Numerical simulation analysis of the shear tests on cemented surface between bedrock and concrete

C J Wu\textsuperscript{1,2}, Y J Lai\textsuperscript{2} and J Yu\textsuperscript{1}

1 School of Transportation and Civil Engineering, Nantong University, Nantong, Jiangsu, 226019, China
2 Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, 200092, China

Abstract. Based on anchorage foundation of Ganjiang Highway Bridge situated on weakly weathered argillaceous siltstone, numerical simulation analysis of shear tests were carried out to investigate the shear strength of cemented surface, which is between anchorage foundation concrete and bedrock surface. In order to evaluate the effect on shear strength effectively due to the cemented surface roughness, random distribution of parameters is firstly introduced to quantify the roughness and the Monte-Carlo method is employed to simulate the morphology of cemented surface. Secondly, numerical simulation analysis on shear tests is implemented to study the effect of different cemented surface roughness on shear strength. At last, a new evaluation method of cemented surface shear strength is put forward based on the numerical simulation with random contact interface. In addition, the results from numerical simulation method are compared with the field direct shear test, and it is validated that the results are highly consistent.

1. Introduction
The gravity anchorage of suspension bridge mainly depends on the bonding and friction of the cemented surface between the massive anchorage foundation concrete and the bedrock underlying to transfer the huge tension safely to the foundation, which is derived from the main cable. It is so difficult to evaluate the shear strength of cemented surface between the bedrock and anchorage foundation concrete due to the large base area of anchorage and the great difference in the rock property, weathered degree, roughness and other factors of the underlying bedrock. However, the friction coefficient of cemented surface is often determined according to the classification level of rock mass and the design code. The real roughness of cemented surface and the geometry form of anchorage foundation \cite{1} are usually neglected, which actually will lead to great change. So it seems to be unreasonable for current engineering design.

In order to accurately determine the shear strength of cemented surface between bedrock and concrete foundation, laboratory and field shear tests are often employed in practical projects. For example, Ji et al. \cite{2-4} conducted experimental studies on the cemented surface between bridge or dam foundation and underlying bedrock. In addition, in the further study of the cemented surface, Saiang et al. \cite{5} obtained shear strength and shear displacement characteristics of the cemented surface between concrete and rock under different normal stress conditions by experiments. Tian et al. \cite{6} established the constitutive model of shear stress and displacement through direct shear test of the cemented surface between concrete and sandstone. Guo et al. \cite{7} built up the relationship between the...
strength parameters of mortar and limestone cemented surface and different size of samples, and the press-shear fracture failure mode was proposed based on the stress intensity factor. Tang et al. [8] studied shear strength of the irregular cemented surface between sprayed concrete and granite under the variation of high temperature by experiments. Apparently, among the many influencing factors, the shape and roughness of cemented surface have the most important influence on shear strength and failure mechanism. Unfortunately, a method to effectively evaluate the influence of the characteristic morphology of cemented surface on shear strength hasn’t been established in current research.

At present, there are already many research achievements on the cemented surface and structural surface, but there is still much limitation in practice. For example, laboratory tests are often based on relatively intact rock samples, which differ greatly from rock mass on site. The quantity of field test samples is always limited because of high cost, and test results are usually discrete. Therefore, a new numerical simulation method for shear test on the cemented surface between concrete and underlying bedrock will be proposed based on the anchorage foundation of Ganjiang Highway Bridge, which situated on the weakly weathered argillaceous siltstone. In this method, the characteristic parameters with random distribution will be introduced to quantify the roughness of cemented surface, and the Monte-Carlo simulation method will be adopted to simulate the morphology of cemented surface. And then, a random contacting numerical calculation model will be established to investigate the shear strength of cemented surface with different level of roughness. Finally, this new numerical simulation method will be verified by the comparison of results from physical tests and numerical simulation.

2. Shear failure mechanism of cemented surface

The shear failure of cemented surface is mainly determined by the relative strength of the upper and lower part on cemented surface, the cohesion between two sides, and the roughness of cemented surface. The shear test of cemented surface between concrete and bedrock is essentially the shear test of cemented surface between one material and another. The roughness of cemented surface will increase the interlock action between two parts, and improve the shear resistance greatly. When the roughness of cemented surface is large enough to exceed the critical value, and lead to high level of interlock between the bedrock and concrete, the shear failure surface will occurs among the weak party (as shown in Figure a and b). When the cemented surface is relatively smooth and the bonding strength between bedrock and concrete is relative low, the failure surface occurs just on the cemented surface (as shown in Figure c). When there are weak surfaces or joints existing in the rock mass, the failure may occur inside the rock mass (as shown in Figure d). A schematic diagram of potential shear failure surfaces under different conditions is shown in Figure 1. The above analysis is based on the ideal situation in which the concrete material or bedrock is isotropic and uniform. In fact, for the same test sample, the rock mass or concrete always has different defects or different structural characteristics. Therefore, the shear failure surface usually doesn’t appear as the same as anticipated.

