Evaluation of Land Subsidence Hazardousness in Cangzhou Section of Beijing-Shanghai High-Speed Railway

Juyan Zhu[1,2], Haipeng Guo[1,2*], Jiqiang Wang[1,3], Yunlong Wang[1,2], Xiucheng Chi[1,3], Di Ning[1,2], Wei Feng[2]

[1]Hebei Cangzhou Groundwater and Land Subsidence National Observation and Research Station, Cangzhou 061000, China
[2]China Institute of Geo-Environment Monitoring, Beijing, 100081, China
[3]The Fourth Team of Hydrogeological and Engineering Geology, Hebei Bureau of Geo-exploration, Cangzhou,061000, China

Abstract: Cangzhou area is one of the most severe areas of land subsidence in the North China Plain, which is a serious threat to major linear projects such as the South-to-North Water Diversion Project and high-speed railroads, and there is an urgent need to carry out a hazardousness assessment for major linear projects. In this paper, the land subsidence hazardousness evaluation was carried out for the northern section of the Beijing-Shanghai high-speed railway in Cangzhou. The evaluation indexes include the slope of land subsidence rate, the severity of land subsidence, the groundwater levels impact and the engineering geological conditions; the evaluation method is hierarchical analysis method and weighted comprehensive evaluation method; the evaluation data period is 2005-2013. The evaluation model was constructed by applying the Spatial Analyst module in ArcGIS, and based on the evaluation results, the land subsidence hazardousness zoning was delineated, and recommendations for the prevention and control of land subsidence were put forward.

1. Introduction

Land subsidence is an environmental geological phenomenon in which the regional ground elevation is reduced due to the compression of loose soil under the influence of natural factors and human factors. It is a permanent loss of environment and resources that cannot be compensated, and it is a bad result of the destruction of geological environment system[1]. At present, land subsidence is one of the main geological hazards in the North China Plain (the NCP). With the rapid development of rail transit in recent years, land subsidence has a certain impact on linear engineering in the NCP, which is mainly manifested in the change of track smoothness and the deterioration of subgrade structure stability caused by uneven settlement.

The likelihood and intensity of land subsidence in a given area over a given period of time in response to predisposing factors [2]. It is of great theoretical and practical value to evaluate the hazardousness of land subsidence and explore suitable evaluation index system and method to reduce the social and economic loss caused by land subsidence[3,4].

In this paper, North of Cangzhou section of Beijing-Shanghai high-speed Railway was selected as the evaluation area, the main evaluation factors and weight coefficients of the evaluation area were determined, and then the evaluation model was constructed to carry out the land subsidence hazardousness zoning and evaluation, providing a theoretical basis for the future decisions of this linear engineering.

2. Overview of the evaluation area

The evaluation area is 2 km area along the Beijing-Shanghai high-speed railway in Cangzhou(Fig.1), The overall terrain is high in the south and low in the north, which belongs to the alluvial sea plain area. The secondary landform types include the small highland area of the river channel, the flat area of the flood slope, the flood depression area and the flood plain area. The strata in this area are Quaternary Holocene and Upper Pleistocene loose sediments, and the lithology is silt, silty clay and clay interdeposit, with a small amount of silty sand and silty soil.

1970~2008, the cumulative settlement in the evaluation area was greater than 800 mm, and the overall trend was smaller in the north and south, and the maximum cumulative settlement was greater than 1200 mm; 2007~2013, the cumulative settlement in the evaluation area was greater than 50 mm, the value in the north and south was larger, but in the middle area was smaller, and the maximum cumulative settlement was greater than 200 mm(Table 1). The sedimentation rate has shown a downward trend since 2008. The average sedimentation rate in 2013 was about 17 mm/a, and the sedimentation rate in 2013 was somewhat lower than that in 2012, and the sedimentation rate in most regions was less than 40 mm/a (Table 2).

