Surface subsidence prediction for the WUTONG mine using a 3-D finite difference method

Nengxiong Xu, Pinnaduwa H.S.W. Kulatilake, Hong Tian, Xiong Wu, Yinhua Nan, Tian Wei

1. Introduction

The WUTONG coal mine covers an area of approximately 37.36 km² and is located in Handan City, Hebei Province, the People's Republic of China. WUTONG's southwest side is adjacent to the Yuecheng Reservoir (Fig. 1). As one of China's large-scale reservoirs, the Yuecheng Reservoir has a total storage capacity of up to 1.3 billion m³ and provides flood control, irrigation, water supply, power generation, etc. A part of an auxiliary dam for the reservoir is within the mine area (Fig. 1). It is essential to predict surface subsidence before mining begins to prevent the dam from being damaged from mining-induced surface subsidence and to maximize the mining area to extract the greatest possible amount of coal.

Research on coal mining subsidence prediction has taken place for nearly two centuries. Empirical formulas, curves, graphs and influence functions have been developed based on numerous measurements of mining subsidence [1–9]. Although they are quite simple to understand, such methodologies have not explicitly taken into account the effect of geologic structures, geomechanical properties and in situ stress of the rock masses at the mine site on subsidence prediction. Therefore, the empirical models are very much site-dependent, and they can only be applied to similar sites. In contrast, the numerical methods that are based on theories of continuum and/or non-continuum mechanics predict subsidence through a mechanistic approach, using rock and coal mass geologic, physical and mechanical properties. The suggested models from this group are random field theory based models [10–11], elastic or visco-elastic theory based models [12–14], and continuum or discontinuum numerical models [15–19]. The boundary element method mainly deals with the excavation surface without modeling the complicated geology that exists due to the presence of different lithology above the coal seam. Therefore, its capability of subsidence prediction is not strong as the capabilities of the finite difference method (FDM) and finite element method (FEM). Both the FEM and FDM can handle nonlinear and non-homogeneous characteristics of rock masses. Therefore, they have become important tools for coal mining subsidence prediction. The FDM uses an explicit solution procedure in contrast to FEM's implicit solution procedure. An advantage of the explicit method is that, because matrices are never formed as in the implicit procedure, large displacements and complex constitutive models for rock units are possible with no additional computing effort. The
FDM seems to be an appropriate method to perform subsidence modeling, especially because the Lagrangian formulation permits materials to yield and flow and the grid to deform in a large-strain mode [15]. To obtain accurate subsidence prediction through numerical modeling, the following steps should be taken: (1) use a simplified geologic system in the numerical model to capture the essential features of the actual geologic system, including the in situ stress; (2) select constitutive models that capture the salient mechanical behavior of the rock masses studied in the numerical model; (3) use physical and mechanical property values that reflect accurate behavior of the rock masses studied; (4) simulate mining history reasonably well.

Two inch diameter samples used for intact rock in the laboratory contain micro-cracks. The spatial distribution of these cracks varies from one sample to another. In addition, some material heterogeneity can exist in two inch diameter samples. The minor discontinuity geometry that exists in rock masses is highly variable. The discontinuities that exist in a rock mass can be open, closed or filled with gouge or cementing material. In addition, different levels of roughness ranging from slickensided surfaces to very rough surfaces can be expected on open discontinuities. Therefore, unfortunately, significant variability and uncertainty exist in estimating rock mass mechanical properties, either through laboratory or field tests. Thus, for reliable subsidence prediction, rock mass mechanical properties should be calibrated using available subsidence monitoring data. Such a procedure is described in the paper.

In this paper, the mining-induced subsidence of the WUTONG coal mine is predicted by FDM. FLAC®4.0 software, developed by the Itasca Consulting Group, Inc. [20], is used in this study. First, the mechanical parameters of the coal and rock masses in the mining area are estimated by a back analysis method that combines an experimental design procedure with a numerical simulation. Then, the surface subsidence outcomes induced by four different mining scenarios are numerically predicted. Finally, after examining these predictions, a suitable mining scenario for preventing damage to the dam is proposed for future mining activities.

