Geomechanics and Engineering, *Vol. 12, No. 1 (2017) 35-52*
DOI: https://doi.org/10.12989/gae.2017.12.1.035

Grouting effects evaluation of water-rich faults and its engineering application in Qingdao Jiaozhou Bay Subsea Tunnel, China

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(*Received December 15, 2015, Revised July 22, 2016, Accepted September 10, 2016*)

Abstract. In order to evaluate the grouting effects of water-rich fault in tunnels systematically, a feasible and scientific method is introduced based on the extension theory. First, eight main influencing factors are chosen as evaluation indexes by analyzing the changes of permeability, mechanical properties and deformation of surrounding rocks. The model of evaluating grouting effects based on the extension theory is established following this. According to four quality grades of grouting effects, normalization of evaluation indexes is carried out, aiming to meet the requirement of extension theory on data format. The index weight is allocated by adopting the entropy method. Finally, the model is applied to the grouting effects evaluation in water-rich fault F4-4 of Qingdao Jiaozhou Bay Subsea Tunnel, China. The evaluation results are in good agreement with the test results on the site, which shows that the evaluation model is feasible in this field, providing a powerful tool for systematically evaluating the grouting effects of water-rich fault in tunnels.

Keywords: extension theory; grouting effects; entropy method; water-rich fault; subsea tunnel

1. Introduction

Ever since Berunei, a French inventor first introduced grouting technology in 1802, grouting has been widely used in construction, transportation, water conservancy, mining and other areas for the purpose of water blockage and improvement of strata. Grouting has solved many difficulties and obtained good results in various projects (Kaushinger *et al*. 1992, Yoshitake *et al*. 2004).

Water inrush greatly endangers the safety of tunnel construction, and it leads to water accidents frequently. Hundreds of water inrush accidents occurred in China and around the world, which brought out huge casualties and economic losses (Li *et al*. 2013). A large number of water inrush cases in engineering practice indicate that the water-rich fault fracture zone is one of the key controlling factors during the tunnel construction (Tani 2012). Therefore, it is essential to take some effective countermeasures to advance reinforcement of the water-rich faults before

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ISSN: 2005-307X (Print), 2092-6219 (Online)

excavation to assure the safety of tunnel construction and operation.

Grouting and blocking water treatment is one of the key technologies for building water-rich fault tunnel. Hence, the effects of grouting indicate whether a project could succeed or not. However, the current detection methods for evaluating grouting effect are not well-established. The detection technology is underdeveloped, and the detection methods are still a weak link in the grouting construction technology. Currently, there is no specific criterion for the evaluation of grouting effects, and the finished grouting work is not scientifically and reasonably assessed (Xue *et al*. 2011). Detection methods are commonly used as follows: (1) analytical method; (2) check-up hole method; (3) geophysical prospecting method (Ohtsu and Watanabe 2002, Chen *et al*. 2015); (4) construction sampling method (Association Francaise Travaux Souterrain 1991, Kim *et al*. 2013); (5) change guess method (Aggelis *et al*. 2008); (6) comprehensive method (Zhang *et al*. 2006, Xue *et al*. 2011). Recently, there are a lot of research studies on the detection methods of grouting effects. However, the assessment of grouting effects only provides qualitative evaluation, aiming at detection methods or combining some methods. While research on multi-index comprehensive evaluation and classification of grouting effect is relatively less. Some researchers have made quantitative assessment by using artificial neural network evaluation methods (Kawamura *et al*. 1995) or AHP fuzzy comprehensive evaluation methods (Gong 2007). Though they have made certain contributions with their results involve many subjective factors in determining index weight, which affects the accuracy of the evaluation to some extent. It is urgent to make quantitative and comprehensive assessment of grouting effects. Therefore, in the present study, extension theory is applied to the evaluation of grouting effects of water-rich fault in tunnels based on a large number of engineering cases. Meanwhile, the grades of grouting effects are classified, and they can clearly determine the possibility of excavation based on the assessment results.

Extension evaluation method is different from other evaluation methods, and the differences consist in the fact that it has a unified evaluation model. In particular, the distance concept in real variable function can expand, enabling the range of correlation function to extend and enabling the evaluation index to turn from a single determined value to an interval value, which can more comprehensively evaluate the extent of the object belonging to the set. In the theory of extension, the correlation function of matter element determines the positive domain, negative domain and zero boundary. Therefore, it can be more finely reflect the state of an object. At the same time, the introduction of zero boundary provides an effective tool to describe something from quantitative to qualitative change. Because the extension set can describe the variability, it can be consideredin the state of the object from the perspective of development. Correlation function values in $(-\infty, +\infty)$ this brings convenience to the quantitative evaluation of the object (Li 2000). This method can reasonably evaluate the quality of the tunnel grouting. The advantage of entropy weight method to determine the weight lies in reducing the interference caused by subjectivity determining the weight as much as possible. In the present study, the entropy method is used to determine weight coefficient of each assessment factor of grouting effects, and the extension theory is used to assess the grouting effects of water-rich fault in tunnels, which is a new method for assessing the grouting effects.

2. Extension theory and extension model

Extenics (Cai 1990, 1999), founded by Chinese Professor Cai Wen in 1983, is a trans-disciplinary science spanning the fields of philosophy, mathematics, and engineering to solve incompatible problems. The theory offers possibility of expanding rules and methods of innovation by a formal model. Extenics describes variability of objects, develops qualitative description into quantitative description, and transforms incompatibility problems into compatible problems, and builds multi-index evaluation model to assess objects, opening up a new method for assessing objects. This method was applied to risk assessment of the project (An *et al*. 2011), stability evaluation for high rock slope (Zhao *et al*. 2015) and rock mass quality evaluation (Jia *et al*. 2003). Extenics takes matter-element theory and extension mathematics as its theoretical framework. Thereof, matter-element is the logic cell of extenics. N is the name of the given object, and v is the magnitude value of the characteristics c of it, the ordered triple $R = \{N, c, v\}$ is the basic element to describe objective, referred to as matter-element. The three factors of matter-element are composed of N, c, v.

