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RANKING OF ASSESSMENT INDICES FOR LAND SUBSIDENCE INDUCED RISK USING TR-AHP METHOD IN SHANGHAI, CHINA

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Abstract
Land subsidence has caused catastrophic damages to urban infrastructures in mega-cities. This paper uses trapezoidal fuzzy numbers (TFN) combined with Analytical Hierarchy Process (AHP) for ranking the assessment indices of land subsidence induced risk in Shanghai, China. For this purpose, the assessment structure for land subsidence induced risk is established on the basis of trapezoidal fuzzy AHP (Tr-AHP). Subsequently, the latter method is used to calculate the weight of each assessment index. The results show that, for the hazard index, land subsidence intensity yields the largest weight; while for the vulnerability index, the highest weight corresponds to the population density. The method applied in this paper provides a valuable reference for the risk assessment of land subsidence in mega-cities.
Keywords: assessment indices, land subsidence, Tr-AHP

1. Introduction

Land subsidence is a geological hazard that can be induced by natural factors (e.g. consolidation of newly reclaimed ground, peat carbonation, earthquake), human being activities (e.g. exploration of underground resources) (Shen et al., 2013; Xu et al., 2012), underground constructions (Wu et al., 2017; Shen et al., 2015, 2017a, b), and long-term operation of urban facilities (Shen et al., 2014; Wu et al., 2017a). In the recent years, groundwater artificial recharge projects have been performed to control this problem. For instance, Shen et al (2015, 2017b) and Wu et al (2015a, b, 2016) conducted a series of researches on pumping and artificial recharge in shallow aquifer to control land subsidence. Indeed, the occurrence of such events within a modern mega-city, can cause disastrous damages to infrastructure systems, and/or even lead to costly maintenance operations.

Shanghai is located in eastern China, bounded by Jiangsu Province to the north, Zhejiang Province to the south, Hangzhou Bay to the south-east, and China Sea to the east. Fig. 1 shows the administrative region and overall distribution of land subsidence in Shanghai from 1921 to 2010. As shown in this figure, the largest land subsidence in urban area is up to 2.6 m. Given the adverse effects of land subsidence on the prosperous development of the society, effective countermeasures must be undertaken to alleviate it. Moreover, the assessment of risks induced by land subsidence must be carried out. The objective of this paper is to rank the assessment indices for land subsidence induced risk using the Tr-AHP method.

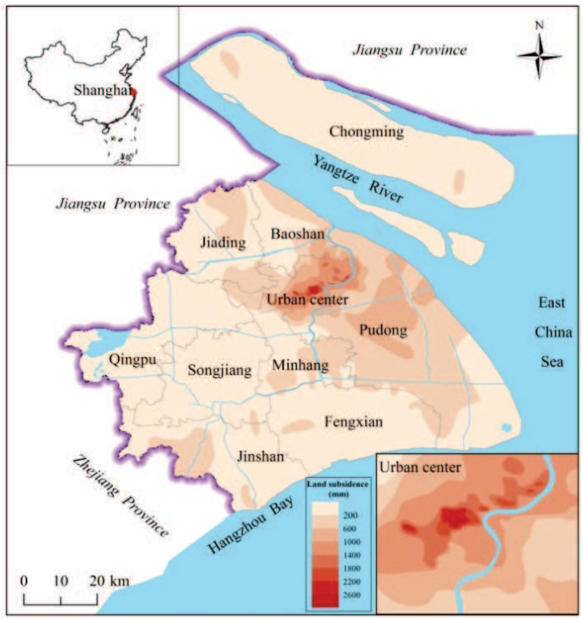

Fig. 1 Overall land subsidence in Shanghai (from 1921 to 2010)

2. Methodology

2.1 Theory of Tr-AHP

A trapezoidal fuzzy number (TFN) is defined as: $M=(m_1, m_2, m_3, m_4)$, where $0 \le m_1 \le m_2 \le m_3 \le m_4$; m_1 and m_4 are the lower and upper limits of M; m_2 and m_3 are the interval variables of M. Fig. 2 shows the membership function of a trapezoidal fuzzy number. The membership function of $\mu_M(x)$ for M is defined by Eq. 1. As shown in Fig. 1, if $m_2=m_3$, M is a TFN; if $m_1=m_2$, and $m_3=m_4$; M is an interval number; if $m_1=m_2=m_3=m_4$, M is a real value. Therefore, a TFN can arithmetically handle and intuitively interpret fuzzy numbers in a variable way.

