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Advances in stability analysis and optimization design of large underground caverns under high geostress condition

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ABSTRACT

The demand for underground space and sustainable energy has driven the need for underground structures. Large underground caverns, being an underground structure carrier, offers a feasible solution. However, the stability analysis and optimization design of large underground caverns is always a great challenge due to the high geostress, complicated rock condition, and high sidewalls and large spans in size. By collecting and reviewing a large amount of relevant research literature from 1970 to 2023, the efforts on the advances in stability analysis methods and optimization design of large underground caverns are described, then the research trends in this field through keywords were found and typical deformation and break modes of large underground caverns with high geostress are summarized. The review reveals that stability analysis and optimization are the recent active research topics. There are seven typical deformation and break modes of large underground caverns under high geostress, four stability analysis methods and four theories of optimization design of large underground caverns. With the progress of science and technology and society, intelligent design, mechanized construction and greening construction are the development trend in this field. The research results can provide a constructive reference for the stability analysis and optimization design of large underground caverns under high geostress.

1. Introduction

In order to make efficient use of water and meet the energy demand, a large number of large-scale underground projects (Fig. 1) containing underground caverns have been constructed in China [1–7]. In generally, the surrounding rock in underground caverns is prone to appearing unfavorable brittle failure behavior [8], e.g., rockburst, block falling, spalling, threatening the safety of on-site builders and equipment. In addition, due to the influence of topography and geomorphology, a large number of hydropower stations have been constructed in the southwest high mountain deep valleys areas, such as Longtan, Pangshui, Jinping II, Xiangjiaba, and Wudongde, as well as Shuangjiangkou and Xulong hydropower stations that are under construction (Table 1). These underground caverns often have large sizes, high sidewalls, complex geological, and obvious cavern group effect and size effect, which lead to outstanding problems of peripheral rock deformation and cracking during the construction period. Furthermore, the excavating effects of multiple large caverns often increase the difficulty of both understanding the failure mechanisms of hard rock and assessing the stability of the entire cavern system. In recent years, there are more and more studies on the stability analysis and optimization design of large underground caverns under high geostress. Therefore, reviewing the research trends in this field is of important theoretical and practical significance.

Many scholars have summarized the existing research results and the key scientific issues [7–10], and summarized the following characteristics: (1) The three-dimensional stratum and geological conditions around underground caverns are complex. (2) It has the high initial stress of surrounding rock and the stress path in the construction process is changeable. (3) There are various forms of instability events surrounding the underground caverns. Some geotechnical engineering practices indicate that the most instability events of the surrounding rock under high geostress are often caused by weakened geotechnical structures (e.g. joints, weakened interlayer shear belt, faults)[9]. The mechanical response mechanism of the unloading process of the surrounding rock of the cave chamber excavated in the rock mass

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containing the structural surface is very complicated, and its nature is the process of constant adjustment of the rock stress field. Especially under high geostress, this unloading process is very likely to cause the cracking, spalling, shearing, collapse of the surrounding rock [10].

Over the last decades, several analytical, field tests and numerical analysis have been used to study the stability of large underground caverns under high geostress. Ma et al.[11] studied the stability of the surrounding rock under different excavation schemes, and obtained the cracking process of surrounding rock under different excavation schemes, the depth of crack expansion and the vertical displacement of the arch and bottom floor. Jiang et al.[12] established a closed stability optimization design and corresponding technical flowchart of large underground caverns, and presented an improved feedback analysis model. Wang et al.[13] takes the Baihetan underground powerhouse as a case study, revealed the multi-cavern effect between adjacent caverns through on-site experiments, and analyzed the stress evolution induced by excavation and the failure mechanism. Kumar et al. [14] used a real-time remote microseismic monitoring network to research the stability of the surrounding rock of underground caverns. Menéndez et al. [15] combined with the fluid dynamics and geomechanical behavior to study the stability of the powerhouse cavern and the effect of air pressure on the tunnels and shafts during the operation phase of the turbine. Although there are many studies about the stability analysis of large underground caverns [16–20], almost all studies only focus on a specific practical project. None of the review articles on stability analysis and optimization design of large underground caverns under high geostress.

In this paper, science citation index (SCI) articles in this field more than 50 years were analyzed to research the stability analysis and optimization design of large underground caverns under high geostress. This paper, firstly, systematically summarizes the typical deformation and break modes of large underground caverns under high geostress, then studies the four stability analysis methods of surrounding rock and relevant optimization design theory of large underground caverns. In Section 6, the design method for dynamic feedback analysis and optimization are reviewed. Finally, the development trend and conclusions are drawn in Sections 7 and 8, respectively. The aim of the review is to address the following questions: (1) What is the current research status and hot research issue in the field? (2) What are the typical deformation and break modes of large underground caverns under high geostress? (3) What are the existing stability analysis methods and optimization design of large underground caverns under high geostress? (4) What are the development trends in this field?

2. Bibliometric analysis

2.1. Countries and published SCI articles

In recent decades, the stability analysis and optimization design of large underground caverns under high geostress have attracted great attention worldwide. According to our search strategy, we detected the articles and reviews by searching for keywords of "hydropower station / hydropower project and high geostress / high geostress / high crustal stress / high in-situ stress / high ground stress / underground opening" in the Engineering Village database, whose language was English. A total of 1150 SCI articles were left. Since 1970, the research has been increasing rapidly, from 1 article in 1970–103 articles in 2023(Fig. 2).

The output of SCI articles in this field dates back to 1970, and the number of SCI articles published in 1970 and 2020 can be divided into three time periods: (1) The embryonic period (before 1990). The number of SCI articles in this field was limited, with an average of less than 10 articles per year. (2) The period of steady growth (1990–2010). The oil crisis in 1990 promoted the development utilization of water resources and related research fields, and the articles more than 10 articles per year. (3) Rapid growth period (2010–2020). From 2010–2020, the research of underground caverns has been increasing rapidly, and from 2020 onwards, the number of SCI articles exceeded 100 per year. As the global carbon neutrality goal continues to advance, it is initially expected that the number of related research achievements in this field will remain at a high level in the recent years.

The top 10 countries in terms of the number of SCI articles were China, the United States, Canada, India, Japan, Australia, Iran, the United Kingdom, Turkey, and France, shown in Fig. 3. China is far ahead with 635 SCI articles. China's earliest article in this field dates back to 1985, and has developed rapidly in recent years, surpassing the United States in terms of the number of SCI articles since 2004, and has remained the first in the world. Furthermore, the collaboration between authors from different countries was performed in Fig. 4. The countries that work most closely with others are China, the United States, Australia and France. Meanwhile, some countries, such as Israel, Thailand, and Singapore have little cooperation.