2.1 The determination of matter-element

As for tunnel with water-rich fault P to be evaluated, there are collected related data or analytic results about the tunnel grouting effects, which are expressed by R. R is named as the matter-element to be evaluated.

$$R = \begin{bmatrix} P & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \tag{1}$$

Wherein P is one specific tunnel to be evaluated, and v_j is the magnitude value of P about c_j, i.e., detailed index of P, $j = 1, 2, 3\ldots, n$.

2.2 The determination of classical domain and joint domain

When N_{0t} is the standard matter, assuming that the value range V_{0t} of c_i : $V_{0t} = \langle a_{0ti}, b_{0ti}\rangle$, the matter-element matrix of classical domain and joint domain can be respectively expressed as follows

$$R_{0j} = \left(N_{0j}, C, V_{0ji}\right) = \begin{bmatrix} N_{0j} & c_1 & V_{0j1} \\ & c_2 & V_{0j2} \\ & \vdots & \vdots \\ & c_n & V_{0jn} \end{bmatrix} = \begin{bmatrix} N_{0j} & c_1 & \langle a_{0j1}, b_{0j1}\rangle \\ & c_2 & \langle a_{0j2}, b_{0j2}\rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{0jn}, b_{0jn}\rangle \end{bmatrix} \tag{2}$$

where R_{0j} is the j-th same syndrome element, N_{0j} is the i-th grade of grouting effect, c_i is the evaluation index of N_{0j} ($j = 1, 2, 3 \ldots, n$); and $V_{0ji} = \langle a_{0ji}, b_{0ji}\rangle$ is a value scale of N_{0j} about index c_i, which is individual evaluation rank of the corresponding factors, $j = 1, 2, 3\ldots, m$.

$$R_p = \left(P, C, V_p\right) = \begin{bmatrix} P & c_1 & V_{p1} \\ & c_2 & V_{p2} \\ & \vdots & \vdots \\ & c_n & V_{pn} \end{bmatrix} = \begin{bmatrix} P & c_1 & \langle a_{p1}, b_{p1}\rangle \\ & c_2 & \langle a_{p2}, b_{p2}\rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn}\rangle \end{bmatrix} \tag{3}$$

Wherein P is all the grades of grouting effect of water-rich fault; and the joint domain of P is

V_{pj} : $V_{pj} = \langle a_{pj}, b_{pj}\rangle$; $j = 1, 2, 3\ldots, m$. Obviously, $\langle a_{0ji}, b_{0ji}\rangle \in \langle a_{pj}, b_{pj}\rangle$.

2.3 The determination weight coefficient

The entropy weight method (Liang *et al*. 2010) is an objective weighting method. According to the degree of variation of each index, we can calculate the entropy weight of each index by using information entropy, adjust the weight of each index in accordance with the entropy, and thus obtain more objective weight.

If the information entropy of an index E_j is smaller, it indicates that the degree of index variation is greater, and when the information provided is more, the index plays greater role in the comprehensive evaluation, and the weight is bigger. On the contrary, when the information entropy of one index E_j is higher, it indicates that when the degree of index variation becomes smaller, the amount of information available is less, the role it plays gets smaller in the comprehensive evaluation, and so its weight.

2.3.1 Data standardization

Supposedly, the index $v_1, v_2, \ldots v_i$ represents the evaluation value of index before standardization, and the value after standardization can be expressed as $Y_1, Y_2, \ldots Y_i$:

$$Y_i = \begin{cases} \dfrac{v_i - \min(v_i)}{\max(v_i) - \min(v_i)} (\text{For the value is the smaller, which is the better}) \\ \dfrac{\min(v_i) - v_i}{\max(v_i) - \min(v_i)} (\text{For the value is the bigger, which is the better}) \end{cases} \tag{4}$$

Wherein min (v_i) represents the minimum value of index before standardization, then max (v_i) represents the maximum value of index before standardization.

2.3.2 Information entropy of index

According to the definition of the information entropy of information theory, the information entropy of a set of data can be expressed in the following form

$$E_j = -\ln(n)^{-1} \sum_{i=1}^{n} p_i \ln p_i \tag{5}$$

Thereof, $p_\mathrm{i} = Y_i \Big/ \sum_{i=1}^{n} Y_i$, if $p_i = 0$, then $\lim_{p_i \to 0} p_i \ln p_i = 0$, $i = 1, 2, 3\ldots, n$.

2.3.3 Index weight

According to the formula (6) to calculate the information entropy of each index as $E_1, E_2, \ldots E_n$, the weight of each index can be calculated through the information entropy acquired.

$$E_j = -\ln(n)^{-1} \sum_{i=1}^{n} p_i \ln p_i \tag{6}$$

Thereof, $\sum_{i=1}^{n} w_i = 1$, $i = 1, 2, 3\ldots, n$.