* Corresponding author: pengfei7971@sohu.com

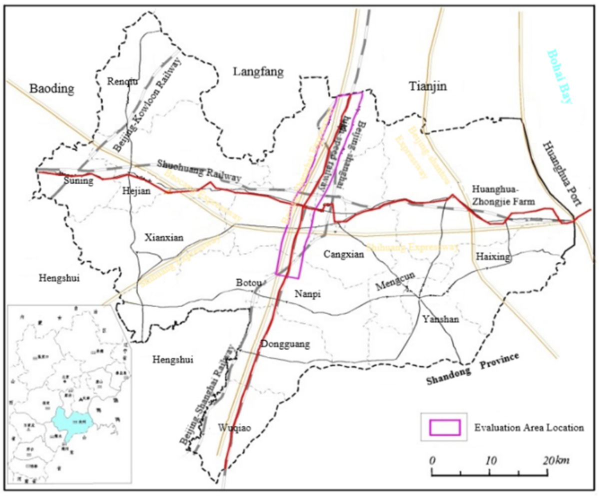

Fig. 1. The sketch map of the evaluation area location.

Table 1. The zoning table of accumulative land subsidence in the evaluation area from 2007 to 2013.

Cumulative subsidence zoning (mm)	Area (km^2)	Area ratio (%)
50～100	8.7	1.6
100～150	82.4	15.3
150～200	183.5	34.0
>200	265.2	49.2

Table 2. The zoning table of the rate of land subsidence of the evaluation area in 2003.

Subsidence rate zoning (mm)	Area in 2012 (km^2)	Area in 2013 (km^2)	Compared to 2012
0～10	11.3	193.9	↑ 1617%
10～20	162.5	104.1	↓ 36 %
20～30	119.9	64.6	↓ 46 %
30～40	158.0	100.7	↓ 36 %
>40	88.1	0	Almost disappear

3. Determination of evaluation methods

Firstly, through the Analytic Hierarchy Process(AHP), the evaluation factors are selected, the hierarchy structure is established, the construction matrix is established, the factor weight is determined, and then the evaluation model is established. Secondly, the Weighted Comprehensive Appraise(WCA) is used to partition and evaluate the hazardousness of the evaluation area. Finally, combined with the existing data, the whole zoning results are evaluated, and the feasibility of the whole zoning scheme is evaluated and analyzed to ensure the rationality of the hazardousness zoning results.(Fig.2)

The evaluation methods used in this study are AHP and WCA. AHP is a hierarchical weight decision analysis method proposed by Professor Saaty of the University of Pittsburgh, an American operations research scientist, in the early 1970s. The method takes a complex multi-objective decision problem as a system, decomposes the target into multiple objectives or criteria, and then decomposes several levels of multi-indicators (or criteria and constraints). The hierarchical single ranking (weight) and total ranking are calculated by qualitative index fuzzy quantization method, which can be used as a systematic method of objective (multi-index) and multi-scheme optimization decision. The specific operation steps include: (1) establishing the hierarchical model, (2) constructing the comparison matrix, (3) calculating the weight vector and doing the consistency test, (4) normalizing calculation and evaluating the partition.

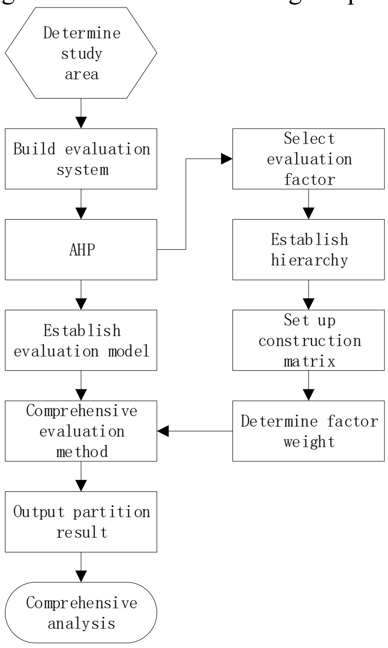

Fig.2. The map of technical proposal.