2. Geology and mining history of the site

2.1. Geology

2.1.1. Faults

Within the WUTONG coalfield, seven major faults exist: F1, F2, F3, F5, F17, F25 and F31 (Fig. 1). The fault zones of these faults are approximately 10–30 m in width. They are composed of mudstone and mylonitic rocks as well as breccia. The basic features of the faults are summarized in Table 1.

2.1.2. Strata and coal seams

The WUTONG coal mine is located east of the Fengfeng coalfield and is covered by Cenozoic strata. It has been revealed through drilling that the stratigraphic sequence in WUTONG, in the order from oldest to newest, is Ordovician, Carboniferous, Permian, Tertiary and Quaternary, as described below.

(1) The Ordovician (O) stratum, 285–654 m thick, is composed of dark gray or blue-gray limestone. The limestone is pure in quality and high in strength, with fissures generally filled with calcite.

(2) The Carboniferous (C) stratum, 119–149 m thick, is comprised of dark gray or black-gray sandstone and siltstone, with interbeds of 6–8 thin limestone layers.

(3) The Permian (P) stratum has an average thickness of 1000 m. The sequence is divided into the following four formations, from the bottom to top.
The Shanxi formation is composed of light-gray to gray, medium- to fine-grained sandstone, gray sandy mudstone and siltstone.

The Xiaosihezi formation is mainly composed of gray, dark gray, gray-green, and purple-mottled siltstone.

The Shangshishizi formation is mainly composed of gray, light gray, gray-green and yellow medium- to thick-bedded gravel feldspar coarse sandstone.

The Shiqianfen formation is mainly composed of purple, purplish red or light purple-red medium- to thick-bedded fine-grained sandstone.

The No. 2 coal seam, which is approximately 3.3 m thick on average and is located in the Carboniferous stratum, is the main minable seam in the WUTONG mine. As a result of faulting, the average mining thickness was 3.3 m, and the mining depth varied in the mined area on Fig. 2a. Each panel is 150 m wide and 500–2000 m long. From 2001 to 2007, seven mining panels in the No. 2 coal seam were excavated in the north-central WUTONG mine, as shown in the mined area on Fig. 2a. Each panel is 150 m wide and 500–1000 m long. The fully mechanized top-coal-caving technique was adopted to extract the coal. In the mined area, the average mining thickness was 3.3 m, and the mining depth varied in the range of approximately 500–1400 m. The surface subsidence was monitored during mining. The maximum settlement measured was 1.62 m. However, because the mined area was at least 3 km distance from the auxiliary dam, the coal mining activity did not affect the dam at all.


displacement. Thus, the boundary condition of FLAC3D is a fixed boundary on the bottom, left, right, and back surfaces of the domain. The geometric shape of each stratum and its contact with the Tertiary stratum are simulated in the model. The geometric shape of each stratum is represented by a thin layer that was 3.3 m in thickness. The model also contains all the faults listed in Table 1.

The rectangular region enclosed by the red lines shown in Fig. 1 was selected as the computational model domain based on the spatial distribution of current and future areas for mining. As shown in Fig. 1, the x-axis of the Cartesian coordinate system is N 20° E, and the z-axis points in the vertical upward direction. The model dimensions are 10.5 km × 9 km; the lower left corner has coordinates of (21100 m, 1300 m), and the upper right corner has coordinates of (21100 m, 14500 m) and (31600 m, −5500 m), respectively. As the lowest altitude of the coal seam roof is −1300 m, the simulated elevation of the model ranges from −1550 m to 250 m. The nearest horizontal distance from the mining boundary to the model boundary is 2 km.

2.2. Generalization of strata and faults

The Ordovician, Carboniferous, Permian, Tertiary and Quaternary strata, as well as the coal seam in the Carboniferous stratum, are simulated in the model. The geometric shape of each stratum interface was constructed based on sampling data. These data are a series of spatial points located on geological interfaces and obtained from geological maps, borehole logs and other resources. The coal seam is represented by a thin layer that was 3.3 m in thickness. The model also contains all the faults listed in Table 1. Each fault is a fractured zone approximately 10–30 m in width and composed of mudstone, mylonitic rocks and breccia. Typically, a fault can be simulated with interface elements using FLAC3D when the thickness of the fault zone is small. However, when a fault zone is more than 10 m in thickness, it is inappropriate to simulate a fault using a single interface. Therefore, a thin layer with a certain thickness is used to represent each fault in this paper (Table 1). A layer for a single fault is composed of two boundary surfaces. These surfaces are constructed based on sampling data obtained from geological maps and borehole logs.