2.4 The establishment of correlation function

The correlation function of matter element N_j in regard to grouting effect level is as follows

$$k_{tj}(v_{ti}) = \begin{cases} \dfrac{\rho(v_{ji}, v_{oti})}{\rho(v_{ji}, v_{pi}) - \rho(v_{ji}, v_{oti})}, v_i \notin V_{ji} \\ \dfrac{-\rho(v_{ji}, v_{oti})}{|v_{ji}|}, v_i \in V_{ji} \end{cases} \tag{7}$$

$$\rho(v_{ji}, v_{oti}) = \left| v_i - \frac{a_{ji} + b_{ji}}{2} \right| - \frac{a_{ji} - b_{ji}}{2} \tag{8}$$

$$|v_{oti}| = b_{ji} - a_{ji} \tag{9}$$

$$\rho(v_{ji}, v_{pi}) = \left| v_i - \frac{a_{pi} + b_{pi}}{2} \right| - \frac{a_{pi} - b_{pi}}{2} \tag{10}$$

Wherein $k_{tj}(v_{ti})$ is the correlation degree function of standard matter element level t; $i = 1, 2, 3 \ldots n$; $j = 1, 2, 3\ldots, m$; and $t = 1, 2, 3, 4$.

2.5 Comprehensive evaluation

After obtaining the weight coefficient of each feature, then the correlation degree $k_{tj}(N_j)$of the matter element N_j concerning grade is represented by the following formula

$$k_{tj}(N_j) = \sum w_i k_{tj}(v_j) \tag{11}$$

$$k_{jt_0}(N_j) = \max\{k_{tj}(N_j)|_{t=1,2,3,4}\} \tag{12}$$

Therefore, t_0 is the grade of matter element N.

In order to further evaluate tropism of the grade of matter element, the characteristic value of class variables for the evaluation matter-element can be expressed as

$$\overline{k_{tj}}(N_j) = \frac{k_{tj}(N_j) - \min\limits_j k_{tj}(N_j)}{\max\limits_j k_{tj}(N_j) - \min\limits_j k_{tj}(N_j)} \tag{13}$$

$$t^* = \frac{\sum\limits_{j=1}^{m} j \bullet \overline{k_{tj}}(N_j)}{\sum\limits_{j=1}^{m} \overline{k_{tj}}(N_j)} \tag{14}$$

Wherein t^* is the characteristic value of grade variables of the evaluation matter element, and the trend of grade N to the superior or inferior can be judged according to the value of t^*.

3. The procedures of extension evaluation

When evaluating the grouting effects of water-rich fault in tunnels based on the extenics, the calculation flowchart of extension model is shown in Fig. 1, the detailed calculation and evaluation steps are as follows:

(1) Determine the evaluation index and evaluation standard of grouting water-rich fault. The determination of index should follow the principles of comparability, relativity, integrity and representativeness. The indexes of different dimensions should be under normalization in order to compare expediently.
(2) Build matter element. Construct a matter element of classical domain and a matter element of joint domain according to the data of evaluation standard and determine the matter element to be evaluated based on the grouting faults.
(3) Determine the weight coefficient of each evaluation index by applying the entropy weight method.
(4) Establish correlation function and use the weight coefficient resulted to calculate the correlation degree regarding to grade of grouting effect based on Eq. (11).
(5) Assess the grouting effect grade of water-rich fault in tunnels according to Eqs. (12)-(14).

4. Engineering application

4.1 Engineering background

In China, the subsea tunnel in Jiaozhou Bay, Qingdao is located between Tuandao and Xuejiadao. The total length of the tunnel is 6170 m, and it is the longest subsea tunnel in China so far. The width of sea surface is about 3.5 km at the tunnel axis, and the maximum water depth is about 42 m. As the express urban tunnel, Jiaozhou Bay Tunnel has a two-way six lanes, the design speed is 80 km/h. The submarine area tunnel passed through volcanics without exception, and they are mainly weathered granite, granite porphyry, volcanic breccias, volcanic tuff breccia and rhyolite porphyry. The surrounding rocks are divided into four levels, i.e., I, II, III, IV.

The tunnel crosses over 18 main fault fracture zones, among which the rock mass in the F4-4 fault fracture zone is fragmentation-inlaid fragmentation structure (see Fig. 2); main fissure belongs to a closed type, but a few others are micro open type, and the disseminated sign of fissure plane is not conspicuous. The fracture zone width is less than 30m while the permeable rate is 5~10 Lu. In this paper, the grouting effect of the fault is the object of evaluation.

4.2 The selection of evaluation indexes

Grouting is a systematic engineering of multifactor, multiple target and multi parameter, so the grouting effect evaluation is also a complex systematic engineering of multiple criteria. The analysis for each component factor during assessing is very challenging. Based on the grouting purpose of water-rich fault in tunnel and the corresponding test methods of grouting effects, in this

