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# Analysis of elastoplasticity and rheology due to mining subsidence

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**At present, as the easily mining resources are being increasingly depleted, the exploitation of coal under buildings, water-bodies and railways is imminent for the sustainable production. Probability integral method is a general method for mining subsidence in the coal system. Because of poor understanding of mining subsidence for other sections, the authors suggest probability integral method for the study of coal mining under buildings, water-bodies and railways. Moreover, the calculation result of probability integral method should be corrected by numerical simulation method. Based on practical projects, the impact has been evaluated on the security of Xifeihe left embankment under coal mining. Combining with the results of probability integral method, we propose that the 600 m far from embankment is a good rationality. This article provides the basis for the rational exploitation of coal resource which is a major practical problem under the premise of Water Infrastructure Security. Furthermore, it also can be served as a reference for the similar projects, such as mining Xiaolangdi reservoir area, mining Yuecheng reservoir and mining the major channels of Middle Route South to North Water Transfer.**

mining subsidence, numerical simulation, the elastoplasticity model, rheological model, the evaluation of embankment safety

## 1 Introduction

As early as the end of the 19th century, overlying strata movement and damage induced by coal mining and the damage of drift and the ground building had received researchers' attention. Thus preliminary observations and records were made. In the 1930s, mining subsidence had become a research subject in some countries advanced in coal mining. From the 1950s onward, this area of research work has progressed steadily. Especially since the 1970s it has reached a new height thanks to the rapid development of the coal industry, the increasing demand for mining under water body, building body and railway (called as "three downsides" later on), and the new emergence of on-site test instruments and the extensive use of computers. At present, mining subsidence as an important part of the science of mining has been one of fundamental theories for mining under "three downsides" as well as protecting the drift. Beginning with observation on site, currently mining subsidence observation has already developed from the single spot to the observation station constituted by two or several lines even as an observation net. Observations in site provide a great deal of data for the regulation of mining subsidence, and many research conclusions are drawn on the basis of the observations. In China, the observations began in the 1950s, and since 1954, tens to scores of observation stations have been built up in main mining areas. Thus, complete data were acquired concerning the regulation of mining subsidence, which was the basis for establishing a calculation method. After more than 30 years extensive research, the original coal industry department promulgated *Regulations for Setting Coal*

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*Pillar and Mining Pressed Coal under Buildings, Water Bodies, Railways, and Main Roadways* (called *Regulations for Three Downsides*[1] hereafter) in August,1985. The regulation was re-revised in May, 2000. *Regulations for Three Downsides* provides systemic summaries of the research of mining subsidence.

Probability integral method is one of main calculation methods for mining subsidence in China and even in the world, which is recommended in *Regulations for Three Downsides*. This method makes important contributions to the development of coal resources in China, but in practical use there are some problems: (1) Calculation results are inconsistent with prediction results because many stations have been removed and the parameters are not corrected by monitor data after big changes of the well geological condition at times; (2) Nowadays, the development of coal resources has already entered a stage in deep mining, but all of original calculation parameters were determined in shallow mining conditions. So sometimes the parameters are not reasonable while used in deep mining; (3) It is not maturity that probability integral method is used for mining subsidence in steep coal seam; (4) In recent years, coal under "three downsides" has been mined gradually. Other ministries, such as the Ministry of Water Resources, of Communications, of Railroad and of Construction etc., know little of probability integral method, so each department has a certain problem in communicating a consultation. Authors have engaged in the research of mining under “three downsides”. We propose that it is a comprehensive research involving many sections. In aspects of calculation and prediction of mining subsidence, calculation methods approved by the related department besides probability integral method are used to proofread and validate it. Numerical simulation method is widely accepted, which also has certain limitations, but its results are still more authentic as long as the calculation parameters, the model, the boundary conditions and other factors are accurate. Based on practical projects, elastoplasticity and rheology are analyzed by FLAC-3D programme and the results are validated by probability integral method.

## 2 The brief introduction of FLAC-3D principle

The code of FLAC-3D (the Fast Lagrangion Analysis of Continue) is a finite difference code [0] developed by Itasca and it has various constitutive models. It can simulate mechanic behavior of breakage or plastic flow while geologic materials reaching the strength limit or yielding strength, can analyze the process of gradual breakage and losing stability, and especially can be applied to simulate the big deformation problem. Moreover, FLAC also establishes the interface unit to simulate slip, open and close behavior of the fault, joint and friction boundary. Therefore, it is suitable for dealing with mining subsidence.

FLAC is similar with other numerical methods. The first step is to define the spatial discretization of the calculation domain to form limited cells and associated nodes. In the research domain, each cell and node should meet the demand of the equilibrium.

FLAC adopts Lagrange difference formula. The characteristic of particle in the medium is defined by the vectors $x_i$, $u_i$, $v_i$, $\mathrm{d}v_i/\mathrm{d}_t$, respectively representing the space position, the deformation, the speed and the acceleration. The direction of tensile or expansion is positive.

FLAC-3D uses the explicit formulation to get the solution of time step to all motion equations, thereby tracing progressive process of material breakage. It is very important to study the time effect and the three-dimensional effect for coal mining. FLAC-3D has five rheological models: ① the classical viscoelasticity model; ② double exponential associate model; ③ the model of nuclear waste storage related to rheological formation; ④ the elastoplasticity model; and ⑤ crushed-salt constitutive model. The first model is classical Maxwell material model; the second is used for the mining project; the third for thermodynamic analysis correlated with the storage of underground nuclear waste; the fourth is the changed model including plastic characteristic on the basis of the third model; the fifth is the changed model including volume and deviatonic stress characteristics on the basis of the third model.

As mentioned above, double exponential associate model is most suitable for calculation and prediction of mining subsidence.