3.3. Computational mesh

The geological model was meshed using a set of triangular prism elements. A triangular prism has two triangular ends and three quadrangular sides. The triangular prism was selected instead of the more typical hexahedral mesh because the elevation of the strata in the WUTONG mine varies significantly in magnitude, and the nodes in a hexahedral mesh can give rise to relatively large displacements during the computing process. The displacements may result in extremely distorted elements and may cause computational problems. FLAC3D allows various options for shapes, including hexahedrons, tetrahedrons, pyramids, triangular prisms, etc. [20]. Hexahedral elements are not used in this study, although they are normally the best choice for numerical simulation.

### Table 1

<table>
<thead>
<tr>
<th>Fault</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F5</th>
<th>F17</th>
<th>F25</th>
<th>F31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
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<tr>
<td>Avg. dip direction (°)</td>
<td>93</td>
<td>114</td>
<td>110</td>
<td>109</td>
<td>93</td>
<td>295</td>
<td>145</td>
</tr>
<tr>
<td>Avg. dip angle (°)</td>
<td>73</td>
<td>77</td>
<td>81</td>
<td>83</td>
<td>78</td>
<td>80</td>
<td>79</td>
</tr>
<tr>
<td>Avg. fault throw (m)</td>
<td>200</td>
<td>60</td>
<td>300</td>
<td>210</td>
<td>30</td>
<td>315</td>
<td>85</td>
</tr>
<tr>
<td>Avg. fault thickness (m)</td>
<td>10</td>
<td>28</td>
<td>26</td>
<td>32</td>
<td>14</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>
The detailed approach to prism meshing is as follows. First, the model is divided into 28 layers vertically with each layer having a thickness of 3.3–80 m. The closer a layer is to the coal seam roof, the thinner the layer is set; the farther the layer is from the roof, the thicker it is set. Then, in the horizontal direction, each layer is meshed into 111,698 elements. The element size is made smaller as it approaches the mining panel. Finally, a mesh is formed with a total of 1,675,940 elements and 3,127,544 nodes. Fig. 3 shows the computational mesh used with FLAC3D. The same figure also shows an enlarged view of fault and surrounding rock elements around a fault.

3.4. The constitutive model and yield criterion

The incremental elastic–plastic constitutive model and Mohr–Coloumb yield criterion [20] are used in this study.
3.5. Boundary conditions and the initial state of stress

Displacement boundary conditions [20] are used in this study. In the computational model (Fig. 1), the mesh points with coordinates $x = 21,100$ m or $x = 31600$ m were not allowed to move along the $x$-axis; the mesh points with coordinates $y = -14,500$ m or $y = -5500$ m were not allowed to move along the $y$-axis, and the mesh points with the coordinate $z = -1550$ m were not allowed to move along the $z$-axis. In this study, the free surface has an irregular geometry, and the computational model is a non-uniform grid [20]; therefore, gravity along with the lateral stress coefficient at rest, $k_0$, given by $k_0 = \mu/(1 - \mu)$, where $\mu$ is the Poisson's ratio were used to apply the in situ stresses.

4. Back analysis on mechanical parameters of the rock-masses

One of the key factors influencing the reliability of a numerical simulation is whether the mechanical properties of the rock masses are estimated accurately. As stated earlier, significant uncertainty exists in estimating accurate values for rock mass mechanical parameters. In this study, the rock mass mechanical parameters are estimated in the following way:

First, the values of the deformation modulus, $E$, Poisson's ratio, $\mu$, cohesive strength, $C$ and the internal friction angle, $\phi$ of rock masses of different strata are estimated empirically based on the available literature that relates intact rock and discontinuity properties to rock mass properties.

Then, the aforementioned mechanical parameter values are determined by combining the back analysis with an orthogonal experimental design technique (explained later) [21] and numerical simulation.

