a wide range of applications in the field of safety. Zhu Mingchang et al (Zhu et al. 2021) constructed the STAMP control model for the safety of LNG ship-to-ship barging system, used the STPA method to identify unsafe control behaviors in barging operations, and proposed the causal factors in the system; Zhao Jiangping et al (Zhao et al. 2020) analyzed the causes of traffic accident control failure from the perspectives of physical layer, basic layer, operation layer and supervision layer by constructing a safety control structure for hazardous chemical road transportation traffic.

At present, there are few cases of applying STAMP-STPA method to the field of gas storage. Based on the above background, this paper proposes to build a safety control model based on the STAMP-STPA method, integrated personnel, management, and technical levels, to analyze the safety of the construction process of gas storage, and to provide strong support for the risk control of the construction period of oil and gas reservoir-type gas storage.

2. Methods

2.1. *STAMP model fundamentals*

The STAMP model studies safety from a control perspective, views accidents as the result of a linear superposition of a series of events, and considers the lack of constraints in the system as the root cause of accidents. The model consists of safety constraints, a hierarchical safety control structure and a process model (Gong et al. 2018). In the hierarchical safety control structure, the higher levels give control and safety constraint instructions to the lower levels and the lower levels provide feedback information; the process model guarantees system equilibrium by correcting the internal state of the system.The

STAMP model considers that the fundamentals of safe system operation lie in effective safety constraints, reasonable safety control and accurate information feedback (Hu et al. 2021).

2.2. *STPA fundamentals*

Systems Theoretic Process Analysis (STPA) is a systemic safety assessment method based on STAMP that eliminates hazards before they occur or controls them in operation by identifying potential causes of accidents (Liao et al. 2023). This method divides the components in a complex system into controllers, actuators, control processes and sensors, and determines the overall safety of the complex system by analyzing the failure scenarios of each component.

3. Case study

3.1. *STAMP-STPA analysis of drilling and construction operations*

The STAMP-STPA analysis process for gas storage reservoir drilling and construction operations is shown below.

3.1.1. *Identify safety risks and constraints*

During drilling construction operations, drilling and cementing fluids tend to leak into the formation due to the low formation pressure coefficient, which can affect subsequent construction operations and contaminate the reservoir. The pressure difference between the fluid in the well and the formation pressure during the drilling process is taken as a safety constraint. Controlling the drilling pressure field, properly adjusting the drilling fluid density, and determining reasonable drilling parameters before drilling construction are all constraining barriers to prevent well leakage accidents, and the pressure difference is controlled through the corresponding constraining barriers.

3.1.2. *Establishing a control and feedback model*

In the drilling construction operation control model, the construction team and each construction process, including equipment, constitute the controlled objects of the system; professional supervisors and safety supervisors act as sensors to supervise the construction team's operation, and professional technicians act as sensors to provide solutions when problems arise in the construction operation process and to evaluate the current construction status and provide technical support. Managers as controllers give operation instructions to operators according to the received construction site information and particular construction plan. The workers are regarded as executors, and under the supervision of the supervisor and the operating instructions of the manager, they carry out construction work in accordance with the contents of technical instructions.

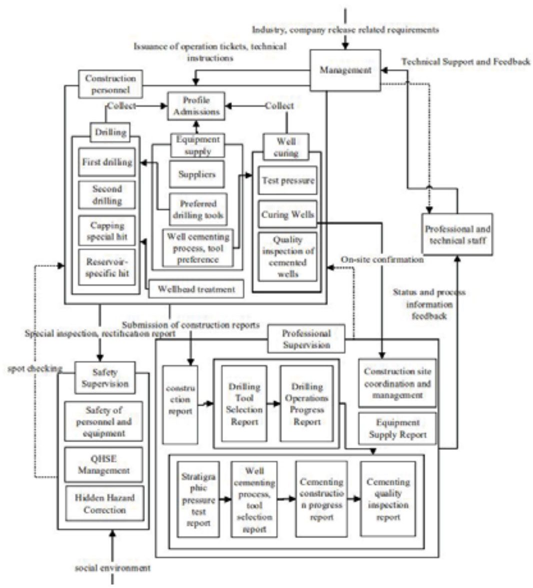

Fig. 2. Drilling construction operations control and feedback model

3.1.3. *Identify unsafe control behaviors*

According to the control and feedback model of drilling and construction operations, the systematic risks are analyzed from the perspective of four types of unsafe control behaviors in three aspects: personnel operation, organization and management, and construction technology. The risk factors obtained from the analysis can be translated into safety constraints for drilling and construction operations, and it is necessary to ensure that the system control behavior conforms to the safety constraints when preventing and controlling the risks of the construction process.

