Mechanism Analysis of Fall Accidents Based on Rheological-Catastrophic Theory

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Abstract. To investigate the mechanisms underlying fall accidents , this study first analyzes the rheological mutation process from a relatively safe state to accident occurrence on construction sites using rheological theory. It then examines the process of danger level changes among the causal factors of fall accidents at height, leading to their mutual coupling and ultimately causing accidents, based on cusp catastrophe theory. Finally, the study validates and analyzes these findings using real-world cases. The results indicate that construction projects often remain in a risky state for extended periods. When the temporal and spatial coupling of these critical factors occurs, the situation can rapidly deteriorate into an emergency, leading to accidents. The time and location of fall accidents are often determined by human factors, while the severity of injuries is influenced by physical and environmental factors. To prevent fall accidents at height, measures should be taken in emergencies to prevent the coupling of direct causal factors and, in non-emergency situations, long-term measures should be implemented to intervene during the rheological stage.

Keywords: Fall accidents; Rheological theory; Cusp catastrophe theory; Mechanism of accident causation

1 Introduction

The situation facing China's construction safety sector remains severe, with frequent accidents and persistently high casualties, posing a significant social issue that urgently needs to be addressed. Among various types of accidents, high-altitude fall accidents, due to their high incidence and fatality rates, rank first among the "five major hazards," posing a severe threat to the lives of construction workers. Therefore, conducting an in-depth analysis of the mechanisms behind high-altitude fall accidents is crucial for formulating effective preventive measures and curbing their frequent occurrence.

Scholars at home and abroad have conducted extensive and in-depth theoretical research and analysis on the causes of high-altitude fall accidents. Xue Xiaojie[1] studied the causal factors of high-altitude fall accidents in construction engineering based on

an improved ISM-MICMAC method; Xu Hu [2] investigated the correlation levels and degrees of influence among various factors contributing to high-altitude fall accidents using frequency statistics and χ2-PCC; Oliveira [3] analyzed the probability distribution curve of high-altitude fall accidents in the United States based on the Human Factors Analysis and Classification System (HFACS); Kayastha [4] integrated safety insights into Building Information Modeling (BIM) to assess the factors affecting fall accidents among Hispanic construction workers. However, most of these studies have focused on static analysis of accidents, failing to fully reveal the dynamic evolution of risk factors over time in high-altitude fall accidents and the comprehensive impact of multiple factors coupling on the accidents.

Multiple factors interact and intertwine during the construction process, collectively leading to accidents. Safety rheological theory and cusp catastrophe theory have been widely used in accident cause analysis. He Sha [5] studied blowout accidents using a safety rheological-catastrophe model; Jiang Xin [6] studied the evolution mechanism of emergencies in high-risk operations in water conservancy projects using a cusp catastrophe model; Li Jue [7] studied the occurrence mechanism of building collapse accidents using a cusp catastrophe model. However, currently, neither rheological theory nor catastrophe theory has been applied to the study of high-altitude fall accidents. In the actual process of high-altitude fall accidents, there is a potential risk fluctuation period, and the correlation between management factors and direct causes does not necessarily immediately lead to an accident. Sudden changes in the system are often the result of coupling among direct factors. Therefore, this paper treats high-altitude fall accidents as an independent system within the construction safety framework, combining rheological theory with cusp catastrophe theory to delve into the mechanisms behind high-altitude fall accidents, aiming to provide more scientific theoretical support and practical guidance for preventing such accidents.

2   Analysis of Causal Factors of Fall Accidents

The investigation reports of falls from heights accidents categorize the causes into direct and indirect ones. The direct causes of accidents are usually human factors, material factors, and environmental factors. Indirect causes are mostly management-related factors. By studying the underlying causes of accidents and rectification measures, it is found that inadequate administrative oversight is the most fundamental cause of accidents and the basis for the occurrence of all factors. Therefore, the contributing factors to falls from heights accidents are divided into five major categories: "human, material, environment, management, and societal".

2.1   Direct Cause Factors

Human factors are significant contributors to accidents and occur most frequently. Falls from heights accidents are often caused by construction workers' violations of operational procedures and their lack of safety awareness. Unsafe actions by humans can also

lead to mechanical equipment failures and poor working environments, thereby increasing the probability of accidents.

During work at heights, protective safety measures, such as safety ropes and safety nets, are essential. Once these protective measures fail, workers will be in a dangerous state. Additionally, basket overturns and failures of transportation equipment often result in multiple casualties.