4.1. Determination of the initial values of rock mass mechanical parameters

Rock mass is composed of intact rock and discontinuities. The mechanical parameters of intact rock obtained by laboratory experiments are quite different from those of rock masses [22–26]. Estimations by Mohammed et al. [23] provide the following values for rock masses: a mean deformation modulus equal to 47% of the corresponding intact rock; a mean uniaxial compressive strength equal to 28% of the laboratory intact rock strength, and a mean tensile strength equal to 50% of the laboratory intact rock tensile strength. For a granitic gneiss rock, Kulatilake et al. [24]
obtained a mean rock mass deformation modulus equal to approximately 30% of the intact rock Young's modulus. For Aspo diorite rock located at a depth of 485 m at Aspo Hard Rock Laboratory, Sweden, Kulatilake et al. [25] estimated the mean rock mass modulus to be 51% of the intact rock Young's modulus. Additionally, the mean rock mass Poisson's ratio was estimated to be 21% higher than the intact rock Poisson's ratio. In a recent study of a limestone rock mass, Wu and Kulatilake [26] have obtained a mean rock mass strength equal to approximately 45% of intact rock strength. For the same rock mass, they have obtained a mean deformation modulus equal to approximately 50% of the intact rock Young's modulus. The mean shear and bulk moduli for the same rock mass were approximately 40% and 30% of the intact rock shear modulus and bulk modulus, respectively. The mean Poisson's ratio for the rock mass was approximately 14% higher than the intact rock Poisson's ratio.

In this paper, the values of the deformation modulus and Poisson's ratio of rock masses in different strata are estimated empirically based on the aforementioned literature as well as by comparisons with the mechanical parameter values of the coalfields adjacent to the WUTONG mine (Table 3). In this table, for each rock formation, the value of Poisson's ratio for rock mass is approximately 11–20% higher than that of the intact rock and the value of the deformation modulus is approximately 40–60% of the intact rock Young's modulus. The values of C and φ of rock masses are determined through comparisons with those collected from other mines in the Fengfeng coalfield.

4.2. Back analysis on rock mass mechanical parameters

4.2.1. Back-analysis method

Back analysis has often been used to determine values for geotechnical parameters [27–32], especially with the development of numerical simulation techniques that take measured displacement as basic information. Currently, back analysis has been widely adopted in research in combination with numerical simulation and mathematical methods, such as orthogonal experimental design [21], uniform experimental design [21], neural networks [33] and genetic algorithms [34]. In this paper, an approach combining numerical simulation with an orthogonal experimental design [21] is used to back analyze rock mass mechanical parameters. The detailed procedure is as follows:

1. After analyzing the measured data for surface subsidence within the mined area, the Maximum Surface Subsidence Coefficient (MSSC), defined as the ratio of the maximum surface subsidence to the thickness of the coal seam at the corresponding position, is selected as the benchmark value of the test indicator.

2. Selecting the rock mass mechanical parameters as the experimental design factors, a multi-factor and multi-level testing program is formed using an orthogonal experimental design technique, and all the testing schemes are listed in an orthogonal table.

3. A series of numerical simulations are conducted using FLAC3D with the parameter schemes listed in the orthogonal table.

4. A range analysis is performed on the results and a relation is established between the test indicator and each of the experimental factors.

5. Analyzing the results by means of range analysis, the rock mass mechanical parameters are optimized.

4.2.2. Selection of experimental factors

The parameters E, μ, C and φ are selected as the experimental factors in this study. It is observed from Table 3 that there are five strata and faults leading to 11 major rock formations, and the mechanical parameter values of each formation are different from each other. If E, μ, C and φ of all the rock formations are used as the experimental factors, there are 44 factors in total. The back-analysis calculation for such a system is very tedious and difficult. The following simplified approach is used in this study:

First, the average values of E, μ, C and φ resulting from all the rock formations given in Table 3 are calculated. Then, the initial mechanical parameter value divided by the corresponding average value is calculated for each mechanical parameter of each formation. These values are listed as $\frac{E_i}{\bar{E}}$, $\frac{\mu_i}{\bar{\mu}}$, $\frac{C_i}{\bar{C}}$ and $\frac{\phi_i}{\bar{\phi}}$, in Table 3, where $i$ represents the ith rock formation.