2.2. Institutes and authors

As the main place and main body of scientific research activities, research institutions are the basic elements that determine the scientific research level of a country. Through the comparative analysis of the top 8 institutions in the world in terms of the number of SCI articles in the field (Table 2), it can be seen that the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan ranks first with 114 publications, which is the research institution with the largest number of publications in the world in this field, and ranks first in terms of H-index and the mean citations of the SCI articles, which is of high influence in this field, and shows a good research foundation and has achieved rich research results in this field. In addition, Sichuan University, Wuhan University, Shandong University and Northeastern University show high research activity and great influence in this field. The collaboration

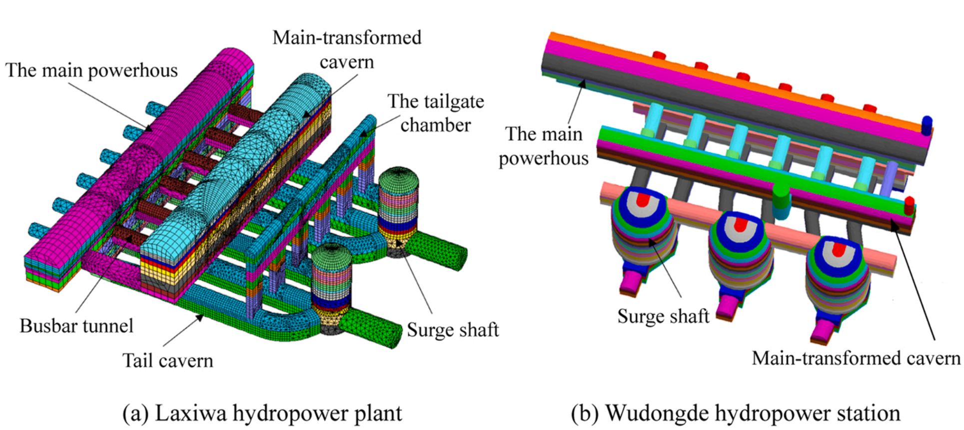

Fig. 1. Typical large-scale hydropower station projects[7].

network between the institutions is shown in Fig. 5. Among the universities and institutions, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan publish the highest number of SCI articles. Overall, there is close cooperation between Sichuan University, Wuhan University, Shandong University and Northeastern University.

Fig. 6 shows the collaboration between the authors. Research has found that academician Feng from Northeastern University, Jiang, Xu and Sheng from Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Dai and Xu from Sichuan University, Xiao and Zhou from Wuhan University, Academician Li from Shandong University, Xu from Hohai University, Li from Wuhan University of Technology, Tang from Dalian University of Technology, Zhou from Chongqing University formed the key intermediaries in the authors' collaborative network.

2.3. Keywords and method

The analysis of the frequency of keyword occurrence can reflect the development and evolution of the posture of the discipline, in order to reveal the research hot spots and research trends of the field in recent years, the articles in the field were analyzed through visual analysis. The SCI literature data were imported into the visualization software VOSviewer to construct the keyword co-occurrence network and carry out the clustering analysis (Fig. 7).

Among them, the different colors of the nodes represent that they belong to different clusters, which can be used to identify the main research direction of the field. It is found that the research topics in the field present four research clusters: a. Stability analysis, rockburst monitoring and mechanisms (yellow). b. Theory of intrinsic theory and modelling, multiparametric studies of mechanical behaviour such as

Table 1
Typical existing and under construction hydropower stations.

Name of hydropower station	Construction time	Installed capacity (MW)	Single-unit capacity× number / (MW× Unit)	Size(length× width× height)/m	Rock classification	Buried depth/m	Major principal stress/MPa
Wujiangdu	1970	1280	5×250+1×30	——	Shale	——	——
Gezhouba Water Control Project	1970	2715	——	——	Sandstone, siltstone and conglomerates	——	——
Baishan	1975	1500	300×5	110×26×149.5	——	90	——
Longyangxia	1976	1280	320×4	396×80×178	Granite	——	——
Lubuge	1982	600	150×4	217.17×10×1138	Sandstone	——	——
Shuikou	1987	1400	200×7	——	——	——	——
Ertan	1991	3300	550×6	280.3×30.7×65.3	Syenite and basalt	——	——
Dachaoshan	1992	1350	225×6	234×26.4×63	Basalt	——	——
Three Gorges	1994	4200	700×6	311.3×32.6×87.30	Granite	77–86	——
Lijiaxia	1995	2000	400×5	414.39×45×175	Red sandstone	——	——
Xiaolangdi	1997	1200	300×4	251.5×26.2×61.44	Sandstone and clayrock	70–100	——
Mianhuatan	1998	600	150×4	129.5×21.9×52.1	Granite	70–140	6.8
Longtan	2001	6300	700×9	388.5×30.3×74.5	Sandstone and argillite	120–240	——
Baise	2001	——	——	147 ×18.8×49.0	Diabase	——	——
Shuibuya	2002	1600	400×4	168.5×23.0×65.4	Limestone and shale	——	——
Xiaowan	2002	4200	700×6	298.4×30.6×79.3	Gneiss	——	——
Goupitan	2003	3600	600×6	230.4×27.0×75.3	Limestone	——	——
Pubugou	2004	3300	550×6	294.1×30.7×70.1	Granite	220–360	21.1–27.3
Pengshui	2005	1750	350×5	252×30×68.5	Limestone and shale	130–200	≈10
Jinping I	2005	3600	600×6	277×29.6×68.8	Marble	110–380	21.7–35.7
Xiluodu	2005	13860	770×18	L:439.74×31.9×75.6 R:443.34×31.9×75.6	Basalt	300–480	18–20
Dagangshan	2005	2600	650×4	226.5×30.8×73.7	Granite	500–600	——
Name of hydropower station	Construction time	Installed capacity (MW)	Single-unit capacity× number / (MW× Unit)	Size(length× width× height)/m	Rock classification	Buried depth/m	Major principal stress/MPa
Xiangjiaba	2006	3200	800×4	255.4×33.4×85.2	Sandstone and few mudstone	——	——
Silin	2006	1050	262.5×4	177.8×27.0×73.5	Limestone	——	——
Laxiwa	2006	4200	700×6	311.7×30.0×73.8	Granite	225–429	−22∼−29
Guandi	2007	2400	600×4	243.4×31.1×76.3	Basalt	200–400	25.0–35.17
Nuozhadu	2007	5850	650×9	418×29×79.6	Granite	180	
Jinping II	2007	4800	600×8	352.4×28.3×72.2	Marble	2525	15.1–23
Houziyan	2011	1700	425×4	219.5×29.2×68.7	——	380	21.53–36.43
Changheba	2011	2600	650×4	228.8×30.8×73.35	Granite	285–480	25.68–31. 96
Lianghekou	2014	3000	500×6	275.9×28.4×66.8	Light Metamorphic and siltstone	400–450	30.44
Wudongde	2015	10200	8500×12	333×30.5×89.8	Rock-like	——	9.7
Shuangjiangkou	2015	2000	500×4	219.48×28.3×68.32	Granite	320–500	16–38
Yangfanggou	2015	1500	375×4	230×30×75.57	Granodiorite	——	12.62–13.04
Maerdang	2016	2320	550×4+120	242.6×29.30×74.10	——	≈200	——
Baihetan	2017	12000	750×16	439×32.2×78.5 439×29×78.5	Basalt	——	22–26
Yebatan	2017	2240	510×4+200	246.8 ×30 ×67	Quartz diorite	220	37.57
Bala	2018	720	240×3	——	Granite	230	——
Jinchuan	2019	860	——	183.5×25.8×65.25	Sandstone, slate and phyllite	90–200	5.81–8.31
Yingliangbao	2019	1200	——	229.12×27.40×63.05	Diorite and granite	400	——
Kala	2021	1080	——	219.5×27.6×75.77	Slate	122–305	11.44
Xulong	2022	2400	600×4	——	——	——	——

