Rock and Soil Mechanics

Volume 41 | Issue 10 Article 8

3-10-2021

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Custom Citation

LUO Shun-tian, YANG Fan-jie, ZHOU Hui, ZHANG Chuan-qing, WANG Xu-hong, LÜ Tao, ZHU Yong, LU Jing-jing, . Multi-index prediction method for maximum convergence deformation of underground powerhouse side wall based on statistical analysis[J]. Rock and Soil Mechanics, 2020, 41(10): 3415-3424.

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Rock and Soil Mechanics 2020 41(10): 3415–3424 ISSN 1000–7598
https: //doi.org/10.16285/j.rsm.2020.5062 rocksoilmech.researchcommons.org/journal

Multi-index prediction method for maximum convergence deformation of underground powerhouse side wall based on statistical analysis

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Abstract: Accurate prediction of surrounding rock deformation is one of the important prerequisites for scientific design and safe construction of large underground caverns. Existing prediction methods for surrounding rock deformation of underground cavern are mainly based on the monitoring data of the constructed locations surrounding rock deformation to predict the deformation trend of unconstructed locations. This causes difficulties in meeting the requirement of accurately predicting the total surrounding rock deformation of in engineering survey and design stage. Based on the statistical analysis of measured data from 31 large underground caverns in China, a method for predicting the maximum convergence deformation of underground powerhouse side wall based on multiple indexes was proposed. Firstly, it is found that the ratio of saturated uniaxial compressive strength to ground stress R/σ, geological strength index (GSI) and material constant of intact rock m_i have great influence on the surrounding rock deformation in the 31 cases. Their calculation methods are also given. Meantime, the ratio of maximum convergence deformation to cavern height (relative deformation value U/H) is used to evaluate the value of surrounding rock deformation. Secondly, through many statistical analyses, the prediction formula between the relative deformation value (U/H) of underground cavern and the three indexes is established. Finally, the method for predicting maximum convergence deformation of underground powerhouse side wall is verified by an engineering example. The results show that the calculated results by this method are very close to the actual results, which indicates the rationality of the proposed method.

Keywords: geotechnical engineering; large underground cavern; side wall of underground powerhouse; maximum convergence deformation; statistical analysis; prediction method

1 Introduction

With the rapid development of the national economy, China's demand for underground space has increased rapidly. And with the gradual increase in multi-functional, large-space, and high-side wall underground cavern projects, it has brought many challenges to the design and construction of underground caverns. The stability of underground caverns surrounding rock is the primary consideration in design and construction of the caverns. An economical and effective underground cavern engineering support plan can greatly ensure the stability of underground cavern surrounding rock and reduce engineering costs. The deformation of surrounding rock is an important factor that determines the design parameters of underground cavern support. In the design of underground cavern support, determining a reasonable design, such as the anchorage cable pre-stress locking tonnage, the size and strength of lining structure etc., must be made based on the predicted surrounding rock deformation. Therefore, accurately predicting the deformation of surrounding rock is of great significance to the scientific design, safe construction and engineering cost control of underground caverns.

Scholars from both domestic and abroad have carried out much research on the prediction of surrounding rock deformation of underground caverns. For example, Zhu et al.[1] took the structural form of underground cavern group of the Ertan Project as research background and considered four basic factors, and gave a displacement prediction formula for the key points of high side wall using a large number of calculation examples. Based on Gaussian Process Regression Theory (GPR), He et al.[2] constructed a mapping model between the natural attributes and deformation of rock mass in the interval of the same design surrounding rock grade, and realized the response prediction of current deformation convergence value of the tunnel face surrounding rock.

Received: 17 January 2020 Revised: 8 June 2020
This work was supported by the National Key R&D Program of China (2019YFC0605103, 2019YFC0605104, 2019YFC0605100) and the Key Projects of the Yalong River Joint Fund of the National Natural Science Foundation of China (U1865203).
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Yang et al.[3] established a relationship between the equivalent elastic moduli of surrounding rock formation at any time according to the regression equation of displacement−time relationship to predicted the deformation of formation around the cave. Zhao [4] used support vector machine to establish the mapping relationship between nonlinear deformation sequences and predicted the surrounding rock deformation. Cai et al.[5] used the firefly algorithm (FA) to determine the delay order and the number of hidden layer units, and used the nonlinear autoregressive (NAR) dynamic neural network to predict, and proposed a tunnel forecast model of surrounding rock deformation based on the FA-NAR dynamic neural network. Wang et al.[6] employed conventional GM(1,1) model, homogeneous exponential function gray model and non-homogeneous exponential function gray model to predict and compare the tunnel surrounding rock deformation. Li et al.[7] proposed a deformation prediction method based on support vector machine, particle swarm algorithm and chaotic mapping to predict the convergent deformation of tunnel surrounding rock. Chen et al.[8] comprehensively considered the tunnel depth, span, strength−stress ratio of surrounding rock and other factors affecting rock mass squeeze deformation and proposed a new prediction method of squeeze deformation based on correction value suitable for basic quality index of rock mass [BQ] in China. Fattahi[9] took rock mass classification (RMR), burial depth, uniaxial compressive strength (UCS) and elastic modulus E_i of rock mass as parameters, using hybrid support vector regression (SVR) and harmony search algorithm, differential evolution algorithm and particle swarm optimization algorithm (PSO) model to calculate the rock mass deformation modulus. Kayacan et al.[10] studied the accuracy of different gray models such as GM(1, 1), gray Verhulst model, and Fourier series modified gray model. Suwansawats et al.[11] utilized artificial neural networks to predict the maximum ground settlement caused by EPB shield construction.

