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Application of Key Technologies in Detailed Geological Hazard Risk Investigation and Analysis of Hazard Development Mechanisms in Western Sichuan Region—A Case Study of Heishui County

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Abstract: ***Detailed geological hazard risk investigation is of great significance for the scientific and effective prevention and control of geological hazards. Aiming at the geological hazard risks under the complex geological environment of western Sichuan, this study systematically and quantitatively analyzed the hazard-inducing conditions, hazard characteristics, and controlling factors of geological hazards in Heishui County through a technical system of "multi-source data fusion-remote sensing interpretation-high-precision monitoring-field verification," and deeply revealed the regional hazard development mechanisms. The results show that: the InSAR monitoring areas with annual deformation rates of 47–89 mm/a have a 92% consistency with field verification; the remote sensing interpretation accuracy rates for landslides (68 sites) and debris flows (5 sites) are 87%; the geophysical prospecting-drilling joint inversion effectively defines the weak sliding zone of strongly weathered sandstone-slate (resistivity 50–200 Ω·m, cohesion 10–25 kPa); and hazard development is synergistically controlled by "slope gradient of 35°–45°-strongly weathered sandstone-slate-daily rainfall ≥50 mm." The research results provide scientific support for regional disaster prevention and technical reference for detailed geological hazard investigation in alpine regions.***

Keywords: Geological hazards, InSAR time-series monitoring, Geophysical prospecting-drilling joint inversion, Hazard-inducing conditions.

1. Introduction

China's southwestern mountainous areas are among the most geologically hazardous regions globally, characterized by "strong concealment, high clustering, and complex disaster chains" [1]. With the deepening of geological hazard prevention concepts, the focus of geological hazard prevention has shifted from "hazard point management" to "dual control of hazard points and risk areas" [2], reflecting not only technological progress but also the inevitable demand for refined risk control. Against this background, revealing hazard development laws through detailed investigations and supporting risk management has become an important research direction [2, 9]. Integrating multi-source technologies such as time-series monitoring (PS-InSAR technology) [3], GIS spatial analysis [4], and analytic hierarchy process-information amount model [5] to break through the limitations of traditional methods and systematically analyze the spatiotemporal evolution patterns and controlling factors of hazard risks has become essential. Taking Heishui County as the research object, this study focuses on the application of key technologies in detailed geological hazard risk investigation [6–8], aiming to provide replicable technical references for refined risk identification, early warning model construction, and prevention strategy formulation in similar mountainous areas, and to facilitate the implementation of the "point-area dual control" prevention system through quantitative analysis of hazard development mechanisms and main controlling factors.

2. Study Area and Data

2.1 Study Area

Heishui County is located on the eastern margin of the Qinghai-Tibet Plateau (30°53′50″ – 32°38′30″N, 102°36′15″ – 103°30′00″E), belonging to the western extension of the Longmen Mountain Fault Zone. The stratum is dominated by Triassic sandstone-slate (T_3z) and limestone (T_3zh), with Quaternary loose deposits (Q) covering river terraces. The region has strong tectonic activity, with a joint density of 3–5 per meter (joint strikes mainly NE, consistent with the regional tectonic stress field direction), leading to fragmented rock masses and a strongly weathered zone thickness of 3–8 m. The alpine deeply incised river valley landform (terrain dropping sharply from northwest to southeast, elevation ranging from 5286 m to 1790 m, deep river incision forming "V"-shaped canyons) and steep slopes (slopes with gradients of 25°–50° account for 78%, with 35°–45° segments being high-hazard areas) are prominent. Frequent heavy rainfall (annual rainfall 800–1200 mm), concentrated in May–September (accounting for over 80% of the annual total) due to topographic uplift, with short-duration heavy rainfall (hourly intensity up to 62.5 mm, observed on June 20, 2024), combined with high porosity of loose deposits (e.g., moraine, colluvial-proluvial deposits), easily triggers debris flows and landslides, making it a county with high susceptibility to geological hazards in Sichuan. The county administers 15 towns and 100 administrative villages, with a 2023 total population of 59,000 (Tibetans accounting for 93.2%) and a GDP of 2.933 billion yuan (tertiary industry accounting for 53.3%). Population and infrastructure are distributed in a strip pattern along river valleys (e.g., Luhua Town has a population density of 12.49 people/km², 2.3 times the county average). Housing is primarily earth-wood structures (68%), with weak disaster resistance, serving as the main disaster-bearing bodies.

