Factors affecting the deformation of the surrounding rock of tunnel based on rough set theory

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Abstract. The deformation of surrounding rock is a common hazard in tunnel engineering, and it can negatively affect the quality and safety of a project. Therefore, the analysis of factors affecting the deformation of tunnels surrounding rock has essential engineering significance. This work selected two subjective factors affecting the deformation of the surrounding rock of a tunnel, namely, the excavation method and the excavation footage, and four objective factors (i.e., the tunnel burial depth, the degree of weathering, the groundwater conditions, and the uniaxial compressive strength of rocks) as the factors affecting the deformation of tunnel surrounding rock. Data on the factors influencing deformation of 25 typical deformation sections of the Tianqiao Mountain Tunnel under construction were collected to establish the condition attributes in the decision table. The actual deformation level was used as the decision attribute in the decision table. Rough set theory was used to perform a completely objective analysis of these six factors. Results of the analysis show that the groundwater conditions are the most influential factor in surrounding rock deformation with a weight of 0.3333, and the degree of weathering is a redundant factor. This study can be used as a guide for reducing or avoiding the deformation of the surrounding rock of a tunnel.

1. Introduction

With the rapid development of infrastructure construction in China, especially the continuous construction of railways and highways to mountainous areas, tunnel engineering has become a critical project in the creation of these projects [1]. When the tunnel is excavated to encounter hard and brittle surrounding rocks under high ground stress conditions, rockburst may occur [2,3]. However, when it meets weak surrounding rocks, deformation of the surrounding rocks is often reported. When the deformation of the surrounding rock cannot be adequately controlled, the deformation will continue to increase and exceed the allowable value, which will result in damage to the tunnel support structure and negatively affect the construction safety of the project [4]. Therefore, the analysis of the factors affecting the deformation of the surrounding rock of a tunnel has guiding significance for controlling the deformation of surrounding rock of tunnels.

In recent years, many scholars have carried out related research on the deformation factors of tunnel surrounding rocks. Anagnostou [5] proposed that the main factors for deformation of surrounding rocks are rock strength and burial depth, and large deformations of surrounding rocks can occur in any type of rock mass. Han et al. [6] studied the influence of the water content of the surrounding rock on the deformation of the surrounding rock by carrying out uniaxial and triaxial tests on the rock; they observed that the strength of the surrounding rock is reduced by 40% under high water content. Xue et al. [7] used data mining techniques to analyze data from the Menghua Railway Tunnel and observed that the most significant factor affecting the surrounding rock deformation of the loess tunnel is the support closure time, followed by the burial depth and groundwater conditions. Xue
et al. [8] used the Universal Discrete Element Code software to establish a numerical simulation model. They conducted field tests to reveal the failure mechanism of coal mining roadways under water saturation and weathering.

However, the above studies were based on objective factors such as the geological conditions of the tunnel and the properties of the surrounding rocks. They did not consider the subjective elements of the project construction, such as construction methods and excavation footage. Therefore, this paper considers the actual engineering situation of the Tianqiao Mountain Tunnel as the studied area, collects the data of 25 major deformation sections in this tunnel, and uses rough set theory to analyze six subjective and objective factors affecting the deformation of the surrounding rock.

2. Overview of the studied tunnel
The Tianqiao Mountain Tunnel is located in Guzhang County, Hunan Province, China. It is the controlling project of the Zhangjihuai railway section in the Erzhan high-speed railway. The total length of the tunnel is 6905 m, and the maximum buried depth is about 450 m. The terrain along the tunnel fluctuates greatly, and it belongs to denuded low mountain landform. The entrance side of the tunnel has a steep mountain slope, and the height of the mountain toward the exit gradually decreases. The ditch in the mountainous area of the tunnel is narrow and long, with a relative height difference of about 100–500 m. Three faults pass through the tunnel, and the faults are mainly north–north–east. The main properties of the faults are high brittleness and compressibility. The surface water system in the tunnel area is relatively developed. The shallow buried section of the tunnel entrance and exit passes through multiple creeks, and groundwater develops. The lithology of the surrounding rocks in the tunnel site is thin-layer strip limestone, argillaceous limestone, and carbonaceous shale. Their joints are highly developed, and the rock mass is fragmented and dense. Therefore, the surrounding rock of the tunnel tends to deform.