In summary, although a lot of research has been carried out on the prediction of underground caverns surrounding rock deformation, the current research work is mainly focused on predicting the deformation trend of surrounding rock at the unconstructed part based on the monitoring data of the constructed part. In the engineering survey and design stage, there are few studies on the prediction of surrounding rock deformation of underground caverns. In the actual construction of underground caverns, in order to improve the lack of prediction of surrounding rock deformation in design stage and considering the complexity of underground engineering geological conditions, a large number of scholars have proposed dynamic feedback analysis methods for underground engineering construction to guide the project's design and construction. For example, Jiang et al.[12] combined theoretical tracking analysis with real-time engineering control, inverse calculation of surrounding rock mechanical parameters and subsequent tracking feedback analysis, and proposed support adjustment measures and real-time reinforcement support programs. Some scholars also adopted the dynamic inverse analysis method to invert the surrounding rock parameters using existing construction monitoring data, and then use the surrounding rock parameters obtained from inversion to predict the surrounding rock deformation at the next moment[13]. This method is of great benefit to engineering design and construction when the predicted value of surrounding rock deformation is not significantly different from the actual deformation during construction. However, when the predicted value of surrounding rock differs greatly from the actual value, it will greatly increase the project workload of design and construction and increases engineering costs.

In view of this, based on the statistical analysis of measured data of 31 large-scale underground chambers in China, this paper develops a multi-index prediction method for the maximum convergent deformation of a large-scale underground powerhouse side wall suitable for the engineering investigation and design stage, including determination of three indicators that affect the deformation of surrounding rock, i.e. strength−stress ratio R/σ, geological strength index (GSI), and complete rock material constant m_i and their calculation method. The proposed method for prediction of surrounding rock deformation is verified through engineering examples.

2 Case analysis

With the continuous development of China's underground engineering construction level, the number and scale of underground caverns are getting larger and larger. In order to study the law of surrounding rock deformation of large underground caverns, this paper investigated and analyzed 31 cases of large-scale underground engineering in China. As the current China's large-scale underground projects are mainly concentrated in the field of hydropower construction underground engineering, the case study in this article is also mainly carried out for the underground cavern group of hydropower projects. The basic principles of engineering case investigation are as follows:

(1) Since the underground cavern group of hydropower projects are large in scale, and underground powerhouse is its core part in terms of function and scale, the case study is mainly carried out for the underground powerhouse.

(2) Since the surrounding rock deformation in different parts of the underground powerhouse is inconsistent, the prediction cost is high if the deformation of surrounding rock at each point is predicted and studied. In view of this, some scholars have conducted research

on the selection of key points of surrounding rock deformation. For example, after extensive calculations by Zhu et al.[14], the study found that the central point of the downstream side wall of underground powerhouse is the key point, and the displacement value is mostly one of the maximum values around the cave. The side wall of underground powerhouse is its weak location, and most of the key points are in the middle of side wall. Therefore, this paper takes the maximum convergent deformation of the surrounding rock of the underground powerhouse side wall as the prediction target.

(3) A large number of research results from domestic and abroad[14−17] have shown that surrounding rock deformation is closely related to the following factors: chamber size, lithology, surrounding rock type, rock hardness, initial stress, excavation and support plan and sequence, groundwater, etc.

In the case study, information on structural characteristics, rock mass characteristics, excavation methods and support measures of 31 underground tunnel main powerhouse is summarized in Fig. 1, Tables 1 and 2, respectively. It should be noted that due to the construction of large underground caverns, curtain for cutting off water is usually implemented to minimize the impact of groundwater on surrounding rocks near the caverns. The research in this article is carried out on the premise that groundwater has little effect on surrounding rock near the chamber. Therefore, the research information in this case no longer considers the influence of groundwater on surrounding rock deformation.

Through the inductive analysis of Fig.1, Table 1, and Table 2, we can see that:

(1) The engineering structure of the underground powerhouse has developed into a trend of "large space and high side walls", and the scale is getting larger and larger. Such as Baihetan, Wudongde and other hydropower stations, the maximum length of underground chambers can reach 438 m, maximum span of 34 m, and maximum height of 89.8 m.

(2) Since hydropower projects are generally located in areas with good engineering geological conditions, the types of surrounding rocks of underground powerhouses in the research cases are mainly II to III.

(3) Affected by the engineering geological environment, the mechanical properties and in-situ stress levels of underground powerhouses in different cases are quite different. For example, the average rock saturated uniaxial compressive strength of hydropower stations such as Foziling, Dagang and Dongfeng is more than 100 MPa, while the average rock strength of Ertan hydropower stations is about 30 MPa. In terms of in-situ stress values, hydropower stations such as Jinping I and II, Houziyan, and Shuangjiangkou are all in a state of high in-situ stress, while the maximum principal stress value of the Foziling Hydropower Station is lower than 5.3 MPa.

(4) In addition, the differences in the measured maximum value of the convergent deformation of the surrounding rock of the underground powerhouse in different research cases are also evident. For example, the convergent deformation values of surrounding rocks at Houziyan, Lianghekou and Changheba hydropower stations exceed 100 mm, while the convergent deformation values of surrounding rocks at Manwan, Dachaoshan and Yantan hydropower stations are less than 40 mm.

(5) Through Table 2 it is shown the construction technology in China for hydropower projects is relatively mature, and the excavation methods and support schemes differ little. Generally, it follows the layered excavation principle of "planar multi-process, three-dimensional multi-level" (the height of storey is mainly in the range of 6−8 m). At the same time, the system of anchor rods and anchor cables is used as the main support (the distance between anchor rods and the one between anchor cables are mainly in the range of 1−1.5 m and 4−6 m, respectively), supplemented by local reinforced support, and combined with random support principle.

3 Multi-index prediction method

In order to investigate the law of surrounding rock deformation in large underground caverns and predict the deformation of surrounding rock, this paper firstly studies the influence indexes and corresponding calculation methods of surrounding rock deformation based on the statistical analysis of measured data of 31 large underground caverns in China. Then, a prediction formula for the maximum convergent deformation of surrounding rock of the underground powerhouse side wall is developed using statistical analysis, which constitutes a multi-index prediction method for the maximum convergent deformation of large underground powerhouse side wall in the engineering investigation and design stage.