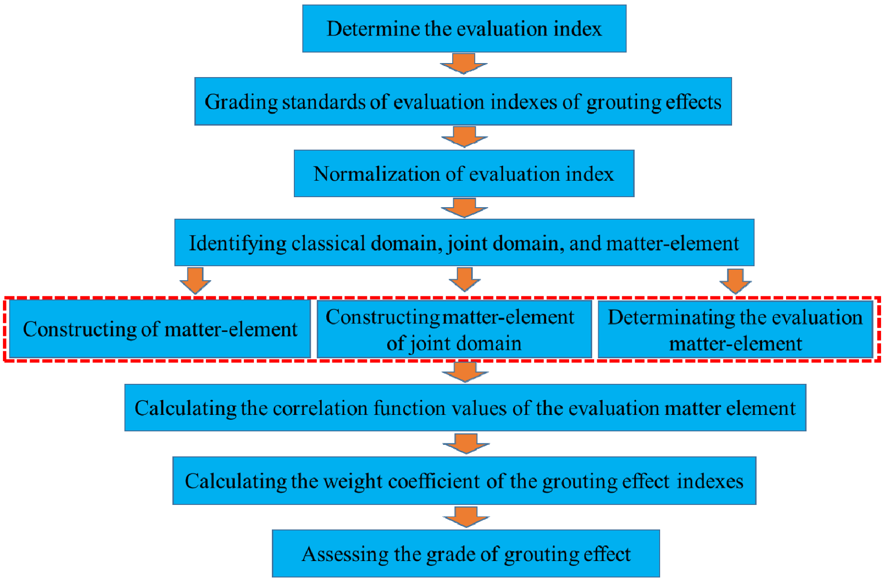

Fig. 1 Flowchart of extension model

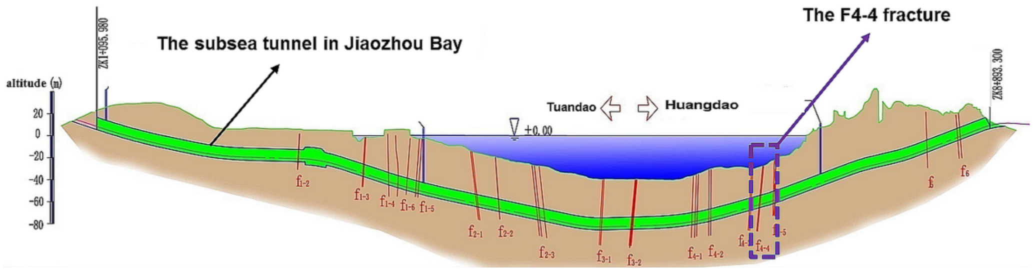

Fig. 2 Fracture zone sketch map of the subsea tunnel in Jiaozhou Bay

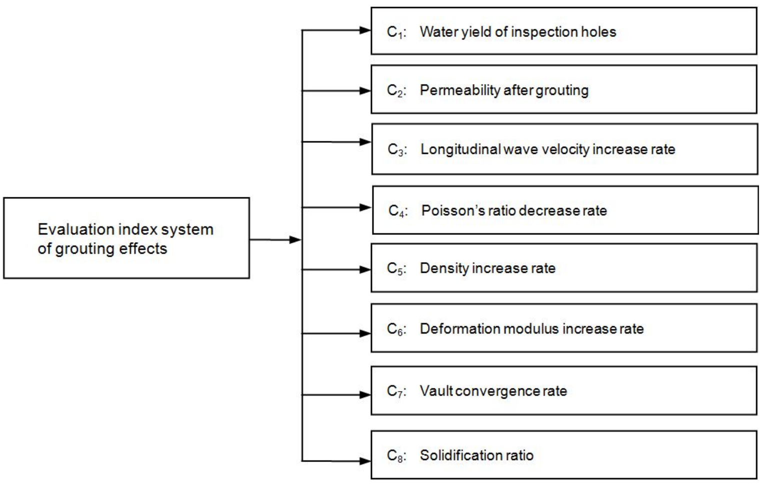

Fig. 3 Evaluation index system of grouting effects

study we selected the following 8 factors which can best reflect the grouting effect of water-rich fault in tunnel, and construct a scientific and reasonable grouting effect evaluation index system (see Fig. 3).

(1) Water yield of inspection hole (c_1)

For the grouting engineering with the aim of water blockage, the water yield of check-up hole is the most direct reflection to detect the effect of water blockage, which can visually judge whether the effects of grouting meet the design requirement.

According to the study on the evaluation of grouting (Zhao 2009), the water yield of check-up hole is divided into four grades, i.e., $0 < c_1 \leq 0.05$ *L/min*, 0.05 *L/min* $< c_1 \leq 0.10$ *L/min*, 0.10 *L/min* $< c_1 \leq 0.15$ *L/min*, 0.15 *L/min* $< c_1 \leq 1.0$ *L/min*.

(2) Permeability after grouting (c_2)

The permeability after grouting can be detected by packer permeability test, which is the most important and reliable way to detect the effect of grouting. Through this test, we obtained the permeability coefficient of the surrounding rocks after grouting, and then calculated the rate of crack and porosity of the surrounding rocks after grouting, thus the grouting effects of rock mass can be assessed objectively.

According to the statistics on effects after grouting, the permeability after grouting is divided into four levels: $0 < c_2 \leq 1.0$ *Lu*, 1.0 *Lu* $< c_2 \leq 3.0$ *Lu*, 3.0 *Lu* $< c_2 \leq 5.0$ *Lu*, 5.0 *Lu* $< c_2 \leq 10.0$ *Lu*.

(3) Longitudinal wave velocity increase rate (c_3)

The longitudinal wave velocity can reflect fissures of the rock mass and the filling of fissures. After the fissure water or the loose rock mass replaced by grout or bonded and stiffened, the integrity and continuity of the rock mass is improved, and the longitudinal wave velocity of the rock mass increases accordingly, since the longitudinal wave velocity is an important index to evaluate the grouting effect. The longitudinal wave velocity can be obtained by the Tunnel Seismic Prediction (TSP), TSP is a more advanced detection technology, the detecting principle of TSP system is shown in Fig4. According to the contrast detect results after grouting, the longitudinal wave velocity increase rate is divided into four levels: $0 < c_2 \leq 3.0\%$, $3.0\% < c_2 \leq 6.0\%$, $6.0\% < c_2 \leq 9.0\%$, $9.0\% < c_2 \leq 11.0\%$.