The excavation methods adopted by the Tianqiao Mountain Tunnel are divided into four types: full-face excavation, two-bench excavation, three-bench excavation, and three-bench excavation plus temporary inverted arch (Table 1).

| Excavation methods                         | Deformation grade |
|--------------------------------------------|-------------------|
| Full-face excavation                       | Grade 1           |
| Two-bench excavation                       | Grade 2           |
| Three-bench excavation                     | Grade 3           |
| Three-bench excavation + Temporary inverted arch | Grade 4       |

3. Rough set theory
Rough set theory was proposed by Polish mathematician Z. Pawlak in the 1980s [9]. It is a scientific theory for analyzing and processing data. It can discretize data and establish a data classification system. Rough set theory can eliminate the ambiguity between data, remove redundant information based on retaining essential information in the data, analyze the roughness of knowledge, and find the dependency relationship between data attributes based on knowledge mining. Its process does not require any information outside the data, and it is entirely driven by data samples. It can objectively obtain information from imprecise, incomplete, and inconsistent data sets. Rough set theory is a mathematical tool used to represent imperfection and uncertainty based on the discriminability of objects in a set. It does not require any prior information and can effectively analyze inaccurate and incomplete information. Therefore, the rough set method can be used to deal with uncertain information objectively. The purpose of rough set theory to calculate the weight of each evaluation index in decision-making has been widely used in many fields [10,11]. The specific steps are as follows: i) construction of a decision table, ii) reduction of evaluation indicators, and iii) calculation of the weight of each evaluation index.
3.1. Construction of a decision table
A decision table is an expression of a knowledge information system, including conditional attributes and decision attributes, which are defined as follows:

\[ S = (U, C \cup D, V, f) \] (1)

where \( U \) is the universe, also known as a finite set of non-empty objects, and \( C \cup D \) is a subset. Among them, \( C \) is the conditional attribute set, \( D \) is the decision attribute set, \( V \) is the range of the attribute, and \( f \) is an information function, which is the information value given by each attribute of each object in the collection.

The construction of a decision table should first discretize the data samples in the decision table and screen for samples with duplicate or conflicting information. A decision table is constructed from the filtered data samples.

3.2. Reduction of evaluation indicators
One of the core functions of rough set theory is the reduction of evaluation indicators. Many evaluation indicators are included in the decision system. However, they are of different importance, and there may be redundant evaluation indicators. Rough set theory can remove one of many evaluation indexes while keeping the classification ability of the knowledge base unchanged. If rough set theory holds the knowledge classification ability constant, then it can remove one of many evaluation indicators and observe whether the classification ability of the knowledge base changes, thereby deleting duplicate or unimportant evaluation indicators.

3.3. Calculation of weight of each evaluation index
The evaluation indicators in the decision table refer to conditional attributes. The steps for analyzing each conditional attribute based on rough set theory are as follows:

Step 1: Calculate the dependency degree \( \gamma_c(D) \) of all decision attribute set \( D \) on each condition attribute set \( C \):

\[ \gamma_c(D) = \frac{1}{U} \sum_{i=1}^{m} |\gamma_c(D_i)| \] (2)

where \( U \) represents the number of samples in the decision table, and \( |\gamma_c(D_i)| \) represents the number of compatible samples in the decision table.

Step 2: Calculate the dependency of all decision attribute set \( D \) on each condition attribute set \( C_{c-i} \):

\[ \gamma_{c-i}(D) = \frac{1}{U} \sum_{i=1}^{m} |\gamma_{c-i}(D_i)| \] (3)

where \( C_{c-i} \) represents the condition attribute set generated after the condition attribute set \( C \) deletes a condition \( i \), and \( |\gamma_{c-i}(D_i)| \) represents the number of compatible samples in the decision table after the condition attribute \( i \) is deleted.