2.2 Data Source

Research data cover four core elements: geological, meteorological, socio-economic, and hazard data. (1) Geological data include a 1:50,000 regional geological map (systematically reflecting stratum lithology and structural features), a 1:10,000 high-precision topographic map (for slope and aspect analysis), and 2743.14 meters of drilling data (to verify geophysical inversion results). (2) Meteorological data consist of continuous observation records from 6 rain gauge stations from 2013 to 2023 (including hourly rainfall intensity and daily cumulative rainfall). (3) Socio-economic data are derived from the third national land use survey map and population density distribution maps of 100 administrative villages (to clarify the spatial distribution of disaster-bearing bodies). (4) Hazard data integrate 228 historical hazard points (including 90 landslides, 118 debris flows, and 20 collapses).

3. Key Technical Methods and Analysis

3.1 InSAR Time-Series Monitoring and Deformation Feature Extraction

An improved time-series InSAR monitoring technology, based on small-baseline subset InSAR (SBAS-InSAR) and persistent scatterer InSAR (PS-InSAR), was applied to process 38 Sentinel-1 satellite SAR images (spatial resolution 5 m×20 m, time interval 12 days) covering the study area from 2022 to 2024, extracting surface deformation information and obtaining long-term fine surface deformation monitoring results.

3.1.1 Data Preprocessing

Using the image from June 15, 2023, as the main image, orbital parameter correction and registration with a 30 m resolution DEM were performed to reduce topographic phase errors, controlled within 0.1 pixels. Fifty-two small baseline pairs with time baselines <60 days and spatial baselines <200 meters were selected to generate differential interferograms, and phase unwrapping was conducted using the minimum cost flow algorithm to suppress atmospheric noise interference.

3.1.2 Deformation Inversion and Verification

Through time-series analysis, the annual average deformation rate (-90–+90 mm/a) of Heishui County was inverted, identifying 38 abnormal deformation areas (deformation rate >40 mm/a). Field verification showed that 10 of these 38 deformation areas coincided with historical hazard points, and 28 were newly identified hazards (2 verified as active landslides by drilling), with a consistency rate of 92%. For example, the Chalas Bami Slope in Luhua Town, with an InSAR-monitored annual deformation rate of 82 mm/a, was verified as a new medium-sized landslide (area 440,753.14 m²) through field investigation, revealing trailing edge tension cracks (width 5–10 cm) and local leading edge collapse.

3.2 Remote Sensing Interpretation Marker Extraction and Hazard Identification

Geological hazards in the area are controlled by conditions such as geological environment, meteorological hydrology, vegetation coverage, and human engineering activities, characterized by numerous and widespread small-scale hazards, uneven spatiotemporal distribution, and concentrated outbreak periods. Using GF-2 images (0.8 m resolution) and DEM (5 m resolution), combined with geological environment features, three-dimensional interpretation markers of "morphology-tone-topography" were established to identify 73 suspected hazard points (68 landslides, 5 debris flows; no collapse hazard points were interpreted). Comparison with historical hazard point locations showed that 27 of the interpreted hazard points were historical, with all hazardous bodies being small to medium in scale.

3.2.1 Landslide Interpretation Markers

Morphological features: Armchair-shaped landform (steep scarp at the trailing edge, arc-shaped mound in the middle), clear landslide boundary (boundary line curvature >0.5). Tone features: Fresh sliding surface appears grayish-white (reflectance 15%–25%), debris accumulation appears grayish-yellow (reflectance 10%–18%), distinct from surrounding vegetation (reflectance 5%–8%). Topographic features: Slope gradient 25°–45°, slope aspect angle with the regional main structural line (NE direction) <30°, catchment area 0.1–1 km².

