Supplementary Material

Accounting for Climate Uncertainty in Landslide Hazard Assessment: A Quantitative Weighting Framework for Meizhou City, South China

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This supplementary material consists of three main sections. Section S1 provides an overview of the expert panel. Section S2 details the questionnaire provided to the expert panel. Section S3 presents a side-by-side comparison of the matrix values for the first level (climate-related risk factors) and the experts' judgments, along with consistency results.

S1. Expert Panel Overview

The expert panel consists of twelve professionals covering design, research, and asset management functions, all of whom are involved in landslide prevention and control efforts in Guangdong Province and Meizhou City. Among them, six participants (50%) are geotechnical engineers primarily engaged in slope investigation, design, and geological hazard mitigation; three (25%) are meteorological experts familiar with the climatic characteristics of Meizhou City and disaster-causing factors such as typhoons and rainfall; three (25%) are slope maintenance managers responsible for the daily inspection and maintenance of highway slopes and potential geological hazard sites. The experts' affiliations are evenly distributed across universities, the Provincial Geological Environment Monitoring Station, the Municipal Meteorological Bureau, and transportation departments.

In terms of experience: eight experts have 11–20 years of professional experience, two have 6–10 years, and two have 0–5 years (all of whom are young technical personnel who have participated in geological hazard investigations in Meizhou in recent years). Most respondents indicated that they had observed the actual impact of climate change (such as extreme rainfall, increased typhoon intensity, and abnormal high temperatures in winter) on slope stability in Meizhou, demonstrating that the experts possess practical familiarity with the disaster-causing factors under study.

When asked, "To what extent do current slope design/geohazard prevention codes fully account for climate-related changes?" on a scale of 1 (not considered) to 5 (fully considered), 58.3% of experts rated 3, 25% rated 2, and 16.7% rated 4, with an average score of 2.9. This indicates that experts generally believe there is significant room for improvement in current standards regarding the incorporation of quantitative weights for climate-related hazard factors. This diverse disciplinary perspective and geographical representation aligns with the panel size (5–15 members) recommended for AHP studies and provides balanced insights across the fields of design, operations, and research.

S2. Expert Panel Survey

S2.1. Overview of Survey Questions

To align with the hierarchical structure proposed by this study and capture the preferences of experts at each level, a structured AHP questionnaire was designed. Based on the fundamental principle of the Analytic Hierarchy Process—that a complete set of pairwise comparisons must be conducted for *n* alternative elements [1,2]—a total of 54 pair-wise comparisons were derived:

$$\frac{n\,(n-1)}{2} \qquad \text{(S1)}$$

This structure ensures that the relative priorities of each level within the hierarchy are fully weighted. The actual survey contained 55 questions, with one additional question included for consistency verification. The survey was distributed online and is expected to take 25–30 minutes to complete. Experts were provided with clear definitions and examples of each hazard factor, landslide type, and slope component. The questionnaire required each expert to complete a set of subsections to collect demographic information, general knowledge, and pairwise comparison judgments using the 1–3–5–7–9 AHP scale (see Table S1).

Based on the model's hierarchical structure, the number of pairwise comparisons is as follows:

- **Level 1** (4 climate-related disaster factors): 6 paired comparisons
  - Causative factors: rainfall, temperature fluctuations, typhoon-induced heavy rains, freeze-thaw cycles
  - Number of pairwise comparisons:

$$\frac{4\,(4-1)}{2} = 6.$$

- **Level 2** (3 types of landslides): For each risk factor, pairwise comparisons are made among the 3 types of landslides. There are 4 risk factors in total. Since there are 3 types of landslides and 2 risk factors to choose from for each factor, the total number of combinations is 4 × 3 = 12.
  - Landslide types: shallow soil landslides, deep rock landslides, rockfalls
  - Number of pairwise comparisons under each risk factor:

$$\frac{3\,(3-1)}{2} = 3.$$

- **Level 3** (3 slope components): For each of the three landslide types, pairwise comparisons are made among the three slope components. Since there are three landslide types, and there are 3 × 2 = 9 possible combinations for each type, the total number of combinations is 3 × 3 = 9. Multiplying this by the 4 triggering factors yields 4 × 9 = 36.