3.1 Indexes and their calculation method

Existing studies have shown that the stability of the underground cavern surrounding rock is affected by the size of the chamber, lithology, type of surrounding rock, rock hardness, initial stress, excavation and support plan and sequence. This article focuses on the influence of several main factors: lithology, surrounding rock type, rock hardness, chamber size, initial stress and rock integrity, etc. In order to describe the factors influencing surrounding rock deformation more concisely, based on the existing research results[14−17] and analyzing the engineering structural features and rock mass information in Fig.1 and Table 1, this article gives the three influencing indicators for the underground cavern surrounding rock deformation: the strength-to-stress ratio R/σ, the geological strength index (GSI), and the material constant m_i of the intact rock. These three indicators can all be determined through detailed survey of the engineering geology in the engineering survey and design stage. Finally, the non-dimensional analysis method is used to put forward the ratio of the maximum convergent deformation of the surrounding rock side wall to the height of the cavern (relative deformation value U/H)

to evaluate the magnitude of surrounding rock deformation.

Among them, the ratio of saturated uniaxial compressive strength R_b to maximum principal stress σ_1, i.e. the strength-to-stress ratio R/σ, can comprehensively reflect the engineering mechanical characteristics of surrounding rock, and is currently one of the commonly used evaluation indicators in underground engineering. In the calculation, the uniaxial compressive strength value adopts the average value of saturated uniaxial compressive strength of the rock in the cavern area, and the in-situ stress value selects the maximum principal stress value at the middle of the cavern.

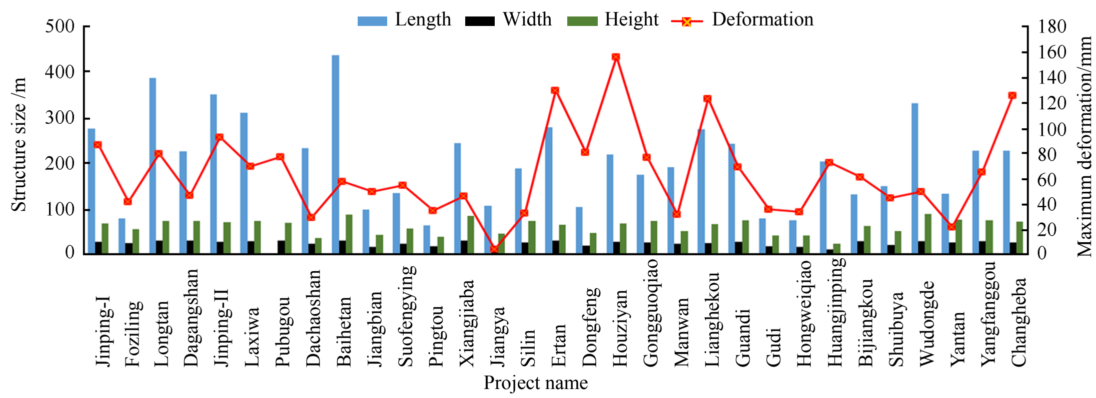

Fig. 1 Summary of structure size and surrounding rock deformation of main underground powerhouse

Table 1 Summary of underground cavern rock mass characteristics

Project name	Main rock mass	Mechanical parameters of surrounding rock /MPa	Project name	Main rock mass	Mechanical parameters of surrounding rock /MPa
Jinping-I	III$_1$, Marble with green schist, Mostly intact, blocky, fresh	R_b=60−75, σ_1=20.0−35.7, σ_3=4−12	Dongfeng	Mostly III, Limestone, shale, hard, Mostly intact, layered, strong corrosion	R_b=100−104, σ_1=12.1, σ_3=5.7
Foziling	III, Granite gneiss, hornblende plagioclase gneiss, relatively intact, massive, fresh	R_b=104.7−158.7, σ_1= 2.9−5.3, σ_3=−1.1−1.5	Houziyan	III$_1$, Limestone, relatively intact, fresh and good quality	R_b=54.65−109.29, σ_1= 21.53−36.43, σ_3=6.20−22.32
Longtan	II−III, Sandstone, siltstone and mud slate, soft to hard, slightly weathered and fresh	R_b=40−130, σ_1=12−13, σ_3=3−5	Gongguoqiao	II, III, Metamorphic sandstone, sandy slate intercalated with gray-white metamorphic quartz sandstone, fresh	R_b=125, σ_1=10−14, σ_3=5−8
Dagangshan	II−IV, Granite, diabase, rock dikes and other rock dikes are interspersed and developed, and are slightly weathered	R_b=100−108, σ_1=11.37−19.28, σ_3=5.6−8.3	Manwan	I, II$_1$, Rhyolite, relatively intact, slightly weathered	R_b=25−45, σ_1=12−30, σ_3=4−10
Jinping-II	II−III, Carbonate rock, thick and massive, intact, slightly weathered	R_b=44.7−114, σ_1=10.9−41.11, σ_3=4.9−9.9	Lianghekou	III$_1$, Metamorphic sandstone and silty slate, hard, relatively intact, slightly weathered−fresh	R_b=60−100, σ_1=30.44, σ_3=10.27
Laxiwa	III−IV, Granite, metamorphic sandstone, limestone, hard, slightly weathered	R_b=110, σ_1=29, σ_3=10	Guandi	II, III, Porphyritic basalt, breccia agglomerate lava, relatively intact, sub-blocky, fresh	R_b=90, σ_1=24, σ_3=8
Pubugou	II−III, Granite, relatively intact, slightly weathered−fresh	R_b=100−110, σ_1= 21.1−27.3, σ_3=5−7	Gudi	III, Basalt, hard rock, good integrity, fresh	R_b=60−100, σ_1=9.5−10.53, σ_3=2.5−4.8
Dachaoshan	Mostly II, III−IV, Basalt, volcanic breccia lava, hard, relatively intact, fresh	R_b=85−102, σ_1=13−16.9, σ_3=3−7.2	Hongweiqiao	III, Metamorphic sandstone with a small amount of slate, hard, slightly weathered−fresh	R_b =70−100, σ_1=12.5−17.86, σ_3 =3.5−6.9
Baihetan	II−III, Basalt, breccia lava, intact, slightly weathered	R_b=100−200, σ_1= 19−26, σ_3=6.7−8.7	Huangjinping	II, III, Mostly III, Plagioclase granite, quartz diorite, relatively intact, slightly weathered−fresh	R_b=100−105, σ_1=21−25, σ_3=5.5−6.7
Jiangbian	II, Biotite granite, hard, relatively intact, slightly weathered	R_b=108,σ_1=8.45−18.6, σ_3=−4.89−−8.87	Shuangjiangkou	III, Porphyritic biotite feldspar granite, intact, slightly weathered−fresh	R_b=65−90,σ_1=16−37.82, σ_3=3.14−10.88
Suofengying	II−IV, Limestone, medium-thick layer, massive, slightly weathered	R_b=40−65,σ_1=14, σ_3=2−5	Shuibuya	II−IV, Limestone, sandstone and shale, poor quality, weakly weathered	R_b=20−80,σ_1=6.44−25, σ_3=1.5−4.6
Pingtou	III−IV, Limestone, siltstone, siliceous rock intercalated with dolomite, dolomite, thin to thick	R_b=65−90, σ_1= 11.6−14.27, σ_3=2.4−6.8	Wudongde	II, III, Limestone, dolomite and quartzite, relatively intact, slightly weathered−fresh	R_b=30−50,σ_1=6−12, σ_3=2−4
Xiangjiaba	II, slightly weathered, siltstone, fine sandstone, mudstone, rock mass joints and fissures are relatively developed	R_b=100, σ_1=8.2−12.2, σ_3=3.5−5.1	Yantan	II, III, Diabase, relatively intact and fresh	R_b=100−110,σ_1=9, σ_3=2.5−5
Jiangya	II, Limestone, shale, stone coal seam, relatively intact, hard and fresh	R_b=80−100, σ_1=17.22, σ_3=2.5−3.9	Yangfanggou	II, III, Granodiorite, relatively intact, slightly weathered−fresh	R_b=80−100,σ_1= 12.62−13.04,σ_3=5.08−8.04
Silin	II−IV, Claystone, limestone, shale, medium-thick to thick, karst developed	R_b=80, σ_1=17, σ_3=6	Changheba	Mostly III, II, IV, Granite, sub-blocky, partially inlaid, slightly weathered	R_b=100,σ_1=25.68−31.96, σ_3=10.2−15.6
Ertan	II, Syenite, gabbro, a small amount of altered basalt, good quality	R_b=30, σ_1=18−26, σ_3=4.86−9.36	—	—	—