Table 1. Unsafe control practices in drilling and construction operations.

Unsafe control behavior	Risks arising from	Security restraints
No controlling behavior provided	The wellhead was not treated before drilling, affecting the installation of the blowout preventer, and there is a risk of leakage from the wellhead in the event of a blowout.	Conduct multiple audits when developing the construction process , and review the construction process in real-time.
Wrong or unsafe control behavior	The constructors adopted the wrong drilling and cementing methods, and the quality of the good structure and cementing was poor.	The strict control of the construction process and construction quality
Control of early/delayed onset of behavior	The cementing time is too short, and the cement slurry is tested before it is fully set, which reduces the quality of cementing and affects the gas tightness of the reservoir.	Professional designers should set a certain safety margin for cement paste setting time ;clarify the construction process.
Control behavior ends too early/ lasts too long.	The quality of the cementing test is too short, or the pressure is too low, which does not measure the actual pressure capacity of the wellbore.	Operators should comply with the operating procedures to strictly control the detection time.

3.1.4. *Analysis of key risk factors*

After identifying the risks resulting from unsafe control behaviors, the key risk factors for unsafe control behaviors leading to accidents, such as well leaks during drilling, are summarised based on the basic control deficiencies proposed by STAMP-STPA.

Inadequate implementation of control behaviors.

(i) Reliability of construction personnel: Construction personnel did not treat wellheads and install blowout preventers before drilling; cementing time was too short, and test pressure was before the cement slurry was fully set. Deviations in the way construction personnel obtain information; inadequate competence or poor attitude of the personnel.

(ii) Construction techniques: wrong drilling and cementing methods; wrong sequence or deviation in the operation of cap and reservoir special drilling; wrong setting of construction parameters when drilling and cementing; cementing water mud cannot penetrate the formation, or cement slurry cannot withstand the effect of alternating stress.

(iii) Equipment reliability: Defects in methods and operations of cementing quality testing, casing gas tightness testing, pressure testing, and deviations between the results and the actual; suppliers provide wrong cementing tools and drilling tools.

(iv) Organizational management: managers did not issue operation tickets and technical instructions to construction personnel; managers issued wrong or unsafe instructions to construction personnel and suppliers.

Insufficient or incorrect feedback.

(i) External environment: improper selection of the reservoir site in the early stage; new wells near faults and poorly sealed areas, which affect the gas reservoir confinement (Yang et al. 2011); inadequate, incorrect, or lost information on the geological, climatic, and meteorological environment of the construction area.

(ii) Feedback generation stage: incomplete or incorrect acquisition of formation pressure parameters during drilling; failure to monitor reservoir cap sealing; failure to monitor reservoir faults.

(iii) Feedback information transmission stage: The lack of a sound management system and a sound regulatory mechanism leads to inaccurate or delayed feedback information from controllers at all levels.

3.2. *STAMP-STPA analysis of gas storage ground facility installation operations*

3.2.1. *Identify safety risks and constraints*

The main safety risk of oil and gas reservoir-type storage ground engineering is the failure of ground facilities and equipment, leading to natural gas leakage, which can lead to fire and explosion accidents (Yang et al. 2011). For station equipment installation, unstable construction staffing, quality problems of the equipment itself, and weak supervision of equipment installation all lead to poor quality control (Wu. 2021). The failure of equipment and facility installation is considered a system-level risk. The safety of construction operations is ensured by setting restraint barriers to avoid equipment manufacturing defects and poor personnel operation behavior as safety constraints.

3.2.2. *Establishing a control and feedback model*

In the construction process, construction operators must install equipment following certain procedures and comply with the operating procedures strictly. Supervisors need to supervise the construction quality following the provisions of quality control points. Safety supervisors are responsible for supervising personnel and equipment safety while responsible for QHSE management and hidden danger rectification; professional supervisors supervise the progress of the project and coordinate the management of the site; professional supervisors and safety supervisors send the construction situation Feedback to professional technicians or management personnel, management personnel issued control instructions to control the construction of operators, while construction personnel needs to feedback the site situation to management personnel on time, thus forming a complete control and feedback loop.