The construction industry site is filled with steel, concrete, and construction equipment, and there are many work activities at heights, making the construction environment generally hazardous. Adverse environmental factors such as rainy and windy weather, messy working environments, or the lack of warning signs can also contribute to falls from heights accidents.

2.2   Indirect Cause Factors

Management factors refer to deficiencies in safety management on the construction site, including incomplete safety rules and regulations, inadequate safety education, poor site supervision, and untimely identification of safety hazards. Management factors have a direct or indirect impact on "human, material, and environmental" factors. The safety culture and rules and regulations of enterprises guide and constrain the behavior of operators.

2.3   Fundamental Cause Factors

In the face of the current severe construction safety accidents, we should identify and address the root causes of the problem. Therefore, the role of administrative oversight in the occurrence of accidents should not be overlooked. Inadequate inspection by administrative departments, inadequate special rectification, or illegal contracting practices in the industry have a significant impact on the occurrence of accidents.

Construction is a complex system with multiple layers and intersections composed of various factors. These factors interact and transform with each other. When analyzing the mechanism of accidents, it is essential to fully consider the overall impact of the interaction of various factors on the system.

3   Analysis of the Rheological Process of Fall Accidents

In the process of building construction, safety and danger coexist, where safety is relative while danger is absolute. The causal factors of accidents in construction interact and dynamically change over time, leading to a gradual increase in system danger until a mutation occurs at a certain moment. This process is consistent with the principles of safety rheology, thus the theory of safety rheology is used to study the occurrence process of fall accidents from heights. The theoretical model of safety rheology is shown in Figure 1.

When quantifying the dangerous state of an object, we use the y-axis to represent the danger level and the t-axis to represent time. The *AE* curve comprehensively

demonstrates the dynamic changes in the safety state. In the initial stage of the object, represented by the *AB* segment, the danger level gradually decreases over time. After reaching point *B*, the system gradually matures and enters the *BC* stage, where the danger level exhibits a stable and slow increase. Upon reaching point *C*, the danger level transitions to the *CD* stage with an accelerated growth rate. With the continuous accumulation of danger, a safety mutation occurs at point *D*, marking the transition from gradual change to mutation. After the safety state of the object is compromised, it will adjust to a new safety state at point *E* [8]. This theory illustrates that accidents do not occur by chance but are the result of danger accumulating over time and reaching a critical point at a specific moment, leading to the collapse of the safety state.

Due to the long-term fluctuation of danger on construction sites, the BC segment is adjusted to show an oscillating upward trend. The rheological model of fall accidents (Figure 2) is divided into the incubation stage *AB*, the oscillation stage *BC*, the triggering stage *CD*, the accident stage *D*, and the rectification stage *DE*.
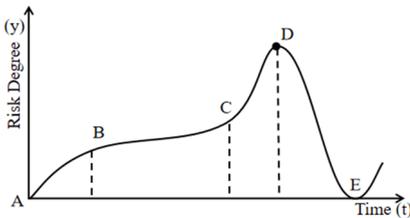

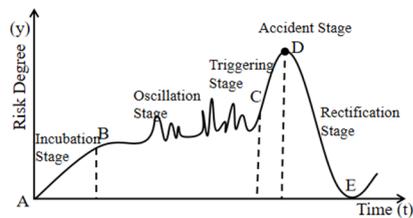**Fig. 1.** Graph of Safety rheology   **Fig. 2.** Rheological model of fall accidents

Incubation stage *AB*: Inadequate Administrative Oversight

During the project preparation and initiation stages, due to inadequate administrative oversight and factors such as illegal contracting, hidden safety hazards are planted for subsequent construction, leading to a decelerated increase in danger levels. As construction progresses, these hidden safety hazards spread through the management systems of all participating parties, and unsafe management factors begin to emerge. Therefore, in order to prevent the evolution from the incubation stage to the shock stage, it is necessary to strengthen administrative supervision capabilities and enhance the establishment of safety production responsibilities and regulatory frameworks.

Oscillation stage *BC*: rheological transition from management factors to Unsafe "Human-Material-Environment" Factors.

With the full-scale commencement of construction operations, various unsafe factors gradually begin to surface. Due to deficiencies in safety management, violations of operational procedures by workers and mechanical equipment failures start to appear on the construction site, leading to a gradual increase in danger levels. Danger levels fluctuate during this stage. For example, when workers perform unsafe actions at a certain time, danger levels rise, but upon receiving criticism and correction from management personnel, the unsafe actions are terminated, and danger levels decline. At most construction sites, the system remains in a dangerous state of oscillation for extended periods without accidents occurring. Therefore, to prevent the evolution from the shock stage to the excitation stage, safety training and education, as well as safety

management measures, should be implemented at the site to control unsafe behaviors of personnel and unsafe conditions of objects.