3.2.2 Collapse Interpretation Markers

Morphological features: Planar morphologies such as arc-shaped, strip-shaped, triangular, and crescent-shaped. Tone features: Lighter tone of the collapse wall, generally no vegetation growth. Topographic features: Talus deposits at the slope toe. Collapses (collapse clusters) are less frequent but cause significant damage to vegetation and topography, with extremely distinct tone features on remote sensing images. Collapse hazard development areas are in steeper slopes, with collapse bodies mainly consisting of weakly consolidated sandstone, pebbly sandstone, mudstone, structurally developed limestone, sandstone-slate, and steep cliffs/scarps formed by loose terrace deposits. Collapsed deposits are uneven and irregular in shape, with conical deposits or large boulders generally visible in lower areas. Image patches are irregular and rough, with collapse surfaces as steep cliffs and boundaries as arc-shaped serrated thin lines.

3.2.3 Debris Flow Interpretation Markers

Sediment source area: Upstream valley slope >35°, with collapse/landslide relics (area proportion >20%). Conduit area: Longitudinal slope of the gully bed 10°–25°, width 5–20 m, images appear linearly dark gray (reflectance 8%–12%). Deposition area: Fan-shaped landform at the gully mouth (longitudinal slope 5°–10°), with multiple tributary gullies visible on the fan surface (density >2/km), reflectance 12%–18%. When vegetation coverage in the sediment source area

<30%, the probability of debris flow initiation increases by 50%.

3.3 Geophysical Prospecting-Drilling Joint Inversion and Slope Structure Analysis

Key or typical slopes were selected to deploy exploration profiles to improve hazard evaluation accuracy. A total of 2.55 km of measured geophysical lines were deployed, with 255 physical points.

Profile WT-L1: Located in Rela Village, Luhua Town, Heishui County, deployed from near the mountain top downslope, with steep terrain, survey line length 1100 m, orientation 78°.

Profile WT-L2: Located in Mudu Village, Zhimulin Town, Heishui County, deployed from near the ridge behind Mudu Village Breeding Farm downslope to Mudu Village, with steep terrain at the tail end, survey line length 950 m, orientation 139°. This profile has boreholes ZK03 (~50 m southwest of 375 m), ZK02 (~130 m southwest of 580 m), and ZK01 (~190 m southwest of 800 m).

Profile WT-L3: Located in Rishiduo Village, Musu Township, Heishui County, with significant topographic relief, survey line length 500 m, orientation 172°. Deployed from near the high-voltage line on the hillside downslope, this profile has boreholes ZK04 (~130 m) and ZK05 (~330 m west).

3.3.1 High-Density Electrical Method Parameter Settings

The Wenner array (electrode spacing a=10 m, n=1–5) was used to measure apparent resistivity (ρs). Data were processed with a smoothing filter (window size 3) and 2D inversion (least squares method) to generate resistivity profiles. Comparison showed that the dipole array has higher resolution in deep exploration (>50 m), while the Wenner array is more sensitive to shallow anomalies (<30 m), so a comprehensive array combining both was adopted.

3.3.2 Comparative Analysis of Drilling and Geophysical Prospecting

Analysis of the apparent resistivity profile of Profile WT-L2 (Mudu Village, Zhimulin Town) showed a maximum exploration depth of ~90 m, with rock layers distributed in a layered structure, divided into five layers: (1) Quaternary colluvial-proluvial deposits (Q_4col+dl), silty clay, 0–11 m depth (resistivity <2.2); (2) moderately weathered slate, 0–40 m depth (resistivity 2.4–3); (3) moderately weathered metamorphic sandstone (0–25 m) and sandstone (2–5 m) (resistivity >2.5); (4) moderately weathered phyllite, 5–40 m depth (resistivity >2.6); (5) moderately weathered mudstone (resistivity <2.5). The profile near boreholes ZK01, ZK02, and ZK03 is in good agreement with drilling data.

Analysis of the apparent resistivity profile of Profile WT-L3 (Rishiduo Village, Musu Township) showed a maximum exploration depth of ~60 m, divided into three layers: (1) Quaternary colluvial-proluvial deposits (Q_4col+dl), blocky gravelly soil, 0–20 m depth (resistivity 1.6–2.8); (2) moderately weathered phyllite, 5–10 m depth (resistivity 1.6–2); (3) moderately weathered slate (resistivity >2). The profile near boreholes ZK04 and ZK05 is in good agreement with drilling data.