Step 3: Calculate the weight \( \omega_i \) of each conditional attribute \( i \):

\[ \omega_i = \frac{\gamma_c(D) - \gamma_{c-i}(D)}{\sum_{i=1}^{m} [\gamma_c(D) - \gamma_{c-i}(D)]} \] (4)

4. Factors influencing the deformation of surrounding rock
The selection of evaluation indicators is critical in the analysis of surrounding rock deformation. Given the nonlinear mechanical properties of the surrounding rock, the stability of tunnel engineering
is related not only to the supporting method but also to the excavation method of construction. The increase in tunnel depth will linearly increase the in situ stress in the rock mass. The higher the lateral pressure of rock mass, the more complex the stress state of the tunnel, thereby leading to more significant deformation hazards. Groundwater is the most active factor causing most engineering hazards. Weak surrounding rocks usually contain muddy structures. Muddy interlayer infiltration of groundwater accelerates the decomposition of rock mass, rapidly reduces the bearing capacity of rock mass, and weakens the strength of rock mass. Therefore, this paper examines subjective and objective factors affecting the deformation of the surrounding rock of the tunnel (Figure 1). Subjective factors include the excavation method \(F_1\) and the excavation footage \(F_2\), whereas objective factors include the tunnel burial depth \(F_3\), the degree of weathering \(F_4\), the groundwater conditions \(F_5\) and the uniaxial compressive strength of rocks \(F_6\). These indicators are used as the condition attribute set in the decision table, and the deformation level of the surrounding rock is used as the decision attribute set in the decision table. This paper uses a four-level classification method and establishes a rating system for the deformation of each evaluation index (see Table 2). Among them, the quantitative indicators are processed continuously, and the qualitative indicators are processed discretely.

![Figure 1. Factors affecting the deformation of surrounding rock.](image)

| Evaluation index | Deformation of the surrounding rock |
|------------------|-------------------------------------|
| \(F_1\)          | Excavation method \(F_1\)            |
| \(F_2\) \((m)\)  | Excavation footage \(F_2\)           |
| \(F_3\) \((m)\)  | Tunnel burial depth \(F_3\)          |
| \(F_4\)          | Degree of weathering \(F_4\)         |
| \(F_5\) \((m^3/d)\)| Groundwater conditions \(F_5\)        |
| \(F_6\) \((MPa)\)| Uniaxial compressive strength of rocks \(F_6\) |

Table 2. Classification of six factors affecting the deformation of surrounding rocks of the tunnel.

| Evaluation index | Deformation Grade 1 | Deformation Grade 2 | Deformation Grade 3 | Deformation Grade 4 |
|------------------|---------------------|---------------------|---------------------|---------------------|
| \(F_1\)          | Full-face excavation| Two-bench excavation| Three-bench excavation| Three-bench excavation + Temporary inverted arch |
| \(F_2\) \((m)\)  | >6                  | 4–6                 | 2–4                 | <2                  |
| \(F_3\) \((m)\)  | <50                 | 50–100              | 100–150             | >150                |
| \(F_4\)          | Weak weathering     | Medium weathering   | Strong weathering   | Complete weathering |
| \(F_5\) \((m^3/d)\)| <150                | 150–300             | 300–450             | >450                |
| \(F_6\) \((MPa)\)| >50                 | 35–50               | 20–35               | <20                 |

Through monitoring the surrounding rocks of the typical deformed section of the Tianqiao Mountain Tunnel, geological surveys, construction ledger records, and indoor laboratory tests on rocks, various evaluation index values for 25 typical deformed tunnel sections were collected. These sections were built into a decision table (see Table 3). To eliminate the dimensional impact between different...
indicators, the indicators of the decision table were discretized to form the final decision table (see Table 4).