Triggering stage *CD*: cumulative disturbances of "Human-Material-Environment" factors

When disturbances from human, material, and environmental factors accumulate to a certain degree, the danger level of the system increases sharply. For example, at construction sites involving work at heights, workers have begun to frequently perform tasks without wearing safety harnesses, and due to violations of safety regulations, scaffolding installations do not meet standards. At this point, the danger level at the construction site is accelerating.

Accident occurrence point *D*: coupling of "Human-Material-Environment" Factors

When at least two hazardous factors couple in terms of time and location, the system undergoes a mutation, and a fall accident occurs instantaneously.

Rectification stage *DE*: emergency response and handling of the accident

After the accident occurs, emergency rescue is carried out immediately, followed by an investigation into the cause of the accident and rectification measures. The system then returns to a stable state. There is no absolute safety on construction sites, and the system enters the next dangerous rheological process.

To conduct a more in-depth and comprehensive study of the rheological-catastrophe evolution mechanism of high-altitude fall accidents, the catastrophe theory of cusp catastrophe is used to investigate the evolution process from point *C* to point *D* on the rheological curve.

4 Analysis of the Catastrophe Mechanism of Fall Accidents

4.1 Introduction to the Theoretical Model

In the mid-1960s, the French mathematician Thom founded catastrophe theory. This theory is built upon mathematical principles such as singularity theory and stability theory, providing an in-depth exploration of changes in the state of things and their stability. Catastrophe theory employs potential function curves to depict the state of a system, which are composed of state variables and control variables. Based on different potential function forms, catastrophe theory is subdivided into seven types. Among them, the equilibrium surface of the cusp catastrophe model is a three-dimensional curve graph, which is relatively clear and simple to study. Additionally, the two-dimensional plane composed of control variables facilitates accident analysis, making it a mature tool applied to catastrophe research in various accident types. Therefore, the cusp catastrophe theory is used to describe the catastrophe process of high-altitude fall accidents, with the state variable denoted as *x*, representing the safety of the system, and the control variables denoted as *u* and *v*.

The equilibrium surface equation of the cusp catastrophe is:

$$V(X) = 4x^3 + 2ux + v \tag{1}$$

Take the second derivative of the potential function:

$$V'(x) = 12x^2 + 4x \tag{2}$$

Combine (1) & (2), eliminate x, get bifurcation equation (3):

$$\Delta = 8u^3 + 27v^2 = 0 \tag{3}$$

The cusp catastrophe model has three lobes: superior (stable), middle (catastrophic), and inferior (stable). The fold line's projection on the u-v plane is the bifurcation set, and the middle lobe's projection forms the bifurcation point set B.

The equilibrium surface equation $V'(x) = 0$ is a cubic equation, and the number of real roots is determined by Δ. When $\Delta > 0$, the equation has only one real root, located on either the upper or lower lobe of the surface, and the system is in a relatively stable state. When $\Delta = 0$, the equation has a double root (where $u \neq 0$ and $v \neq 0$) or a triple root (where $u = v = 0$), corresponding to two curves and their intersection point on the bifurcation set, respectively. At this point, the system is in a critical state. When $\Delta < 0$, the equation has three distinct real roots, and the control point (u, v) lies within the set of bifurcation points, indicating that the system is in a state of mutation.

4.2   Analysis of the Evolution Mechanism of Fall Accidents

Combining environmental and material factors as one variable, and human factors as another, the fall accident model becomes one with one state (x, for system safety) and two control variables (u, v). Figure 3 illustrates the system's catastrophic process as control variables change.

(1) Evolution of System Stability

Curve $a_1 \rightarrow a_2$, $d_1 \rightarrow d_2$: When either the regularization factor v or the bifurcation factor u is in a relatively safe state, despite the continuous variation in the risk of the other control variable, the system's change curve remains far from the middle lobe area, indicating a relatively stable state. Its practical significance lies in the fact that when the human (or material) factor is in a safe state or with minimal risk, as the unsafe state of the material (or human) continues to increase, the risk of the system also increases. However, if the projection of this curve onto a two-dimensional plane does not pass through the set of bifurcation points, the system's state does not undergo a catastrophic change, and therefore, a fall accident from heights will not occur. For example, during work at heights, if the safety guardrail is insufficient in height or missing, but the workers do not violate safety regulations during construction and wear safety harnesses and lanyards, then no fall accidents will occur as long as the personnel do not fall. Alternatively, if a worker accidentally stumbles due to physical reasons during work at heights, but there are guardrails for protection, or a safety net below catches the falling worker, then no fall accidents from heights will occur.