The normalizing form of Norton exponential law is expressed as

$$\dot{\varepsilon}_{cr} = A\overline{\sigma}^{n},$$

where $\dot{\varepsilon}_{cr}$ is the rheological rate; $A$ is the material property and $A = 10^{-7}\ \mathrm{MPa}^{-3}\cdot\mathrm{a}^{-1}$ (or $10^{-25}\ \mathrm{Pa}^{-3}\cdot\mathrm{a}^{-1}$); $n$ is the material property and $n = 3$.

## 3 Example analysis

### 3.1 Brief introduction of the project

Xifeihe left embankment is an important part of Huaibei embankment. It is a class I embankment, whose flood control function is obvious. Guotou Xinji Yangcun colliery is a nation super huge preparing mine, with the design production capacity of 5000000 tons/a. According to the current program, parts of Guotou Xinji Yangcun colliery lie under Xifeihe left embankment, shown in Figure 1. It causes the contradiction between coal mining and safety of the embankment. On one hand, Xifeihe left embankment belongs to the protective part of Huaihe embankment, and for the important embankment project, it is not allowed to mine under the ground in general. On the other hand, a great deal of coal resources are under Xifeihe left embankment, and coal mining under the embankment is carried out for economic and social benefits. On the basis of the predecessor's research production, FLAC-3D is used to evaluate the influence of Xifeihe left embankment under mining. Its results are carried on the contrast and validation with the results by probability integral method, and finally it has obtained better results. The research production was authenticated by experts in November, 2005.

### 3.2 Determination of rock-soil engineering mechanics parameters in the mine area

There are no measuring and testing data in Yangcun colliery, so it is difficult to select rock-soil engineering mechanics parameters. Given that Yangcun colliery is quite close to the third Xinji colliery, both of which belong to the same coal-bearing strata, this research is mainly on the basis of the field monitor data of the third Xinji colliery and FLAC-3D is used to carry out the analysis of "inversion" and finally determine the parameters.

The basis of the inversion analysis is field monitor data of the first west mine area in the third Xinji colliery. It began to mine in the first west mine area in 1997, while the movement of the earth's surface was observed. Mining was almost completed in 2000. Invaluable monitor data were obtained during each mining as well as the whole process. The typical profile has three whole monitor curves respectively in 1998, 2001 and 2004. The monitor data in 1998 and 2001 were collected close to the end time of each exploitation on the whole and can be used to inverse the basic rock-soil mechanics parameters. And the monitor data in 2004 can be used to inverse the rheological parameter of overlying rock-soil in the mine area.

The three-dimensional calculation model of the first west mine area in the third Xinji colliery is shown in Figure 2(a) and the measured typical profile in Figure 2(b). The basis of this research includes the parameters adopted in the model experiment in Huainan University of Science & Technology, the data in the rock-soil mechanics parameters database set up by China Institute of Water Resources and Hydropower Research, and the data from Huainan mine area[2]. The initial value of calculation parameters is presented on the basis of comprehensive analysis. Otherwise, it is difficult to determine rheological parameter. For simplifying the calculation, we get $A_2$=0 and $A_1$ determined by inversion with consulting the compressive strength of different strata. The parameters of "inversion" are shown in Table 1.

In order that the inversion results can reflect the actual situation of the rock-soil, the process of mining is set up step by step in the inversion calculation. The process is divided into two steps: the first step is to simulate the monitor curve of mining in 1998; the se-