![Figure 1. Schematic diagram of shear failure plane.](image)

3. Numerical analysis of shear test on cemented surface
3.1. Numerical model and calculation method of random contact interface

In reality, the morphology of cemented surface is complex and irregular, which has a critical effect on the shear strength of cemented surface. However, the process of field shear tests is complicated. The test results are disperse and not very precise. It also requires lots of labour force, material resources and time. Although the shear deformation characteristics and failure modes of cemented surface can be concluded by experiments, the influence of roughness on the shear mechanism of cemented surface can't be evaluated from the perspective of microscopic mechanism. Therefore, in order to effectively measure the effect of roughness on the shear strength of cemented surface, it is very necessary to quantify the roughness and depict the degree of morphological surface by some variables. Random contact numerical model is proposed by using the Monte-Carlo method [9] in this paper. Some characteristic parameters of random distribution are introduced to describe the convex body size and spatial distribution, and simulate the roughness on cemented surface. And then random contact numerical shearing test will be carried out by DEM to investigate the shear strength, failure modes and the influence of roughness on shear deformation characteristics of cemented surface.

3.1.1. Establishment of the random geometry model

First define a baseline, and make \( n \) datum points uniformly distributed on the baseline. It is assumed that each point represents corresponding waving value \( h \) which ranges randomly from zero to the maximum waving value \( h_{\text{max}} \). Connect each waving point and a hypothetical curve will appear to model any morphological cemented surface. So there are two random parameters involved, \( n \) and \( h \). It is relatively easy to determine the maximum waving value \( h_{\text{max}} \). So it is quite necessary to set the value for \( n \) reasonably so that the generated curve can be well fit for the actual cemented surface. After the generation of surface curve, the upper and lower parts on each side can be further built according to the geometry of test sample, which is illustrated in Figure 2.

3.1.2. Generation of random parameters

According to the conception of stochastic modelling, variable \( h \) is the key parameter during the establishment of model as well as variable \( n \). For a certain cemented surface, the maximum value \( h_{\text{max}} \) is fixed when the variable \( h \) randomly in the interval \([0, h_{\text{max}}]\). It is not difficult to model morphology of the cemented surface when the Monte-Carlo simulation method is used to generate random numbers of variables under relevant distribution rules in any interval to simulate the distribution of random variables conveniently, so variable \( h \) can be created by the Monte-Carlo simulation method. Meanwhile, if the value of variable \( n \) is larger, it means that there are more datum points on the baseline and it represent that the cemented surface is rougher. Otherwise, the surface is smoother while the value of \( n \) is smaller.

3.1.3. Establishment of random contact numerical calculation model

After the above random variables are determined, the geometric model can be generated through the secondary development platform of AutoCAD soft, and then the numerical calculation model can be further established through FLAC3D, as shown in Figure 3.
The Interface module provided by the FLAC3D program can effectively simulate the interaction between different materials on both sides of the contact surface, including squeeze, separation and relative slip. Since the finite-difference program FLAC3D can only generate regular elements, and cannot divide irregular geometric blocks, the geometric Figures can firstly imported into the ANSYS program by the secondary development of the interface program between AutoCAD soft and ANSYS program. And then, numerical calculation model will be established after meshing in the ANSYS program regardless of the geometry of model. At last, with the help of the Interface program between ANSYS and FLAC3D, the generated computational model can be imported from ANSYS program into FLAC3D program. And then the Interface element with reasonable constitutive model and mechanical parameters can be adopted on the cemented surface. After above steps, the numerical calculation model of random contact interface between concrete and bedrock can be established.

![Figure 3. Two-dimensional numerical calculation model.](image)

3.2. Simulation results of morphology by random contact interface model

3.2.1. Random distribution of convex body on cemented surface

Random contact interface models with different morphology of cemented surface can be generated according to the above processes. The n value is selected to be 10, 20, 35 and 50 while $h_{\text{max}}$ is 1%~5% of the side length of the concrete test sample. The geometric dimension of concrete on the upper part of the model is 50cm×35cm, and that of bedrock on the lower part is 150cm×35cm. The width of the model is 1cm, and the size of the model is determined by referring to the field shear tests. Finally, Figure 4 clearly illustrates different morphology of the random contact interface model. It can be seen from the Figure that when the $h_{\text{max}}$ is the same, the larger the value n is, the more complicated the cemented surface curve will be. The larger the roughness is, the larger the corresponding cemented area will be.