Based on the hierarchical structure, a total of 54 pairwise comparison questions were derived (6 at Level 1, 12 at Level 2, and 36 at Level 3). The actual survey contained 55 questions, as one additional consistency verification question was included.

Table S1 Scale definitions provided for survey responders

Scale value	Definition
1	X and Y are equally important
2	X is slightly more important than Y (or 1/3 when Y is slightly more important than X)
5	X is moderately more important than Y (or 1/5 when Y is moderately more important than X)
7	X is strongly more important than Y (or 1/7 when Y is strongly more important that X)
9	X is extremely more important than Y (or 1/9 when Y is extremely more important than X)
2, 4, 6, 8	If one of the prior scale values is not applicable and you cannot decide (i.e., It is between 1 and 3) you can select the intermediate values 2, 4, 6, 8 (or 1/2, 1/4, 1/6, 1/8 for the reciprocal)

S2.2 List of Survey Questions

The following are the paired comparison questions from the survey, listed by hierarchical group.

Level 1: Climate-related disaster factors (4)

1. When assessing the impact of climatic factors on landslide risk in Meizhou City, how significant is rainfall compared to temperature fluctuations?
2. How significant is rainfall compared to typhoon-induced downpours?
3. How significant is rainfall compared to freeze-thaw cycles?
4. How significant are temperature fluctuations compared to typhoon-induced downpours?

5. How significant are temperature fluctuations compared to freeze-thaw cycles?
6. How significant are typhoon-induced downpours compared to freeze-thaw cycles?

Level 2: Landslide Types (3 types) — Repeat for each disaster-causing factor

In the following questions, replace the "disaster-causing factor" with: rainfall, temperature changes, typhoon-induced heavy rain, or freeze-thaw cycles (4 sets in total, 3 questions per set).

7. Under the influence of [disaster-causing factor], how significant is the impact of shallow soil landslides on the overall slope stability compared to deep rock landslides?
8. How significant are shallow soil landslides compared to rockfalls?
9. How significant are deep rock landslides compared to rockfalls?

Level 3: Slope Components (3) — Repeated for each disaster-causing factor and each landslide type

In the following questions, there are 12 combinations resulting from the interaction of disaster-causing factors (4) and landslide types (3). For each combination, three pairs of comparisons are made among the three components, resulting in a total of 36 questions.

Taking the "rainfall–shallow soil landslide" combination as an example:

10. When rainfall acts on shallow soil landslides, how significant is the overburden compared to the bedrock interface in terms of triggering the landslide?
11. How significant is the overburden compared to the tensile fracture zone?
12. How significant is the bedrock interface compared to the tensile fracture zone?

(The question format is the same for the remaining combinations; only the hazard factors and landslide types have been changed.)

S3. Pairwise Comparison Matrices and Consistency Results

Pairwise comparison matrices were constructed separately for each level of the hierarchical structure (first-level disaster-causing factors, second-level landslide types, and third-level slope components). Each expert was required to complete the corresponding matrix at each level. The original matrices from the twelve experts for the first level (four climatic hazard factors) are presented below (Tables S2.a through S2.l). Due to space limitations, the detailed matrices for the second and third levels are not included here, but the calculation process and methodology are identical.

Table S2.a Level 1 Expert 1 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	5.00	2.00	7.00
Temperature fluctuations	0.20	1.00	0.33	3.00
Typhoon-induced heavy rain	0.50	3.00	1.00	5.00
Freeze-thaw cycles	0.14	0.33	0.20	1.00

Table S2.b Level 1 Expert 2 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	7.00	3.00	8.00
Temperature fluctuations	0.14	1.00	0.20	2.00
Typhoon-induced heavy rain	0.33	5.00	1.00	6.00
Freeze-thaw cycles	0.13	0.50	0.17	1.00

Table S2.c Level 1 Expert 3 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	4.00	1.00	5.00
Temperature fluctuations	0.25	1.00	0.33	2.00
Typhoon-induced heavy rain	1.00	3.00	1.00	4.00
Freeze-thaw cycles	0.20	0.50	0.25	1.00

Table S2.d Level 1 Expert 4 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	3.00	0.50	6.00
Temperature fluctuations	0.33	1.00	0.20	3.00
Typhoon-induced heavy rain	2.00	5.00	1.00	7.00
Freeze-thaw cycles	0.17	0.33	0.14	1.00