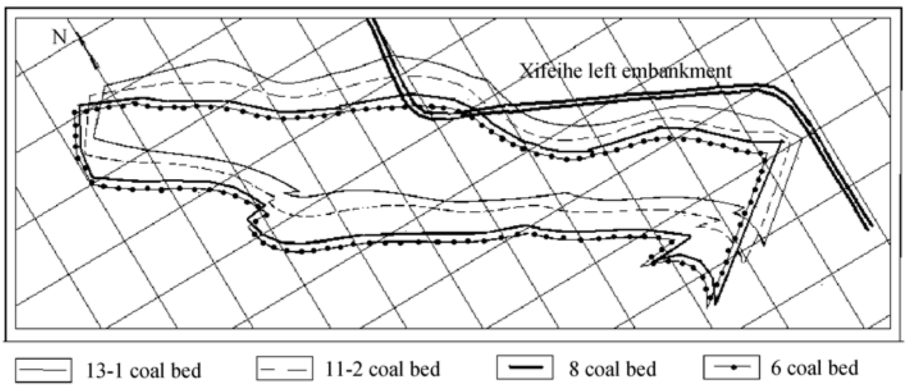


**Figure 1** Position relation between the well field of Yangcun colliery and Xifeihe left embankment.

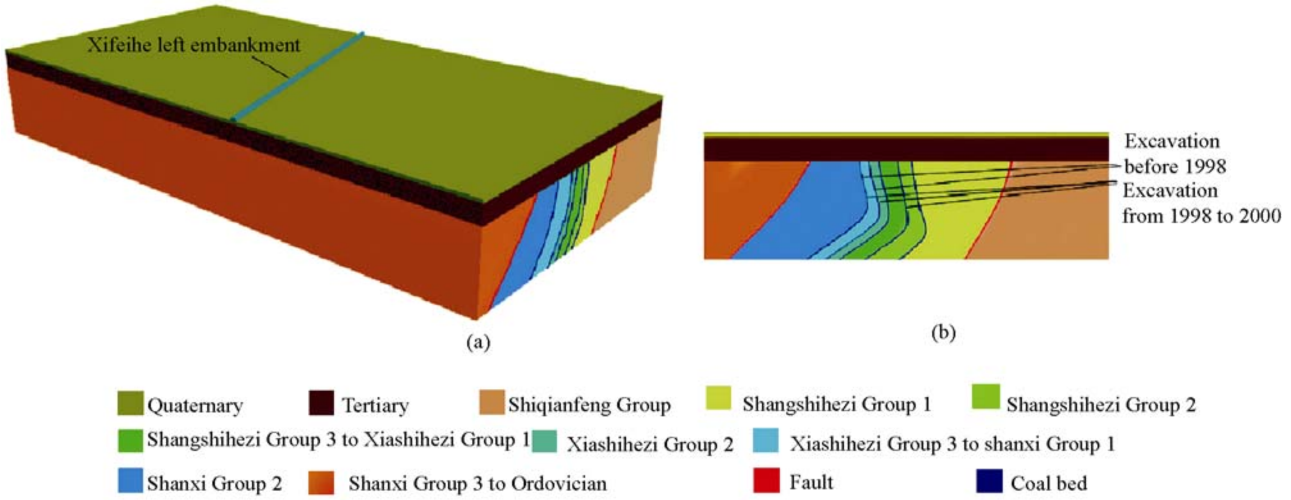


**Figure 2** Three-dimensional model of the first west mine area in the third Xinji colliery by inversion. (a) Three-dimensional geological model; (b) typical profile in the three-dimensional geological model.

**Table 1** Lithologic characters and mechanical index of coal beds, rock formations and faults ( initial value/end value)

| Code | Lithology | Initial value/end value | | | | | |
|---|---|---|---|---|---|---|---|
| | | Bulk weight (kN/m$^3$) | Poisson's ratio | Cohesive strength (MPa) | Friction angle (°) | Deformation modulus (GPa) | Rheological parameter $A$ |
| 0 | silt, silty sand | 18.7/18.7 | 0.34/0.34 | 0.02/0.034 | 22/24 | 0.08/0.03 | |
| 1 | clay sand, fine sand, gravel-bearing medium and fine sand, clay, medium and fine sand | 18.7/18.7 | 0.32/0.34 | 0.05/0.034 | 22/24 | 0.1/0.08 | |
| 2 | marlite, calcareous clay, medium and fine sand | 18.7/18.7 | 0.31/0.34 | 0.15/0.034 | 25/24 | 1.45/0.13 | |
| 3 | mudstone, Fine and coarse sandstone, interbedded quartzy sandstone, sandstone and conglomerate | 25/25 | 0.31/0.321 | 0.15/0.082 | 35/30 | 1.6/1.5 | |
| 4 | grey mudstone, sandy mudstone which are dominant | 25/25 | 0.31/0.321 | 0.15/0.082 | 32/30 | 1.6/1.5 | |
| 5 | geryish-white fine , medium sand or quartzy sandstone, grey mudstone, which are dominant, interbedded fine, medium sandstone and quartzy sandstone | 27.1/27.1 | 0.27/0.302 | 0.40/0.245 | 40/36 | 2.5/1.7 | $1\times10^{-26}$ |
| 6 | grey, geryish-white fine-coarse sand | 25/25 | 0.27/0.321 | 0.35/0.082 | 35/30 | 2.0/1.5 | |
| 7 | marine mudstone, Limestone which are dominant, interbedded sandstone | 26.6/26.6 | 0.31/0.321 | 0.3/0.245 | 38/34 | 1.9/1.6 | |
| 8 | Triassic sandstone, mudstone, sandy mudstone and fine sandstone or interbedded sandstone and mudstone | 27.6/27.6 | 0.31/0.321 | 0.8/0.6 | 25/24 | 1.6/1.42 | |
| 9 | light gray and light flesh red limestone, dolomitic limestone | 28.1/28.1 | 0.28/0.321 | 0.45/0.245 | 45/40 | 2.5/1.7 | |
| 10 | coal bed | 14.2/14.2 | 0.3/0.328 | 0.12/0.1 | 23/20 | 0.5/0.4 | |
| 11 | crush belt of fault | 14.2/14.2 | 0.30/0.35 | 0.12/0.034 | 23/22 | 0.7/0.6 | |

cond step is to simulate the monitor curve of mining in 2001. The results are shown in Figures 3 and 4. In this paper, the rheological parameter is also carried on "inversion" analysis and the results are shown in Figure 5. The rock-soil engineering mechanics parameters of Yangcun colliery are shown in Table 1.

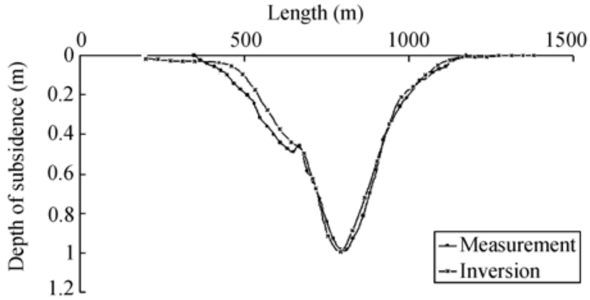


**Figure 3** Comparison between measured value and "inversion" value under mining of the typical profile (May, 1998).

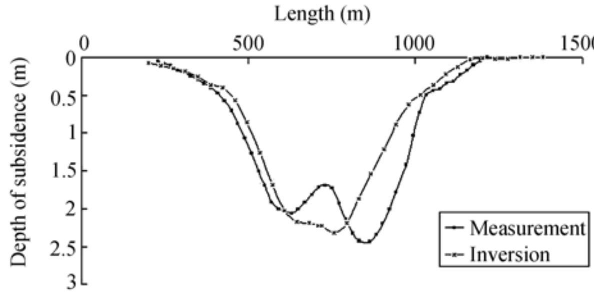


**Figure 4** Comparison between measured value and "inversion" value under mining of the typical profile (September, 2001).