Curve $e_1 \rightarrow e_2$: Both u and v are changing, and the system's risk is also constantly evolving. The balance shifts from the superior lobe to the inferior lobe. Although the control variables approach the critical state, they never pass through the bifurcation point set. No coupling occurs among the causal factors, and no accident happens.For instance, during work at heights, both human and material unsafe conditions coexist

and evolve towards a dangerous state. However, during this evolution, certain disturbances are encountered, causing the system to begin moving away from the mutation zone and avoiding the occurrence of an accident. This trajectory corresponds to the oscillating phase in the rheological process of fall accidents from heights.

(2) Evolution of System Catastrophic State

Curve $f_1 \rightarrow f_2 \rightarrow f_3 \rightarrow f_4$: As the factors related to humans and materials in the system change simultaneously, the phase point moves from point f_1 to point f_2 in the superior lobe. At point f_2, a sudden jump occurs, passing through the middle lobe and reaching point f_3 in the inferior lobe of the surface. From point f_3, the phase point follows the trajectory to reach point f_4. The phase point transitions from the equilibrium region of the superior lobe to the equilibrium region of the inferior lobe through a mutation. The process of this mutation is the occurrence of fall accidents. The projection of the phase point's trajectory passes through the set of bifurcation points. Therefore, the occurrence of fall accidents is the result of the trajectory of the two control variables related to human and material factors passing through the middle lobe surface. For instance, at a preset hole, there was no cover plate placed over it, nor were there any protective railings or warning signs set up. During the construction process, workers did not wear safety harnesses or helmets, and they kept approaching the hole to work without checking the surrounding situation, ultimately leading to a fall from the hole.
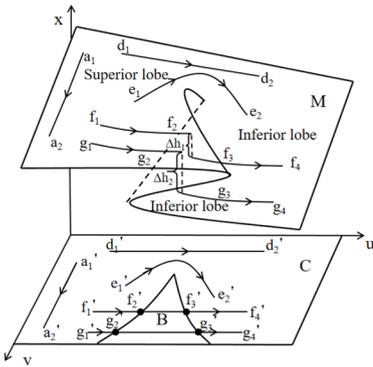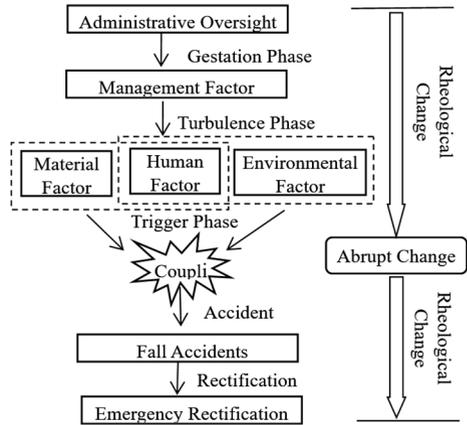

Fig. 3. Catastrophe model of fall accidents   **Fig. 4.** Rheological-abrupt process diagram of causal factors for fall accidents

Comparing curve $g_1 \rightarrow g_2 \rightarrow g_3 \rightarrow g_4$ with curve $f_1 \rightarrow f_2 \rightarrow f_3 \rightarrow f_4$, the trend of v's change is consistent. However, the mutation value Δh_1 is less than Δh_2, and the segment $f_2'f_3'$ is shorter than $g_2'g_3'$. The energy released during the mutation process of curve g is greater than that of curve f. Therefore, in the process of fall accidents, the danger level of objects and the environment determines the severity of the accident's losses. For example, during a fall accident, a poor-quality safety harness often results in a general safety accident, while factors such as overturned cradles or transportation equipment often lead to more serious accidents.

Therefore, the occurrence of fall accidents is the result of the simultaneous existence and combined action of two control variables: unsafe factors related to both humans and objects. Only when the curve on the equilibrium surface passes through an unreachable region (i.e., when the projection of this curve on the control variable plane passes through the set of bifurcation points) will a catastrophic change occur. When only one unsafe factor is present, it generally does not trigger a catastrophic change, but the safety of the system will be compromised.

When the system undergoes a catastrophic change, the degree of mutation in the system's state is determined by different jump values. When fall accidents becomes unavoidable, reducing the dangerous value associated with objects can mitigate the severity of the accident and minimize the impact caused by the fall accidents.