The traditional AHP method uses a single value to express the decision maker's opinion in a pairwise comparison. However, the AHP method is often criticized due to its inability to adequately handle the inherent uncertainty and imprecision in expressing of decision maker's opinion. The trapezoidal AHP (Tr-AHP) uses a TFN instead of a crisp value for overcoming the shortcomings of the traditional AHP. If $C = [M_{ij}]_{n\times n}$ is a trapezoidal fuzzy judgment matrix, and $M_{ij}=(m_{1ij}, m_{2ij}, m_{3ij}, m_{4ij})$ is a TFN, there is a real value $m_{2ij} \le p_{ij} \le m_{3ij}$ that can satisfy the consistence of the simple matrix $P=[P_{ij}]_{n\times n}$, so that the trapezoidal fuzzy judgment matrix $C=[M_{ij}]_{n\times n}$ meets the consistency demand.

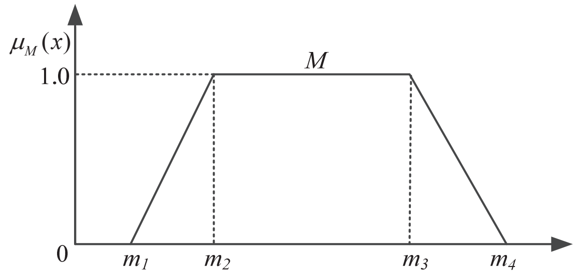

Fig. 2 Membership function of a trapezoidal fuzzy number (M)

$$\mu_M(x) = \begin{cases} 0, & (x < m_1) \\ \dfrac{x - m_1}{m_2 - m_1}, & (m_1 \le x \le m_2) \\ 1, & (m_2 \le x \le m_3) \\ \dfrac{m_4 - x}{m_5 - m_4}, & (m_3 \le x \le m_4) \\ 0, & (x > m_4) \end{cases} \tag{1}$$

2.2 Weight calculation

According to the trapezoidal fuzzy judgment matrix $C=[M_{ij}]_{n\times n}$, the weight index is calculated using geometric mean method as shown in Eq. (2).

$$\vec{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4}) = (\frac{m_{1i}}{m_4}, \frac{m_{2i}}{m_3}, \frac{m_{3i}}{m_2}, \frac{m_{4i}}{m_1}) \tag{2}$$

where w_{j1}, w_{j2}, w_{j3}, w_{j4} are the weight index of trapezoidal fuzzy judgment matrix, and $0<w_{j1}\le w_{j2}\le w_{j3}\le w_{j4}<1$, m_{1i}, m_{2i}, m_{3i}, and m_{4i} are the value of trapezoidal fuzzy judgment matrix $C=[M_{ij}]_{n\times n}$, and it can be calculated using Eq. (3).

$$\begin{gathered} m_{1i} = \left(\prod_{j=1}^{n} m_{2ij}\right)^{1/n}, \quad m_{2i} = \left(\prod_{j=1}^{n} m_{2ij}\right)^{1/n}, \quad m_{3i} = \left(\prod_{j=1}^{n} m_{3ij}\right)^{1/n}, \quad m_{4i} = \left(\prod_{j=1}^{n} m_{4ij}\right)^{1/n} \\ m_1 = \sum_{j=1}^{n} m_{1j}, \quad m_2 = \sum_{j=1}^{n} m_{2j}, \quad m_3 = \sum_{j=1}^{n} m_{3j}, \quad m_4 = \sum_{j=1}^{n} m_{4j} \end{gathered} \tag{3}$$

As shown in Eq. (4), the expected value for weight index is the arithmetic mean of w_{j1}, w_{j2}, w_{j3}, w_{j4}, which is then normalized using Eq. (5).

$$w'_j = \frac{w_{j1} + w_{j2} + w_{j3} + w_{j4}}{4} \tag{4}$$

$$w_j = \frac{w'_j}{\sum_{j=1}^{m} w'_j} \tag{5}$$

2.3 Establishment of Tr-AHP assessment structure

Land subsidence risk is the combination of hazard and vulnerability indices. Fig. 2 shows the assessment structure for land subsidence induced risk based on Tr-AHP. As shown in Fig. 3, the hazard index includes five factors (H_1, H_2, H_3, H_4, H_5), while there are seven factors(V_1, V_2, V_3, V_4, V_5, V_6, V_7) for the vulnerability index . The comprehensive risk assessment level proposed in this study is thus evaluated on the basis of these twelve factors. Based on the results of this evaluation, countermeasures for dealing with the prevention zones at different risk levels could thus be readily set up.