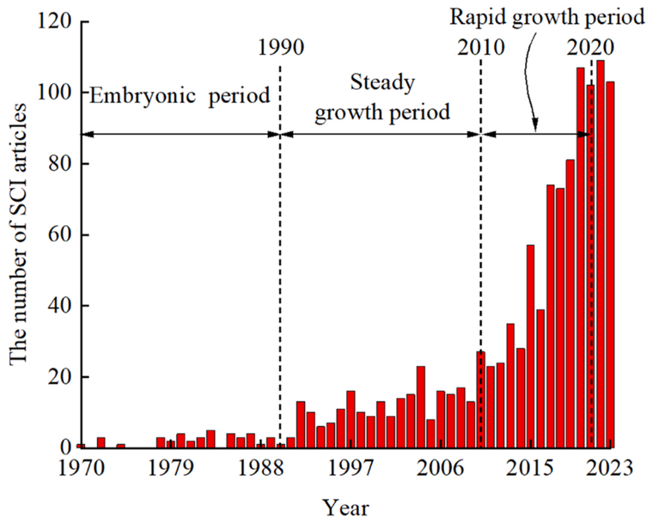

Fig. 2. Annual publication curve.

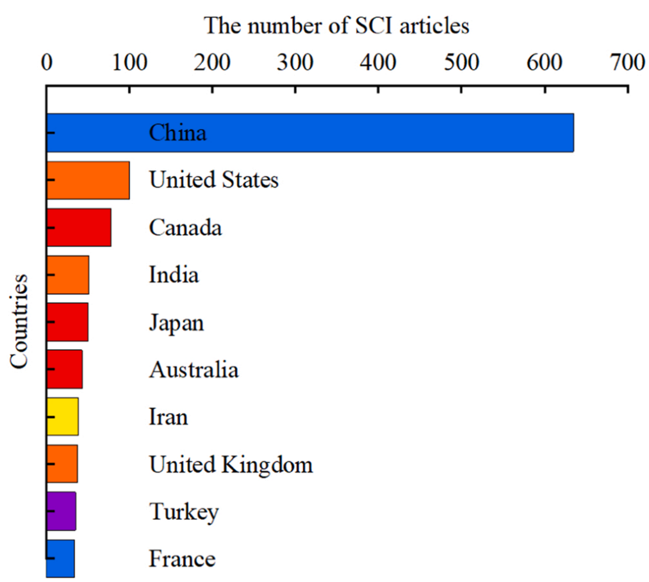

Fig. 3. Top 10 countries in terms of the number of SCI articles in this fields.

strength, inverse analysis and other theories (red). c. Evolution of deformation, failure and instability processes (blue). d. Rock failure mechanisms, mechanical behaviour during excavation (green). Table 3 lists the top 6 keywords, and the top keywords with the highest co-occurrence frequency including stability-microseismic monitoring, rock mass-underground cavern, failure-deformation, numerical simulation-damage.

The cooccurrence density view of keywords is shown in Fig. 8. The density of each point depends on the number of elements in the surrounding area and the importance of these elements. The lower the density the closer to the blue-green colour. Fig. 8 shows the top 10 cooccurrence hot keywords are: stability, underground cavern, deformation, numerical simulation, rock mass, model, mechanisms, energy, prediction, failure. It can be seen that the stability of underground caverns, the mechanical properties of the rock mass, the study of numerical simulation methods are hot research issues in the field.

According to the bibliometric research, China continues to lead the globe in this field. The Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, was the most productive institution for highly published SCI articles. The country with the highest number of

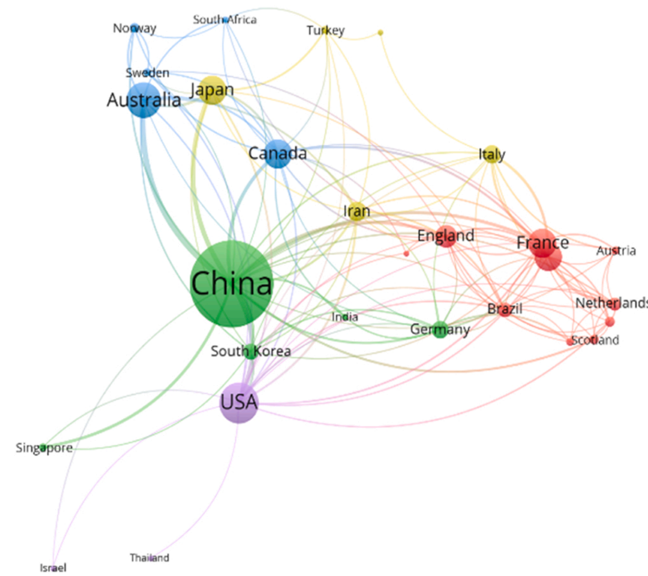

Fig. 4. The collaboration between the authors.

Table 2
Publications of top10 institutions.

Institution	Publications	Total citations	Mean citations	H-index
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan	114	2853	25.03	33
Sichuan University	76	1688	22.21	25
Wuhan University	66	1171	17.74	20
Shandong University	54	1308	24.22	20
Northeastern University	44	1960	44.55	17
China University of Mining and Technology	28	374	13.36	11
Hohai University	28	238	8.5	7
Wuhan University of Technology	25	227	9.08	9

articles is China, the United States ranked second, and Canada ranked third. The scholarly institutions with the most impact in this area include the Institute of Rock and Soil Mechanics, Wuhan, Wuhan University and Shandong University. The author with the most published SCI articles is Academician Feng from Northeastern University, China. Jiang from Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China and Xu from Sichuan University, China ranked second. Stability analysis and optimization design comprise the future research directions and potential topic hot spots for large underground caverns.

3. Typical deformation and break modes of large underground caverns under high geostress

Back analysis of engineering practice has indicated that many underground caverns accidents are related to the high geostress during excavation [8]. By using bibliometric analysis, the typical deformation and break modes of large underground caverns under high geostress can be expressed as follows:

(1) Rockburst (Fig. 9). Under high geostress, the rockburst induced by excavation causes stress redistribution in the surrounding rock, the surrounding rock cracks and generates new cracks under the action of secondary stress. With the expansion of the new cracks, penetration, which result in rockburst failure ultimately.