### Table 3. Decision table of 25 data from the studied tunnel.

| No. | Condition attribute | Decision attribute |
|-----|---------------------|--------------------|
|     |                     | $F_1$ | $F_2$ (m) | $F_3$ | $F_4$ (m$^3$/d) | $F_5$ (MPa) | $F_6$ | Deformation grade |
| 1   | 1                   | 1     | 5         | 25    | 1            | 60     | 52    | 1                |
| 2   | 2                   | 6.5   | 2         | 28    | 1            | 73     | 63    | 1                |
| 3   | 2                   | 4.5   | 3         | 37    | 2            | 126    | 55    | 1                |
| 4   | 2                   | 4.5   | 5         | 55    | 1            | 112    | 43    | 1                |
| 5   | 2                   | 4.5   | 5         | 57    | 2            | 171    | 37    | 2                |
| 6   | 2                   | 5     | 4         | 46    | 2            | 189    | 55    | 2                |
| 7   | 3                   | 5     | 6         | 64    | 1            | 243    | 46    | 2                |
| 8   | 3                   | 5     | 7         | 71    | 2            | 354    | 61    | 2                |
| 9   | 3                   | 4.5   | 8         | 85    | 3            | 378    | 47    | 2                |
| 10  | 2                   | 3     | 13        | 130   | 3            | 412    | 46    | 3                |
| 11  | 2                   | 4.5   | 14        | 142   | 2            | 393    | 45    | 3                |
| 12  | 2                   | 4.5   | 16        | 160   | 2            | 275    | 32    | 2                |
| 13  | 4                   | 4     | 22        | 220   | 2            | 256    | 24    | 2                |
| 14  | 4                   | 1     | 27        | 278   | 4            | 482    | 15    | 4                |
| 15  | 4                   | 3.5   | 14        | 143   | 2            | 356    | 30    | 3                |
| 16  | 3                   | 3.5   | 145       |       | 3            | 314    | 29    | 3                |
| 17  | 3                   | 4.5   | 141       |       | 1            | 277    | 36    | 2                |
| 18  | 4                   | 4.5   | 136       |       | 3            | 187    | 43    | 3                |
| 19  | 4                   | 6.5   | 127       |       | 1            | 243    | 46    | 1                |
| 20  | 4                   | 5     | 97        |       | 2            | 311    | 59    | 1                |
| 21  | 3                   | 5     | 84        |       | 1            | 142    | 54    | 2                |
| 22  | 3                   | 5     | 64        |       | 3            | 319    | 41    | 3                |
| 23  | 2                   | 5     | 44        |       | 2            | 228    | 43    | 3                |
| 24  | 3                   | 6.5   | 52        |       | 1            | 321    | 39    | 2                |
| 25  | 2                   | 3.5   | 56        |       | 1            | 115    | 46    | 2                |

### Table 4. Discretized decision table.

| No. | Condition attribute | Decision attribute |
|-----|---------------------|--------------------|
|     |                     | $F_1$ | $F_2$ | $F_3$ | $F_4$ | $F_5$ | $F_6$ | Deformation grade |
| 1   | 1                   | 1     | 2     | 1     | 1     | 1     | 1     | 1                |
| 2   | 2                   | 1     | 1     | 1     | 1     | 1     | 1     | 1                |
| 3   | 2                   | 2     | 1     | 2     | 1     | 1     | 1     | 1                |
| 4   | 2                   | 2     | 2     | 1     | 1     | 2     | 1     | 1                |
| 5   | 2                   | 2     | 2     | 2     | 2     | 2     | 2     | 2                |
| 6   | 2                   | 2     | 1     | 2     | 1     | 2     | 1     | 1                |
| 7   | 3                   | 2     | 2     | 1     | 2     | 2     | 2     | 2                |
| 8   | 3                   | 2     | 2     | 2     | 3     | 1     | 2     | 2                |
| 9   | 3                   | 2     | 2     | 3     | 2     | 2     | 2     | 2                |
| 10  | 2                   | 3     | 3     | 3     | 3     | 2     | 3     | 3                |
| 11  | 2                   | 2     | 3     | 2     | 3     | 2     | 3     | 3                |
| 12  | 2                   | 2     | 4     | 2     | 2     | 3     | 2     | 3                |
| 13  | 4                   | 2     | 4     | 2     | 2     | 3     | 2     | 3                |
| 14  | 4                   | 4     | 4     | 4     | 4     | 4     | 4     | 4                |
| 15  | 4                   | 3     | 3     | 2     | 3     | 3     | 3     | 3                |
The data in the decision table were calculated and analyzed by using the rough set in Eqs. (1)–(4), and the weight of each evaluation index to the surrounding rock deformation level was obtained, that is, the degree of influence on the surrounding rock deformation level was determined (see Table 5 and Figure 2). Table 5 and Figure 2 show that the groundwater conditions exerted the most significant weight to the surrounding rock deformation; it provided the most considerable degree of influence on the surrounding rock deformation. Simultaneously, the degree of weathering was found to be an irrelevant conditional attribute after rough set theory calculation.

Table 5. Calculation results of each factor by rough set theory.

| Index      | $F_1$ | $F_2$ | $F_3$ | $F_4$ | $F_5$ | $F_6$ |
|------------|-------|-------|-------|-------|-------|-------|
| Dependence | 0.92  | 0.92  | 0.92  | 1     | 0.84  | 0.92  |
| Importance | 0.08  | 0.08  | 0.08  | 0     | 0.16  | 0.08  |
| Weight     | 0.1667| 0.1667| 0.1667| 0     | 0.3333| 0.1667|

Figure 2. Degree of influence of six factors on the deformation of surrounding rocks by rough set theory.
5. Discussion
The objective data from on site were used to reduce the evaluation index and calculate the weight by using rough set theory, and results were highly objective. The subjective influence of decision-makers was not considered. However, in the decision-making system, the subjective will of the decision-maker is usually part of the decision-making process, and subsequent research needs to include this subjective influence.