Second, in the orthogonal experiments, the average values of the deformation modulus, Poisson's ratio, cohesion and internal friction angle, E, μ, C and φ, representing all the rock formations are taken as the experimental factors. Then, the mechanical parameters of the ith formation are given as $\bar{E}_i$, $\bar{\mu}_i$, $\bar{C}_i$ and $\bar{\phi}_i$, respectively. It should be noted that the average values of the mechanical parameters of the rock formations listed in Table 3 are different from the experimental factors (E, μ, C and φ). The former are determined from the empirical formulae, while the latter are variables that change with the orthogonal experimental scheme. However, the parameter value ranges for the latter are determined by the former.

4.2.3. Selection of the test indicator

A test indicator is a variable that assists in judging whether the experimental results are reasonable. The indicator should satisfy the following two conditions: first, its values should change with the values of the experimental factors, and second, its benchmark value can be obtained by specific means, such as field measurements. The MSSC is used as the test indicator in this study because it is very sensitive to changes in rock mass mechanical parameters.

Table 3

Initial values selected for mechanical parameters of the representative rock formations and faults.

<table>
<thead>
<tr>
<th>No.</th>
<th>Strata</th>
<th>Rock formation</th>
<th>E (GPa)</th>
<th>μ</th>
<th>C (kPa)</th>
<th>φ (°)</th>
<th>$\frac{E}{\bar{E}}$</th>
<th>$\frac{\mu}{\bar{\mu}}$</th>
<th>$\frac{C}{\bar{C}}$</th>
<th>$\frac{\phi}{\bar{\phi}}$</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Q</td>
<td>0.06</td>
<td>0.36</td>
<td>56.8</td>
<td>22.6</td>
<td>0.011</td>
<td>1.558</td>
<td>0.069</td>
<td>0.773</td>
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<tr>
<td>2</td>
<td>T</td>
<td>1.95</td>
<td>0.35</td>
<td>209.8</td>
<td>20</td>
<td>0.356</td>
<td>1.515</td>
<td>0.254</td>
<td>0.684</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>P</td>
<td>6.48</td>
<td>0.16</td>
<td>963.5</td>
<td>34</td>
<td>1.185</td>
<td>0.693</td>
<td>1.166</td>
<td>1.162</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>P</td>
<td>6.55</td>
<td>0.13</td>
<td>985.3</td>
<td>34</td>
<td>1.197</td>
<td>0.563</td>
<td>1.193</td>
<td>1.162</td>
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<tr>
<td>5</td>
<td>P</td>
<td>6.23</td>
<td>0.15</td>
<td>969.8</td>
<td>34</td>
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<tr>
<td>6</td>
<td>P</td>
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<tr>
<td>7</td>
<td>P</td>
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<td>0.21</td>
<td>865.3</td>
<td>27</td>
<td>0.965</td>
<td>0.909</td>
<td>1.047</td>
<td>0.923</td>
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<tr>
<td>8</td>
<td>P</td>
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<td>0.31</td>
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<tr>
<td>9</td>
<td>P</td>
<td>7.5</td>
<td>0.21</td>
<td>579.6</td>
<td>28</td>
<td>1.371</td>
<td>0.909</td>
<td>1.186</td>
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<tr>
<td>10</td>
<td>P</td>
<td>19.02</td>
<td>0.14</td>
<td>2867.6</td>
<td>40</td>
<td>3.477</td>
<td>0.606</td>
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<tr>
<td>11</td>
<td>P</td>
<td>0.1</td>
<td>0.34</td>
<td>52.3</td>
<td>25.2</td>
<td>0.018</td>
<td>1.472</td>
<td>0.063</td>
<td>0.861</td>
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</table>
and its benchmark value can be determined by surface displacement monitoring.

4.2.4. Surface subsidence monitoring data in the mined area

(1) Surface subsidence monitoring points
From 2001 to 2007, 7 mining panels (Fig. 4) in the central-north area of WUTONG Mine were extracted. A total of 79 surface subsidence monitoring points were set up in the mined area along the measuring line $L$ shown in Fig. 4 to record the values of surface subsidence during the mining period starting 2001.