(2) Spalling and falling (Fig. 10). It is a common macroscopic failure of surrounding rock is the result of initiation, expansion, coalescence or

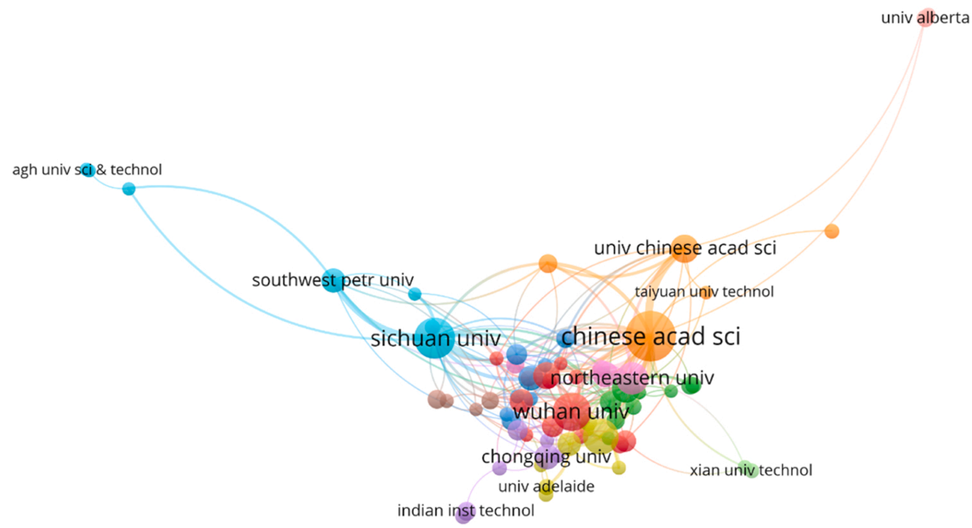

Fig. 5. The collaboration between the institutions.

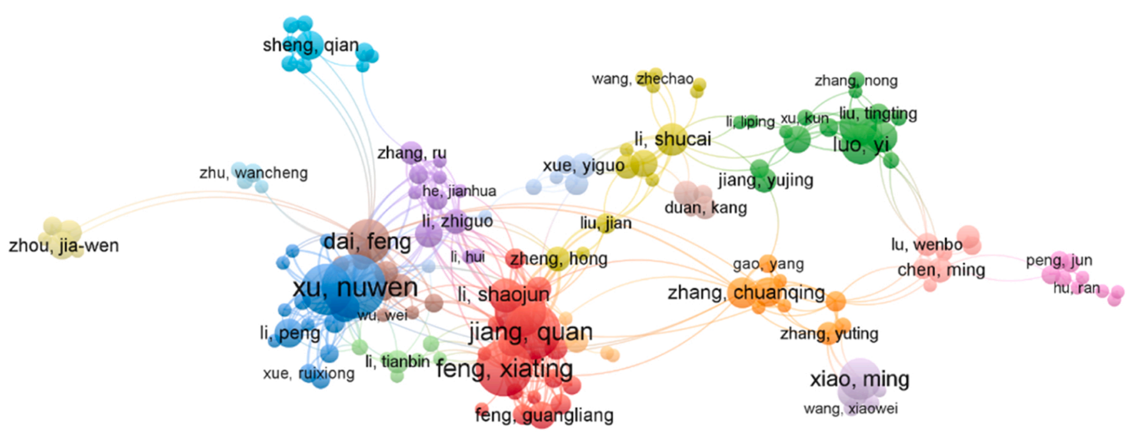

Fig. 6. The collaboration between the authors.

penetration of fractures inside rock masses, has the characteristics of suddenness and destructiveness.

(3) Time-dependent deformation of rock mass, which is considered as the gradual cracking and deformation of rock failure. During the excavation of Jinping I underground powerhouse, the surrounding rock of the lateral arch at the downstream of the powerhouse began to show aging fracture after 2 years of excavation, and a deep fracture of more than 10 m appeared (Fig. 11).

(4) Relaxation failure behavior of surrounding jointed / fractured rock. The diversion tunnel on the right bank of Baihetan has a large depth and a wide range of relaxation failure behavior of the columnar joint rock mass (Fig. 12), which results in the increase of surrounding rock support cost and the lag of construction progress.

(5) Shear deformation of weak fault / interlayer / dislocation zone (Fig. 13). The middle wall between Jinping II underground powerhouse and main-transformed cavern is affected by the fault, and the local surrounding rock occurred large shear deformation, which resulted in the bolt breaking.

(6) The expansion and relaxation of rock fractures (Fig. 14). The excavation of an underground cavern by drilling and blasting generally results in the formation of a zone of rock failure around the area. This zone affects the mechanical behavior of the surrounding rock masses in the construction area, thereby reducing the stability and safety factor, and increasing the probability of structural deformation and failure.

(7) Collapse failure. The surrounding rock of Kunyang Phosphate's No.2 Mine is mainly dolomite, and the surrounding rock at the top is extremely broken and severely weathered. The surrounding rock at the middle and lower part of the roadway contains a lot of soil, so it has no self-stabilizing ability after excavation, and collapses (Fig. 15). This kind of failure can also be observed in the Wudongde underground caverns.

4. Advances in stability analysis methods

4.1. Engineering analogy method

Engineering analogy method is a method that refers to the reference to the geological conditions, rock mass characteristics, support design options and on-site monitoring data of similar projects that have been constructed, and conduct a comprehensive comparative analysis with the proposed project [23]. At present, the common engineering analogy methods in the stability analysis of the surrounding rock include the core quality index method (RQD) [24], HC classification method [25], Q-system classification [26], GSI classification [27], and RMI classification [28,29]. With the accumulation of engineering analogous design and construction data, the improvement of monitoring technology and equipment, and feedback analysis experience and the increasing improvement of research and analysis methods, a variety of new empirical analysis methods of surrounding rock stability such as automated monitoring system, safety diagnostic system and expert system for cave chamber surrounding rock stability have been applied.