Table S2.e Level 1 Expert 5 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	6.00	2.00	7.00
Temperature fluctuations	0.17	1.00	0.25	2.00
Typhoon-induced heavy rain	0.50	4.00	1.00	5.00
Freeze-thaw cycles	0.14	0.50	0.20	1.00

Table S2.f Level 1 Expert 6 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	5.00	1.00	6.00
Temperature fluctuations	0.20	1.00	0.20	2.00
Typhoon-induced heavy rain	1.00	5.00	1.00	5.00

Freeze-thaw cycles	0.17	0.50	0.20	1.00

Table S2.g Level 1 Expert 7 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	2.00	0.33	4.00
Temperature fluctuations	0.50	1.00	0.20	3.00
Typhoon-induced heavy rain	3.00	5.00	1.00	6.00
Freeze-thaw cycles	0.25	0.33	0.17	1.00

Table S2.h Level 1 Expert 8 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	4.00	1.00	5.00
Temperature fluctuations	0.25	1.00	0.25	2.00
Typhoon-induced heavy rain	1.00	4.00	1.00	5.00
Freeze-thaw cycles	0.20	0.50	0.20	1.00

Table S2.i Level 1 Expert 9 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	7.00	3.00	9.00
Temperature fluctuations	0.14	1.00	0.20	3.00
Typhoon-induced heavy rain	0.33	5.00	1.00	7.00
Freeze-thaw cycles	0.11	0.33	0.14	1.00

Table S2.j Level 1 Expert 10 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	3.00	0.50	5.00
Temperature fluctuations	0.33	1.00	0.17	2.00
Typhoon-induced heavy rain	2.00	6.00	1.00	7.00
Freeze-thaw cycles	0.20	0.50	0.14	1.00

Table S2.k Level 1 Expert 11 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	5.00	2.00	6.00
Temperature fluctuations	0.20	1.00	0.33	2.00
Typhoon-induced heavy rain	0.50	3.00	1.00	4.00

Freeze-thaw cycles	0.17	0.50	0.25	1.00

Table S2.l Level 1 Expert 12 Pairwise Matrix

	Rainfall	Temperature fluctuations	Typhoon-induced heavy rain	Freeze-thaw cycles
Rainfall	1.00	2.00	0.50	4.00
Temperature fluctuations	0.50	1.00	0.20	3.00
Typhoon-induced heavy rain	2.00	5.00	1.00	5.00
Freeze-thaw cycles	0.25	0.33	0.20	1.00

S3.1. Consistency Results

Consistency analysis confirmed that the set of expert judgments aggregated using the geometric mean is internally consistent and suitable for AHP calculations. The maximum eigenvalue of the first-level aggregation matrix λ_{max} = 4.22, with a consistency index (CI) of 0.073 and a consistency ratio (CR) of 0.081, which is below the acceptable threshold of 0.10. The CR values for each disaster-causing factor in the second-level slope types range from 0.017 to 0.069, indicating good consistency among experts when focusing on specific disaster-causing factors. For the third-level 3×3 pairwise comparison matrices, the CR values were all 0.000, indicating perfect consistency in expert judgments at this level. The geometric mean aggregation process successfully harmonized individual perspectives without amplifying inconsistencies, and expert reasoning remained stable from the first to the third level. The low CR values also suggest that expanding the expert panel in the future is unlikely to reverse the relative rankings but may help refine confidence intervals regarding the weights.

Table S3 Consistency Results with the Geometric Mean

Level	λmax	CI	CR
Level 1 (Disaster-causing factors)	4.22	0.073	0.081
Level 2 Rainfall	3.05	0.025	0.043
Second Level: Temperature Variation	3.03	0.015	0.026
Second Level: Typhoon-induced Heavy Rainfall	3.08	0.040	0.069
Second Level: Freeze-Thaw Cycle	3.02	0.010	0.017
Third Level (All 3×3 Matrices)	2.00	0.000	0.000

References

[1] Saaty TL. The analytic hierarchy process: planning, priority setting, resource allocation. McGraw-Hill; 1980. doi:10.1016/0270-0255(87)90473-8

[2] Saaty, T.L. *Priority setting in complex problems*. IEEE Trans. Eng. Manage. 1983, **30**, 140–155. https://doi.org/10.1109/TEM.1983.6448657