WCA assumes that each index i has a varying degree of influence on a specific factor j due to the different quantization values of index i. This is expressed by the following mathematical formula:

$$V_j = \sum_{i=1}^{n} W_i \cdot D_{ij}$$

Where: Vj is the total value of evaluation factors; Wi is the weight of indicator i. Dij is the value of index i for factor j; n is the number of evaluation indicators.

WCA comprehensively considers the influence degree of each factor on the overall object, synthesizes the advantages and disadvantages of each specific index, and uses a quantitative index to concentrate, so as to express the advantages and disadvantages of the entire evaluation object, which is a common calculation method at present.

In this study, the weight of each factor is obtained by WCA, and comprehensive evaluation is carried out on the basis of consulting relevant data and obtaining empirical values. Then the weight of each level factor is superimposed and weighted respectively to obtain the weight value on the evaluation unit.

4. Hazardousness zoning and evaluation

4.1. Selection of evaluation factors

The hazardousness of land subsidence in linear engineering area is affected and controlled by many factors, among which the development speed of land subsidence, the change trend of groundwater level and the engineering geological conditions of the evaluation area are the main controlling factors. Therefore, the slope of land subsidence rate (A), the severity of land subsidence (B), the groundwater levels impact (C) and engineering geological conditions (D) are selected as the evaluation factors in this zonal evaluation (Fig.3-6).

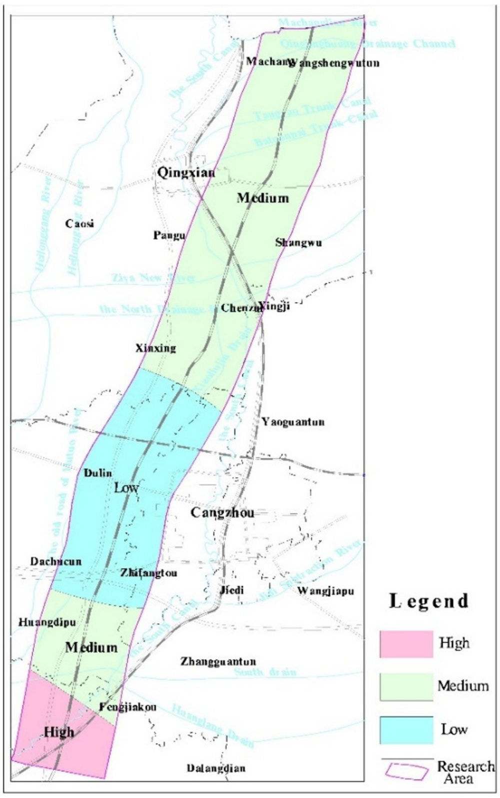

Fig.3. The zoning map of the slope of land subsidence rate in the evaluation area.

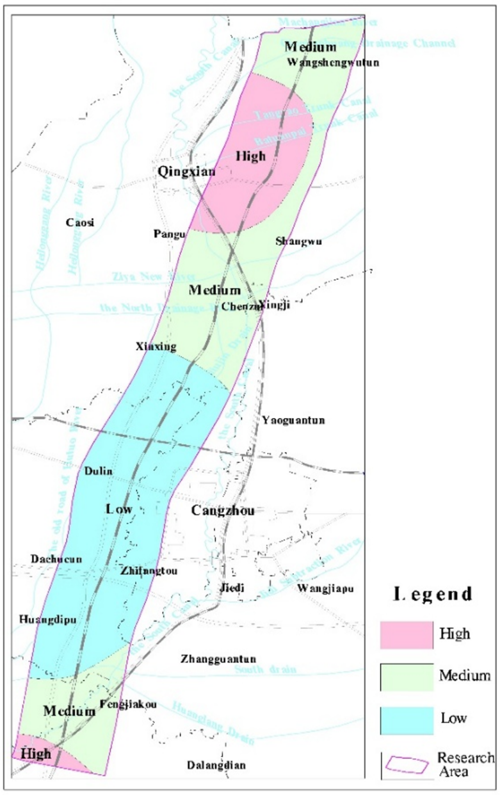

Fig.4. The zoning map of the land subsidence severity in the evaluation area.