![Figure 4. Geometric profile model.](image)

(a) $n=10$, $h_{\text{max}}=15\text{mm} (3\%)$

(b) $n=25$, $h_{\text{max}}=15\text{mm} (3\%)$

(c) $n=35$, $h_{\text{max}}=15\text{mm} (3\%)$

(d) $n=50$, $h_{\text{max}}=15\text{mm} (3\%)$
3.2.2. Contact area of cemented surface
The convex morphology of cemented surface depends on two parameters, \( n \) and \( h_{\text{max}} \), which also reflect that the contact area of cemented surface depends on them. Table 1 shows the statistical analysis results of the cemented area generated by different values of \( n \) and \( h_{\text{max}} \) under different random processes, and 10 random simulations were conducted for each case. In the table, the area of undulating surface of samples is also the cemented area between concrete and bedrock while the width of samples is 1cm.

| Undulating parameters | Samples | Area of cemented surface (\( S/cm^2 \)) |
|-----------------------|---------|--------------------------------------|
| \( n \) | \( h_{\text{max}} \) (mm) | Average \( (S) \) | Maximum \( (S_{\text{max}}) \) | Minimum \( (S_{\text{min}}) \) | Standard deviation \( (S_{\text{d}}) \) |
| 0 | 0 | 50 | - | - | - |
| 5 | 10 | 50.046 | 50.077 | 50.017 | 0.00238 |
| 10 | 10 | 50.215 | 50.420 | 50.072 | 0.01230 |
| 15 | 10 | 50.388 | 50.925 | 50.170 | 0.02575 |
| 20 | 10 | 50.819 | 51.577 | 50.283 | 0.05261 |
| 25 | 10 | 51.282 | 52.459 | 50.505 | 0.07740 |
| 5 | 10 | 50.208 | 50.321 | 50.125 | 0.00628 |
| 10 | 10 | 50.762 | 51.265 | 50.484 | 0.02782 |
| 15 | 10 | 52.010 | 52.392 | 51.546 | 0.02622 |
| 20 | 10 | 53.679 | 54.829 | 52.274 | 0.08741 |
| 25 | 10 | 55.310 | 55.451 | 52.831 | 0.11004 |
| 5 | 10 | 50.544 | 50.649 | 50.377 | 0.00712 |
| 10 | 10 | 52.283 | 53.024 | 51.603 | 0.04245 |
| 15 | 10 | 54.829 | 55.762 | 53.766 | 0.06360 |
| 20 | 10 | 57.727 | 59.700 | 56.229 | 0.10554 |
| 25 | 10 | 61.449 | 63.247 | 57.826 | 0.18544 |
| 5 | 10 | 51.129 | 51.455 | 50.776 | 0.01927 |
| 10 | 10 | 53.993 | 55.216 | 53.114 | 0.07487 |
| 15 | 10 | 57.943 | 60.724 | 56.505 | 0.12424 |
| 20 | 10 | 64.640 | 65.773 | 62.404 | 0.10576 |
| 25 | 10 | 69.973 | 72.036 | 66.986 | 0.14511 |

3.2.3. Geometric properties of cemented surface area
The variation trend of cemented surface area under different values of \( n \) and \( h_{\text{max}} \) can be obtained by the statistical analysis of undulating cemented surface area, as shown in Figure 5. It is described in the curves that \( h_{\text{max}} \) represents the waving height of convex body on cemented surface. The larger the value of \( h_{\text{max}} \) is with the same value of \( n \), the more drastic waving difference of the undulating surface will be, and the corresponding cemented surface area will be larger. The value \( n \) reflects the distribution frequency of the convex body on the undulating surface. With the same value of \( h_{\text{max}} \), the larger the value of \( n \) is, the more convex body on the undulating surface is distributed, and the larger the cemented surface area is. In addition, the cemented surface area increases nonlinearly with increasing of \( n \) or \( h_{\text{max}} \), as well as the increasing speed.
Figure 5. Area of cemented surface with different n and $h_{\text{max}}$.