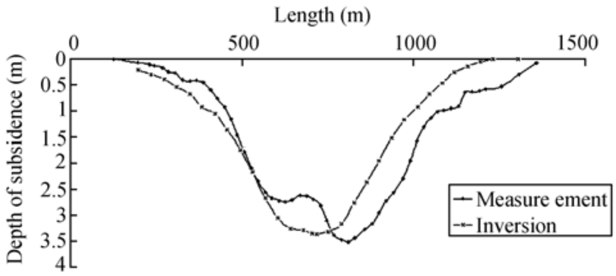


**Figure 5** Comparison between measured value and "inversion" value under mining of the typical profile (June, 2004).

### 3.3 Influence of coal mining on Xifeihe left embankment

(1) Model. Yangcun colliery is located in the county of Lixin, Fengtai and Yingshang in Anhui Province. The geologic setting is a monoclinal structure of the trend NW accompanying sub-first grade fold. The thickness of Cenozoic unconsolidated formation is large (494.00—790.33 m). The coal bed is buried deeply, and the range of the dip angle is generally 20°—30°. The coal bed of mining includes four layers: 13, 11, 8 and 6 layer. The east boundary of the geological model is fault $F_5$, the west is the profile line 6-6, the south is $F_{101}$ and the north is $F_{102}$. The geological model is shown in Figure 6. In the figure, the positive direction of *Y* axis represents N, the positive direction of *X* axis represents W and *Z* axis represents elevation. The length of the model is 10578 m from east to west, and the width of the model is 660 m from south to north. The depth is from land surface (±0.0 m) to −1370 m. Xifeihe left embankment goes through the mine area from west to east.

Because the selected calculation scope is very large and the influence of coal mining on the movement of the boundary is smaller, the bottom of the model chooses the fixed end restraint and lateral restraint is applied to lateral surface.

(2) Analysis of elastoplasticity. Above all, the elastoplasticity constitutive model is adopted. Yield criterion is Mohr-Coulomb criterion and the end value of calculation parameters is shown in Table 1. The faults are simulated by solid units. This research has five programmes: ① the pillar is reserved under the industrial square and the whole is exploited; ② the pillar is reserved under the industrial square and the mine boundary is 500 m far from the embankment; ③ the pillar is reserved under the industrial square and the mine boundary is 600 m far from the embankment; ④ the pillar is reserved under the industrial square and the mine boundary is 800 m far from the embankment; and ⑤ the pillar is reserved under the industrial square and the mine boundary is 1000 m far from the embankment. The predicted maximum of ground deformation index of Xifeihe left embankment under mining for each programme is shown in Table 2.

(3) Analysis of probability integral method. In this paper, probability integral method is also applied to the ground deformation caused by mining. The parameters