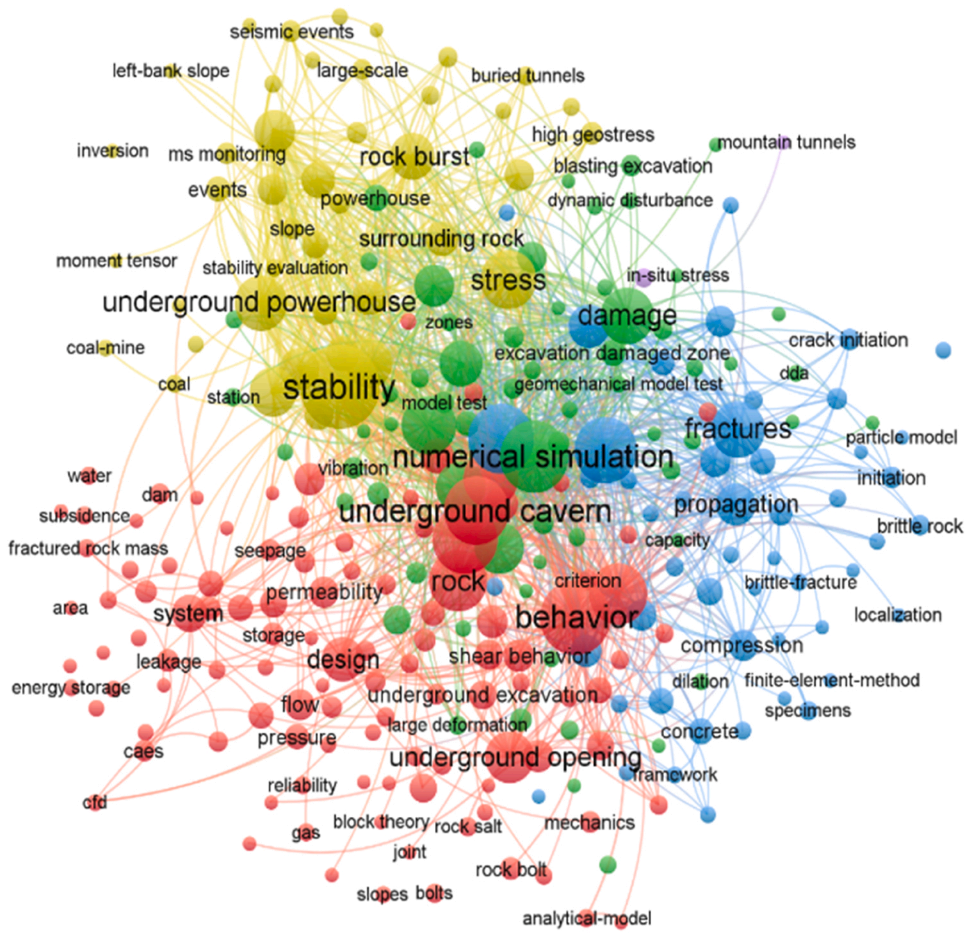

Fig. 7. Co-occurrence map of keywords.

Table 3
Top 6 keywords in the SCI articles.

Yellow	Red	Blue	Green
stability-microseismic monitoring	rock mass-underground cavern	failure-deformation	numerical simulation-damage
stress-stability	model-rock	deformation-evolution	excavation-damage large deformation
mechnism-stress	behavior-design	fracture-crack initiation	masses- simulation
rockburst-microseismic monitoring	strength-rock	evolution-failure	displacement-evolution
microseismic monitoring-early warning	design-back analysis	acoustic emission	failure mechanism-excavation
surrounding rock-stability	parameters-design	propagation-crack initiation	damage-blasting excavation

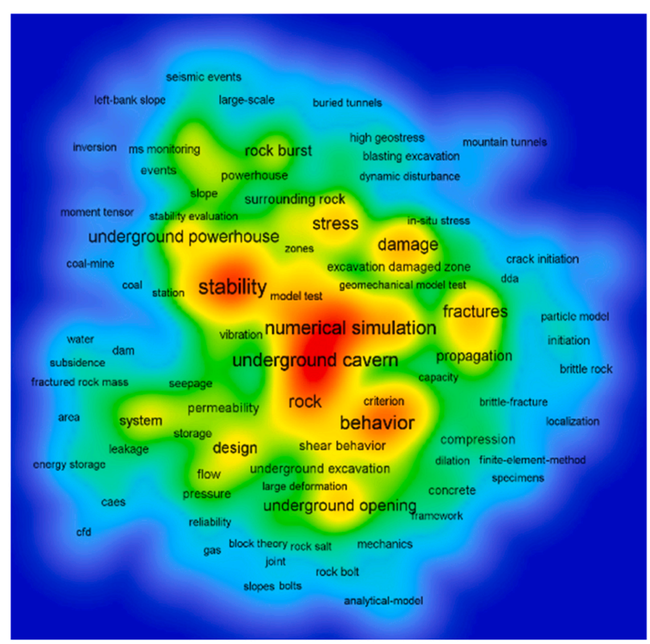

Fig. 8. Cooccurrence density view of keywords.

4.2. *Theoretical analysis methods*

In this study, the common theoretical analysis methods in the stability analysis of underground cavern surrounding rock mainly include block theory, loosening circle theory, reliability analysis method, rock mechanics analysis method, mutation theory and so on. Block theory is an effective method suitable for stability analysis of engineering geotechnical bodies proposed by Shi et al.[30], which has been widely emphasized by scholars after the theory was proposed, and the block theory was firstly introduced to China by Liu et al.[31], who made a systematic and comprehensive introduction. Zhu et al. [32] established a multi-factor and multi-indicator judgment method for the seismic stability analysis of the surrounding rocks of large underground cavern groups based on the block theory and Newmark method. Han et al. [33]

Fig. 9. Rockburst [3].

Fig. 10. Block falling[7].

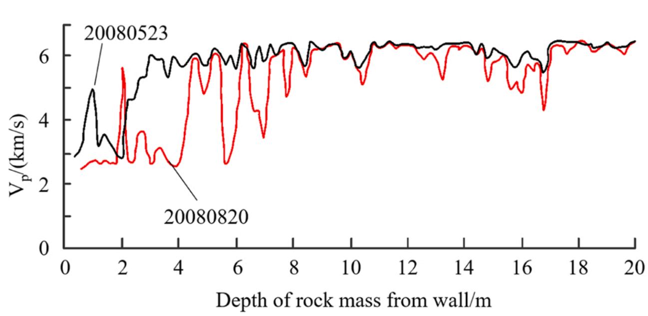

Fig. 11. The time-dependent fracturing of the surrounding rock for underground powerhouse of Jinping I hydropower station[7].

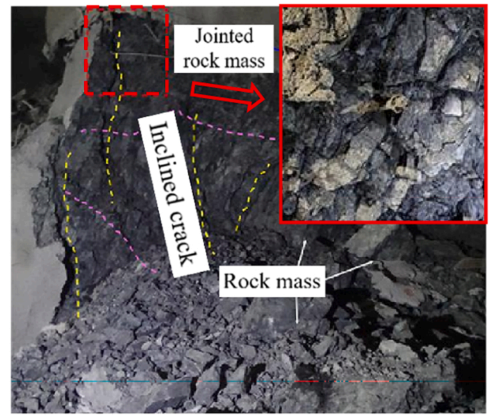

Fig. 12. The relaxation failure behavior of the joint rock mass for Baihetan hydropower station[7].

Fig. 13. The local surrounding rock occurred shear deformation of the middle wall between Jinping II underground powerhouse [7].

proposed a block theory based on the complex fault structure to accurate prediction of the location of the dangerous block. Jia et al. [34] proposed an extended method combining the traditional key block theory method with the force transfer algorithm, which takes into account the interaction between the internal blocks.

However, the above block stability analysis method adopts many assumptions in calculating the safety coefficient of critical blocks, and the consideration of the factors affecting the block stability is not sufficient, which has certain limitations in the study of the block stability of cave chambers under complex geological conditions.