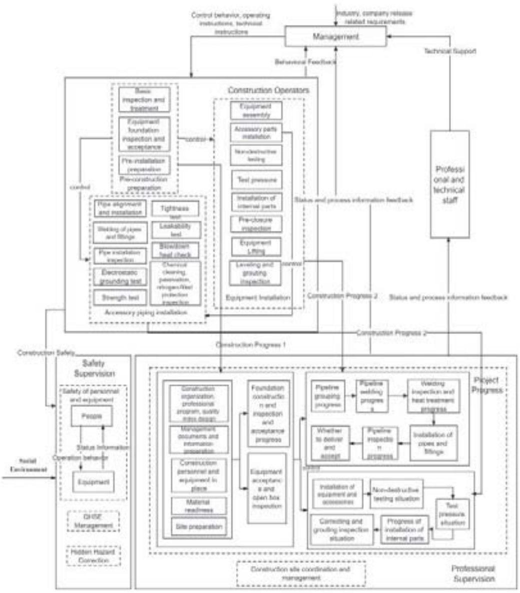

Fig. 3. Ground facility installation operation control and feedback model

3.2.3. *Identify unsafe control behaviors*

Table 2. Handling unsafe control practices for facility construction operations(part).

Unsafe control behavior	Risks arising from	Security restraints
No controllin g behavior provided	lifting equipment did not carry out wire rope inspection, wire rope disconnected accident occurred.	Check the wire rope for wear and tear; determine the safety factor of the wire rope; test off before lifting.
Wrong or unsafe control behavior	Improper operation of the operator when lifting equipment, lifting unbalanced fall	Pay attention to the working condition of the operator; standardize the use of safety belts and other protective equipment.

Control of early/delayed onset of behavior	Equipment is not closed in time, and impurities in the equipment affect the normal operation of the equipment.	After passing the equipment cleaning inspection, close the equipment in time and fill in the cleaning inspection records
Control behavior ends too early/ lasts too long.	Equipment water pressure test has not yet qualified or the equipment is not cleaned before the installation of internal parts, resulting in equipment wear and tear damage	The inner parts should be installed after the equipment has passed the water pressure test and been cleaned up.

3.2.4. *Analysis of key risk factors*

Inadequate implementation of control behaviors.
(i) Personnel reliability: Inadequate safety awareness or overload of operators, resulting in misuse behavior; inadequate construction techniques to properly execute control instructions; inadequate personnel competence or poor attitude.

(ii) Equipment functional integrity: Inadequate foundation acceptance; equipment installation process did not comply with the operating procedures; equipment trial run did not meet the relevant standards.

(iii) Organizational management: Supervisors are not in place to supervise construction safety, and equipment sites are cluttered, causing object strike injuries and electrocution accidents; Inadequate control of construction progress by professional supervisors; inadequate or wrong technical delivery; quality and safety management organization is not perfect.

Inadequate or incorrect feedback includes:

(i) Feedback information generation stage: Insufficient or incorrect acquisition of various status parameters during equipment commissioning; operators do not discover the problems in construction in time.

(ii) Feedback information transmission stage: construction quality and safety control procedures are not established, the implementation of supervision and management is not in place, and the responsibility of supervision and management personnel is not strong.

(iii) Influence of external factors: the construction environment is harsh, the surrounding environment is not examined, and the construction pollution affects the operation of the surrounding infrastructure.

3.3. *Comparative analysis of methods*

In order to verify the applicability and superiority of the STAMP-STPA method for the construction period of a gas storage reservoir, an accident tree method, a hazop analysis method and the STAMP-STPA method were used to analyze the risk of drilling operations and to list the possible risk factors.

3.3.1. *Accident tree analysis*

The accident tree for drilling and construction operations is shown in Figure 4.

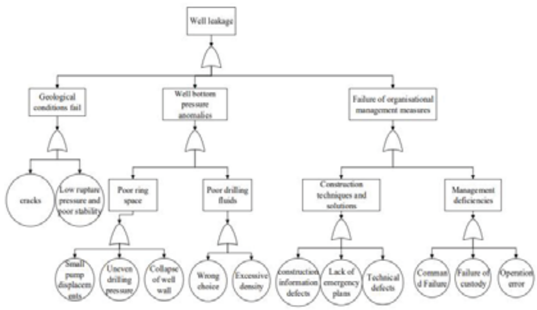

Fig. 4.Accident tree analysis of drilling and construction operations

3.3.2. *Hazop analysis*

In this case study, the hazop method was used to analyze the risk factors present in the drilling and construction operations of the gas storage reservoir. The possible causes of deviations and the consequences of deviations were analyzed and the results are shown in Table 3