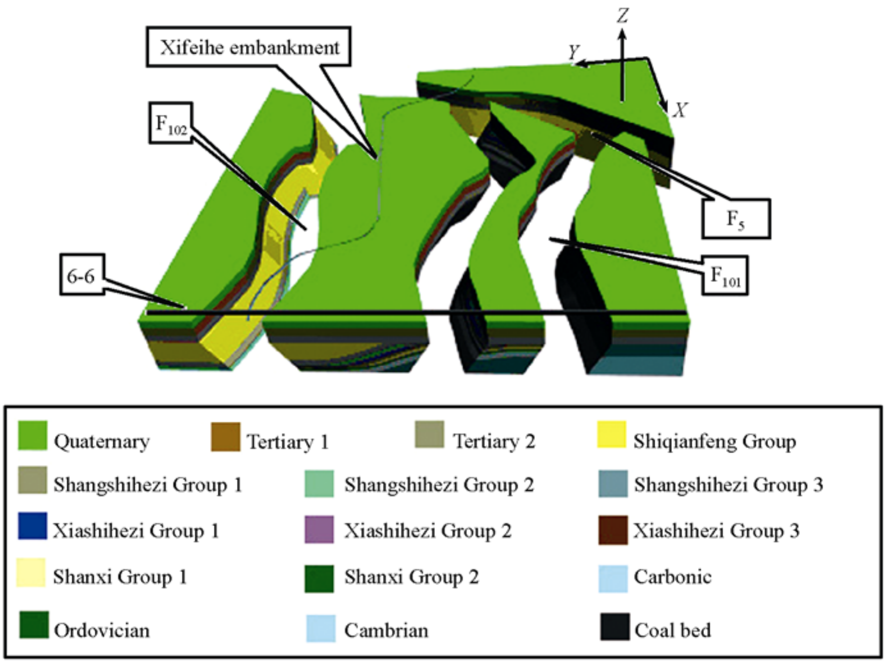


**Figure 6** Three-dimensional geological model of Yangcun colliery.

**Table 2** Maximum subsidence index of the embankment for each programme ( elastoplasticity model)

| Programme | Sequence of mining | Along axis direction of the embankment | | Vertical axis direction of the embankment | | Subsidence direction | |
|---|---|---|---|---|---|---|---|
| | | Displacement (m) | Tensile strain (mm/m) | Displacement (m) | Shearing deformation (mm/m) | Displacement (m) | Subsidence deformation (mm/m) |
| ① | after mining of 13 coal bed | +1.4 | +1.2 | −1.3 | +1.4 | −2.9 | +2.0 |
| | after mining of 11 coal bed | +2.1 | +2.0 | −2.0 | +2.0 | −4.1 | +3.8 |
| | after mining of 8 coal bed | +2.8 | +2.5 | −2.6 | +2.4 | −5.2 | +4.3 |
| | after mining of 6 coal bed | +3.1 | +3.0 | −3.2 | +2.9 | −6.2 | +5.6 |
| ② | after mining of 13 coal bed | +0.3 | +0.75 | −1.0 | +0.7 | −0.52 | +0.6 |
| | after mining of 11 coal bed | +0.5 | +1.25 | −1.5 | +1.1 | −0.81 | +1.0 |
| | after mining of 8 coal bed | +0.7 | +1.70 | −2.1 | +1.5 | −1.16 | +1.4 |
| | after mining of 6 coal bed | +1.0 | +2.20 | −2.5 | +1.8 | −1.41 | +1.8 |
| ③ | after mining of 13 coal bed | +0.24 | +0.70 | −0.74 | +0.58 | −0.34 | +0.3 |
| | after mining of 11 coal bed | +0.46 | +1.22 | −1.16 | +0.89 | −0.55 | +0.48 |
| | after mining of 8 coal bed | +0.66 | +1.68 | −1.66 | +1.13 | −0.8 | +0.83 |
| | after mining of 6 coal bed | +0.85 | +2.12 | −2.15 | +1.42 | −1.06 | +1.24 |
| ④ | after mining of 13 coal bed | +0.18 | +0.53 | −0.51 | +0.42 | −0.17 | +0.19 |
| | after mining of 11 coal bed | +0.37 | +1.03 | −0.95 | +0.75 | −0.42 | +0.34 |
| | after mining of 8 coal bed | +0.47 | +1.36 | −1.27 | 0.93 | −0.54 | +0.55 |
| | after mining of 6 coal bed | +0.56 | +1.66 | −1.63 | +1.14 | −0.68 | +0.84 |
| ⑤ | after mining of 13 coal bed | +0.19 | +0.30 | −0.38 | +0.30 | −0.10 | +0.15 |
| | after mining of 11 coal bed | +0.29 | +0.42 | −0.59 | +0.56 | −0.17 | +0.24 |
| | after mining of 8 coal bed | +0.38 | +0.60 | −0.80 | +0.70 | −0.25 | +0.32 |
| | after mining of 6 coal bed | +0.45 | +0.80 | −0.96 | +0.82 | −0.30 | +0.40 |

come from *Regulations for Three Downsides*. The results are shown in Figure 7. The maximum of ground deformation of Xifeihe left embankment by this method is shown in Table 3.

(4) Rheological Analysis    Rheological analysis is also carried out. Because rheological calculation is time consuming, only programme ③ (600 m far from the embankment) and programme ④ (800 m far from the embankment) have been done in this paper. The maximum of ground deformation of Xifeihe left embankment by this method is shown in Table 4.

(5) Influence evaluation.  It is defined by Coal Department that allowable value of horizontal deformation $\varepsilon$ is less than or equal to 4mm/m for earth dam and embankment without spilling water facilities in *Regulations for Three Downsides*. But it is not defined in Water Conservancy Department. Based on practical projects, tensile strain should not be generated in the dike body for Xifeihe left embankment which is the grade I marine structure.

On the basis of the predecessor's research and mining engineering practice of more than 40 years under Huaihe in China[2,3], the index in Regulations for Three Downsides is as a control index for deformation destroy of Xifeihe left embankment by mining, where horizontal deformation ε is less than or equal to 4 mm/m, slope is less than or equal to 6 mm/m and diameter of curvature is more than or equal to 104 m. Meanwhile, the authors try to reduce the index above and bring forward the index of safety of the embankment which is approved by every department considering the importance of Xifeihe left embankment. This index may be conservative, but it can be corrected gradually by field monitoring so as to be reasonable.

The reduction index of deformation of the embankment is proposed preliminarily in this paper. Horizontal deformation $\varepsilon$ which is less than or equal to 2 mm/m, horizontal shearing deformation and subsidence deformation, both of which are less than or equal to 4 mm/m, are as the index.

Based on the control index and the reduction index of deformation of the embankment, the results are shown:

(1) Using the control index, the results of probability integral method indicate that it is most serious to destroy the embankment with programme ①. The length of the embankment is about 2300 m of which degree is more than the control index; the degree of embankment breakage with programme ② is slower than the degree with programme ① and the length of the embankment is about 902 m of which degree is more than the control index; the degree of embankment breakage with programme ③, ④ and ⑤ is less and there is no embank-

