

Appendix A. Definitions and data sources for regional-background and stage-specific indicators

Table A1. Regional site characteristics and key technical-control indicators (16 items): quantification methods and data sources

Criterion	Indicator (code)	Definition	Quantification and data source
C18 Regional site characteristics	Building structural type and construction standard (X70)	Structural system, construction period, and seismic-design level of the earthquake-damaged building	Structural-type classification and seismic-fortification-intensity rating; field survey and local design drawings
C18	Site geology and terrain conditions (X71)	Effects of liquefaction, soft soil, sloping terrain, and narrow streets on debris stability and equipment deployment	Site-class and slope grading; geotechnical information and field investigation
C18	Aftershock intensity and frequency (X72)	Ongoing disturbance of debris stability caused by aftershock activity	Aftershock count per unit time and maximum-magnitude class; seismic-network observations (rolling update)
C19 Shoring/bracing group (activated in S1)	Shoring-system selection and load verification (X73)	Appropriateness of the shoring configuration and adequacy of load verification	Pass rate of design-compliance checks and verification coverage; technical-plan review records
C19 Shoring/bracing group	Jacking capacity and synchronization (X74)	Capacity matching and synchronized control of multi-point jacking	Load safety factor and synchronization deviation (mm); equipment specifications and field monitoring
C19 Shoring/bracing group	Shoring-system monitoring, review, and secondary reinforcement (X75)	Post-installation load monitoring/review and timely secondary reinforcement as operations progress	Monitoring-point coverage, review frequency, and reinforcement response time; operation records
C19 Slab-breaching group (activated in S2)	Breaching-method suitability (X76)	Compatibility of the method with component material, thickness, reinforcement, and casualty location	Pass rate of method-component compatibility checks; technical plan and component survey
C19 Slab-breaching group	Breaching vibration and structural-disturbance control (X77)	Control of breaching-induced vibration affecting residual structures and survivable spaces	Vibration-velocity measurement (mm/s) relative to limits; field vibration monitoring
C19 Slab-breaching group	Dust and spark control (X78)	Effectiveness of wet operations, dust shielding, and spark-control measures	Pass rate of control-measure checks and measured dust concentration; operation records and environmental monitoring
C19 Slab-breaching group	Breaching-opening location and dimensions (X79)	The opening avoids primary load-bearing components and casualties while meeting rescue-access requirements	Opening-location deviation and dimensional-compliance checks; plan-to-field comparison
C19 Debris-removal group (activated in S3)	Lifting plan and lifting-point selection (X80)	Lifting sequence, lifting-point layout, assessment of connected components, and trial-lift execution	Pass rate of plan-review checks and records of trial-lift implementation
C19 Debris-removal group	Machine-human coordination and blind-spot control (X81)	Coordination of mechanical and manual work and personnel control in equipment blind spots	Compliance with coordination procedures and number of blind-spot intrusion alarms; field-management records
C19 Debris-removal group	Removal sequence and unloading control (X82)	Execution of layered/segmented removal and control of unloading rate	Sequence-compliance rate and debris-displacement rate (mm/h); operation and monitoring records
C19 Casualty-transport group (activated in S4)	Medical coordination and crush-syndrome management (X83)	Pre-extrication medical intervention, crush-syndrome prevention, and coordination of onward transfer	Timing of medical intervention and compliance with treatment procedures; medical records
C19 Casualty-transport group	Casualty-condition monitoring and communication (X84)	Continuous vital-sign monitoring and psychological support/communication throughout rescue	Continuity of vital-sign monitoring and communication frequency; medical and operation records
C19 Casualty-transport group	Transport, evacuation, and site-handover organization (X85)	Transport route, stretcher-team organization, equipment withdrawal sequence, and site handover	Contingency-plan compliance and pass rate of withdrawal checks; operation records

Appendix B. Consistency of the cascading recursion with non-homogeneous DBN forward filtering

B.1 Cascading-consistency proposition and applicability conditions

Proposition B1 (numerical consistency under the same marginal-independence approximation). For a given stage sequence, node k , and evidence sequence $e_{0:k}$, the WPC-BN prediction-and-update recursion is numerically identical to forward filtering in a stage-conditioned non-homogeneous DBN implemented with the same marginal-independence approximation and time-point definitions.