The composition and number of samples control the accuracy of the rough set solution. The more representative the sample, the higher the number of samples involved in the study and the more reliable the calculation results will be. Therefore, typical data must be collected when using rough set theory for calculation. For example, the data obtained in this paper were all typical deformation data.

After rough set theory calculations, groundwater conditions were observed to be the most influential factors in the deformation of surrounding rock, and the degree of weathering was not considered a redundant factor. Groundwater is undoubtedly the most dynamic and dominant factor in the project. In the construction of tunnel engineering, drainage measures are needed to reduce the impact of groundwater. The degree of weathering can be indirectly reflected in the uniaxial compression of the rocks. The degree of weathering is usually only an empirical indicator, and the uniaxial compressive strength of the rock is a reliable indicator of the properties of the rock. Therefore, the degree of weathering is reduced in the reduction index of rough set theory.

6. Conclusion
This paper examined six subjective and objective factors affecting the deformation of the surrounding rock of the tunnel. These factors were the excavation method, the excavation footage, the tunnel burial depth, the degree of weathering, the groundwater conditions, and the uniaxial compressive strength of rocks. These factors were used as conditional attributes of the decision table, and the actual deformation level of the tunnel was used as the decision attribute of the decision table. The data of 25 typical deformation sections from the Tianqiao Mountain Tunnel in China were collected to construct a complete decision table. Rough set theory was used to analyze the influence of these six factors on the deformation of the tunnel surrounding rock. Results showed that the impact of groundwater conditions was the greatest with a degree of 33.33%, and the degree of weathering was a redundant factor with a degree of 0%. The excavation method, the excavation footage, the tunnel burial depth, and the uniaxial compressive strength of rocks were the factors that must be considered for the deformation of the surrounding rock during tunnel excavation.

References
[1] Jiang G, Lee C M and Yue H 2010 Tunneling through intercorporate loans: The China experience J. Financ. Econ. 98(1) 1–20.
[2] Xue Y, Bai C, Kong F, Qiu D, Li L, Su M and Zhao Y 2020 A two-step comprehensive evaluation model for rockburst prediction based on multiple empirical criteria Eng. Geol. 268 105515.
[3] Xue Y, Bai C, Qiu D, Kong F, and Li Z 2020 Predicting rockburst with database using particle swarm optimization and extreme learning machine Tunn. Undergr. Sp. Tech. 98 103287.
[4] Zhang H, Chen L, Zhu Y, Zhou Z and Chen S 2019 Stress field distribution and deformation law of large deformation tunnel excavation in soft rock mass Appl. Sci. 9(5) 865.
[5] Anagnostou G 1993 A model for swelling rock in tunnelling Rock Mech. Rock Eng. 26(4) 307–331.
[6] Han L, Zuo Y, Guo Z, Zhang L, Chen X and Mao J 2017 Mechanical properties and deformation and failure characteristics of surrounding rocks of tunnels excavated in soft rocks Geotech. Geol. Eng. 35(6) 2789–2801.
[7] Xue Y, Zhang X, Li S, Qiu D, Su M, Li L, Li Z and Tao Y 2018 Analysis of factors influencing tunnel deformation in loess deposits by data mining: a deformation prediction model Eng. Geol. 232 94–103.
[8] Xue G, Gu C, Fang X, and Wei T 2019 A Case Study on Large Deformation Failure Mechanism and Control Techniques for Soft Rock Roadways in Tectonic Stress Areas *Sustainability* **11**(13) 3510.

[9] Pawlak Z 1982 Rough sets *Int. J. Comput. Inform. Sci.* **11**(5) 341–356.

[10] Nauman M, Azam N and Yao J 2016 A three-way decision making approach to malware analysis using probabilistic rough sets *Inform. Sci.* **374** 193–209.

[11] Shiraz R K, Fukuyama H, Tavana M and Di Caprio D 2016 An integrated data envelopment analysis and free disposal hull framework for cost-efficiency measurement using rough sets *Appl. Soft Comput.* **46** 204–219.