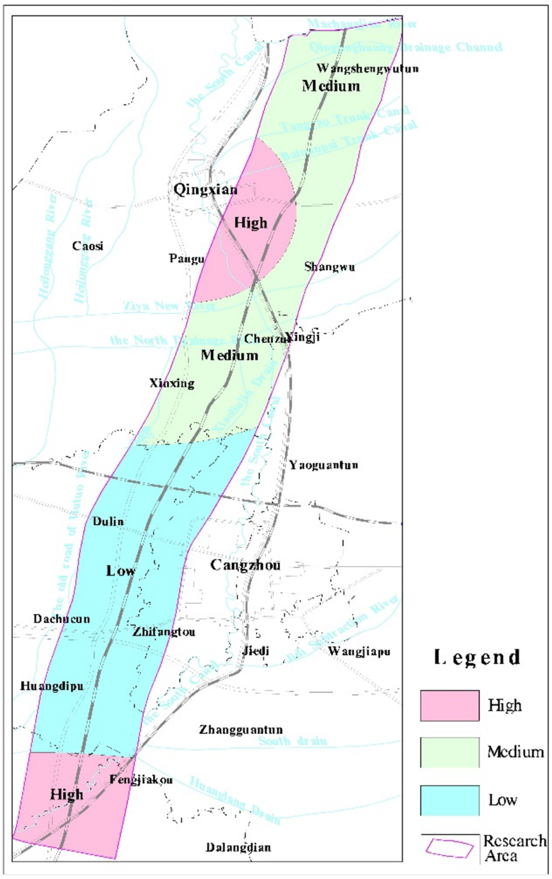

Fig.5. The zoning map of the groundwater levels impact in the evaluation area.

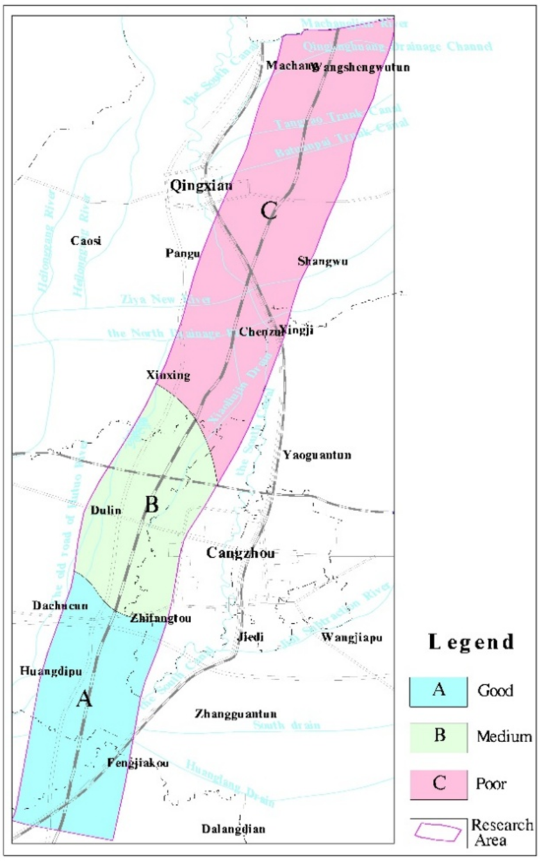

Fig.6. The zoning map of the engineering geological conditions in the evaluation area.