Note: The values of saturated uniaxial compressive strength, principal stress, and main rock mass information are collected according to representative lithology and surrounding rock grades in each case.

Table 2 Summary of excavation methods and supporting measures of main underground cavern powerhouse

Project name	Excavation method	Support measure	Project name	Excavation method	Support measure
Jinping-I	Planar multi-process, three-dimensional multi-level	Mortar anchor rod and pre-stressed anchor rod, anchor rod spacing and row spacing: 0.6−0.75m; pre-stressed anchor cable, spacing 3−4 m	Dongfeng	Layered excavation	Common mortar anchor rod, prestressed anchor cable with a spacing of 4 m, hanging net, shotcrete
Foziling	Layered excavation	Prestressed and common bolts, 3 m apart	Houziyan	Layered excavation	System anchor rods with a spacing of 1−1.5 m; prestressed anchor cable and steel fiber shotcrete
Longtan	Planar multi-process, three-dimensional multi-level	Prestressed anchor cables with a spacing of 4.5 m×(4.5−6 m) and anchor rods with a spacing of 1.5 m are arranged alternately, shotcrete.	Gongguoqiao	Layered excavation	System anchor rods are staggered with a spacing of 1−1.5 m; prestressed anchor cables with a spacing of 4 m
Dagangshan	Layered excavation	1.2 m spacing between anchor rods and 4.5 m spacing between anchor cables, shotcrete	Manwan	Layered excavation	Anchor rods with a spacing of 1.5 m; prestressed anchor cables with a spacing of 4.5 m; and shotcrete
Jinping-II	Excavation in layers, parallel and cross excavation	The prestressed anchor cables with a spacing of 4.5 m and the anchor rods with a spacing of 1.5 m are arranged at intervals, with shotcrete	Lianghekou	Divide into 9 major layers (including protective layer) and 13 small layers from top to bottom	Bolt support, shotcrete
Laxiwa	Arch first, excavation downward layer by layer, and work on multiple working faces at the same time	Anchor rods with a spacing of 3 m, staggered arrangement, partially prestressed anchor cables	Guandi	Excavation in 11 layers	Systematic anchor rod with a spacing of 1.5 m, and a prestressed anchor cable with a spacing of 4.5 m
Pubugou	Layered excavation	Anchor rods with a spacing of 1.5 m between rows and rods; and anchor cables with a spacing of 4−4.5 m between rows and rods, shotcrete	Gudi	Layered excavation	Anchor rods are arranged at intervals of 1.5 m, shotcrete
Dachaoshan	Planar multi-process, three-dimensional multi-level	Systematic anchor rods with a spacing of 1−1.5 m; anchor cables with a spacing of 4−4.5 m, shotcrete	Hongweiqiao	Excavation in 7 layers from top to bottom	System anchor rods of 3−4 m spacing, hanging nets, shotcrete
Baihetan	Vertical multi-level, planar multi-process, 10 layers from top to bottom	Common mortar anchor rods and pre-stressed anchor rods with a spacing of 1.2 m; pre-stressed anchor cables with a spacing of 3.6−6 m, shotcrete	Huangjinping	Excavation in 10 layers	Inter-row spacing 1−1.5 m system anchor rod spacing arrangement, inter-row spacing 3 m anchor cable, hanging net, shotcrete
Jiangbian	Vertical multi-layered, planar multi-process, and it is divided into 6 layers from top to bottom	Anchor rods with a spacing of 2 m in staggered arrangement, shotcrete	Shuangjiangkou	3 layers, 10 stages of excavation	Systematic anchor rods with a spacing of 1.5 m; anchor cables with a spacing of 4−4.5 m, shotcrete
Suofengying	Three-dimensional multi-level	Anchor rods with a spacing of 1.2 m between rows and anchor rods, prestressed anchor cables, hanging nets, shotcrete	Shuibuya	Layered excavation	Systematic anchor rod, anchor cable, shotcrete
Pingtou	Layered excavation	Rigid support, anchor rods with a spacing of 1.5m; 5 m spacing between prestressed anchor cables	Wudongde	Layered excavation	System anchor rod with a spacing of 2.5 m; pre-stressed anchor cable with a spacing of 3.5 m, spray layer
Xiangjiaba	Layered excavation	Anchor rods with a spacing of 1.5 m, pre-stressed anchor cables and shotcrete with a spacing of 4.5 m.	Yantan	Excavation in layers, the pilot tunnel is 30−50 m ahead, and both sides expand	Systematic anchor rod and mortar anchor rod with a spacing of 1.5m; anchor cables with a spacing of 5 m, with steel mesh and shotcrete
Jiangya	Layered excavation	Anchor rod, hanging net, shotcrete	Yangfanggou	Excavation in 9 layers	Mortar anchor rods with a spacing of 1.5 m; prestressed anchor cables with a spacing of 4.5 m
Silin	Planar multi-process, three-dimensional multi-level, Excavation in 9 layers from top to bottom	Anchor rods with a spacing of 1.2 m, staggered arrangement, prestressed anchor cables with a spacing of 3.6 m	Changheba	Layered excavation from top to bottom	Common mortar anchor rods with a spacing of 1.5 m, prestressed anchor cables with a spacing of 5 m×4.5 m, and shotcrete with netting
Ertan	Excavate the top arch first and excavation downward layer by layer	Systematic grouting anchor rods with a spacing of 1.5 m; prestressed anchor cables with a spacing of 6 m	—	—	—