3.3. Constitutive model and mechanical parameters of contact interface

As the main problem of bridge anchorage, the mechanical behaviour of interface between concrete and bedrock directly affects the interaction between engineering structure and subgrade. As for the contact surface between different parts, many scholars have adopted different contact surface element models to study the mechanical properties of contact surface [10, 11]. The contact interface element adopted in this paper is the thickness-free element inherent in FIA3D program. The constitutive relation abides by the linear sliding Coulomb friction criterion, which can reflect the characteristics of shear force, ultimate tensile strength, and dilatancy on the contact surface. Figure 6 is about the schematic diagram of constitutive model elements, and its model equations are as below:

$$F_{n,\text{max}} = cA + \tan \phi (F_n - \rho A)$$  \hspace{1cm} (1)

$$F_{n,t+\Delta t} = k_n \mu_n A + \sigma_n$$  \hspace{1cm} (2)

$$F_{s,t+\Delta t} = F_{s,t} + k_s \Delta u_{s,t+1/2\Delta t} A + \sigma_{s,t}A$$  \hspace{1cm} (3)

**Figure 6.** Constitutive model of contact interface.

Where: $F_{n,t+\Delta t}$ is the normal force of contact node at time $(t + \Delta t)$; $F_{s,t+\Delta t}$ is the tangential friction force at time $(t + \Delta t)$; $u_n$ is the penetration between nodes on the contact interface;
\( \Delta u_{s2} \) is the relative shear displacement increment; \( \sigma_n \) is the initial normal stress; \( \sigma_{s2} \) is the initial shear stress; \( A \) is the area of each contact node.

The parameters involved in the interface element mainly include cohesion, friction Angle, dilatancy angle, normal stiffness, tangential stiffness and tensile strength of the contact interface. The determination of each parameter depends on the mechanical properties of interface element and mechanical properties of the material. The normal stiffness and tangential stiffness of contact interface are related to equivalent stiffness \( K_e \), which can be determined by Formula (4):

\[
K_e = \max \left[ (K + \frac{4}{3}G) \right] / \Delta Z_{\text{min}}
\]

(4)

Where, \( \Delta Z_{\text{min}} \) is the normal minimum size of adjacent elements of contact interface, \( K \) is the volume modulus of rock mass, and \( G \) is the shear modulus. Meanwhile, according to the results of field shear tests, geological survey reports and relevant bridge foundation design codes, the calculation parameters of interface elements, concrete and bedrock are determined comprehensively. The final calculated values of each parameter are shown in Table 2 and 3.

| Table 2. Physical and mechanical parameters of Material. |
|-------------------------|-------------------|-------------------|
|                         | Unit weight (kN/m\(^3\)) | Elastic module (MPa) | Poisson |
| Weakly weathered argillaceous siltstone | 26.2 | 5.25\times10^2 | 0.3 |
| C30 grade concrete | 25 | 3\times10^4 | 0.2 |

| Table 3. Parameters of interface element. |
|-------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                         | Normal stiffness (MPa) | Tangential stiffness (MPa) | Cohesion (MPa) | Friction (°) | Tension strength (MPa) | Dilatancy (°) |
|-------------------------|-------------------------|-------------------------|-------------------|-------------------|-------------------|-------------------|
|                         | 7.1\times10^2 | 1.05\times10^2 | - | 21.8 | - | - |

3.4. Numerical simulation results of shear tests

3.4.1. Statistical analysis of shear strength on cemented surface under random generation

As illustrated in Figure 7 and 8, they are the statistical analysis curves of shear strength results with different variable \( n \) and \( h_{\text{max}} \). From the numerical perspective, we are interested in which manner \( n \) and \( h_{\text{max}} \) influence the shear strength on the cemented surface. According to the numerical calculation results, the shear strength of cemented surface has following characteristics:

1) With the increasing of \( n \) or \( h_{\text{max}} \), the contact area of cemented surface gradually increases, and so does the corresponding shear strength of cemented surface. It is also proved that the shear strength is basically in a linear relationship with the contact area.

2) When the cemented area \( S \) is less than 52.5cm\(^2\), no more than 5% relative to the smooth cementing surface \( S_0 \) (50cm\(^2\)), the curve of shear strength is fitting linear very well.

3) When the roughness of cemented surface is large enough caused by \( h_{\text{max}} \) or \( n \), more than 5% of original smooth cemented area, The shear failure will happen not only to overcome the cementation and friction between the upper and lower parts, but also the upper parts should climb over the convex body on cemented surface. And the difficulty completely depends on the distribution and shape of convex body. So In these occasions, the increase of shear strength varies greatly, and it deviates from linear fitting curves greatly.