(2) Surface subsidence measurements

The engineers of the WUTONG Mine measured the elevation and calculated the subsidence at each monitoring point every 6 months. Their measuring methodology was guided by the Code of Measuring Practice for Coal Mine [35], which is a general standard followed with respect to measurements associated with coal mines in China. Precise leveling instruments, with precision of 0.5 mm/km, were used to measure the elevations at the selected points.

(3) Measured subsidence

From 2001 to 2008, the engineers had conducted subsidence measurements about 12 times. However, because some of the data have been lost, only five surface subsidence profiles along line $L$ were available for this study (Fig. 5). The data for these profiles come from five measurements conducted on the dates of 6/18/2003, 7/26/2004, 8/15/2006, 9/21/2007 and 8/28/2008, respectively. The horizontal locations of Panel01 through Panel07 are shown at the bottom of Fig. 5. The five subsidence profiles are briefly explained as follows:

- **Subsidence profile of June 18, 2003**
  Mining was completed at Panel06 in June 2002, and the surface movement caused by Panel06 had reached a stable state. Excavation at Panel04 had progressed about 60%, and its influence on surface movement had not reached a steady state. A distinct surface settlement center appeared above Panel06 and Panel04 with a maximum settlement of 0.42 m (Fig. 5).

- **Subsidence profile of July 26, 2004**
  Mining was completed at Panel06 and Panel04, while about 45% of Panel07 had been finished. Two surface settlement centers appeared above the three mining panels, in which the maximum settlement reached 0.82 m (Fig. 5).

- **Subsidence profile of August 15, 2006**
  By August 15, 2006, the completed mined panels included Panel04, Panel06, Panel07, Panel05 and Panel02. The maximum settlement reached 1.49 m above the mining panels Panel04, Panel06, Panel07 and Panel05; while another center of settlement with a maximum value of 1.05 m appeared above Panel02 (Fig. 5).

- **Subsidence profile of September 21, 2007**
  Except for Panel01 and Panel03, mining was completed at all other panels prior to June 2006; and the mining-caused settlement was almost stable by September 2007. Four centers of settlement appeared on the ground with a maximum settlement of 1.6 m (Fig. 5).

- **Subsidence profile of August 28, 2008**
  By October 30, 2007, mining was completed at all panels, and surface settlement caused by the excavation reached a stable state by August 28, 2008 with a maximum settlement of 1.62 m (Fig. 5 and point $Q$ in Fig. 6).

Since the mining-induced surface subsidence was basically stable by August 28, 2008, the maximum settlement on this date is treated as the criterion for back analysis of the rock mechanical parameters. According to the measured subsidence, within the mined area, the measured maximum settlement is 1.62 m with MSSC being 0.49. Therefore, the measured MSSC value of 0.49 will be taken as the benchmark value of the test indicator of the orthogonal experiment.

4.2.5. The orthogonal experiment and analysis of results

4.2.5.1. Orthogonal experimental design. Four factors and five levels were selected to perform the orthogonal experiment. Following the orthogonal experimental method [21], an orthogonal experimental table was designed (Table 4). In Table 4, the second through fifth columns are the experimental factors. Table 4 lists 25 test schemes; each row represents a level of the four factors. After the level of each factor is set, the value of each factor can be determined according to Table 5. In this manner, the values of the four rock mass mechanical parameters were determined.

4.2.5.2. Computational results of the orthogonal experimental schemes. Using the values of each scheme listed in Table 4 as the mechanical parameter values, Panel01 through Panel07 mining was simulated numerically by one step using FLAC$^+$ computational model described in Section 3. The last column of Table 4 lists the MSSC-values obtained from the 25 experimental schemes.
4.2.5.3. Range analysis performed on the orthogonal experimental results. The changing relation between the indicator and each of the factors is analyzed statistically according to the range analysis method [21]. Taking the factor \( E \) as an example, the procedure of range analysis is illustrated as follows:

- From Table 4, select the schemes in which the values of \( E \) are set as the value of the 1st level and calculate the average MSSC-value of these schemes. For convenience, this average value is called the Average MSSC.

