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Study on Chain Reaction of Landslides in Special Strata under Extreme Rainstorm Conditions

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Abstract: In July 2024, Typhoon "Gaemi" struck Zixing City, Hunan Province, triggering an extreme rainstorm with a maximum 24-hour rainfall of 642.5 mm, breaking the historical record in Hunan Province. The heavy rainfall induced a large number of geological disasters, mainly shallow landslides and slope debris flows, showing a significant "landslide --- debris flow --- flood" chain reaction characteristic. Based on the emergency investigation report of the "7·27" geological disaster in Zixing City and the post-disaster review report, combined with survey data from 706 geological disaster sites, this paper systematically analyzes the disaster mechanism and chain process of special strata such as granite and shallow metamorphic rocks under extreme rainfall conditions. The results show that special strata, with intense weathering and loose structure, are prone to high-altitude, shallow, and clustered landslides under short-term heavy rainfall; landslide masses mix with surface runoff during movement, transform into debris flows, further block river channels to form barrier lakes, trigger secondary flood disasters, and form multi-hazard compound chains. This paper reveals the causes of chain reactions from geological conditions, rainfall characteristics, topography, and human activities, and proposes an integrated disaster prevention and mitigation suggestion of "identification --- monitoring --- warning --- governance", providing a scientific basis for disaster prevention and control under similar geological and climatic conditions.

Keywords: Extreme rainstorm; Special strata; Landslide; Chain reaction; Geological disaster; Zixing City

1. Introduction

Against the backdrop of global climate change, the frequency and intensity of extreme rainfall events have significantly increased, and geological disasters in mountainous areas present new characteristics of large scale, sudden occurrence, and prominent chain effects. From July 26 to 28, 2024, affected by Typhoon "Gaemi", Zixing City in Hunan Province experienced a historically rare extreme rainstorm, with a maximum 24-hour rainfall of 642.5 mm and a maximum hourly rainfall intensity of 132.2 mm, both setting records in Hunan Province [1-2]. The heavy rainfall triggered a large number of landslides and debris flow disasters, causing 23 deaths and missing persons, with direct economic losses reaching 305 million CNY [3-4]. Zixing City has complex geological structures, with special strata such as granite and shallow metamorphic rocks widely distributed. These strata have thick weathering layers, loose structure, and strong permeability, making them highly prone to shallow sliding under extreme rainfall conditions, accompanied by obvious chain disaster reactions.

Currently, domestic and international research on rainfall-induced landslides mostly focuses on general soil layers or single disaster types, and there is a lack of systematic research on the chain disaster mechanism of special strata (such as granite and shallow metamorphic rocks) under extreme rainstorms. Relying on the emergency investigation report of the "7·27" geological disaster in Zixing City and the post-disaster review report, combined with field survey data from 706 geological disaster sites, this paper systematically analyzes the chain reaction types, formation mechanisms, and disaster characteristics of landslides in special strata, aiming to provide theoretical support and practical reference for geological disaster risk prevention, control, and emergency response in similar areas.

2. Geological Environment Overview of the Study Area

2.1 Topography and Geomorphology

Zixing City is located on the western side of the Luoxiao Mountains, with high terrain in the southeast and low in the northwest. The highest elevation is 2042.1m (Bamian Mountain), and the lowest is 106m (Chengjiangkou). According to the terrain, it can be divided into three levels: the northwestern upland (106-208m), the central hill-valley area (about 300 m), and the northeastern and southern hilly mountainous area (about 500 m). The area features deeply incised valleys, with terrain slopes generally greater than 25°, providing favorable topographic conditions for landslide development.

The geomorphology within the area is mainly controlled by stratigraphic lithology, magmatic activity, and geological structure, resulting in complex and diverse forms. Based on genetic types and morphological characteristics, it can be divided into four types: erosional tectonic landform, erosional-karst tectonic landform, erosional-denudational tectonic landform, and erosional-depositional landform. These are further subdivided into ten geomorphic sub-types: granite mid-mountain landform, granite low-mountain landform, shallow metamorphic rock mid-mountain landform, shallow metamorphic rock low-mountain landform, clastic rock mid-mountain landform, clastic rock low-mountain landform, red bed clastic peak cluster-terrace combination landform, carbonate rock karst hill-isolated peak-blind valley hill landform, carbonate rock peak cluster-depression combination landform, and valley-terrace landform.

2.2 Stratigraphic Lithology

The exposed strata in the area are mainly granite (γ_5) and shallow metamorphic rocks (Z-O), which together account for 45.5% of the total area of the city (Table 1). The granite weathering layer is relatively thick, with residual-slope deposits mainly consisting of sandy clayey soil, which is loose in structure and highly permeable. Shallow metamorphic rocks have well-developed joints and fissures, with fragmented rock masses, and weathering products are mostly gravelly soil. These two types of strata are classified as "prone-to-collapse-and-slide rock groups" and are highly susceptible to shallow landslides and slope debris flows under rainfall conditions

Table 1: Statistical Table of Major Prone-to-Collapse-and-Slide Rock Groups in Zixing City.