4) It is also proved that the shear strength is different with the same cemented surface area. It is indicated that the shear strength of cemented surface depends not only on the area of cemented surface, but also the distribution, location, height and shape of the convex body on cemented surface.

5) Sliding Coulomb friction criterion is employed for numerical calculation. Therefore, the failure mode of cemented surface is only considered when shear relative slip failure occurs. Under this condition, the shear strength of cemented surface can be fitted by the following formulas.
\[
\tau = \sigma (\mu_0 + \Delta\mu) \\
\Delta\mu = A \times (S - S_0)
\]

Where: \(\mu_0\) is the friction coefficient of smooth bonding surface; \(\Delta\mu\) is the increase of friction coefficient caused by the roughness of cemented surface; \(S\) is the area of undulating cemented surface; \(S_0\) is the area of smooth cemented surface; \(\sigma\) is the normal stress applied in the normal direction; \(A\) is the correlation fitting coefficient. The fitting parameters of each curve are shown in Table 4.

\[\text{Figure 7. Shear strength distribution of cemented surface with the same n and different } h_{\text{max.}}\]
Figure 8. Shear strength distribution of cemented surface with the same $h_{\text{max}}$ and different $n$.

Table 4. Fitting parameters of shear strength.

| Undulating parameter ($n$) | Fitting parameter ($A$) | R-square value | Undulating parameter ($h_{\text{max}}$) | Fitting parameter ($A$) | R-square value |
|---------------------------|------------------------|----------------|----------------------------------------|------------------------|----------------|
| $n=10$                    | 0.139                  | 0.835          | $h_{\text{max}}=5$ mm                 | 0.242                  | 0.917          |
| $n=20$                    | 0.106                  | 0.873          | $h_{\text{max}}=10$ mm                | 0.153                  | 0.888          |
| $n=35$                    | 0.114                  | 0.798          | $h_{\text{max}}=15$ mm                | 0.124                  | 0.918          |
| $n=50$                    | 0.131                  | 0.941          | $h_{\text{max}}=20$ mm                | 0.130                  | 0.899          |
|                           |                        |                | $h_{\text{max}}=25$ mm                | 0.122                  | 0.947          |

3.4.2. The shear strength of the cementing surface considering the roughness is determined
The interaction between anchorage foundation and bedrock is actually shear action between concrete and bedrock, and the contact surface between two is uneven. It is stipulated in the test code that the rock surface undulation in the shear test about cemented surface between concrete and rock should be 1%–2% of the length of shear direction. The plane size of shear test samples in the large-scale direct field test of Ganjiang Bridge anchor engineering are 50cmx50cm, and the allowable maximum waving height $h_{\text{max}}$ is within 1cm. Field test results show that the shear failure happened almost in relative slip failure mode.

Therefore, on the basis of random numerical shear test results, the average shear strength on cemented surface with various undulations was studied regarding the influence of roughness on
cemented surface when the value of $h_{\text{max}}$ given less than 25 mm and the value of $n$ less than 50. It is illustrated in Figure 9, and the surface fitting equations is as follow:

$$\tau = \sigma (\mu_c + \Delta \mu)$$

(7)

$$\Delta \mu = a \times (n/100)^b \times (h_{\text{max}}/50)^c$$

(8)

Where, the fitting result of each correlation coefficient is: $a = 53.8; b = 1.82; c = 1.57$.

4. Evaluation of Numerical Models

As a validation of the numerical approach, comparisons between the experimental shear strength from field tests and the predicted shear strength based on the analytical equations were performed. Table 5 details the measured morphological characteristics of cemented surface for each field experimental sample. Based on these parameters, the predicted shear strength were calculated using equations 7 and 8 as above. Table 6 lists all the results of predicted shear strength, field experimental shear strength as well as error rates with both methodologies. It can be concluded that there is an allowable error rate between the numerical calculation and the experimental results, but it is also verified that Numerical model and calculation method of random contact interface is applicable to model the cemented surface between concrete and bedrock.