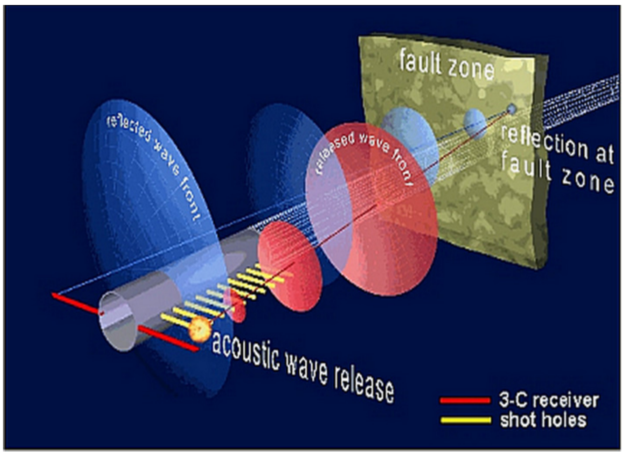

Fig. 4 Detection principle diagram of TSP

(4) Poisson’s ratio decrease rate (c_4)

Poisson's ratio reflects the mechanics and strength properties of the surrounding rock. Normally, the surrounding rocks of small Poisson's ratio are hard and brittle, and the surrounding rock of big Poisson’s ratio is soft and plastic. The bigger the decreasing rates of the Poisson’s ratio, the greater the mechanic and strength of the surrounding rocks increase, for Poisson’s ratio is another important index to evaluate grouting effect.

(5) Density increase rate (c_5)

For a tunnel fault, the surrounding rocks are relatively fractured. Fissures and pore spaces are relatively developed, and the density is relatively low. Grout fills into the fissures and pore spaces in the surrounding rocks, with the result that the density of the surrounding rocks is greatly improved. The filling of grout is denser, the density becomes the bigger, so then the grouting effect is better.

(6) Deformation modulus increase rate (c_6)

The deformation modulus of the surrounding rocks is a measurement of the ability to resist deformation of surrounding rocks. The bigger the value, the bigger the stress needed for the deformation of the surrounding rocks, and the stiffness of the surrounding rock increases. Therefore, the rate of deformation modulus increase is also an important index to reflect the grouting effect.

(7) Vault convergence rate (c_7)

The vault convergence rate reflects vault deformation and convergence after excavation of the tunnel. Larger convergence rate shows faster vault deformation, convergence and faster stability of the surrounding rocks, indicating that the grouting effect is more obvious. By monitoring measurement, obtain the vault convergences of the tunnel after excavation. Based on the statistical results of long time monitoring measurement, the stability time of tunnel vault settlement is greatly influenced by grouting, the value of deformation is very obviously decreasing after grouting (Zhao 2009, Xue *et al*. 2011, Wang *et al*. 2011), from 22~35 cm down to 5.8~16.48 cm. According to statistical data analysis, considering different surrounding rock, different grouting design standards, different grouting technology, four grades of the vault convergence rate are established, i.e., $0 < c_7 \leq 15\%$, $15\% < c_7 \leq 30\%$, $30\% < c_7 \leq 40\%$, $40\% < c_7 \leq 100\%$.

(8) Solidification ratio (c_8)

After injecting into the fractured rock mass to fill the fissure, the grout is condensed with the surrounding rocks into rock. Bigger condensation of the grout indicates greater ratio of filling fissure and higher density of the rock mass after grouting. Therefore, the opportunity of pervious water is lower and the grouting effect is better.

According to the principle of best solidification, solidification ratio is divided into four levels: $0 < c_8 \leq 70\%$, $70\% < c_8 \leq 80\%$, $80\% < c_8 \leq 90\%$, $90\% < c_8 \leq 100\%$.

4.3 Grading standards of evaluation indexes of grouting effects

Since there is no formal and authoritative criterion available for the evaluation of the grouting effects, we referred to the grading standard on the relevant evaluation index in the paper of Zhao (2009) in combination with the grouting design requirements for the water-rich fault F4-4 of subsea tunnel in Jiaozhou Bay. In summary, the grouting effects are divided into 4 levels in this paper, grade I, grade II, grade III, grade IV, representing excellent, good, qualified, unqualified, the

Table 1 Grading standards of evaluation indices of grouting effects

Evaluation indices	Grading of grouting effect				Design requirements
	I	II	III	IV	
Water yield of inspection holes (L/min)	0~0.05	0.05~0.10	0.10~0.15	0.15~1	≤ 0.10
Permeability after grouting (Lu)	0~1	1~3	3~5	5~10	≤ 3.0
Longitudinal wave velocity increase rate (%)	9~11	6~9	3~6	0~3	≥ 6.0
Poisson's ratio decrease rate (%)	10~14	7~10	4~7	0~4	≥ 7.0
Density increase rate (%)	13~17	8.0~13	3~8.0	0~3	≥ 8.0
Deformation modulus increase rate (%)	45~78	30~45	15~30	0~15	≥ 30.0
Vault convergence rate (%)	40~100	30~40	15~30	0~15	≥ 40.0
Solidification ratio (%)	90~100	80~90	70~80	0~70	≥ 80.0

Table 2 Measured value of evaluation indices of grouting effects

Evaluation indices	Measured value
Water yield of inspection holes (L/min)	0.106
Permeability after grouting (Lu)	1.27
Longitudinal wave velocity increase rate (%)	0.8
Poisson's ratio decrease rate (%)	7.1
Density increase rate (%)	3.6
Deformation modulus increase rate (%)	19.1
Vault convergence rate (%)	44
Solidification ratio (%)	95

Table 3 Grading standards of evaluation indices of grouting effects (dimensionless)

Grading of evaluation	I	II	III	IV
Water yield of inspection holes	0.95~1	0.90~0.95	0.80~0.90	0~0.80
Permeability after grouting	0.9~1	0.7~0.9	0.5~0.7	0~0.50
Longitudinal wave velocity increase rate	0.92~1	0.54~0.92	0.27~0.54	0~0.27
Poisson’s ratio decrease rate	0.71~1	0.50~0.71	0.28~0.50	0~0.28
Density increase rate	0.76~1	0.47~0.76	0.29~0.47	0~0.29
Deformation modulus increase rate	0.57~1	0.38~0.57	0.19~0.38	0~0.19
Vault convergence rate	0.40~1	0.30~0.40	0.15~0.30	0~0.15
Solidification ratio	0.9~1	0.80~0.90	0.70~0.80	0~0.70

level of each evaluation index is shown in Table1, and the test value of each evaluation index is shown in Table 2.