![Fig. 5. Measured and calculated surface subsidence profiles along line L, shown in Fig. 4.](image)

![Fig. 6. Calculated surface subsidence contours (at a 0.1 m interval) for the verification example.](image)

<table>
<thead>
<tr>
<th>Scheme</th>
<th>( \bar{E} )</th>
<th>( \bar{\mu} )</th>
<th>( \bar{C} ) (kPa)</th>
<th>( \bar{\phi} ) (°)</th>
<th>Average MSSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.85</td>
<td>0.27</td>
<td>449</td>
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<td>2</td>
<td>4.16</td>
<td>0.25</td>
<td>810</td>
<td>22.4</td>
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<tr>
<td>3</td>
<td>6.47</td>
<td>0.23</td>
<td>911</td>
<td>25.3</td>
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<td>11.09</td>
<td>0.19</td>
<td>1374</td>
<td>31.2</td>
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</tr>
</tbody>
</table>

Table 4
Formed orthogonal experimental design table and results of test schemes.

Table 5
Selected values for the five levels of the experimental factors.
Similarly, calculate the Average MSSC values when \( E \) is set as the values of the levels II, III, IV and V, respectively. These Average MSSC values describe the relation between the indicator MSSC and \( E \).

- Calculate the difference between the maximum and the minimum of the five Average MSSC values. This difference is named the range value of MSSC associated with \( E \).

Using the above steps, the changing relation between the test indicator and each of the experimental factors (Fig. 7) and the range values of the MSSC of all the experimental factors were obtained. Note the range values of \( E, \mu, C \) and \( \phi \) are 0.066, 0.084, 0.243 and 0.163, respectively. Obviously, for the MSSC, the range values of \( C \) and \( \phi \) are much greater than those of \( E \) and \( \mu \), indicating that changes in \( C \) and \( \phi \) have greater impacts on the MSSC than changes in \( E \) and \( \mu \).

4.2.6. Selection of the rock mass mechanical parameters

The MSSC of the 3rd scheme is 0.493, and, of the 25 schemes, it is the closest to that measured. Thus, the scheme 3 MSSC is selected to estimate rock mass mechanical parameter values. Using the MSSC of 0.493 in the statistical changing relations shown in Fig. 5, the values of the four experimental factors are estimated as \( E = 2.4 \) GPa, \( \mu = 0.24 \), \( C = 773 \) kPa and \( \phi = 22^\circ \).

5. Verification test

Another simulation within the mined area was conducted using the estimated rock mass parameter values in the same FLAC

![Fig. 7. Calculated average MSSC for the experimental factors.](image)

![Fig. 8. Vertical displacement contours of the rock mass in section I-I of Fig. 6.](image)

![Fig. 9. Boundaries selected for mining and boundaries of regions affected by mining for four scenarios. C1, C2, C3, C4 are four different boundaries of mining area of the four scenarios; c1, c2, c3, c4 are boundaries of mining-affected regions of the four scenarios.](image)
computational model to verify the reliability of the estimated rock mass parameters.

Fig. 6 shows the surface subsidence contours produced by the results of FLAC3D. As shown in Fig. 6, the measured maximum surface settlement point Q (the green point), with a subsidence of 1.62 m, and the calculated maximum surface settlement point P (the red point), with a value of 1.6 m, are very close to each other.

Fig. 5 is a comparative map between the measured and calculated surface subsidence curves on line L shown in Fig. 4. It can be observed that on line L, the subsidence values of the calculation tally closely with those measured on August 28, 2008.

Fig. 8 shows the vertical displacement contours of the rock formations on section I–I, shown in Fig. 6. The maximum settlement displacement of the coal seam roof is 3.3 m after mining, which coincides with the phenomenon of the roof collapsing after mining.

The aforementioned analyses show that the rock mass parameters estimated from the back analysis can be used in predicting mining-induced subsidence in the mining area.