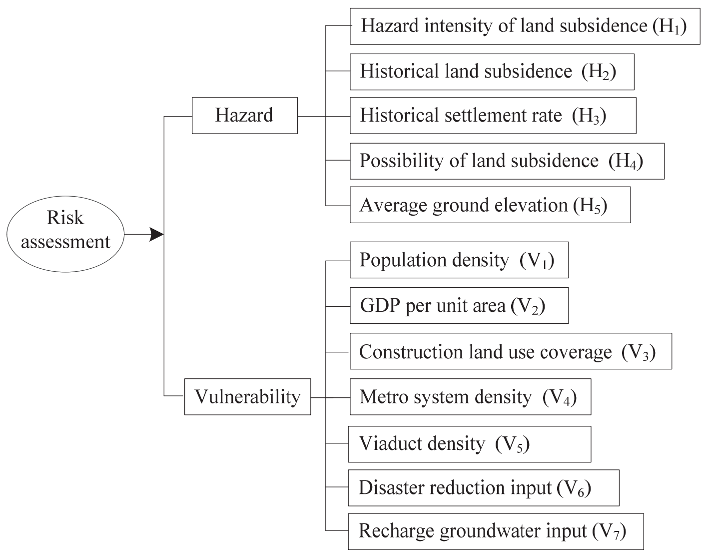

Fig. 3 Assessment structure for land subsidence induced risk

3. Results

The defuzzifized judgment matrixes of hazard index and vulnerability index were established as $P_{\text{hazard}}=[P_{\text{ij}}]_{5\times 5}$ and $P_{\text{vulnerability}}=[P_{\text{ij}}]_{7\times 7}$ in Eq. (6). After testing the sensitivity and consistency of the simplified TFN judgment matrixes, the values of *CR* for matrixes P_{hazard} and $P_{\text{vulnerability}}$ were respectively 0.0474 and 0.0468. In other word, the two simplified TFN judgment matrixes meet the consistency demands. Accordingly, the following weights were considered for the ranking of assessment indices.

$$P_{hazard}=\begin{bmatrix} 1' & 1' & 3' & 5' & 7' \\ 1' & 1' & 3' & 4' & 5' \\ (\frac{1}{3})' & (\frac{1}{3})' & 1' & 2' & 2' \\ (\frac{1}{5})' & (\frac{1}{4})' & (\frac{1}{2})' & 1' & 2' \\ (\frac{1}{7})' & (\frac{1}{5})' & (\frac{1}{2})' & (\frac{1}{2})' & 1' \end{bmatrix} P_{vu\ln erability}=\begin{bmatrix} 1' & 1' & 3' & 2' & 5' & 6' & 7' \\ 1' & 1' & 3' & 2' & 4' & 6' & 6' \\ (\frac{1}{3})' & (\frac{1}{3})' & 1' & 3' & 2' & 4' & 5' \\ (\frac{1}{2})' & (\frac{1}{2})' & (\frac{1}{3})' & 1' & 3' & 4' & 5' \\ (\frac{1}{5})' & (\frac{1}{4})' & (\frac{1}{2})' & (\frac{1}{3})' & 1' & 3' & 4' \\ (\frac{1}{6})' & (\frac{1}{6})' & (\frac{1}{4})' & (\frac{1}{4})' & (\frac{1}{3})' & 1' & 1' \\ (\frac{1}{7})' & (\frac{1}{6})' & (\frac{1}{5})' & (\frac{1}{5})' & (\frac{1}{4})' & 1' & 1' \end{bmatrix} \quad (6)$$

According to the simplified judgment matrixes, trapezoidal fuzzy numbers are used to establish the TFN judgment matrixes. The weight of each assessment index was determined using Eq. (2) to Eq. (5). Table 1 lists the weights for assessment indices determined by TFN.

Table 1 Weights of assessment indices determined by TFN

Assessment indices	$\vec{w}_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$	w_j
H_1	(0.3124,0.3154,0.3179,0.3288)	0.3187
H_2	(0.2668,0.2683,0.2734,0.2784)	0.2717
H_3	(0.1663,0.1696,0.1733,0.1749)	0.1711
H_4	(0.1324,0.1334,0.1358,0.1361)	0.1344
H_5	(0.0977,0.1047,0.1055,0.1084)	0.1041
V_1	(0.2309,0.2316,0.2371,0.2374)	0.2343
V_2	(0.2157,0.2187,0.2192,0.2246)	0.2196
V_3	(0.1551,0.1554,0.1565,0.1567)	0.1559
V_4	(0.1454,0.1487,0.1510,0.1513)	0.1491
V_5	(0.1069,0.1091,0.1095,0.1110)	0.1091
V_6	(0.0674,0.0700,0.0714,0.0725)	0.0703
V_7	(0.0576,0.0623,0.0625,0.0645)	0.0617

4. Conclusion

In this study, the primary risk assessment index structure of land subsidence was established on the basis of thorough analyses of land subsidence induced hazards and vulnerability risk, as well as precious discussions with experts. For more reasonable evaluation results, traditional AHP was combined with TFNs instead of crisp numbers for calculating the assessment indices; which combination better reflects human thinking and expert knowledge in the area of a fuzzy environment. The results show that the largest weights of hazard and vulnerability indices are obtained respectively for land subsidence intensity and population density. The methodology applied in this paper will be valuable for future the assessment of risks induced by land subsidence.

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