4.4 Normalization of evaluation index

In order to facilitate the calculation, the evaluation index of different dimensions must be under normalization. The values in Tables 1 and 2 are calculated by Eq. (4) and the computed values are

Table 4 Measured value of evaluation indices of grouting effect (dimensionless)

Evaluation indices	Measured value
Water yield of inspection holes	0.10
Permeability after grouting	0.87
Longitudinal wave velocity increase rate	0.07
Poisson's ratio decrease rate	0.51
Density increase rate	0.21
Deformation modulus increase rate	0.24
Vault convergence rate	0.44
Solidification ratio	0.95

respectively shown in Tables 3 and 4.

4.5 Identifying classical domain, joint domain, and matter-element

4.5.1 Construction of matter-element

The four grouting effect grades (I, II, III, IV) are denoted as N_{01}, N_{02}, N_{03}, N_{04}, and matter element and segment element of each effect grade level are constructed

When t = 1, the grouting effect for grade is I, the value range of evaluation index is expressed as: <0.95, 1.0>, <0.90, 1.0>, <0.92, 1.0>, <0.71, 1.0>, <0.76, 1.0>, <0.57, 1.0>, <0.40, 1.0>, <0.90, 1.0> .

$$R_{01} = \begin{bmatrix} N_{01}, & c_1, & \langle 0.95, 1.0 \rangle \\ & c_2, & \langle 0.90, 1.0 \rangle \\ & c_3, & \langle 0.92, 1.0 \rangle \\ & c_4, & \langle 0.71, 1.0 \rangle \\ & c_5, & \langle 0.76, 1.0 \rangle \\ & c_6, & \langle 0.57, 1.0 \rangle \\ & c_7, & \langle 0.40, 1.0 \rangle \\ & c_8, & \langle 0.90, 1.0 \rangle \end{bmatrix} \tag{15}$$

In the same way, when t = 2, 3, 4, the value ranges of evaluation index are expressed as follows:

Grouting effect for grade II (t = 2).

$$R_{02} = \begin{bmatrix} N_{02}, & c_1, & \langle 0.90, 0.95 \rangle \\ & c_2, & \langle 0.70, 0.90 \rangle \\ & c_3, & \langle 0.54, 0.92 \rangle \\ & c_4, & \langle 0.50, 0.71 \rangle \\ & c_5, & \langle 0.47, 0.76 \rangle \\ & c_6, & \langle 0.38, 0.57 \rangle \\ & c_7, & \langle 0.30, 0.40 \rangle \\ & c_8, & \langle 0.80, 0.90 \rangle \end{bmatrix} \tag{16}$$

Grouting effect for grade III ($t = 3$).

$$R_{03} = \begin{bmatrix} N_{03}, & c_1, & \langle 0.80,\ 0.90\rangle \\ & c_2, & \langle 0.50, 0.70\rangle \\ & c_3, & \langle 0.27, 0.54\rangle \\ & c_4, & \langle 0.28, 0.50\rangle \\ & c_5, & \langle 0.29, 0.47\rangle \\ & c_6, & \langle 0.19, 0.38\rangle \\ & c_7, & \langle 0.15, 0.30\rangle \\ & c_8, & \langle 0.70, 0.80\rangle \end{bmatrix} \tag{17}$$

Grouting effect for grade IV ($t = 4$).

$$R_{04} = \begin{bmatrix} N_{04}, & c_1, & \langle 0,\ 0.80\rangle \\ & c_2, & \langle 0,\ 0.50\rangle \\ & c_3, & \langle 0, 0.27\rangle \\ & c_4, & \langle 0, 0.28\rangle \\ & c_5, & \langle 0, 0.29\rangle \\ & c_6, & \langle 0, 0.19\rangle \\ & c_7, & \langle 0, 0.15\rangle \\ & c_8, & \langle 0,\ 0.70\rangle \end{bmatrix} \tag{18}$$

Wherein, N is the grouting effect grade; c_1 is water yield of inspection hole; c_2 is permeability after grouting; c_3 is the longitudinal wave velocity increase rate; c_4 is the Poisson's ratio decrease rate; c_5 is the density increase rate; c_6 is the deformation modulus increase rate; c_7 is the vault convergence rate; and c_8 is the solidification ratio.