4.2. Quantitative grading of evaluation factors

Combined with the actual situation of the evaluation factors, the quantitative processing is carried out. The slope of land subsidence rate has great influence on the safe operation of linear engineering, especially after operation. The slope of land subsidence rate in 2013 along the route was selected as the reference value, and the evaluation area was divided into three areas with high, medium and low land subsidence rate slope, whose scores (FA) were 10, 5 and 1, respectively. Under the comprehensive consideration of the current development rate of land subsidence and accumulated land subsidence, the evaluation area was divided into high, medium, and low serious land subsidence area, whose scores(FB) were 10, 5 and 1 respectively. Since the shallow groundwater in the evaluation area has a small variation range, the evaluation mainly considers the deep groundwater. According to the variation amplitude of the deep groundwater level from 2005 to 2013, the current situation of the groundwater drop funnel and the intensity of groundwater exploitation, the evaluation areas were divided into high, medium, and low water levels influence areas, the scores(FC) were 10, 5 and 1 respectively. According to the bearing capacity of natural foundation, comprehensive topography, landform, groundwater burial conditions and engineering construction experience, the engineering geological conditions of the study area are divided into three areas: poor engineering geological conditions (C), medium engineering geological conditions (B), and good engineering geological conditions (A), whose scores(FD) were 10, 5 and 1 respectively.

4.3. Determination of weight coefficient of evaluation factors

According to the importance of the main controlling factors of land subsidence, a clear hierarchical relationship was established, and a comparison matrix was constructed according to the 1-9 scale method created by T.L.SAATY to evaluate the evaluation factors and their correlation degrees. The determination of the comparison matrix in this study referred to relevant literature such as the preliminary study on the classification standard of land subsidence hazardousness and the application of fuzzy evaluation method in the hazardousness assessment of land subsidence disaster in Cangzhou City [5-10]. These previous research results and experience have laid the foundation for the rationality of this study results. The comparison matrix and factor weight are shown in Table 3.

Table 3. The table of factors weight and comparison matrix.

Factors	Engineering geological conditions	Groundwater levels impact	Severity of land subsidence	Slope of land subsidence rate
Engineering geological conditions	1	1/3	1/5	1/9
Groundwater levels impact	3	1	1/3	1/3
Severity of land subsidence	5	3	1	1/5
Slope of land subsidence rate	9	3	5	1

By calculation, the maximum characteristic root λmax of the factor matrix is 4.264, then the consistency index CI= (λ-n) /(n-1), the solution of CI and RI is 0.088 and 0.9, then CR=CI/RI=0.098<0.1, the calculation results show that the degree of inconsistency of factors in the matrix is within the allowable range. The weight coefficients of each evaluation factor are calculated by the following formula.

$$\mathrm{W_i} = \frac{1}{\mathrm{n}} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}$$

Table 4. The table of weight coefficients of each factor.

Factors	Engineering geological conditions	Ground water levels impact	Severity of land subsidence	Slope of land subsidence rate
weight	0.050	0.139	0.240	0.571

4.4. Hazardousness zoning

With the ArcGIS software platform, the evaluation units were measured according to the weighted comprehensive evaluation method based on the four hazardousness assessment factors and their weight coefficients. Finally, the results were normalized to the interval [0,1] by using normalization processing. Based on the Spatial Analyst module, 19 evaluation units were finally obtained. Based on the actual evaluation experience, the grading standards of land subsidence hazardousness were preliminarily determined, as shown in Table 5.

Table 5. The table of hazardousness classification of land subsidence in the evaluation area.

Hazardousness index	Hazardousness class
0≤V＜0.25	Very low
0.25≤V＜0.50	Low
0.50≤V＜0.75	Medium
0.75≤V≤1.00	High

According to Table 5, the evaluation zones were divided into high hazardousness zones (I), medium hazardousness zones (II), low hazardousness zones (III) and very low hazardousness zones (IV). The same attributes of adjacent regions were combined and integrated into 6 evaluation units, and the evaluation results of these zones were shown in Fig.7 and Table 6.