In the engineering geological evaluation of underground chambers, currently the most widely used indicators are the geological strength index (GSI) in the generalized Hoek-Brown strength criterion and the material constant m_i of intact rock[18]. These two indicators can reflect the lithology of underground cavern, the type of surrounding rock, the weathering characteristics and the degree of structural plane development more accurately. Therefore, this paper introduces the two indicators to reflect the engineering geological characteristics of large underground caverns.

The calculation methods for determining geological strength index (GSI) and material constant m_i of the intact rock are introduced as follows:

(1) Geological Strength Index (GSI)

The value table of geological strength index (GSI) is given in the Hoek-Brown criterion[19]. Due to the strong subjectivity of this method, it is difficult to accurately determine the GSI value. Therefore, many scholars have carried out a lot of research on the quantitative value of geological strength index (GSI). For example, Han[20] introduced the rock mass parameter J_v (joint number/m^3) into geological strength index (GSI) to assess geological characteristics of massive jointed rock mass. Su et al. [21] quantified the rock mass structure and weathering condition factors in the geological strength index (GSI) by introducing the rock-mass block index (RBI) and absolute weathering index (AWI).

This paper uses the method from reference [21] to embed the quantitative indicators of rock mass structure and rock mass weathering conditions into the GSI qualitative value table given by Hoek (RBI corresponds to "structure", AWI corresponds to "surface"), and to obtain quantitative values of geological strength index (GSI). Because the GSI qualitative value table, RBI and AWI specific description are all existing results, they will not be listed here. The specific value method is as follows:

(i) Judging the structure type of rock mass according to the characteristics of surrounding rock and the integrity of rock. Assuming that the rock mass is a layered mosaic structure (30−10), if the expression of rock mass characteristics is vague, take RBI=20; if the description of rock mass characteristics is clear, the RBI value can be reasonably selected in the range of 20−30 or 10−20 according to the description situation and the rule that the better the structure is, the larger the value is.

(ii) Determining the weathering characteristics of rock according to the freshness. Assuming that the rock is in a slightly weathered state (0.90−0.75), the lower the degree of rock alteration, the higher the value in the range of 0.90−0.75. If the degree of alteration is normal, take AWI=0.825.

(iii) Assuming RBI=9 and AWI=0.8, draw a horizontal straight line with RBI=9 and a vertical straight line with AWI=0.8 in the GSI value table given by Hoek. The intersection of the horizontal and vertical straight lines lies at the diagonal line 50−55. And then linearly interpolate between the oblique lines 50−55, the final GSI value is 52.

(2) Material constant m_i of intact rock

The value of the material constant m_i of intact rock can generally use the value table of material constant m_i given by Hoek et al.[19−22]. Considering that this method only gives the interval value of material constant m_i of intact rock, many scholars have proposed some quantitative value methods of m_i, such as:

(i) Estimate the material constant m_i of intact rock using Hoek-Brown strength estimation formula. That is, based on the saturated uniaxial compressive strength R_b, the maximum principal stress σ_1 and the minimum principal stress σ_3, the value of m_i is obtained by Eq. (1) [23]:

$$m_i = \frac{(\sigma_1 - \sigma_3)^2 - R_b^2}{\sigma_3 R_b} \quad (1)$$

(ii) Estimate the material constant m_i of intact rock with the help of the uniaxial compressive strength R_b and the rock tensile strength σ_{tB} (R_b and σ_{tB} are obtained through uniaxial compression test and indirect tensile test)[24]:

$$m_i = 16\sigma_{tB}/R_b - R_b/\sigma_{tB} \quad (2)$$

According to the m_i value table given by Hoek, the m_i value found is a range, which is difficult to obtain a quantitative value. However, in the absence of sufficient geological information, the m_i value calculated by Eqs. (1) and (2) is a specific value. It is difficult to achieve a global description of overall surrounding rock of the cavern. Therefore, this paper uses the following procedure to determine the material constant m_i value of intact rock:

(i) According to the lithology look-up table of the cavern, $m_i \in [a, b]$ is obtained.

(ii) Determine the average saturated uniaxial compressive strength $\bar{R}_b$, the maximum principal stress σ_1 range value $[x_1, x_2]$ and the minimum principal stress σ_3 range value $[y_1, y_2]$ of the cavern, take $\sigma_1 = (x_1 + x_2)/2$, $\sigma_3 = (y_1 + y_2)/2$.

(iii) Substitute $\bar{R}_b$, σ_1 and σ_3 values into Eq. (1) to calculate m_i'. If $m_i' \in [a, b]$, then $m_i = m_i'$; if $m_i' \notin [a, b]$, continue to the next step.

(iv) Because the σ_3 value has a great influence on the m_i value [25], the σ_3 value needs to be adjusted so that the calculated m_i value can fall within the interval $[a, b]$. Keep the values of $\bar{R}_b$ and σ_1 unchanged, take $m_i = a$ and $m_i = b$, respectively, and substitute them into Eq. (1) to calculate $\sigma_3 = y_3$ and y_4.