The proposition holds under four conditions: (i) state evolution satisfies the first-order Markov property; (ii) inter-slice arcs connect only the same persistent variable across adjacent time slices; (iii) after evidence arrives at a node, the system can be updated under a quasi-steady-state assumption; and (iv) after inference at each node, the joint posterior over persistent variables is approximated by the product of their marginal posteriors. Conditions (i)–(iii) define the stage-conditioned first-order formulation used here. Condition (iv) is the factorization adopted for modular cascading. Under the independent per-variable CTMC transition specification used in this study, the predictive transition kernel factorizes across persistent states, so this approximation does not alter the prediction step of Eq. (B2); it affects only next-node initialization after within-node evidence has induced posterior dependence among persistent states. Supplementary Section S6.7 defines an exact-joint benchmark for evaluating that dependence when the complete stage-network parameterization is used.

A conventional DBN consists of an initial network B_0 and a transition network $B \rightarrow$ (2-TBN) (Murphy, 2002). Over time slices 0 – T , its joint distribution is:

$$P(Z_{0:T}) = P(Z_0) \prod_{t=1}^T P(Z_t | Z_{t-1}) \quad (B1)$$

Proof of Proposition B1. The standard forward-filtering recursion of a non-homogeneous DBN can be decomposed into a prediction step and an update step:

$$\text{Prediction: } \bar{P}(X_k^i) = \sum_{x \in \{0,1\}} P(X_k^i | X_{k-1}^i = x, S_k, \Delta t_k) P(X_{k-1}^i = x | e_{0:k-1}) \quad (B2)$$

$$\text{Update: } P(Z_k | e_{0:k}) = \frac{P(e_k | Z_k) \bar{P}(Z_k)}{\sum_{z_k} P(e_k | z_k) \bar{P}(z_k)} \quad (B3)$$

Under assumptions (ii) and (iv), prediction can be performed separately for each persistent state variable, and the joint predictive prior is approximated by the product of the marginal predictive priors; the matrix form of Eq. (B2) is Eq. (15) in the main text. Under assumptions (i) and (iii), the update step is equivalent to standard static-BN inference with these predictive priors used as root-node priors. Mathematical induction therefore establishes that the two recursions remain numerically identical at every node under the same approximation. Because the induction assumes the approximation on both sides, Proposition B1 is a statement about implementation equivalence and carries no claim of equivalence to a DBN that propagates the exact joint; the detailed induction is repeated in Supplementary Section S6.1 and the two statements should be read as one result.

Appendix C. Parameterization equations

C.1 Prior-probability quantification based on fuzzy set theory

For a trapezoidal fuzzy number $\tilde{F} = (a, b, c, d)$, the membership function is given by Eq. (C1).

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & a \leq x < b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c < x \leq d \\ 0, & \text{otherwise} \end{cases} \quad (C1)$$

Individual expert weights, weighted aggregation, centroid defuzzification, and the Onisawa transformation are given by:

$$S_k = \sum_{g=1}^5 C_{kg}, w_{e,k} = \frac{S_k}{\sum_{j=1}^n S_j} \quad (C2)$$

$$F = \sum_{k=1}^n w_{e,k} F_k = (\sum w_k a_k, \sum w_k b_k, \sum w_k c_k, \sum w_k d_k), \text{FPS} = \text{Centroid}(F) \quad (C3)$$

$$K = 2.301 \left[(1 - \text{FPS}) / \text{FPS} \right]^{1/3}, F = 10^{-K} (\text{FPS} > 0); \text{FPS} = 0 \Rightarrow F = 0 \quad (C4)$$

where C_{kg} is the score assigned to expert k under criterion g in Table 6, and $F_k = (a_k, b_k, c_k, d_k)$ is the trapezoidal fuzzy number corresponding to that expert's linguistic judgment. Weighted endpoint aggregation is applied directly to the trapezoidal fuzzy numbers rather than conflating membership-function mixing with endpoint operations. The membership functions for the seven linguistic variables VL–VH are shown in Fig. C1, and their trapezoidal parameters are listed in Supplementary Table S2-1.