4.5.2 Constructing matter-element of joint domain

$$R_P = \begin{bmatrix} P, & c_1, & \langle 0, 1.00\rangle \\ & c_2, & \langle 0,\ 1.00\rangle \\ & c_3, & \langle 0, 1.00\rangle \\ & c_4, & \langle 0, 1.00\rangle \\ & c_5, & \langle 0,\ 1.00\rangle \\ & c_6, & \langle 0,\ 1.00\rangle \\ & c_7, & \langle 0,\ 1.00\rangle \\ & c_8, & \langle 0,\ 1.00\rangle \end{bmatrix} \tag{19}$$

4.5.3 Determination the evaluation matter-element

The data in Table 4 is fed into the matter element matrix, forming matter-element to be evaluated. The measured values of elevation indices, $\{c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8\}$ = {0.106, 1.27, 0.8, 7.1, 3.6, 19.1, 44, 95}, each evaluation index is graded, respectively belong to grade III, grade II, grade IV, grade II, grade III, grade III, grade I, grade I. Then, the measured values of elevation indices normalized are shown as follows

$$R = \begin{bmatrix} P, & c_1, & 0.10 \\ & c_2, & 0.87 \\ & c_3, & 0.07 \\ & c_4, & 0.51 \\ & c_5, & 0.21 \\ & c_6, & 0.24 \\ & c_7, & 0.44 \\ & c_8, & 0.95 \end{bmatrix} \tag{20}$$

The evaluation matter element is the water-rich fault tunnel of grouting effect grade evaluation. In fact, to determine the evaluation matter element is to determine corresponding index value of each extensive evaluating water-rich fault tunnels.

4.6 Calculating the correlation function values of the evaluation matter element

In the case of water yield of inspection holes (c_1), the value of correlation function is derived by feeding the relevant data into the Eqs. (8)-(12).

Due to $v_i \notin V_{ji}$, so the correlation function value of c_1 for grade I is calculated as follows

$$\rho(v_{ji}, v_{pi}) = \left| v_i - \frac{a_{ji} + b_{ji}}{2} \right| - \frac{a_{ji} - b_{ji}}{2}$$

$$= \left| 0.10 - \frac{0.95 + 1}{2} \right| - \frac{1.0 - 0.95}{2}$$

$$\rho(v_{ji}, v_{pi}) = \left| v_i - \frac{a_{pi} + b_{pi}}{2} \right| - \frac{a_{pi} - b_{pi}}{2}$$

$$= \left| 0.10 - \frac{1.0 + 0}{2} \right| - \frac{1.0 - 0}{2}$$

Therefore

$$k_{11}(v_{11}) = \frac{\left| 0.10 - \frac{1}{2}(0.95 + 1) \right| - \frac{1}{2}(1.0 - 0.95)}{\left\{ \left| 0.10 - \frac{1}{2}(0 + 1) \right| - \frac{1}{2}(1 - 0) \right\} - \left\{ \left| 0.10 - \frac{1}{2}(0.95 + 1) \right| - \frac{1}{2}(1.0 - 0.95) \right\}} = -0.894 \tag{21}$$

In the similar way, the other correlation function values to be calculated are presented in Table 5.

The grouting effect grade of water-rich tunnel is assessed by extenics method. Correlation

Table 5 Relation degree of evaluation indices of grouting effects

Grading	Evaluation indices of grouting effects							
	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
I	-0.894	-0.187	-0.924	-0.295	-0.723	-0.579	-0.066	0.500
II	-0.888	0.150	-0.870	0.047	-0.553	-0.368	-0.083	-0.500
III	-0.881	-0.233	-0.730	-0.02	-0.275	0.263	0.241	-0.750
IV	0.125	-0.74	0.259	-0.305	0.275	-0.172	-0.397	-0.833

Table 6 Entropy weight of evaluation indices of grouting effects

Evaluation indices	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
Entropy weight	0.06	0.091	0.016	0.157	0.017	0.03	0.348	0.281

degree to each level and level characteristics value can be determined, and the extenics evaluation results can be obtained.

4.7 The weight coefficient of the grouting effect indexes

According to the calculation steps of entropy weight method, the entropy weight coefficient of each index is calculated by Eqs. (5)-(7), the results are shown in Table 6.

4.8 Assessing the grade of grouting effects

The correlation function values in Table 5 and entropy weight values in Table 6 are fed into the Eq. (11) to calculate the correlation degree of the grade of grouting effect in the fault of the tunnel, the correlation degree is written as

$$k_{tj}\left(N_j\right)=\left[-0.043,-0.236,-0.212,-0.476\right] \tag{22}$$

According to Eq. (12)

$$k_{jt_0}\left(N_j\right)=\max\left\{(-0.043,-0.236,-0.212,-0.476)\middle|t=1,2,3,4\right\} \tag{23}$$

The level of the grouting effects is calculated as t_0 = 1, i.e., I is the grouting effect grade of the tunnel.

In order to further evaluate the tendency of grouting effect level, we put the correlation degree into Eqs. (13)-(14) and calculate the variable characteristic value of the grouting effect level as t^* = 1.8, showing that grouting effect belongs to grade I, but it is closer to grade II, precisely the grouting effect is grade 1.8.

In summary, from a qualitative point of view, the grouting effect is between excellent and good, the result is more close to good; from a quantitative point of view, the grouting effect level can be quantified accurately

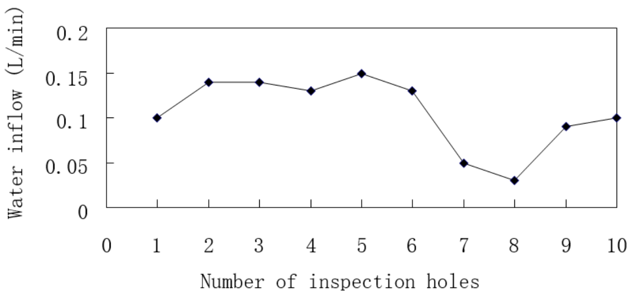

Fig. 5 Inspection holes water after grouting

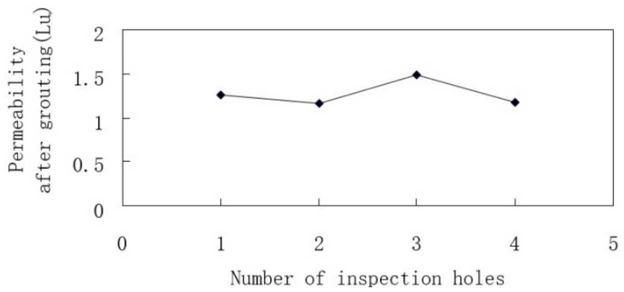

Fig. 6 Rate of permeability of inspection holes

5. Discussion

In order to fully test the grouting effects of water-rich fault F4-4 of subsea tunnel in Jiaozhou Bay, Qingdao, comprehensive detection methods are adopted, including check-up hole method, the TSP geophysical prospecting method, excavation revealed method, borehole TV analysis, *P-Q-t* control method, vault deformation analysis, etc.