(v) The intersection of $[y_1, y_2]$ and $[y_3, y_4]$ is $[y_5, y_6]$, then $\sigma_3 = (y_5 + y_6)/2$, and the values of $\bar{R}_b$ and σ_1 are substituted into Eq.(1), and the value of m_i'' is calculated as material constant m_i of the intact rock in the cavern. Among them a, b, x_1, x_2, y_1, y_2, y_3, y_4, y_5 and y_6 are all constants.

In addition, in order to reflect the influence of underground cavern structure size on the surrounding rock deformation, the non-dimensional analysis method is used to select the ratio of the maximum convergent deformation U of the side wall to the height H of the cavern, that is, the relative deformation value U/H of the side wall, for evaluating the magnitude of the deformation value of the surrounding rock of the side wall.

3.2 Surrounding rock deformation and its influence index

Based on the calculation methods of the above-mentioned influence indexes, various index values of the investigated case were calculated, including the strength-to-stress ratio R/σ, the geological strength index (GSI), the material constant m_i of intact rock and the relative deformation value U/H, as provided in Table 3.

In order to analyze the regularity between the surrounding rock deformation of the underground cavern and the individual impact indicators, the relationships between the strength-to-stress ratio R/σ, the geological strength index (GSI), the material constant m_i of the intact rock and the relative deformation value U/H are respectively analyzed based on Table 3, as shown in Figs. 2−4.

Table 3 Influence indexes of surrounding rock deformation

Project name	R/σ	GSI	m_i	$(U/H)/10^{-3}$	Project name	R/σ	GSI	m_i	$(U/H)/10^{-3}$
1 Jinping-I	2.42	33	9.5	1.260	17 Baihetan	3.81	46	22.5	0.660
2 Foziling	32.06	48	28.0	0.075	18 Jiangbian	8.13	42	32.0	1.130
3 Longtan	10.40	38	17.0	0.470	19 Suofeng	3.75	22	12.0	0.950
4 Dagangshan	7.60	42	23.5	0.630	20 Pingtou	5.99	32	12.0	0.880
5 Jinping-II	4.38	38	9.0	0.670	21 Xiangjiaba	10.00	38	17.0	1.500
6 Laxiwa	3.79	36	19.5	0.930	22 Jiangya	5.23	67	12.0	0.980
7 Pubugou	4.55	48	32.0	1.100	23 Silin	4.71	33	8.0	0.440
8 Dachaoshan	6.25	52	22.5	0.440	24 Ertan	1.36	43	27.0	1.990
9 Dongfeng	8.43	42	12.0	1.68	25 Huangjinping	4.78	43	28.5	1.080
10 Houziyan	2.25	25	12.0	2.28	26 Shuangjiangkou	2.88	67	32.0	1.080
11 Gongguoqiao	10.42	42	17.0	1.06	27 Shuibuya	3.20	22	11.7	0.870
12 Manwan	1.67	33	25.0	0.33	28 Wudongde	4.44	43	13.7	0.560
13 Lianghekou	2.63	62	12.0	1.75	29 Yantan	12.22	45	15.0	0.170
14 Guandi	3.75	67	22.5	0.64	30 Yangfanggou	3.51	58	32.0	0.870
15 Gudi	9.50	57	25.0	0.86	31 Changheba	1.91	52	32.0	1.550
16 Hongweiqiao	5.60	57	17.0	0.81					

Note: The values of GSI and m_i are determineded according to the most representative rock mass characteristics in each case.

Among them, figure 2 shows the scatter diagram of the strength-to-stress ratio R/σ and the relative deformation value U/H. It can be seen that the relative deformation value U/H of the research case is more concentrated in the scatter plot, mainly centered in the interval where R/σ is (0,15), and the relatively large value of the deformation mostly appears at the position of the low strength stress ratio. On the overall trend, with the increase of R/σ, U/H shows a rapid decrease trend, indicating that the relative deformation of the underground cavern surrounding rock is closely related to the engineering mechanical properties of the surrounding rock.

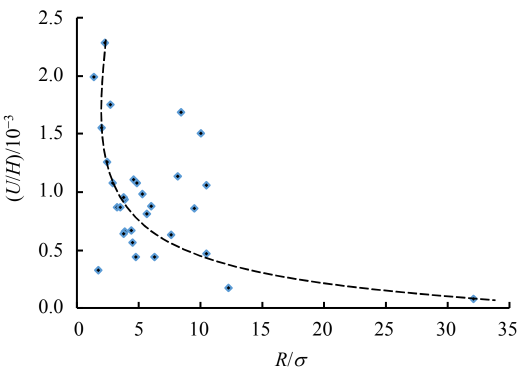

Fig. 2 Scatter plot of R/σ and relative deformation value

Figure 3 plots the relationship between the geological strength index (GSI) and the relative deformation value U/H. It can be observed that most of the U/H in the research cases are in the interval of (30, 60) GSI. It shows that when selecting the site of the underground cavern, the engineering area with better geological conditions is generally selected through detailed geological survey. On the overall trend, as GSI increases, U/H is gradually increasing.

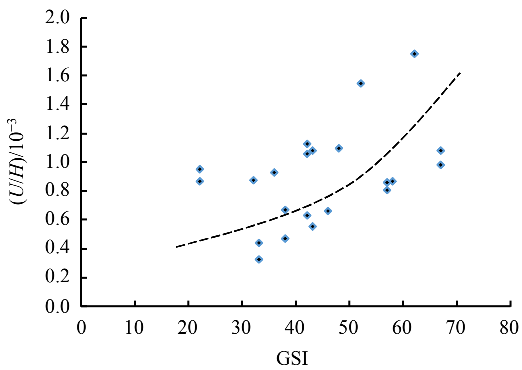

Fig. 3 Scatter plot of GSI and relative deformation value

In addition, the relationship between the material constant m_i and the relative deformation value U/H of intact rock is illustrated in Fig.4. It can be found that U/H in the research case is roughly distributed in the interval where m_i is (5, 35), and the distribution span is relatively large. It shows that the engineering geology in each case is different, and there are many types of surrounding rock lithology. As for the overall trend, U/H increases with m_i, showing an undulating trend.