In order to overcome the shortcomings of conventional block stability analysis methods in application, Gong et al.[35] conducted a quantitatively evaluated the block stability by numerical simulation methods. Although the above analytical methods can obtain better computational results under some specific conditions, when describing the complex geological conditions, it will be exceptionally difficult to establish a suitable mathematical or numerical model, and sometimes some simplified or approximate methods have to be adopted to deal with the problem, so the reasonableness of the computational results still needs to be verified.

The theory of loose circle support was proposed by Dong et al.[36] in the early 1990s for spray anchor support of underground engineering. The loose and broken phenomenon of tunnel surrounding rock has been researched in foreign countries earlier [37], but there has been no clear concept of surrounding rock loose circle and systematic loose circle support theory. As early as the 1970s, Japanese scholars Ikeda and Kazuhiko used modern acoustic measurement technology for the first time on-site measurement of the surrounding rock fragmentation zone, proving the fact that the surrounding rock fragmentation zone exists

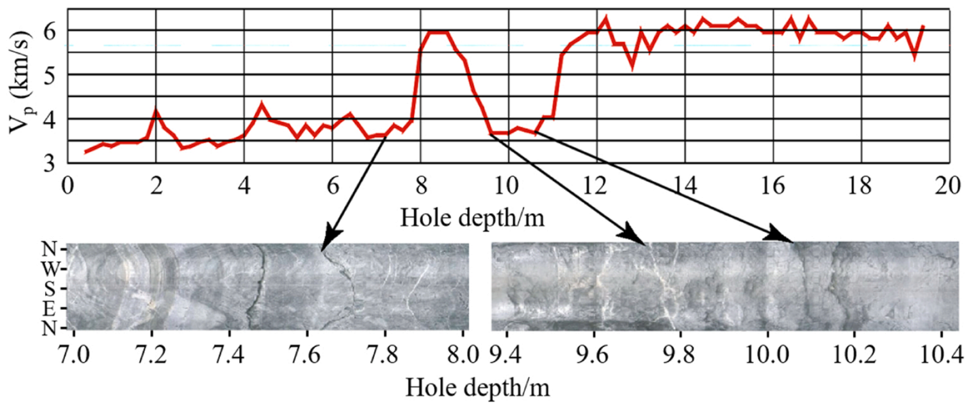

Fig. 14. Drilling panoramic image of the fractures in the deep surrounding rock [21].

Fig. 15. Collapse failure in the underground caverns [22].

objectively in the surrounding rock. And then established a functional relationship between the thickness of the surrounding rock fragmentation zone and the wave velocity of the rock mass, the span of the cave chamber, and the height of the cave chamber can be obtained by Eq. (1).

$$R = 0.0015(D + h)\left(6.0 - \frac{V}{\overline{V}}\right)^2 \quad (1)$$

where R respects thickness of loosening ring, D respects the span of the cavern, h respects the chamber height, V respects the elastic wave velocity of the rock mass, $\overline{V}$ respects the elastic wave velocity in rock specimens.

Nevertheless, the theory of loosening circle support is still half experience and half theory. For the weak rock mass, the joints are extremely developed, especially when the weak rock mass contains different degrees of clay nature expansion minerals, and it is difficult to clearly determine the scope of the loosening circle through the acoustic wave test due to there being fewer studies on the displacement field and stress field evolution law of the loosening circle.

Reliability analysis method is a structural reliability analysis method based on probability theory and mathematical statistics, which fully considers the uncertainty of design parameters. Its main idea is: first of all, the uncertainty of various loading and resistance factors in the engineering structure is quantitatively described by a probabilistic model, and then the structural function is established to judge the actual state of the structure when the variables take different values, and then the probability of structural failure is finally calculated to reflect the degree of structural safety and reliability [38]. The main methods for solving the reliability are direct integration method, Monte Carlo simulation [39,40], stochastic finite element method, approximation methods such as method of moments [41] and indirect methods such as response surface method [42,43].

Rock mechanics analysis (RMA) is a method that uses elastic, elastoplastic and visco-elastic rock mechanics to solve for the stresses and deformations in the surrounding rock of underground chambers. The rock mechanics analysis method has the advantages of high accuracy and speed, but it is no longer suitable when the rock mass exceeds the peak stress and ultimate strain and enters a state of strain-slip and tensile fracture [44]. In addition, due to the many assumptions of the rock mechanics analysis method (such as lithological homogeneity, concrete spray layer closure, etc.), and the geological data can not cover all the geological structural surfaces, so it is not possible to completely consider the effect of weak surface cutting rock mass and other calculation conditions, which limits its application in practical engineering problems. However, the method of rock mechanics analysis can qualitatively grasp some trend laws of surrounding rock deformation and damage, which is of certain guiding significance for engineering practice.

The mutation theory was first proposed by French scientist Thom [45] in 1972. After that, Zeeman [46] further developed it. The theory takes the system potential function as the object of study, uses the mathematical theories such as singularity theory and stability theory to study the mutation manifolds and bifurcation sets of the system potential function, determines the state to which the system belongs, and thus predicts the possible mutations and controls them.

Considering that many rock engineering projects are on the limit of precedent practice, involving large scales, increasing costs, enhanced environmental awareness and the need to understand and predict the consequences of coupled mechanisms involving stress, water, heat and chemical reactions. At the same time, rock mechanics modeling is also becoming more complex and many more component elements and mechanisms can now be included in the numerical codes. Feng et al.[47] presented the rock mechanics modeling and rock engineering design approaches (Fig. 16).

4.3. Numerical analysis methods

Extensive research has been conducted on the stability analysis of underground caverns surrounding rock using finite element method, boundary element method, finite difference method, discrete element method, discontinuous deformation analysis methods. Hao et al.[48] analyzed the effects of joints with different dip angles on plastic zones and displacements of underground caverns using the discrete element method (DEM). Yazdani et al. [49] performed a displacement- based back analysis by employing the finite and discrete element methods and the geomechanical properties of rocks. Tian [50]used the finite element software Abaqus to research the variation in soil and support stress in the bifurcation section of the cavern group under different construction sequence conditions. Fan et al.[51] proposed a virtual block removal