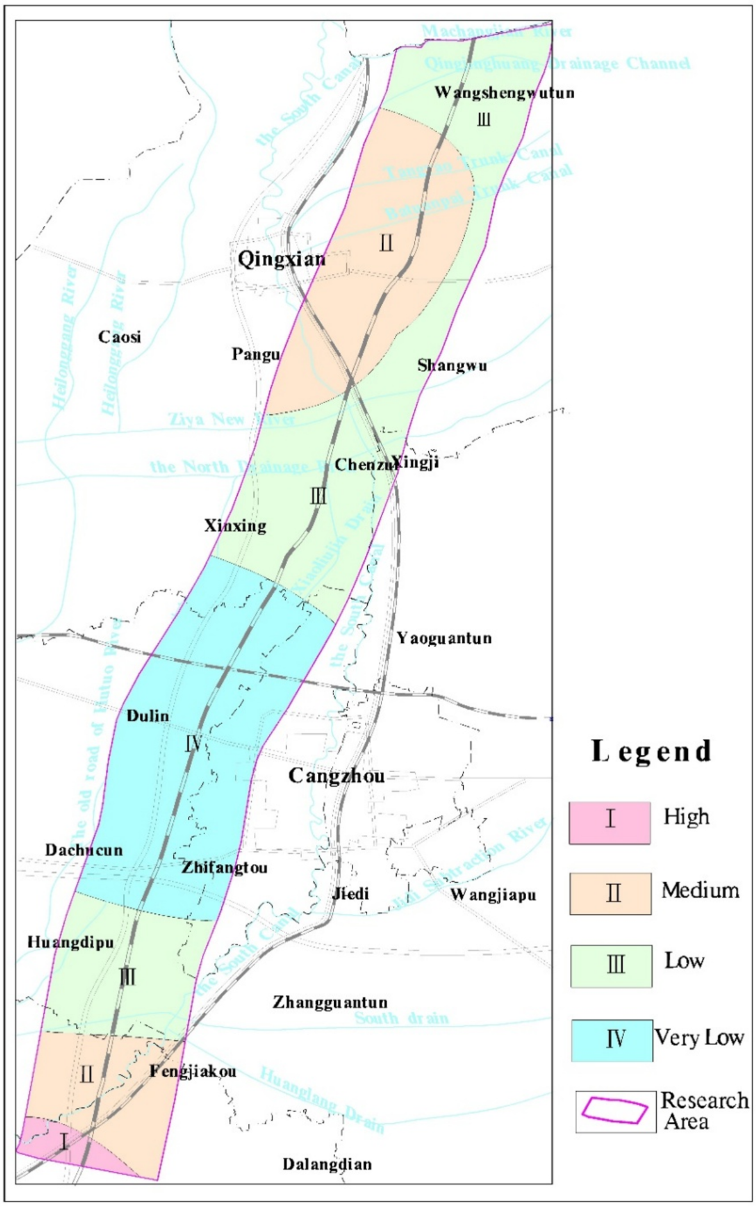

Fig.7. The zoning map for hazardousness of land subsidence in the evaluation area.

Table 6. The properties of land subsidence hazardousness zoning in the evaluation area.

Zone code	Rank	Area (km²)	Proportion (%)	Properties
I	High	11.11	1.98	In 2013, the settlement amount was greater than 20 mm, and the cumulative settlement amount from 2007 to 2013 was greater than 200 mm, the settlement rate slope was large, the groundwater depth was greater than 65 m, the groundwater exploitation intensity was large, the water level had dropped significantly in recent years, and the engineering geological conditions were good.
II	Medium	154.77	27.64	The annual settlement amount was 10-20 mm, the cumulative settlement amount was 150-200 mm, the land settlement rate slope was large, the groundwater depth was greater than 65 m, the groundwater exploitation intensity was large, and the engineering geological conditions were good.
III	Low	229.82	41.04	The annual settlement rate was 10-20 mm, the cumulative settlement amount was 150-200 mm, the ground settlement rate slope was moderate, the underground water depth was generally 55-65 m, the underground water exploitation intensity was general, and the underground water level changed little.
IV	Very low	164.29	29.34	The slope of settlement rate was small, the annual

				settlement rate was less than 10 mm, and the cumulative settlement amount from 2007 to 2013 was less than 150 mm. The deep groundwater depth was generally less than 55 m, the groundwater exploitation intensity was small, and the engineering geological conditions were medium.