3.4 Rainfall Threshold Model Construction and Risk Assessment

Based on 10-year rainfall data (2013–2023) and occurrence times of 73 hazard points, the correlation between rainfall intensities of different durations (1-hour, 24-hour) and hazards was analyzed to construct a rainfall threshold model. Using 1-hour and 24-hour cumulative rainfall before the disaster (I_1, I_{24}) as variables, 5 hazard points with no rainfall records were excluded, leaving 68 samples. Results showed I_1=20–40 mm (75%) and I_{24}=50–70 mm (82%), with a critical value of $I_1 \geq 20$ mm or $I_{24} \geq 50$ mm.

4. Hazard Development Characteristics and Controlling Factors

4.1 Hazard Types and Scale Distribution

A total of 73 hazard points were identified in the entire region, including 68 landslides (93.2%) and 5 debris flows (6.8%). Most hazards are small-scale (area <10^5 m², 82%), with medium-scale (10^5–10^6 m²) accounting for 15% and large-scale (>10^6 m²) only 3%. Hazards are distributed in strip patterns along major rivers and transportation arteries, concentrated along stratum lithology and geological structures: (1) 35% along G347 National Highway, where road cutting forms high and steep free faces (slope >40%) (e.g., Si Bami Landslide in Luhua Town, cutting height 15 m, slope 50°); (2) 30% along the Maoergai River Valley, with river incision rate 2 mm/a and development of unloading fissures on riverbanks (density 2–3/m) (e.g., Erniunai Village Landslide in Qinglang Township); (3) 25% along the Xiaohei River Valley, with intensive human activities (concentrated residential areas and farmland) and high slope modification intensity (land reclamation rate >30%) (e.g., Mudu Village Landslide in Zhimulin Town). Distribution is in good agreement with county-registered geological hazard points.

4.2 Quantitative Control of Hazard-Inducing Conditions

Slope gradient is significantly positively correlated with hazard point density. The hazard point density in the 35°–45° slope segment is 0.02 points/km² (5 times that of the <25° segment), with a critical slope gradient of 35°. In areas with strongly weathered sandstone-slate development, the hazard point density is 0.018 points/km² (3 times that of intact bedrock areas). When the cohesion (c) ≤25 kPa, the probability of instability increases by 40% (75% probability when c=10–25 kPa, and 35% when c>25 kPa). Hazards occurring from June to September account for 85%, and the disaster occurrence rate is 32% when daily rainfall ≥50 mm (8 times that of <50 mm). Statistical analysis of rainfall data from 68 hazard points (2013–2023) established a duration-intensity threshold model: disaster probability reaches 70% when 1-hour rainfall intensity (I_1) ≥20 mm or 24-hour cumulative rainfall (I_{24}) ≥50 mm; and 90% when I_1 ≥30 mm and I_{24} ≥60 mm.

5. Conclusion and Discussion

(1) The combined application of InSAR time-series monitoring (deformation rate >40 mm/a) and remote sensing interpretation (three-dimensional markers) can efficiently identify concealed hazards (consistency rate 92%). Geophysical prospecting-drilling joint inversion (resistivity 50–200 Ω·m corresponding to strongly weathered sandstone-slate) effectively analyzed slope structures and provided key parameters for stability evaluation. The development of slope hazards in Heishui County is synergistically controlled by topography (35°–45° slope), rock-soil mass (c=10–25 kPa), and rainfall (I_{24} ≥50 mm), with key towns (e.g., Luhua Town) at the highest risk level. The rainfall threshold model (I_1 ≥20 mm or I_{24} ≥50 mm) and risk assessment model (accuracy rate 85%) can provide technical support for regional early warning.

(2) It is recommended to promote the "InSAR + remote sensing + geophysical prospecting" multi-technology integrated investigation method in similar mountainous areas to improve the efficiency of concealed hazard identification. For high-risk slopes (deformation rate >50 mm/a), deploy GNSS displacement meters and automatic rain gauges to update the rainfall threshold model in real-time. For slopes of strongly weathered sandstone-slate, adopt combined reinforcement with anti-slide piles (pile length ≥15 m) and interception-drainage works (ditch depth ≥1.5 m). Incorporate extremely high-risk areas into "no-construction zones" in territorial space to restrict new residential areas and projects. In densely populated river valleys, establish a "hazard point-risk area-disaster-bearing body" three-level early warning platform to achieve dynamic visualization of disaster risks.

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