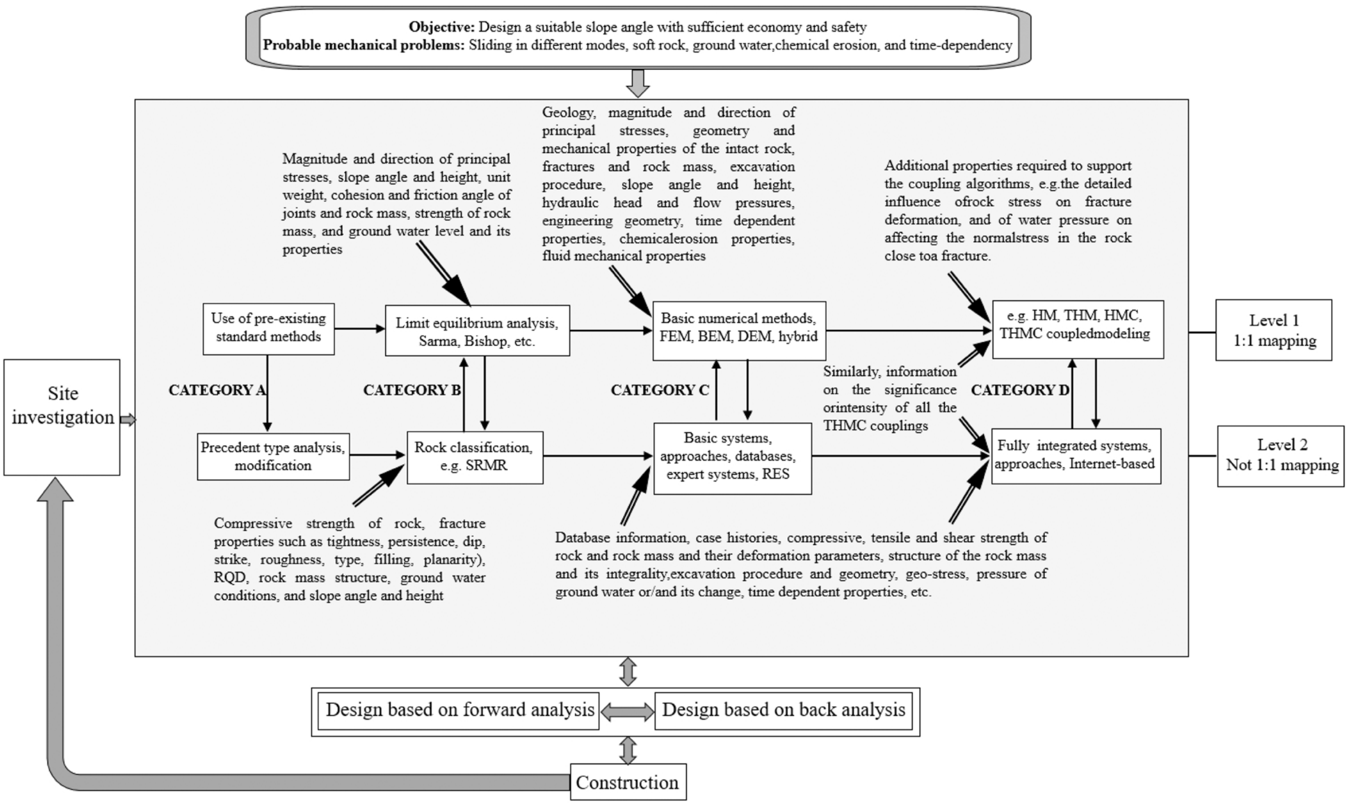

Fig. 16. Evolution of analysis methods and associated input information[47].

algorithm and developed an improved the original three-dimensional discontinuous deformation analysis method by embedding the algorithm into the original program.

Wu et al. [52] used the discontinuous deformation analysis (DDA) to research the influence of regional in situ stress levels, anchorage, rock mass structural conditions, and structural plane strength parameters of a cavern on the deformation of the surrounding rock of a cavern. Fu et al. [53] used the DDA method to study the step-by-step excavation of an underground cavern group in Dagangshan power station, established models of the underground cavern group under different through-joint combinations according to geological exploration data, and analyzed its failure mode and failure mechanism. Jiao et al. [54,55] constructed a method to study the destruction process of jointed rock mass, which is the discontinuous deformation analysis for rock failure (DDARF) method. However, DDARF has a limitation in the process of model building, which is that it can only generate uniform grids, that is, it can either generate all the same fine grids in the whole model, or generate all the same sparse grids in the whole model, which greatly limits the use of DDARF, because considering the simulation accuracy, dense grids should be generated, and if all the grids are generated to be dense grids in the model, the number of grids in the model will be greatly increased, which will not only increase the calculation workload and reduce the calculation efficiency, but also may cause calculation errors and result in calculation failure. This limitation means that DDARF is unsuitable for large-scale geotechnical engineering [56,57].

4.4. Physics simulation experiment methodology

The physical simulation experiment can reproduce the whole failure process and visually display the instability mode of the surrounding rock for underground caverns. Many scholars have used like rock material to simulate underground caverns to test its evolution law of deformation and failure modes under different loads. Combined with the field investigations of the Laxiwa Hydropower Station, Jiang et al. [7] proposed a new cracking-restraint design method for caverns' stability optimization based on the summarization and practice of many underground caverns under high geostress. Zhang et al.[58] carried out a model test of the whole excavation process of the underground cavern chamber based on the node's discontinuous deformation analysis (NDDA) method, and developed a high-precision grating scale miniature multi-point extensometer style displacement monitoring sensor. Qiu et al. [59] investigated the effects of nodal distribution on the rupture process, dynamic strength and local stress evolution of underground caverns based on model test and discrete element method. Liu et al.[60] developed a 3D class of rock-printing materials and proposed a brittle damage evolution model for hard rock tunnels.

5. Theory of optimization design of large underground caverns

During the construction of large underground caverns with high geostress, the stability control of cavern surrounding rock is the primary scientific problem, and how to effectively control the harmful deformation and catastrophic damage of the rock mass through scientifically reasonable and economically reliable excavation and support optimization methods and techniques is an unavoidable technical problem for large-scale underground engineering construction. In the long-term transportation, hydropower station, mine underground engineering practice, domestic and foreign have gradually developed a series of underground engineering excavation and support design methods, such as Terzaghi soil arch theory [61,62], Pratt's pressure arch theory [63], mine tunnelling method [64], new Austrian tunnelling method, new Austrian tunnelling method [65]. The Austrian tunnelling method, load-structure method [66], stratum-structure method / convergence-constraint [67], anchor shotcrete support technology [68], and for China's underground engineering adopted and widely used.

5.1. Engineering analogy and empirical method

In recent years, the engineering analogical empirical method has been widely used in rock underground engineering by combining artificial intelligence technology. Gong et al. [69] used finite difference model combined with co-rdpso optimized BP neural network to invert geotechnical parameters and analyze the stability of tunnels with different working conditions. Li et al. [70] used deep learning and machine learning models to establish an intelligent recognition model of the image of basic geological phenomena in hydraulic caverns to realize the automatic recognition and analysis of basic geological phenomena in the caverns. He et al. [71] integrated multiple machine learning algorithms to establish a comprehensive artificial intelligence design method for the design of anchor spray support in rocky underground projects. Hou et al. [72] developed an intelligent design model for underground cavern support by introducing particle swarm optimization to optimize the parameters of support vector machine, which converts the output indexes of the fixed class into the classification problem of the support scheme, and converts the output indexes of the quantitative class into the regression prediction problem of the support parameters, which reduces the subjective factors of human beings, and improves the design accuracy and reliability.

