Dynamic risk assessment of compound hazards based on VFS–IEM–IDM

A case study of typhoon–rainstorm hazards in Shenzhen, China

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Outline

Background

- With global climate change, many cities have suffered extreme natural hazards more frequently [1]
- There has been an increasing interest in assessing compound hazards, which leads to more severe catastrophes than individual hazards risks [2]
- Typhoons and rainstorms, the compound hazards, are the main natural hazards in Shenzhen [3]
- It is essential to assess the typhoon–rainstorm hazards risk in Shenzhen

Problem statement: compound hazard risk

- The characteristics of compound hazards include: (1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events that amplify the impact
- There are strong connections between different hazard drivers in compound hazards and can be quantified by the probability of losses [4]
- The compound hazards risk is calculated by Eq. (1)

$$Risk = p(\Phi; X) \cdot f(\Phi'; X), \tag{1}$$

where $X = \{x_{ij} | i = 1, 2, \cdots, N; j = 1, 2, \cdots, J\}$ represents the data samples with the sample size N and the number of compound hazards attributes J, Φ and Φ' denote a set of hazard attributes which reflects the characteristics of the compound hazard.

Literature Review

- A Cloquet integral multiple linear regression model has been proposed to overcome the problem of nonlinear additivity of hazard level evaluation [4]
- Information diffusion method, which assess the risk of compound hazards without considering the correlated information between the individual hazards [5, 1]
- Variable fuzzy set model [6] is proposed to solve the compound hazards risk assessment problems
- Fuzzy probabilistic models have been proposed to enhance the accuracy of the risk assessment results [7]
- The probabilistic risk model combined with the concept of dynamic risk assessment has been proposed to estimate the flooding risk [8]

Challenges

A general methodology is lacking for assessing the compound hazards dynamic risk when sample sets are sparse

1. How to deal with the correlation between the hazard drivers?
2. How to assess compound hazards risk when sample sets are sparse?
3. The risk assessment often ignores the temporal dynamics of compound hazards

Framework

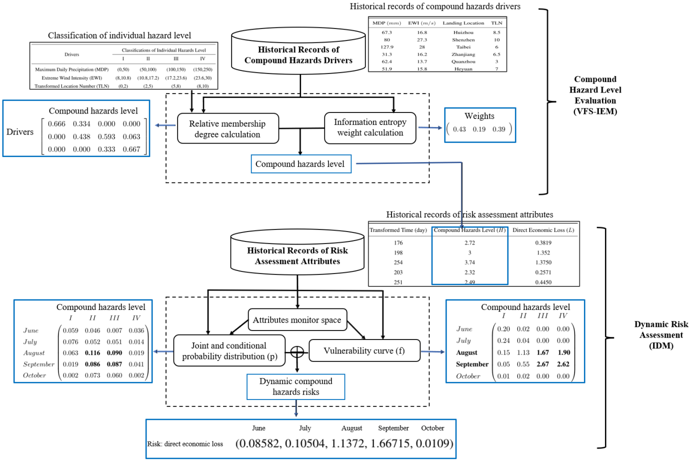


Figure 1: Workflow and illustration of the VFS-IEM-IDM dynamic compound hazards risk assessment model based on case study.

VFS-IEM-IDM model

Risk assessment of compound hazards should consider the correlation between the compound hazard drivers, the problem of data sparsity, and the dynamic property of hazard occurrences.

- Compound hazards level evaluation: VFS-IEM
  - Classifications of individual hazard level
  - Weights of each hazard driver
  - Relative membership matrix
- Dynamic risk assessment model: IDM
  - Conditional probability distribution of compound hazards
  - Fuzzy relationship of hazard-loss
  - Dynamic compound hazards risk

VFS-IEM for compound hazards level

Model formula:

$$\begin{cases} \nu(u)_l = (1 + (\frac{\sum_{r=1}^{R}(\omega_r(1-\mu(u)_{rl}))^\alpha}{\sum_{r=1}^{R}(\omega_r\mu(u)_{rl})^\alpha})^{\frac{\beta}{\alpha}})^{-1} \\ \hat{\nu}(u)_l = \frac{\nu(u)_l}{\sum_{l=1}^{L}\nu(u)_l} \\ H = (1 \quad 2 \ldots L) \cdot \hat{\nu}(u) \end{cases} \tag{2}$$

Drivers	Classifications of individual hazard level			
	I	II	III	IV
Maximum daily precipitation (MDP)	(0, 50)	(50, 100)	(100, 150)	(150, 250)
Extreme wind intensity (EWI)	(8, 10.8)	(10.8, 17.2)	(17.2, 23.6)	(23.6, 30)
Transformed location number (TLN)	(0, 2)	(2, 5)	(5, 8)	(8, 10)

$$\Omega = [\ 0.43 \quad 0.19 \quad 0.39\ ]$$

$$\boldsymbol{\mu}(\overline{u}) = \begin{bmatrix} 0.666 & 0.334 & 0.000 & 0.000 \\ 0.000 & 0.438 & 0.593 & 0.063 \\ 0.000 & 0.000 & 0.333 & 0.667 \end{bmatrix}$$