70% of water yield in the inspection hole is between 0.1 ~ 0.15 L/min (see Fig. 5), and 30% of the hole is dripping and the water yield is between 0.03~0.09 L/min. By using borehole camera system to detect the internal, most fissures have been filled with dense grout, and there is no fissure water in the hole. This ultimately meets the requirement that water yield of the inspection hole is no more than 0.15 L/min per meter, and the grouting effect is better.

Then the test by injecting water into the grout hole is performed for the 4 inspection holes, and the test results are shown in Fig. 6. By analyzing Fig. 6, it shows that the rate of water permeability of all the inspection holes is less than 1.5 Lu, and the permeability of the rock mass belongs to weak permeability, suggesting that the grouting effects are very significant.

The fault before and after grouting are detected by TSP geophysical prospecting method. And by comparing test results, we find that the deformation modulus of the surrounding rocks after grouting increases from 29.4 GPa to 35.0 GPa, and the growth rate is 19.1%. The density and the Poisson's ratio increases by 3.6% and decreases by 7.1% respectively. The above data show that the grouting effect is more significant.

Observed from the excavation surface, there is scarcely any water on the excavation surface, and it is easy to find that the grout spreads along the fissures and fills densely, the stone rate of the grout is high, the integrity of the surrounding rock is ameliorated greatly, and the grade of the

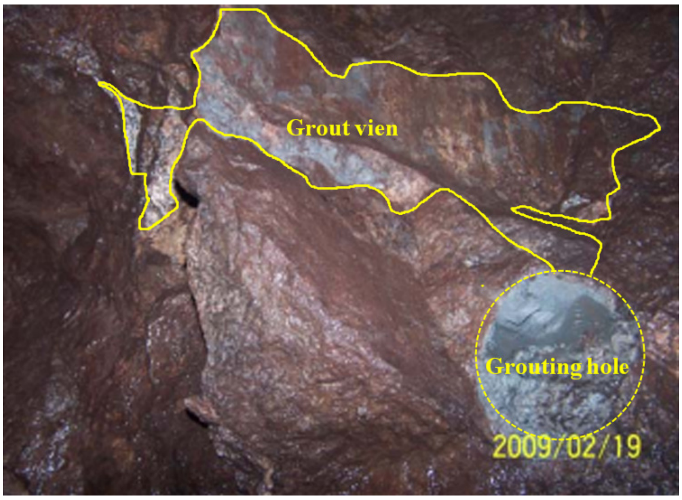

Fig. 7 Grouting context spread

surrounding rocks is enhanced greatly. Fig. 7 shows the grout diffusion after excavation in the working field.

With all the analysis mentioned above, the grouting effect of water-rich fault F4-4 of subsea tunnel in Jiaozhou Bay, Qingdao achieves better results and has met the design requirement. Therefore, the evaluation results obtained from the evaluation model based on extension theory are consistent with the field-observed results.

In theory, the method is relatively rigorous, the calculation is comparatively simple, which is desirable practicability. Meanwhile, this novel method can be applied to comprehensive evaluation of similar problems.

6. Conclusions

Aimed at current grouting effects evaluation situation, the evaluation model of grouting effects in water-rich faults based on extension theory is constructed. The evaluation indexes are ascertained by transforming from single value to interval value. The index weight is allocated by transforming from subjectivity to objectivity. The quantification of grouting effects evaluation is achieved, which makes a new attempt for the exploration of grouting effects evaluation methods.

Grouting purpose of water-rich fault and test method of grouting effects are taken into consideration. The changes of permeability, mechanical properties of surrounding rocks after grouting and deformation of them after excavation are analyzed. Water yield of inspection hole, permeability rate of surrounding rocks after grouting, rate of longitudinal wave velocity increases, rate of density increase, rate of Poisson's ratio decrease, rate of deformation modulus increase, rate of vault convergence and rate of solidification are selected as evaluation indexes, which constitute the evaluation system of grouting effects. The evaluation model is applied to the grouting effects evaluation in water-rich fault F4-4 of Qingdao Jiaozhou Bay Subsea Tunnel, China. The evaluation result is $t_0 = 1$, and the characteristic value is $t^* = 1.8$. Therefore, the evaluation grade of the grouting effects is closer to II. The evaluation result is consistent with the field-observed result, indicating that this evaluation model is feasible, which provides a reference for the grouting effects evaluation of other similar projects. The selection of grouting effects evaluation indexes is under restrictions because of grouting purposes and test methods. Therefore, as for different grouting engineering projects, the potential of evaluation index system is open for further study.

Acknowledgments

All the authors would like to thank the reviewers for their valuable advice and suggestions, which help to improve the level of paper. This paper was supported by the National Basic Research Program of China (973 Program, No.: 2013CB036000), the National Natural Science Foundation of China (Grant No.: 51509147) and Project funded by China Postdoctoral Science Foundation.

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