Table 3. HAZOP analysis of drilling and construction operations(part)

Parameters/ lead words	Deviation	Cause	Consequence
Pressure/High	High drilling pressure	• Shock absorber failure;	• Drill bit wear; • Drill pipe

		• Excessive under-top drive	bending failure
Pressure /Low	Low drilling pressure	• Insufficient underneath the top drive; • Mud density too low	• Drill bit wear; • Slowing down drilling speed
Pressure /high	Pump pressure too high	• Clogging; • High drilling fluid density	Environmental pollution from drilling fluid leakage
Pressure /low	Pump pressure too low	• abnormal high-pressure overflow • Leakage	Collapse in the well
Velocity /high	Drill speed too fast	Improper handling by personnel	• Damage to drilling tools; • Well leakage accident
Velocity /low	Drilling speed too slow	Jammed auger	Damage to drilling tools
Density /low	Low drilling fluid density	Drill encounters abnormal high-pressure overflow	Well surge,Well blowout

3.3.3. *STAMP-STPA analysis*

Combining the unsafe control behaviors of drilling and construction operations obtained from the analysis in Table 1, the risk factors obtained using the STAMP-STPA method were classified into six categories.

Table 4. STAMP-STPA analysis of drilling and construction operations(part)

Cause Category	Cause
Personnel reliability	• Untreated wellhead before drilling. • No blowout preventer was installed before drilling. • Short cementing time and poor cementing quality.
Poor functional integrity of equipment	• Construction personnel did not test the casing for air tightness before placing the casing. • Deviation of solids quality test results from actual.
Organizational management deficiencies	• Management personnel did not issue operating tickets to construction personnel or carry out technical instructions. • Management and professional supervisors were not present at the construction site. • Suppliers supply the wrong cementing tools, drilling tools.
External environment	• Inadequate, incorrect, or missing information on the geological, climatic, and meteorological environment of the construction area.
Construction techniques	• wrong drilling and cementing method. • The wrong sequence of operations for capping and reservoir-specific hits. • Incorrect setting of drilling and cementing construction parameters.
Messaging	• Managers give wrong or unsafe instructions to construction workers and suppliers. • Delay in submission of construction report.

3.3.4. *Comparison of case study results*

The identification capability of the method is measured by the number of risk factors finally obtained by the system safety analysis method (Han et al. 2021).For a gas reservoir type reservoir drilling and construction operation, 13, 15 and 18 risk factors were analyzed using accident tree method, hazop analysis method and STAMP-STPA method respectively. In terms of the number of items identified, the risk identification capability of STAMP-STPA method is 38.5% higher than that of accident tree method and 20% higher than that of hazop method, which indicates that the method can uncover more comprehensive risk factors. The accident tree method and the hazop method cannot analyze the complex interactions of nonlinear systems, and the meticulousness is weak, with high leakage rate of safety hazard identification; while the STAMP-STPA method can fully integrate personnel, technology, organization and information transfer, and is more suitable for risk analysis of complex systems with multi-level association.

4. Conclusion

This paper treats the construction period of oil and gas reservoir-type gas storage as a nonlinear complex system, and creates a STAMP-STPA risk factor identification model for the construction period of gas storage based on the STAMP-STPA approach, with managers as controllers, construction personnel as actuators, and supervisors and technicians as sensors, and carries out safety analysis from the perspective of control.

Through case studies, the risk factors of the construction period of gas storage reservoirs are revealed from four aspects integrating personnel, technology, and organization from multiple perspectives, and the key reasons for the existence of risk factors are revealed from two perspectives of inadequate control behaviors and insufficient feedback information, and the corresponding safety constraints are summarized, which provide strong support for the risk control of the construction period of gas storage reservoirs.

By comparing with the results of traditional safety analysis, it is found that the STAMP-STPA-based method can dig deeper into the risk factors such as information transfer and personnel psychology, and the risk identification ability is significantly improved, which can effectively solve the problem of risk identification with non-linear and non-stationary characteristics during the construction period and improve the accuracy of safety hazard (defect) identification in the process of each engineering connection.

Acknowledgment

This work was supported by the Natural Science Foundation of China (52074323).

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