No.	Type	Rock Group	Stratigraphic Code	Exposed Area (km^2)	Number of Disaster Sites	Distribution Density (sites/100 km^2)
1	Fully-strongly weathered granite	Hard massive granite rock group	γ_5	421.06	195	36.39
2	Fragmented shallow metamorphic rock	Hard-relatively hard shallow metamorphic sandstone slate group	Z-O	522.34	262	38.35
3	Fully-strongly weathered clastic rock	Relatively soft-relatively hard thin-medium thick layered rock group	C_1c	32.12	14	43.75

2.3 Rainfall Characteristics

During Typhoon "Gaemi" (July 26-28), the average rainfall in Zixing City was 409.8 mm, with the maximum point rainfall reaching 673.6 mm (Tian'ershan Station, Xingning Town). Rainfall was concentrated in the early morning of July 27, with 3-5 hour cumulative rainfall exceeding 250 mm, far exceeding the rainfall threshold for geological disasters.Government slope is designated as Grade II, with a safety factor of 1.30.

3. Development Characteristics of Landslide Chain Reactions

3.1 Spatial Distribution of Disasters

This survey verified a total of 706 geological disaster sites, including 628 landslides and 78 debris flows (Table 2, Table 3). The disasters were concentrated in Zhoumensi Town (250 sites), Bamian Mountain Yao Township (260 sites), Bailang Town (63 sites), Xingning Town (56 sites), and Huangcao Town (64 sites). These five townships account for 98.2% of the total disaster sites. From the perspective of rock group distribution, 94.9% of the disaster sites are located in granite (465 sites, 65.9%) and shallow metamorphic rock (205 sites, 29.0%) distribution areas.

Table 2: Statistical Table of Geological Disasters in Townships of Zixing City.

Township Name	Area (km^2)	Number of Geological Hazard Sites	Density (sites/100km^2)
Xingning Town	226.94	56	24.68
Zhoumensi Town	351.53	250	71.12
Bamian Mountain Yao Township	307.47	260	84.56
Bailang Town	378.17	63	16.66
Huangcao Town	374.84	64	17.07

Total	2746.79	706	25.7

Table 3: Statistical Table of "7·27" Geological Disaster Types in Zixing City.

Disaster Type	Number (sites)	Proportion (%)	Deaths/Missing (persons)	Direct Economic Loss (10^4 CNY)
Landslide	628	88.9	18	24,522.66
Debris Flow	78	11.1	5	5,970.00
Total	706	100	23	30,492.66

3.2 Types and Processes of Chain Reactions

The survey indicates that landslide chain reactions mainly manifest in the following three types:

Landslide → Debris Flow Transformation Type: Shallow landslide masses mix with surface runoff during movement, increase in water content, transform into debris flows, significantly increase travel distance, and expand the destruction range. For example, landslides on both sides of the valley in Longxi Village, Bailang Town transformed into debris flows, silting up the road surface and blocking river channels.

Landslide → Blockage → Breach Type: Landslide masses block gullies to form barrier lakes, and subsequent breaches trigger flash floods, exacerbating downstream disasters. This survey found multiple gullies blocked by landslides forming temporary dams.

Multi-Hazard Compound Type: Landslides, debris flows, and floods occur simultaneously, overlapping and forming disaster chains. In areas like Zhoumensi Town and Bamian Mountain Yao Township, landslides, slope debris flows, and flash floods erupted simultaneously, causing compound disasters.

3.3 Summary of Disaster Characteristics

High-altitude Initiation: Landslides mostly initiate from hilltops or gully heads, possessing high disaster potential energy. Remote sensing images show that about 80% of landslide initiation points are located in the middle-upper part of slopes.

Shallow Nature: Slip surface depths are generally less than 3 m, belonging to "peel-off" type landslides, with landslide volumes mostly less than 10,000 m^3 (over 95%).

Rapidity: The process from deformation to disaster occurrence takes only a few minutes, leaving very short warning time.

Concealment: Dense vegetation (forest coverage rate 65%) makes early identification difficult through traditional inspections and remote sensing methods.

4. Analysis of the Causative Mechanism of Chain Reactions

4.1 Controlling Effect of Stratigraphic Lithology

Granite and shallow metamorphic rocks have thick weathering layers (generally 10-50 m), loose structure, and good permeability. After rainstorm infiltration, matrix suction rapidly disappears, shear strength sharply decreases, making them prone to shallow sliding. In this survey, landslides in granite areas were mainly shallow soil landslides, while shallow metamorphic rock areas showed more rock landslides and debris flows. These two types of strata provide abundant material sources for landslides and create material conditions for chain transformation (Table 4).

Table 4: Statistical Table of Prone-to-Collapse-and-Slide Rock Groups in Zixing City.