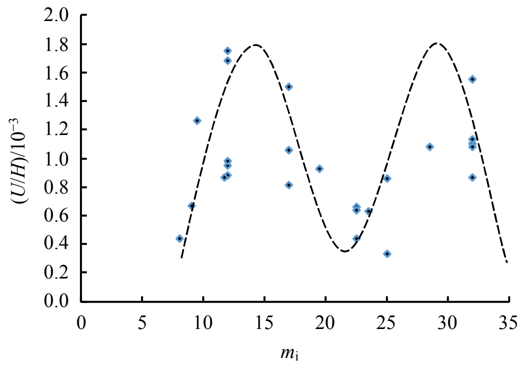

Fig. 4 Scatter plot of m_i and relative deformation value

A comprehensive analysis of Figs. 2 to 4 shows that the strength-to-stress ratio R/σ, geological strength index (GSI) and the material constant m_i of the intact rock in the investigation case all have a certain impact on the relative deformation value U/H of the underground cavern, but the regularity between the above individual influence index and the relative deformation is also more complicated and difficult to describe with a simple function. It should be noted that, in order to study the general trend of GSI, m_i and U/H, in Figs.3 and 4, individual cases with poor regularity are not considered.

3.3 Prediction formula

In order to develop a prediction method for the maximum convergent deformation of the surrounding rock of the side wall of a large underground powerhouse, this paper comprehensively considers the influence of the strength-to-stress ratio R/σ, the geological strength index (GSI) and the material constant m_i of intact rock on the relative deformation value U/H. On the basis of the foregoing research, the relative deformation value U/H of the surrounding rock of the underground cavern side wall and the functional forms of the above 3 influence indexes are constructed, and the Myquart method is used to analyze the constructed data in the global scope of 31 cases of measured data for fitting optimization.

Through a lot of calculation and analysis, and considering the simplicity of the constructed function, the linear superposition function form of U/H and the three indicators（R/σ, GSI and m_i）is expressed as

$$U/H = f_1(R/\sigma) + f_2(\text{GSI}) + f_3(m_i) \tag{3}$$

Finally, based on a large amount of data of the research case, Eq.(3) is repeatedly fitted and optimized using the Myquart method, and the functional form of each individual impact index is selected:

$$f_1(R/\sigma) = P_1 + P_2 \times (R/\sigma) + P_3/(R/\sigma) + P_4 \times (R/\sigma)^2 + P_5/(R/\sigma)^2 + P_6 \times (R/\sigma)^3 + P_7/(R/\sigma)^3 + P_8/(R/\sigma)^4 \tag{4}$$

$$f_2(\text{GSI}) = P_9 \times e^{[P_{10} + P_{11}/(\text{GSI}+P_{12})]} \tag{5}$$

$$f_3(m_i) = P_{13} \times \cos(P_{14} \times m_i + P_{15}) \tag{6}$$

where $f_1(R/\sigma)$ is the influence function of R/σ on U/H; $f_2(\text{GSI})$ is the influence function of GSI on U/H; $f_3(m_i)$ is the influence function of m_i on U/H. P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, P_9 , P_{10}, P_{11}, P_{12}, P_{13}, P_{14} and P_{15} are fitting constants. The values of every parameter are listed in Table 4. The values of above 15 parameters obtained via statistical analysis are universal for all large underground caverns.

In summary, Eqs. (3) to (6) constitute the prediction formula for the maximum convergent deformation of surrounding rock of large underground powerhouse side wall. In order to verify the rationality of the above formula, R/σ, GSI and m_i of the research case in Table 3 are substituted into Eq. (3)−(6), the predicted values of relative surrounding rock deformation value of the research case are calculated and then compare it with the actual measured values of relative deformation values in Table 3 (see Fig. 5).

Table 4 List of fitting constant values

Parameter	Value	Parameter	Value
P_1	−25.005 0	P_9	0.860 0
P_2	4.418 5	P_{10}	1.098 0
P_3	18.755 0	P_{11}	0.156 0
P_4	−0.297 5	P_{12}	−24.382 0
P_5	180.286 5	P_{13}	0.279 0
P_6	5.631×10^{-3}	P_{14}	−0.393 0
P_7	−470.157 0	P_{15}	24.412 0
P_8	323.124 0	—	—

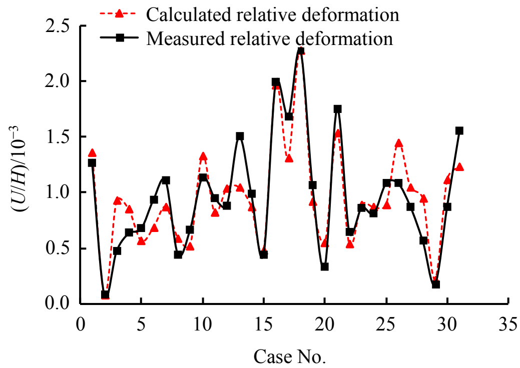

Fig. 5 Relation between calculated value and measured value of relative deformation

It can be seen from the figure that the predicted value of relative deformation in the research case agrees very well with the measured value, and the fitting accuracy R^2 of the two is 0.809, which shows that the prediction formula for the maximum convergent deformation of surrounding rock of the side wall based on the measured data of 31 large underground caverns in China has good reliability.

4 Project verification and application

Based on the statistical analysis of the measured data of 31 large-scale underground chambers in China, this paper studies the three indicators (strength-stress ratio R/σ, geological strength index (GSI) and material constant m_i of intact rock) that affect the deformation of underground cavern surrounding rock. The calculation method is to establish a prediction formula between the relative deformation value U/H of the underground caverns and 3 indicators, which constitutes a multi-index prediction method for the maximum convergence deformation of the large underground powerhouse side wall suitable for the engineering investigation and design stage. In order to test the applicability of the prediction method, the following is the application and verification of the method with Huangdeng Hydropower Station underground powerhouse as the engineering background.