### Table 5. Morphological characteristics of the cemented surface for field experimental sample.

| Sample number | 1   | 2   | 3   | 4   | 5   |
|---------------|-----|-----|-----|-----|-----|
| Maximum waving height ($h_{\text{max}}$/mm) | 10.0 | 6.5 | 4.5 | 8.5 | 9.0 |
| $n$           | 30  | 25  | 16  | 23  | 31  |

### Table 6. Statistics of the predicted shear strength by two methodologies.

| Sample number | 1   | 2   | 3   | 4   | 5   |
|---------------|-----|-----|-----|-----|-----|
| Normal stress (MPa) | 0.52 | 0.27 | 0.48 | 0.60 | 0.73 |
| Shear stress from field tests (MPa) | 0.42 | 0.15 | 0.25 | 0.44 | 0.68 |
| Shear stress from numerical calculation (MPa) | 0.46 | 0.16 | 0.21 | 0.38 | 0.61 |
| Error rate | 9.0% | 3.6% | -14.8% | -14.1% | -10.6% |
5. Conclusion
In this paper, a new method employing DEM with random contact interface was proposed to simulate the interaction between anchorage foundation concrete and bedrock surface in studying the shear strength with different undulation. The simulation method was verified by comparing the numerical results with the field experimental results. Using this method, the shear strength of cemented surface was investigated regarding distribution and shape of the convex body, and roughness on cemented surface. The following findings can be addressed from current study:

(1) Since the roughness of cemented surface has a great impact on shear strength, random variables $h$ and $n$ can be introduced to model the morphological characteristics and quantify the roughness of cemented surface. It is proved that there is nonlinear correlation between the area of cemented surface and variable $n$ or $h$.

(2) It can be concluded from numerical simulation results that the shear strength has almost linear correlation with the cemented area when varying $h_{\text{max}}$ given a fixed $n$ or varying $n$ given a fixed $h_{\text{max}}$. The shear strength of cemented surface can be calculated by fitting equations. However, with the same area of cemented surface, the shear strength may be different mainly because of the influence such as the distribution, height and shape of convex body on cemented surface.

(3) In the case of shear relative slip failure mode, the average shear strength of cemented surface randomly generated with $h_{\text{max}}$ less than 25mm and $n$ less than 50 was evaluate by fitting equations. Compared with field test results, this method was proved to be feasible.

Acknowledgement
The research was supported by the Jiangsu Natural Science Foundation of Youth (grant number BK20180954) and the Natural Science Fund for Colleges and Universities in Jiangsu Province (grant number 17KJD560002).

Reference
[1] Lai Y J, Wu C J and Zhang Z X 2010 Test and numerical analysis of effect of notched sill of gravity anchorage on soft rock ground of suspension bridge Rock and Soil Mechanics 29(3) 593 –602
[2] Ji L, Xu F and Wang B T 2003 Testing study on base resistance of the anchors at Runyang Yangtze Bridge Chinese Journal of Rock Mechanics and Engineering 23(2) 256 –260
[3] Yang L Q, Li Y Y and Lin M Q 2008 Determination of shear strength between rock mass and concrete in Menlou overflow dam monolith Rock and Soil Mechanics 29 515 – 518
[4] Wang B T, Zhu Z D, Zhang F H and Zhang W H 2004 Experiment on the resistance of the base-contact surface of the anchors and rocks Rock and Soil Mechanics 25(11) 1717 –1721
[5] Saiang D, Malmgren L and Nordlund E 2005 Laboratory tests on shotcrete-rock joints in direct shear, tension and compression Rock Mechanics and Rock Engineering 38(4) 275 –297
[6] Tian H M, Chen W Z, Yang D S and Yang J P 2015 Experimental and numerical analysis of the shear behaviour of cemented concrete-rock joints Rock Mechanics and Rock Engineering 48(1) 213 – 222
[7] Guo Z H, Wang W, Lu J, Zhu Z D and Yu X J 2003 Discussion about shear strength and compress-shear rupture criterion of two phase stuff of sand grout-limestone Chinese Journal of Rock Mechanics and Engineering 22(3) 429 – 433
[8] Tang X H, Wang M N, Tong J J, Dong C Y and Wang Y C 2017 Shear strength of cementation plane between shotcrete and granite under high and variable temperature Journal of the China Railway Society 39(12) 131-136
[9] Li S H and Wang Y N 2004 Stochastic model and numerical simulation of uniaxial loading test for rock and soil blending by 3D-DEM Chinese Journal of Geotechnical and Engineering 26(2) 172—177

[10] Desai C S and Nagaraj B K 1988 Modeling for cyclic normal and shear behaviour of interfaces Journal of Engineering Mechanics ASCE 114(7) 1198—1217.

[11] Goodman R E Taylor R L and Brekke T L 1968 A model for mechanics of jointed rock Journal of the Soil Mechanics and Foundations Division ASCE 94(3) 637—660.