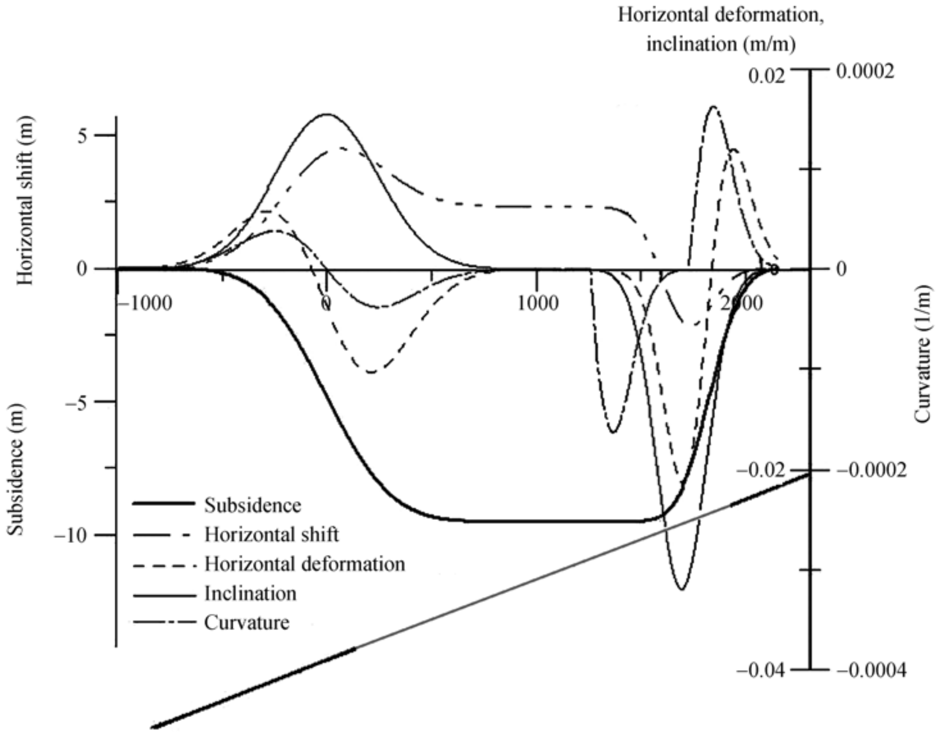


**Figure 7** Calculation results of ground deformation by mining (probability integral method).

**Table 3** Maximum subsidence index of the embankment for each programme (probability integral method)

| Programme | Sequence of mining | Displacement (m) | Inclination (mm/m) | Horizontal deformation (mm/m) |
|---|---|---|---|---|
| ① | after mining of 13 coal bed | 2.25 | 5 | 2 |
| | after mining of 11 coal bed | 4 | 8.4 | 3.5 |
| | after mining of 8 coal bed | 5.3 | 12 | 4.8 |
| | after mining of 6 coal bed | 7.5 | 16 | 6 |
| ② | after mining of 13 coal bed | 0.258 | 1.907 | 1.743 |
| | after mining of 11 coal bed | 0.434 | 3.210 | 2.918 |
| | after mining of 8 coal bed | 0.623 | 4.605 | 4.186 |
| | after mining of 6 coal bed | 0.821 | 6.067 | 5.515 |
| ③ | after mining of 13 coal bed | 0.115 | 1.009 | 1.262 |
| | after mining of 11 coal bed | 0.194 | 1.699 | 2.124 |
| | after mining of 8 coal bed | 0.278 | 2.437 | 3.048 |
| | after mining of 6 coal bed | 0.366 | 3.211 | 3.816 |
| ④ | after mining of 13 coal bed | 0.015 | 0.173 | 0.334 |
| | after mining of 11 coal bed | 0.026 | 0.291 | 0.562 |
| | after mining of 8 coal bed | 0.037 | 0.417 | 0.806 |
| | after mining of 6 coal bed | 0.049 | 0.549 | 1.062 |
| ⑤ | after mining of 13 coal bed | | almost having no effect | |
| | after mining of 11 coal bed | | almost having no effect | |
| | after mining of 8 coal bed | | almost having no effect | |
| | after mining of 6 coal bed | | almost having no effect | |

ment, of which the control index exceeds standard.

(2) Using the reduction index, the results of probability integral method indicate that the degree of embankment breakage with programme ①, ② and ③ is more serious and maximum value of deformation exceeds the reduction index. The degree of embankment breakage with programme ③ is the least and the degree with programme ④ and ⑤ is less. There is no embankment of which the reduction index exceeds standard. The distance of coal boundary from the embankment should not be less than 720m if the value of deformation under mining need be assured within the range of reduction index.

(3) Using the control index, the results of elastoplasticity model indicate that all the results with five programmes are within the range of control index.

**Table 4** Maximum subsidence index of the embankment for each programme (rheological model)

| Programme | Time of mining | Along axis direction of the embankment | | Vertical axis direction of the embankment | | Subsidence direction | |
|---|---|---|---|---|---|---|---|
| | | Displacement (m) | Tensile strain (mm/m) | Displacement (m) | Shearing deformation (mm/m) | Displacement (m) | Subsidence deformation (mm/m) |
| ③ | after mining of 6 coal bed | 0.85 | 2.12 | 2.15 | 1.42 | 1.06 | 1.24 |
| | after one year mining of 6 coal bed | 1.13 | 2.42 | 2.67 | 1.79 | 2.15 | 1.61 |
| | after two year mining of 6 coal bed | 0.86 | 2.44 | 2.59 | 1.82 | 2.39 | 2.08 |
| | after three year mining of 6 coal bed | 0.86 | 2.50 | 2.50 | 1.81 | 2.43 | 2.13 |
| | after four year mining of 6 coal bed | 0.86 | 2.54 | 2.47 | 1.80 | 2.45 | 2.15 |
| | after five year mining of 6 coal bed | 0.90 | 2.54 | 2.48 | 1.78 | 2.45 | 2.16 |
| | after six year mining of 6 coal bed | 0.90 | 2.57 | 2.48 | 1.78 | 2.45 | 2.16 |
| ④ | after mining of 6 coal bed | 0.56 | 1.66 | 1.63 | 1.14 | 0.68 | 0.84 |
| | after one year mining of 6 coal bed | 0.82 | 1.92 | 2.01 | 1.45 | 1.57 | 1.06 |
| | after two year mining of 6 coal bed | 0.54 | 2.00 | 1.90 | 1.52 | 1.74 | 1.40 |
| | after three year mining of 6 coal bed | 0.60 | 2.06 | 1.76 | 1.56 | 1.75 | 1.42 |
| | after four year mining of 6 coal bed | 0.64 | 2.08 | 1.74 | 1.58 | 1.76 | 1.43 |
| | after five year mining of 6 coal bed | 0.78 | 2.12 | 1.74 | 1.58 | 1.76 | 1.43 |
| | after six year mining of 6 coal bed | 0.78 | 2.12 | 1.74 | 1.61 | 1.76 | 1.43 |

(4) Using the reduction index, the results of elasto-plasticity model indicate that it is most serious to destroy the embankment with programme ①. The length of the embankment of horizontal tensile strain, which is more than 0.2%, is about 1527m, and the length of the embankment of horizontal shearing deformation, which is more than 0.4%, is about 1536m; the degree of embankment breakage with programme ② is slower than the degree with programme ① and the length of the embankment of horizontal tensile strain, which is more than 0.2%, is about 206 m; the degree of embankment breakage with programme ③ is slower than the degree with programme ② and the length of the embankment of horizontal tensile strain, which is more than 0.2%, is about 98 m; the degree of embankment breakage with programme ④ is less and there is no embankment of which the control index exceeds standard; the degree of embankment breakage with programme ⑤ is the least and there is no embankment of which the control index exceeds standard.

(5) The results of rheological calculation indicate that all the results with five programmes are within the range of control index. Ground deformation becomes steady-state after six years' mining in the programme ③ and the length of the embankment exceeding control index of deformation destroy increases from 98 m to 446 m; ground deformation becomes steady-state deformation after six years mining in the programme ④ and the length of the embankment exceeding the control index increases from 0 m to 304 m.