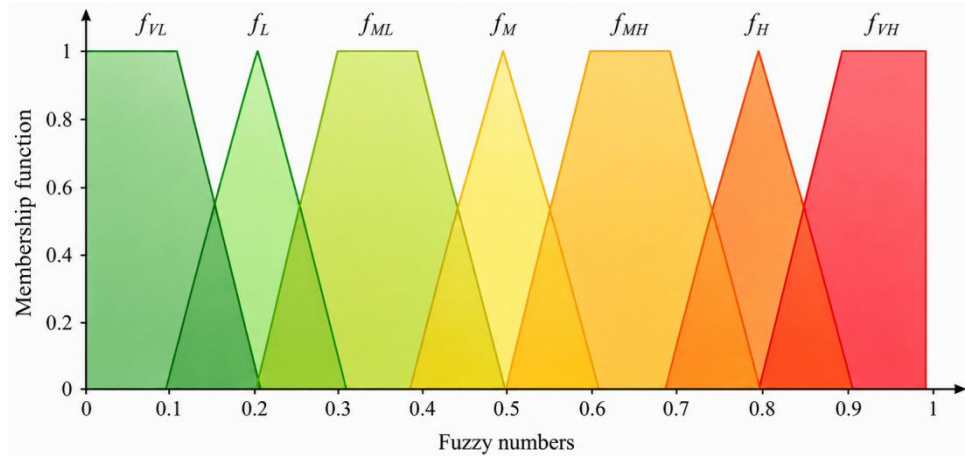


Fig. C1. Membership functions of the seven linguistic variables (VL–VH)

C.2 AHP–entropy–game-theoretic combination weighting

For the AHP consistency test, the random consistency index (RI) is 0.58, 0.90, and 1.12 for $N = 3$, 4, and 5, respectively. After each individual judgment matrix passes the consistency test, the resulting priority vectors are aggregated using expert weights:

$$CI = \frac{\lambda_{\max} - N}{N - 1}, CR = CI / RI < 0.1 \quad (C5)$$

$$W_A(X_i) = \sum_{k=1}^n w_{e,k} w_{ki} \quad (C6)$$

Entropy-based proportions, entropy values, and objective weights are computed as:

$$r'_{ki} = \frac{r_{ki} - \min_k r_{ki}}{\max_k r_{ki} - \min_k r_{ki}}, p_{ki} = \frac{w_{e,k} r'_{ki}}{\sum_k w_{e,k} r'_{ki}}; E_i = -\frac{1}{\ln n} \sum_k p_{ki} \ln p_{ki} \quad (C7)$$

$$W_B(X_i) = \frac{1 - E_i}{\sum_{j=1}^m (1 - E_j)} \quad (C8)$$

Under the first-order condition used to combine the two weight sources, the combination coefficient α is obtained from:

$$G\alpha = b, \text{ where } G_{sr} = \omega_s \bullet \omega_r, \quad b = (\omega_l \bullet \omega_l, \dots, \omega_l \bullet \omega_l)^T \quad (C9)$$

For two weight sources:

$$\begin{bmatrix} \omega_1 \bullet \omega_1 & \omega_1 \bullet \omega_2 \\ \omega_2 \bullet \omega_1 & \omega_2 \bullet \omega_2 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} \omega_1 \bullet \omega_1 \\ \omega_2 \bullet \omega_2 \end{bmatrix} \quad (C10)$$

$$\alpha_s^* = \alpha_s / \sum_{r=1}^l \alpha_r, W^* = \sum_{s=1}^l \alpha_s^* w_s \quad (C11)$$

Appendix D. Structural and inference consistency checks

The following checks were applied to every stage model. (1) Structural consistency: the B- and C-layer backbones are isomorphic across stage models; the full indicator set is unchanged, and only the activated subset varies. (2) Background-node isolation: regional site-characteristic indicators are parentless root nodes and connect only to their corresponding criterion layer. (3) Closure of propagated variables: the persistent-state set (X11, X12, X21, X29, X31, X39–X41) is fixed during model construction and propagated variable by variable; the residual-risk sentinel H(k–1) is activated only under the conditions specified in Section 2.3.4. (4) Parameter-reuse consistency: CPT weights for common indicators are reused across models, CPTs for technical indicators are calibrated by node, and transition rates are calibrated by variable group $\times$ stage type. (5) Inference validity: each model satisfies the three axioms used for Bayesian-network sensitivity checking: Axiom 1, a small increase or decrease in any parent-node prior should induce a small change in the child posterior in the same direction; Axiom 2, the relative influence ordering of parent-node perturbation subsets on the child posterior should remain consistent; and Axiom 3, the combined evidence influence of any parent-node subset should be no smaller than that of any proper subset (Jones et al., 2010). All stage models satisfied the three axioms. The perturbation tests reported in Section 3.4 of the main text for the M2 linear branch were repeated for the remaining branches without exception, using the same perturbation ranges and evaluating the corresponding posterior changes. Cascading propagation was additionally evaluated through the cross-node perturbation tests in Section 3.4.