4.1 Project overview

Huangdeng Hydropower Station is located in Lanping

County, Nujiang Prefecture, Yunnan Province. It is the fifth-level hydropower station of cascade hydropower development scheme for Gushui to Miaowei reach in the upperstream of the Lancang River. The main buildings of the water diversion and power generation system of the hydropower station include the main and auxiliary powerhouses, the main transformer room, the tail water surge shaft and other auxiliary chambers. The size of the main and auxiliary powerhouses is 228 m×30.3 m×76.5 m.

The lithology of the underground powerhouse is metavolcanic fine conglomerate, breccia intercalated with metamorphic tuff, and it is slightly weathered. The rock mass has a blocky and sub-blocky structure. The surrounding rock types are Class II and III. The maximum principal stress in the site area is approximately −10 to −16 MPa, the intermediate principal stress is approximately −4 to −9 MPa, and the minimum principal stress is approximately −2 to −5 MPa. Under uniaxial conditions, the average strength of metamorphic volcanic breccia is 87.49 MPa, metamorphic volcanic tuff is 113.96 MPa and metamorphic volcanic conglomerate is 123.1 MPa. As of May 2016, the largest deformation of the surrounding rock is in the middle of upstream side wall of the plant, about 55 mm.

4.2 Forecast and analysis of deformation

First, based on the geological information of Huangdeng Hydropower Station, three indicators (R/σ, GSI, and m_i) that affect the deformation of surrounding rock are determined as follows:

R/σ: R_b takes the average uniaxial saturated compressive strength of 3 types of lithology $\bar{R}_b$=(87.49+113.96+123.1)/3≈108.183 MPa, and σ_1 takes the maximum value of the interval [−16,−10] σ_1=16 MPa, then $R/\sigma=\bar{R}_b/\sigma_1\approx 6.761$.

GSI: The rock mass has a block structure and a sub-block structure. The surrounding rocks are classified into Class II and III, which belong to the layered mosaic structure (30−10), and RBI=20. The rock is slightly weathered, belonging to a slightly weathered state (0.90−0.75), take AWI=0.825. Draw a horizontal straight line with RBI=20 and a vertical straight line with AWI=0.825 in the GSI value table given by Hoek, intersection of the horizontal and vertical straight lines is between the diagonal 60−65, and then linear interpolate between the oblique lines 60−65, and the final GSI value is 62.

m_i: The lithology is metamorphic volcanic fine conglomerate, breccia with metamorphic tuff. Checking the value table of m_i given by Hoek, $m_i\in[18, 24]$;

$\bar{R}_b$=108.183 MPa, $\sigma_1\in[-16,-10]$ MPa, $\sigma_3\in[-5,-2]$ MPa, take σ_1=−13 MPa, σ_3=−3.5MPa. By substituting the $\bar{R}_b$, σ_1 and σ_3 values into Eq. (1), we get $m_i'\approx 30.671\notin[18, 24]$, so the σ_3 value needs to be adjusted. The $\bar{R}_b$ and σ_1 value remains unchanged, substituting m_i=18 and m_i= 24 into Eq. (1), respectively, results in $\sigma_3\approx$−5.985 and −4.480 MPa. Intersection of interval [−5, −2] and [−5.985, −4.480] is [−5, −4.480], then σ_3=−4.740 MPa, and substituting the values of $\bar{R}_b$ and σ_1 into Eq. (1) yields $m_i''\approx 22.690\in[18, 24]$, and finally m_i=22.690.

And then determine the ratio of the maximum deformation monitoring value of the cavern side wall of Huangdeng Hydropower Station to the height of the cavern, that is, the relative deformation value U/H of the side wall.

U/H (monitoring value): Maximum deformation of surrounding rock U=55 mm, cavern height H=76.5 m, then $U/H=7.190\times10^{-3}$.

Finally, substituting the values of R/σ, GSI and m_i into Eqs. (4)−(6) respectively, leads to $f_1(R/\sigma)\approx-1.635$, $f_2(\text{GSI})\approx 2.589$ and $f_3(m_i)\approx -0.273$; and substituting $f_1(R/\sigma)$, f_2(GSI) and $f_3(m_i)$ into Eq. (3) results in U/H= 0.681. Thus, the predicted deformation value of the cavern surrounding rock 52.097 mm is obtained. Comparing with the actual deformation monitoring value (55 mm) the relative error between the two is (55−52.097)/55×100%≈5.278%<15%. The calculation result of the surrounding rock deformation prediction formula is close to the actual deformation value, and the prediction accuracy is high.

The application case demonstrates that the deformation prediction formula proposed in this paper can more accurately predict the maximum convergent deformation of surrounding rock of the underground powerhouse side wall, and the prediction accuracy is high, which meets the actual needs of the project.

5 Conclusion

Based on the statistical analysis of the measured data of 31 large-scale underground chambers in China, this paper proposes a multi-index prediction method for the maximum convergent deformation of the large-scale underground powerhouse side wall in the engineering investigation and design stage.

(1) Three indicators affecting the deformation of surrounding rock (strength-stress ratio R/σ, geological strength index (GSI), material constant m_i of intact rock) and corresponding calculation methods are studied. The non-dimensional analysis method is used and the ratio of the maximum convergent deformation to the height of the cavern (relative deformation value U/H) is used to evaluate the magnitude of the surrounding rock deformation.

(2) The functional relationship between the relative deformation value U/H of the surrounding rock of the side wall of the underground chamber and three indexes (strength stress ratio R/σ, geological strength index (GSI) and material constant m_i of intact rock) is established .

(3) It constitutes a method for predicting the maximum convergent deformation of the surrounding rock of a large-scale underground powerhouse side wall based on multiple indicators. Relying on the engineering background of Huangdeng Hydropower Station, the prediction method is applied and verified.

(4) The method for predicting the maximum convergent deformation proposed in this paper can reliably predict the deformation of the side wall surrounding rock in the engineering survey and design stage, and can provide important support for the scientific design and safe construction of large underground caverns. It needs to be explained that the accuracy of the prediction method proposed in this paper to predict the maximum convergent deformation of the side wall surrounding rock depends on the detailed and accurate geological evaluation information, and there is still the possibility of optimization in the accurate geological evaluation, and further research is needed.

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