Time	$\alpha = \beta = 1$	$\alpha = \beta = 2$	Average level (H)	Typhoon–rainstorm hazard level (H)
27 Jun 2009	3.07	2.36	2.72	III
19 Jun	3.34	2.65	3.00	III
15 Sep	3.93	3.55	3.74	IV
24 Jul 2010	2.67	1.96	2.32	II
12 Sep	2.68	2.29	2.49	III
22 Sep	3.02	2.45	2.74	III
24 Jun 2011	2.12	1.73	1.93	I
30 Sep	2.87	2.57	2.72	III

IDM for risk assessment

$$\Gamma\left(x_{ij}; s_j^{k_j}\right) = \exp\left(-\frac{\left(x_{ij} - s_j^{k_j}\right)^2}{2\sigma_{x_j}^2}\right), k_j = 1, 2, \cdots, K_j;$$
$$i = 1, 2, \cdots, N,$$

$$\Gamma\left(x_i; S^K\right) = \prod_{j=1}^{J} \Gamma\left(x_{ij}; s_j^{k_j}\right), S^K = \left\{s_j^{k_j} | j = 1, 2, \cdots, J\right\}$$

$$\sigma_{x_j} = \begin{cases} 0.6841(b-a), & \text{for } N = 5; \\ 0.5404(b-a), & \text{for } N = 6; \\ 0.4482(b-a), & \text{for } N = 7; \\ 0.3839(b-a), & \text{for } N = 8; \\ 2.6581(b-a)/(N-1), & \text{for } N \geq 9; \end{cases}$$

where $b = \max_{1 \leq i \leq N} \{x_{ij}\}$, $a = \min_{1 \leq i \leq N} \{x_{ij}\}$.

Model formula: conditional probability

$$p_{k_1,k_2} = \frac{\sum_{i=1}^{N} \Gamma(x_i; S^K)}{\sum_K \sum_{i=1}^{N} \Gamma(x_i; S^K)} \tag{3}$$

$$p_{s_2|s_1}(s_2^{k_2}|s_1) = \frac{p_{k_1,k_2}}{\sum_{k_2=1}^{K_2} p_{k_1,k_2}}, k_2 = 1, 2, \cdots K_2. \tag{4}$$

IDM for risk assessment

$$\Gamma\left(x_{ij};s_j^{k_j}\right)=\exp\left(-\frac{\left(x_{ij}-s_j^{k_j}\right)^2}{2\sigma_{x_j}^2}\right),\ k_j=1,2,\cdots,K_j;$$

$$i=1,2,\cdots,N,$$

$$\Gamma\left(x_i;S^K\right)=\prod_{j=1}^{J}\Gamma\left(x_{ij};s_j^{k_j}\right),\ S^K=\left\{s_j^{k_j}\,|\,j=1,2,\cdots,J\right\}$$

$$\sigma_{x_j}=\begin{cases}0.6841(b-a), & \text{for } N=5;\\ 0.5404(b-a), & \text{for } N=6;\\ 0.4482(b-a), & \text{for } N=7;\\ 0.3839(b-a), & \text{for } N=8;\\ 2.6581(b-a)/(N-1), & \text{for } N\geq 9;\end{cases}$$

where $b=\max_{1\leq i\leq N}\left\{x_{ij}\right\},\ a=\min_{1\leq i\leq N}\left\{x_{ij}\right\}$.

Model formula: fuzzy relationship

$$r_{k_1,k_2,k_3}=\frac{\sum_{i=1}^{n}\Gamma(x_i;(s_1^{k_1},s_2^{k_2},s_3^{k_3}))}{\max\limits_{1\leq k_3\leq K_3}\sum_{i=1}^{n}\Gamma(x_i;(s_1^{k_1},s_2^{k_2},s_3^{k_3}))}. \tag{5}$$

$$f_{s_1^{k_1},s_2^{k_2}}=\frac{\sum_{k_3=1}^{K_3}\varpi(s_3^{k_3})\cdot s_3^{k_3}}{\sum_{k_3=1}^{K_3}\varpi(s_3^{k_3})},k_1=1,2,\cdots,K_1;k_2=1,2,\cdots,K_2. \tag{6}$$