Analysis	Type	Rock Group	Stratigraphic Code	Exposed Area (km^2)	Number of Disaster Sites	Distribution Density (sites/100km^2)
Prone-to-collapse-and-slide	Fully-strongly weathered clastic rock	Relatively soft-relatively hard thin-medium thick layered shale, sandstone rock group	C_1c	32.12	14	43.75
Prone-to-collapse-and-slide	Fragmented-extremely fragmented shallow metamorphic sandstone, slate	Relatively hard thin-medium thick layered shallow metamorphic sandstone, slate (weathered residual-slope layer)	Z_1a, Z_2d, $\in_{1-2}x$, $\in_{2-3}cy$	522.34	262	38.35
Prone-to-collapse-and-slide	Fully-strongly weathered granite	Hard massive granite rock group (granite residual-slope layer)	γ_5	421.06	195	36.39

4.2 Coupling Effect of Rainfall Infiltration and Runoff

Extreme rainfall infiltrates in large amounts within a short time, saturating the slope body and increasing pore water pressure; meanwhile, strong surface runoff erodes the slope surface, forming erosion gullies, further destabilizing the slope body. Monitoring data show that when continuous 5-hour rainfall intensity exceeds 50 mm/h or cumulative rainfall exceeds 250 mm/5h, the probability of landslides and debris flows increases significantly.

4.3 Superimposed Influence of Topography and Human Activities

Steep terrain (>25°) provides sliding potential energy; human activities such as building houses on cut slopes and road construction create free faces, disrupting the original slope balance. The survey found that about 70% of disaster sites are located in areas with housing on cut slopes or road cut slopes, with artificial cut slope heights of 3-8 m, up to more than ten meters, and most without effective support measures.

4.4 Triggering Mechanism of Chain Disasters

After landslide initiation, during movement, the mass mixes with water flow, transforming its fluid properties from solid to liquid; blocking river channels forms temporary dams, and water storage and subsequent breach release energy, triggering secondary flood disasters. This chain reaction is particularly significant in valley geomorphology, such as in Yanping Village, Zhoumensi Town, where landslides blocked streams, and breaches destroyed downstream farmland.

5. Suggestions for Disaster Prevention and Mitigation

5.1 Strengthen Risk Identification and Assessment of Special Strata

Conduct high-precision (1:2000) geological disaster risk surveys, combine with real 3D modeling, and focus on identifying high-altitude and concealed hazard points. Designate granite and shallow metamorphic rock distribution areas as extremely high-risk zones and establish a dynamic risk update mechanism.

5.2 Optimize Warning Models and Emergency Response Mechanisms

Revise geological disaster meteorological risk warning criteria based on the characteristics of chain reactions in special strata and implement upgraded warnings. Establish a comprehensive warning model of “rainfall + stratum + topography”, utilize IoT monitoring equipment (rain gauges, inclinometers, GNSS) to achieve short-term imminent warnings. It is recommended to issue red warnings directly when continuous 5-hour rainfall intensity exceeds 50 mm/h.

5.3 Promote the Combination of Engineering Governance and Ecological Restoration

Implement comprehensive treatment measures such as “anti-slide piles + intercepting drainage + ecological slope protection” for important hazard points (e.g., the 34 hazard points recommended for engineering treatment in this instance). Strengthen vegetation restoration, select deep-rooted tree species, and improve slope erosion resistance. Mandate slope protection engineering for housing construction on cut slopes.

5.4 Strengthen Public Disaster Awareness and Emergency Drills

Carry out “door-to-door” science popularization and publicity targeting the characteristics of a high proportion of middle-aged and elderly people and low willingness to evacuate (82.6% of the deaths and missing persons in this incident were over 60 years old). Organize emergency drills under "isolated island" conditions to improve residents' self-rescue and mutual rescue capabilities.

5.5 Conduct Special Research on Chain Disaster Mechanisms

Establish special funds to study the disaster patterns and chain reaction mechanisms of special strata in the Hunan-Guangdong-Jiangxi mountainous area under extreme rainfall, focusing on key scientific issues such as the landslide-debris flow transformation threshold and barrier dam breach dynamics.

6. Conclusion

The “7·27” geological disaster case in Zixing City indicates that under extreme rainstorm conditions, special strata such as granite and shallow metamorphic rocks are prone to shallow landslides, accompanied by landslide --- debris flow --- flood chain reactions. The disasters are characterized by high-altitude initiation, rapid transformation, and multi-hazard superposition. The disaster mechanism is comprehensively controlled by stratigraphic lithology, rainfall intensity, topography, and human activities.

Future geological disaster prevention and control should focus on special stratum distribution areas, build an integrated “identification --- monitoring --- warning --- governance --- popularization” prevention and control system, enhance the ability to respond to disaster chains under extreme weather, to ensure the safety of life and property of residents in mountainous areas.

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