6. Surface subsidence prediction under different scenarios

To avoid mining-induced damages to the dam, the minimum distance between the mining area boundary and the dam boundary must be long enough. This minimum distance, as specified by the owner of the dam, is approximately 3 km. However, the mine owner advocates for this distance to be as short as possible to extract the maximum possible amount of coal. To identify a suitable mining area boundary, four mining scenarios, S1, S2, S3 and S4, are considered in four respective mining area boundaries: C1, C2, C3 and C4 (Fig. 9). Using FLAC3D, the scenarios and mining area boundaries predict surface subsidence due to mining (Fig. 9).

In Fig. 9, the boundaries of the regions affected by mining for each of the four scenarios are plotted as c1, c2, c3 and c4. In mining scenarios S1 and S2, the values of the maximum surface subsidence on the mining area are 2.15 m and 2.14 m, respectively. The regions affected by mining of these two scenarios have covered part...
of the dam, and the values of the maximum dam subsidence are 0.06 m and 0.02 m. No dam subsidence is the precondition when mining near the dam. Therefore, these two scenarios cannot be selected. When mining with scenario S4, the maximum surface subsidence on the mining area is 2.13 m, and the shortest distance from the boundary of the mining-affected region to the dam foundation is 187 m. S4 is a safe but conservative scenario. The shortest distance between the boundary of the mining-affected area and the dam foundation is 35 m when mining with scenario S3. Therefore, S3 is the best of the four scenarios. The corresponding surface subsidence results of the scenario are described below.

6.1. Surface movement results

In mining scenario S3, 40 mining panels, located in 7 regions R1–R7 (Fig. 10), are proposed in the mining area of the WUTONG mine. Fig. 10 shows the subsidence contours resulting from FLAC3D calculations. Among the mining regions, the maximum surface subsidence of 2.14 m occurs within the mining region R2. The corresponding MSSC value is 0.65; the depth of the coal seam corresponding to the maximum surface subsidence point is 483 m. The closest distance from the boundary of R2 to the boundary of the surface movement area is 770 m. The maximum surface subsidence of R5 is 1.02 m, and the corresponding MSSC is 0.31. The corresponding coal seam roof depth is 1010 m; the closest distance between the boundary of R5 and that of the surface movement area is 1035 m. From Fig. 10, it can be concluded that the deeper the coal seam roof, the smaller the MSSC, and the larger the mining-induced surface movement area. Fig. 10 was used to estimate the shortest distance from the boundary of the mining-induced surface movement area to the dam foundation as 35 m. Thus, it is concluded that coal extraction using this scenario will not cause damage to the dam.

6.2. Movement results of rock strata on a typical cross-section

Fig. 11 provides the contours of the vertical displacement of rock strata on the cross-section II–II shown in Fig. 10. On the section, the surface settlement of point P1 is 1.69 m and that of P2 is 1.81 m, whereas the maximum settlement of the coal seam roof is 3.3 m. P2 is located in the mined area, and the subsidence value of P2 was 1.62 m before the coal was extracted in the mining area. Therefore, the extraction of coal in the mining area has caused more settlement in the mined area. Additionally, Fig. 11 shows that the closer a rock stratum is to the coal seam roof, the larger its settlement value.

7. Conclusions

Mining-induced surface subsidence predictions were performed using FDM to find a possible future mining scenario that would prevent the Yuecheng Reservoir dam from being damaged due to mining at WUTONG. The computational model included a simplified geologic model constructed from available geologic information for the site. Rock mass mechanical parameters for the computational model were estimated through a back analysis procedure that incorporated measured subsidence data, geometric parameters initially estimated through empirical and engineering analogy methods, a statistical experimental design technique and numerical modeling using FLAC3D. Four possible mining scenarios with different mining area boundaries were designed. The subsidence prediction in the mining area was conducted for each of the predetermined mining scenarios using the estimated rock mass mechanical parameters in the FLAC3D computational model. Scenario S3 turned out to be the best one of the four scenarios to provide a solution to the problem tackled in the paper. The predictions from this scenario are as follows:

1. Within the coalfield, the shallower the coal seam, the larger the MSSC. The MSSC in the mining area is 0.65, and the maximum settlement point is located in the mid-west of the coalfield, which is the shallowest area of the coal seam depth, with a depth of 483 m.
2. The nearest distance from the boundary of the surface movement area to the edge of the dam foundation is 35 m.

Therefore, coal mining according to scenario 3 will not cause dam damage.

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