Result of typhoon-rainstorm hazards risk

Year	Date	Transformed time (day)	Compound hazards level (H)	Direct economic loss (L)
2009	27 Jun	176	2.72	0.3819
	19 Jul	198	3	1.352
	15 Sep	254	3.74	1.3750
2010	24 Jul	203	2.32	0.2571
	12 Sep	251	2.49	0.4450
	22 Sep	261	2.74	0.9831
2011	24 Jun	173	1.93	0.0765
	30 Sep	269	2.72	0.4013

$$\hat{P} = \begin{array}{l} \\ \text{June} \\ \text{July} \\ \text{August} \\ \text{September} \\ \text{October} \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{I} & \mathrm{II} & \mathrm{III} & \mathrm{IV} \end{array} \\ \begin{pmatrix} \mathbf{0.398} & 0.311 & 0.049 & 0.243 \\ \mathbf{0.393} & 0.268 & 0.266 & 0.073 \\ 0.218 & \mathbf{0.402} & \mathbf{0.312} & 0.0689 \\ 0.080 & 0.370 & \mathbf{0.373} & 0.177 \\ 0.012 & \mathbf{0.539} & 0.437 & 0.012 \end{pmatrix} \end{array}$$

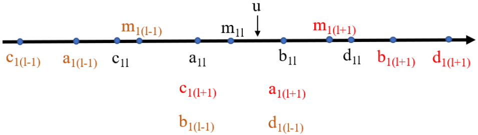
$$f = \begin{array}{l} \\ \text{June} \\ \text{July} \\ \textbf{August} \\ \textbf{September} \\ \text{October} \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{II} & \mathrm{II} & \mathrm{III} & \mathrm{IV} \end{array} \\ \begin{pmatrix} 0.20 & 0.02 & 0.00 & 0.00 \\ 0.24 & 0.04 & 0.00 & 0.00 \\ 0.15 & 1.13 & \mathbf{1.67} & \mathbf{1.90} \\ 0.05 & 0.55 & \mathbf{2.67} & \mathbf{2.62} \\ 0.01 & 0.02 & 0.00 & 0.00 \end{pmatrix} \end{array}$$

$$Risk = (0.08582, 0.10504, 1.1372, 1.66715, 0.0109) \tag{7}$$

where the elements denote the estimated economic losses caused by the typhoon-rainstorm hazards from June to October

Discussion

- Relative membership degree calculation



- Model evaluation: compound hazards level prediction

$$\begin{aligned}\operatorname{logit}(P(H|(\mathrm{MDP}, \mathrm{EWI}, \mathrm{TLN}))) &= 5.07(7.32, 11.15) \\ &- 0.12\mathrm{MDP} - 0.66\mathrm{EWI} - 0.91\mathrm{TLN}\end{aligned}$$

where the different intercept coefficients denote the main effects of different hazard drivers compared to the reference compound hazard level IV. LR-test (p-value<0.001) and the predictive performance $R^2 = 0.898$

Contributions

1. We propose a model, named Variable Fuzzy Set and Information Diffusion (VFS-IEM-IDM), to assess the dynamic risk of compound hazards, which takes into account the interrelations between the hazard drivers, deals with the problem of data sparsity, and considers the temporal dynamics of the occurrences of the compound hazards.
2. We simplify the procedures of calculating relative membership degree to improve the efficiency of compound hazards level evaluation, and we also use a predictive cumulative logistic model to verify the evaluation results.
3. To examine the efficacy of the proposed model VFS-IEM-IDM, a case study of the typhoon-rainstorm hazards occurred in Shenzhen, China is presented.

Q&A

Questions?

References I

[1] MING X, LIANG Q, DAWSON R, et al. A quantitative multi-hazard risk assessment framework for compound flooding considering hazard inter-dependencies and interactions[J]. Journal of Hydrology, 2022, 607 : 127477.

[2] CHOI E, HA J-G, HAHM D, et al. A review of multihazard risk assessment: Progress, potential, and challenges in the application to nuclear power plants[J]. International Journal of Disaster Risk Reduction, 2021, 53 : 19 – 33.

[3] ZHOU L, WU X, JI Z, et al. Characteristic Analysis of Rainstorm-Induced Catastrophe and the Countermeasures of Flood Hazard Mitigation about Shenzhen City[J]. Geomatics, Natural Hazards and Risk, 2017, 8(2) : 1886 – 1897.

[4] HE Z, WENG W. A Risk Assessment Method for Multi-Hazard Coupling Disasters[J]. Risk Analysis, 2020, 4 : 14 – 25.

References II

[5] XU W, ZHUO L, ZHENG J, et al. Assessment of the Casualty Risk of Multiple Meteorological Hazards in China[J]. International Journal of Environmental Research and Public Health, 2016, 13(2): 222–234.

[6] LI Q, ZHOU J, LIU D, et al. Research on Flood Risk Analysis and Evaluation Method Based on Variable Fuzzy Sets and Information Diffusion[J]. Safety Science, 2012, 50(5): 1275–1283.

[7] AMIRI M, ARDESHIR A, Fazel Zarandi M H. Fuzzy probabilistic expert system for occupational hazard assessment in construction[J]. Safety Science, 2017, 93: 16–28.

[8] HUANG. C. A Formal Model of Dynamic Risk Analysis of Natural Disasters[J]. Journal of Catastrophology, 2015, 30(3): 1–9.

Thank You!