According to the hazardousness zoning map and evaluation table, 70.38% of the evaluation area belongs to the low and very low hazardousness area, the groundwater exploitation intensity is relatively small, and the deep water depth is shallow, while the medium and high hazardousness area account for 27.64% and 1.98% respectively, the groundwater exploitation intensity is large, and the deep groundwater depth is deep, and relevant measures need to be taken to slow down the development of land subsidence.

5. Conclusion

AHP and WCA have been widely used to solve multi-objective decision analysis problems, which can organically combine qualitative methods and quantitative methods, so that the complex multi-level comprehensive problems can be simplified into multiple single-objective problems by applying mathematical models, which is convenient for users to carry out systematic analysis. On the basis of determining the weight factor coefficients, the author applied the Spatial Analyst module of ArcGIS software to complete the land subsidence hazardousness zoning of the northern section of the Beijing-Shanghai high-speed Railway, realized the perfect combination of spatial data and attributes, and presented the results in a more intuitive way.

According to the results of hazardousness zoning evaluation, 70.38% of the northern section of Cangzhou of the Beijing-Shanghai high-speed railway belongs to the low or very low hazardousness area, and the groundwater exploitation intensity is relatively small, which can be monitored continuously in the later stage. However, the deep groundwater buried depth is greater than 65m in the medium and high hazardousness areas, so it is necessary to appropriately reduce the exploitation of groundwater, especially the exploitation of deep groundwater, or carry out groundwater recharge in the serious areas along the linear project, which is the most direct and effective measure to slow down the development of land subsidence.

The prevention and research of land subsidence is a long-term and complex social welfare project, which requires the construction of a land subsidence monitoring network system, and continuous operation and improvement, especially along the linear engineering (high-speed rail, etc.), the corresponding groundwater monitoring network and GPS monitoring network should be added, so as to further improve the land subsidence monitoring system of linear engineering.

Acknowledgments

This research is supported by the China Geological Survey (No. 10220222018000009060) and the National Natural Science Foundation of China (No. U2344225).

References

1. ZHENG X. X.(1992) Urban Development in Coastal Areas and Systematic Control on Surface Subsidence. Marine Geology & Quaternary Geology, 12(1):57-65.
2. WANG, H. M.(2010) Study on Hazardousness Evaluation and Control Schemes of Land Subsidence in Shanghai City. Shanghai Geology, 31(4):7-11.
3. ZHOU L.(2023). The Fuzz Comprehensive Evaluation Model of Student Learning Based on AHP. Journal of Jiangxi Normal University (Natural Science), 47(4) : 400-404.
4. Wang, Y.L, et al.(2023) A Study of the Critical Groundwater Level Related to Soil Consolidation Characteristics of Land Subsidence in Cangzhou. Hydrogeology & Engineering Geology, 50(4): 185-192.
5. LI W., YANG X. D., MANG X. J., et al.(2006) Application of Fuzzy Evaluation Method for Ground Settlement Hazard in Cangzhou City. Editorial Office of Site Investigation Science and Technology, 6(6):39-44.
6. MENG L., FENG Q. Y., et al.(2008) Mechanism Analysis and Hazard Assessment on Land Subsidence in Datun Central District of Xuzhou City. The Chinese Journal of Geological Hazard and Control, 19(3):60-63.
7. WANG H. M..(2010) Study on Hazardousness Evaluation and Control Schemes of Land Subsidence in Shanghai City, Shanghai Geology, 31(4):7-12.
8. Yalcin AS, Kilic HS, Delen D.(2022) The Use of Multi-criteria Decision-making Methods in Business Analytics: a Comprehensive Literature Review. Technological forecasting and social change 174:121193.
9. Davydzenka, T., Tahmasebi, P., & Shokri, N. (2024). Unveiling the global extent of land subsidence: The sinking crisis. Geophysical Research Letters, 51, e2023GL104497. https://doi.org/10.1029/2023GL104497.
10. Zhang, Y. W, et al.(2024) Comparative Study on Land Subsidence Monitoring and Control in the Shandong Plain, China and the Greater Houston Area, USA. Hydrogeology & Engineering Geology, 51(1): 167-178.