Thus, the results of numerical simulation method are less than one of probability integral method mostly because of the difference between two calculation methods. Probability integral method is a method analyzing ground subsidence using normal distribution influence function. But the numerical simulation method is an iterative method by the constitutive relationship of rock and soil. It is suggested that two methods should be reciprocally validated in the prediction of ground subsidence.

In this paper, it is proposed that under mining flood protection for Xifeihe left embankment should be assured firstly considering the disadvantage of embankment safety and no waste of coal resource. The results of probability integral method indicate that the result of programme ③ is in the range of control index but it exceeds the reduction index. Excess range is less and the degree is less although in some measure deformation of the embankment can be influenced under mining. The distance of coal boundary from the embankment should not be less than 720m if the value of deformation under mining need be assured within the range of the reduction index. The results of numerical simulation method indicate that the result of programme ③ is in the range of control index but it exceeds the reduction index. Excess range is quite narrow and the degree is very little although in some measure deformation of the embankment can be influenced under mining. Therefore, it is proposed that programme ③ (600 m far from embankment) is the very mining programme. With programme ③ the embankment has no deformation and breakage in the control index and some part of the embankment has deformation and breakage. But the degree is less. Based on practical experiences, the function of controlling flood of the embankment is not influenced by reinforcement. The results of elastoplasticity method are shown in Figures 8—10 and the results of rheological method are shown in Figures 11—13. Otherwise the

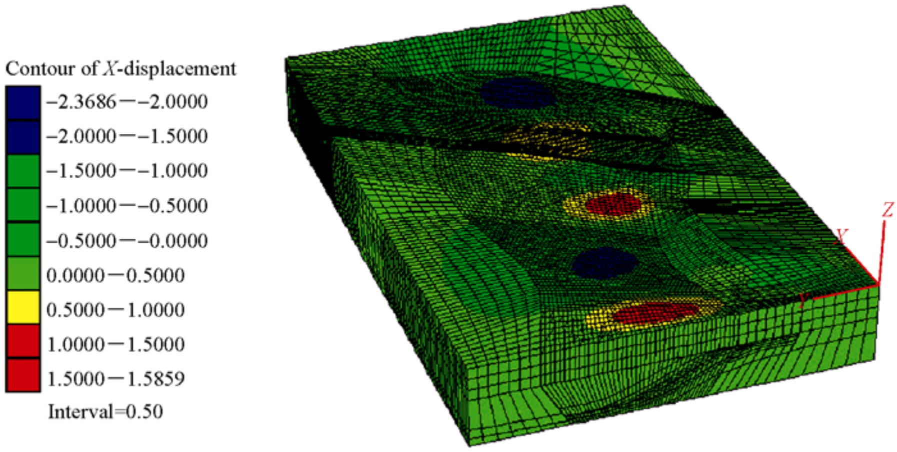


**Figure 8** Constant value domain of horizontal shift in *X* axis under mining with programme ③ (600 m far from the embankment).

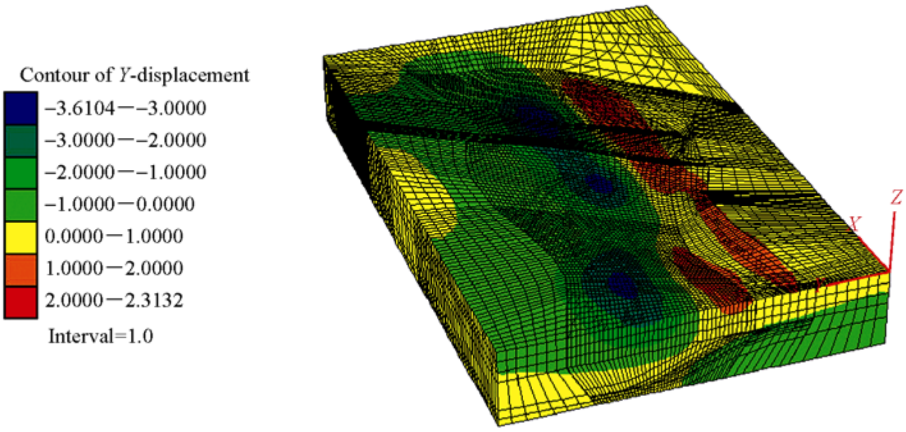


**Figure 9** Constant value domain of horizontal shift in *Y* axis under mining with programme ③ (600 m far from the embankment).

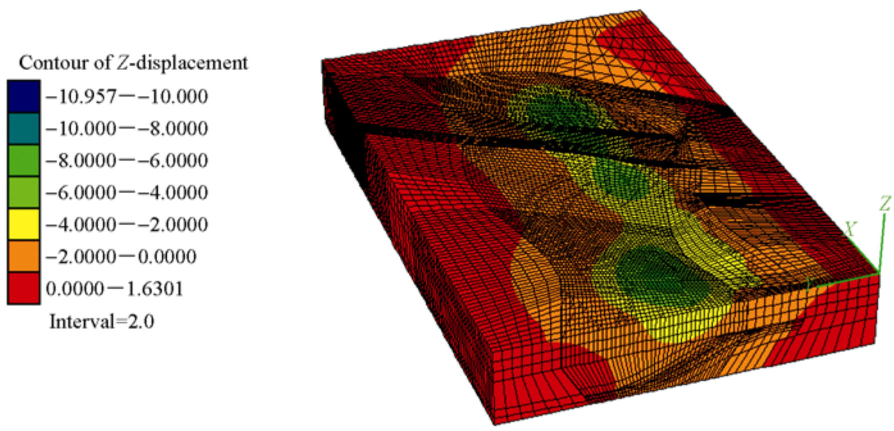


**Figure 10** Constant value domain of horizontal shift in *Z* axis under mining with programme ③ (600 m far from the embankment).