5   Analysis of the Causation Mechanism of Fall Accidents

Through the above analysis, it can be seen that the occurrence of fall accidents is a cyclical evolution of causal factors from rheological to catastrophic changes over time, representing a process where quantitative changes lead to qualitative changes. The rheological process exists for a long time and develops slowly; although it is relatively safe, danger persists throughout. The occurrence of fall accidents is caused by a strong coupling among the "human-material-environment" causal factors at a certain moment, triggering a sudden change in the system. After an accident occurs and rectification measures are taken, the system returns to a safe state and begins a new cycle of rheological changes. The process of rheological and catastrophic changes in causal factors during construction is illustrated in Figure 4.

6   Case Analysis

6.1   Accident Sequence

On August 15, 2023, five workers were performing external facade construction on Building 12 of the Hengyuan Jinxiucheng E-zone project in Yuncheng County, Heze City, Shandong Province. The workers were in a suspension basket without wearing safety harnesses. When the basket was lifted to the 26th floor, the working steel wire rope on the east side broke, causing the basket to overturn. During the basket's rotation and overturning, the five occupants successively fell out of the basket to the ground. The accident resulted in the death of all five workers from high-altitude falls, with direct economic losses totaling approximately RMB 7.26 million[9].

6.2   Rheological-Catastrophic Analysis of Accident Causes

6.2.1 Rheological Process of the Accident.

Incubation stage: The project was constructed without approval, and there was chaos in contracting and subcontracting management. Various administrative departments failed to effectively supervise, inspect, and promptly stop illegal and noncompliant

construction activities. Inadequate administrative oversight leads to lax safety management among project managers, who fail to fulfill their safety management responsibilities, thereby creating potential hazards for dangerous conditions on the project site.

Oscillation stage: The contractor exceeded its qualification, had chaotic safety management, neglected safety responsibilities, and lacked a safety production system. The project department didn't assign safety personnel, failed inspections, and allowed illegal use of suspension baskets. The project remained dangerous from the start until just before the accident, in a dynamic equilibrium. Triggering Stage: The steel wire rope of the suspension basket had already reached the scrapping standard and had not undergone routine maintenance and regular inspections. Construction personnel habitually violated safety regulations, assembled suspension baskets without proper certification, illegally rode in high-altitude work suspension baskets, and did not wear safety harnesses as required. The danger level rapidly increased during this stage.

6.2.2 Catastrophic Process of the Accident.

Mutation phase: The mutation in this accident was caused by the coupling of unsafe physical factors and unsafe human factors. The working steel wire rope of the suspended platform for high-altitude operation broke, and the safety lock failed to effectively lock the safety steel wire rope. At the same time, the workers had a weak safety awareness, illegally overfilled the suspended platform, and did not wear safety belts. The simultaneous occurrence of several hazardous factors led to the accident.

Imagine that even if the working steel wire rope broke, the safety lock could have effectively locked the safety steel wire rope, the workers did not illegally ride the platform, and wore safety belts during the ride. Perhaps the accident would not have occurred. Alternatively, if the workers had illegally ridden the platform, but the working steel wire rope had not broken or the safety lock had effectively locked the safety steel wire rope, this accident would not have happened. Therefore, the mutation in the system state this time was due to the coupling of human and physical factors at a specific time and place.

7   Conclusion

By adopting a systematic and holistic approach, this study integrates rheological theory and cusp catastrophe theory to delve into the causal mechanisms underlying fall accidents during construction processes. The key findings are summarized as follows:

Firstly, fall accidents in construction projects are the consequence of rheological-catastrophic transformations among various causal factors within the system. The prolonged presence of the system in the rheological stage signifies that hazards linger, yet accidents remain dormant.

Secondly, accidents occur when the causal factors within the construction system accumulate and intensify to a critical level, leading to a strong coupling in both temporal and spatial dimensions. This coupling triggers an abrupt change in the system's state. At this juncture, physical and environmental factors play a pivotal role in determining the severity of the high-altitude fall accident.

Lastly, the application of the rheological-catastrophic model to case analysis provides a clearer insight into the evolutionary process of high-altitude fall accidents. This understanding enables the formulation of targeted emergency or non-emergency management and control strategies, tailored to the specific stage of the construction system. To prevent accidents, in emergency situations, it is crucial to prevent the coupling of causal factors and to stop construction or take safety measures before reaching the critical state of mutation. In non-emergency situations, it is necessary to cut off the evolution process of the causal factors leading to high-altitude fall accidents. Measures should be taken during the incubation and oscillation stages of the accident to reduce the risk level at the construction site and address the problem at its source.

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