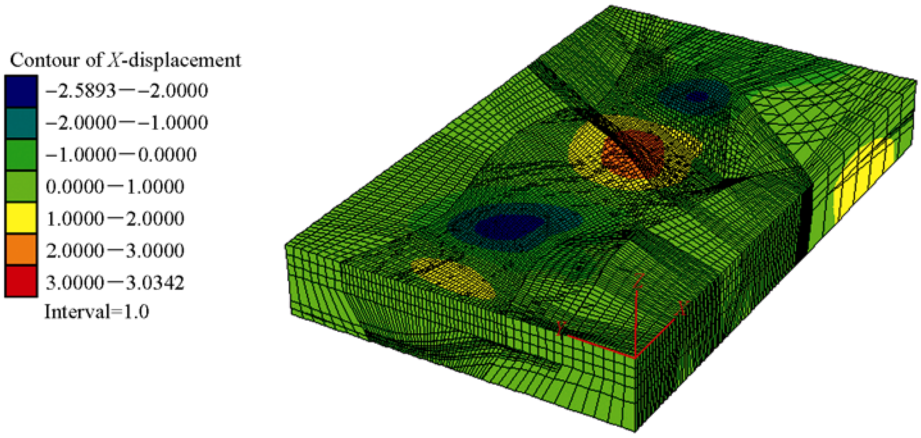


**Figure 11** Constant value domain of horizontal shift in *X* axis after six years mining with programme ③ (600 m far from the embankment).

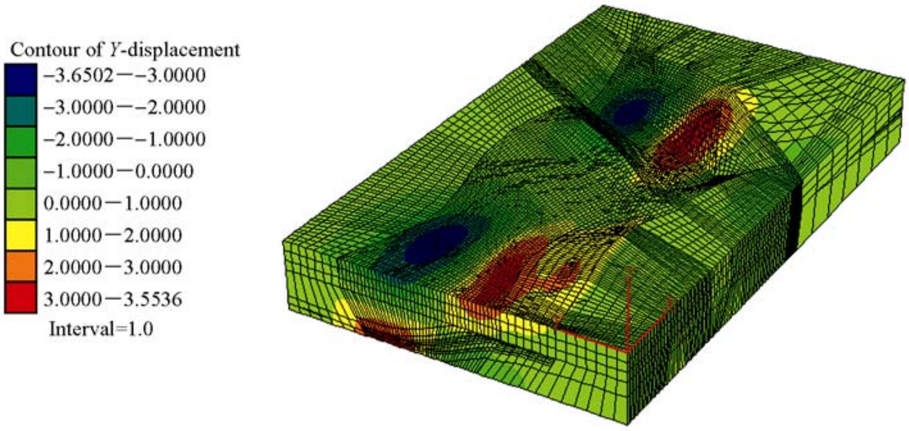


**Figure 12** Constant value domain of horizontal shift in *Y* axis after six years mining with programme ③ (600 m far from the embankment).

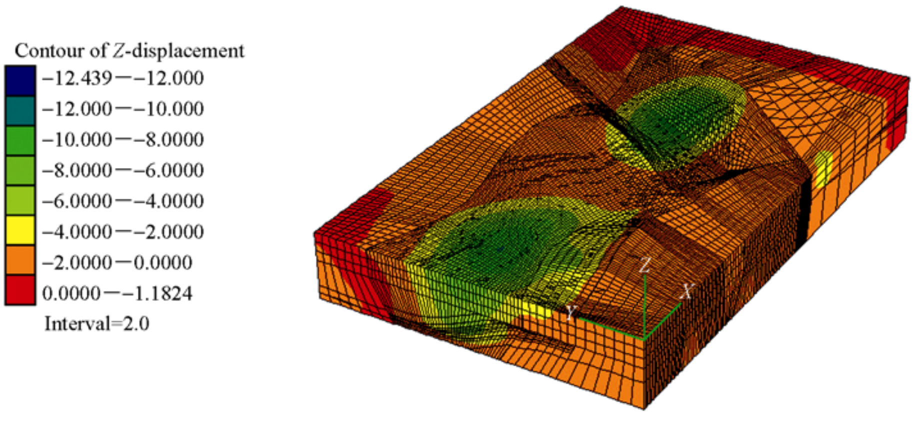


**Figure 13** Constant value domain of horizontal shift in *Z* axis after six years mining with programme ③ (600 m far from the embankment)

scheme of "720 m far from embankment" meets the control index and the reduction index. But much of coal resources can be wasted. At the same time, considering the importance of Xifeihe left embankment it is proposed that monitoring deformation of ground and embankment should be reinforced in the process of mining. The mining boundary can be adjusted based on the monitoring results. In the circumstances the embankment can be assured safe to run, coal resources should be mined properly.

## 4 Conclusions

(1) Probability integral method is used for mining

subsidence, but people in other departments know little about this method. It is proposed that the results are also cross-checked and validated by numerical simulation method.

(2) At present, *FLAC-3D* is one of numerical simulation methods for mining subsidence. The authors have conducted many practical project researches by this method and acquired better results in recent years, like influence of mining of Shenjiazhuang colliery and Liuhe Industry Corporation on the safety of dam under Yuecheng reservoir. These research products have been authenticated by experts and adopted by correlative administrative division in charge[4−6].

(3) The factors, which are modeling, choice of parameters and determination of constitutive relationship can also induce deviation of calculation results from practical projects with numerical simulation method. It is taken into account in the practical application.

(4) Combined with the results of probability integral method, it is proposed that the scheme of "600 m far from embankment" is the very mining programme, which is authenticated by professional experts. This production can be served as a reference for the similar projects, such as mining Xiaolangdi reservoir area, mining Yuecheng reservoir and mining the major channels of Middle Route South to North Water Transfer[7−13].


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