5.2. Quantitative computational analysis

In terms of quantitative calculation and analysis, most methods are based on the established elastic-plastic strength theory using load-structure or stratigraphic structure model to analyze the support and surrounding rock parameters. Zhong et al.[73] explored the support timing of the initial support of the mine method through theoretical analysis, combined with the Mohr-Coulomb criterion, and correlated the excavation footage with the overall safety indexes proposed by them as the key indexes of the support timing in the study, and used numerical simulation to make the relevant demonstration. Lei et al. [74], Chen et al. [75] used theoretical analysis and numerical simulation combined with on-site measured data to optimize the support parameters of spray-anchor support in subway tunnels constructed by mining method. The design optimization of the initial support structure of mine method tunnels was carried out by means of theoretical analysis and on-site monitoring analysis, etc.

5.3. Integrated design approach

Integrated design approach is a new underground engineering design and monitoring construction method, which can better solve the problem that the mechanical parameters of rock mass and geostress are not easy to determine. Jiang et al.[10] proposed a new concept of cracking-inhibition design method for stability optimization of large hard rock underground cavern groups under high geostress and its basic principle, key technology and implementation process on the basis of the research and practice of optimization of excavation scheme and support parameters of several deep / high-stress underground cavern groups. Dong et al.[76] put forward the theory of peripheral rock loosening circle, its basic point is: all hard rock hairy hole, its peripheral rock loosening circle are close to zero, at this time the elastic-plastic deformation of the roadway rock, although the existence of, but do not need to support, the larger the loosening circle, the greater the convergence of deformation, the more difficult to support, the purpose of support lies in the prevention of peripheral rock loosening circle of the development of the process of deformation in the harmful. Hou et al.[77,78] put forward the theory of strengthening the strength of the surrounding rock, that the interaction between the anchor and the surrounding rock constitutes the anchor solid, the anchor can improve the mechanical parameters of the anchor solid, improve the strength of the anchor solid, so that the strength of the rock mass, especially the strength after the peak and the residual strength is strengthened. He et al.[79] put forward the coupling combination support theory, the theory that tunnel support damage is mainly caused by the support body and the surrounding rock mass in the strength, stiffness and structure of the body in the existence of uncoupling. In order to take appropriate support transformation technology, so that they are coupled with each other, soft rock tunnel support should be divided into two support, the first is flexible face support, the second is the main part of the point support. Li et al. [80] carried out digital borehole camera observation and analysis of the formation and evolution process of the excavation damage zone of the TBM in the deeply buried tunnel of the Jinping Grade II Hydropower Station and explored the mechanism of the formation and evolution of the excavation damage zone.

6. Design method for dynamic feedback analysis and optimization

The construction process of large cavern group system is open, dynamic, nonlinear, irreversible, with stress path dependence of the complex system, by this complex system of many factors are uncertain or even unknown, so can only use the idea of feedback to control the system in the direction of people's expectations [81]. According to key features of deformation and failure of surrounding rocks at high geostress, Feng et al.[82] proposed a way for fast feedback analysis and design optimization of caverns group during construction (Fig. 17).

Zhao et al. [83] proposed an evolutionary support vector machine method for inverse displacement analysis by combining support vector machine with genetic algorithm, which utilized the non-linear reasoning of support vector machine and the optimization finding ability of genetic algorithm, respectively. Tian et al. [84] used the improved ant colony algorithm to calculate the soil parameters of earth-rock dams and achieved some beneficial results. Jiang et al. [85] proposed a new method for intelligent inversion of rock mass parameters of large cave complexes based on the loosening circle displacement incremental monitoring information using an evolutionary neural network genetic algorithm. Qi et al. [86] proposed a particle swarm optimization (MVPSO) inversion algorithm with particle migration and variability, and applied it to the inversion analysis of rock mass mechanical parameters of the right bank slope of Dagangshan Hydropower Station. Based on the design process of surrounding rock support for a large underground cavern of Laxiwa Hydropower Station, Shi et al. [87] proposed a dynamic adjustment method of surrounding rock stability and support design. On this basis, Jiang et al. [7] developed an artificial intelligence method to determine the global optimization procedure of cave excavation, which can reduce the total volume of its brittle damage and perimeter rock deformation, and identify the local intensity of possible brittle damage of the perimeter rock.

7. Development trends

Considering the demand, technical level and development status of large underground caverns in China, this review depicts the development skeleton of stability analysis method and optimization design as shown in Fig. 18, and the development trends in this field can be summarized as intelligent design, mechanized construction and greening construction.

(1) Intelligent design

The construction and operation of large-scale underground cavern projects face complex natural and social environments, which require the use of digitalisation, informatisation and intelligent control technologies to achieve safe, high-quality, high-efficiency and green construction of the projects. Fan et al.[104] developed the corresponding intelligent control technology and management system around the key elements of low-heat cement concrete performance, concrete temperature control, dam working condition and iDam platform in the construction practice of Wudongde and Baihetan projects. Based on the construction of the Baihetan arch dam, Tan et al.[105] established the

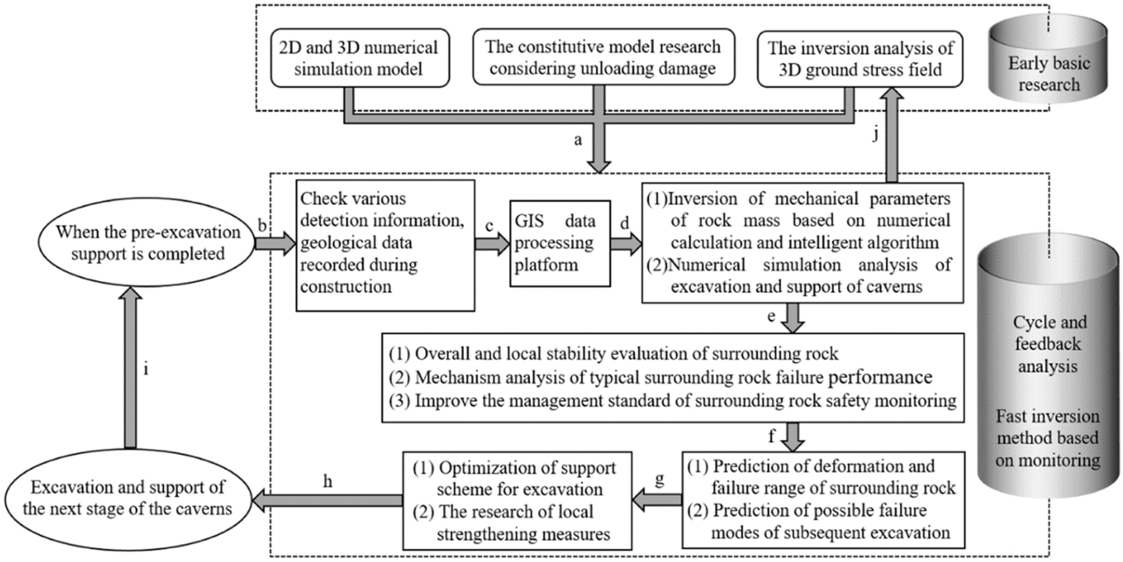

Fig. 17. Flowchart of fast feedback analysis and design optimization of caverns group during construction (based on Feng [82]).

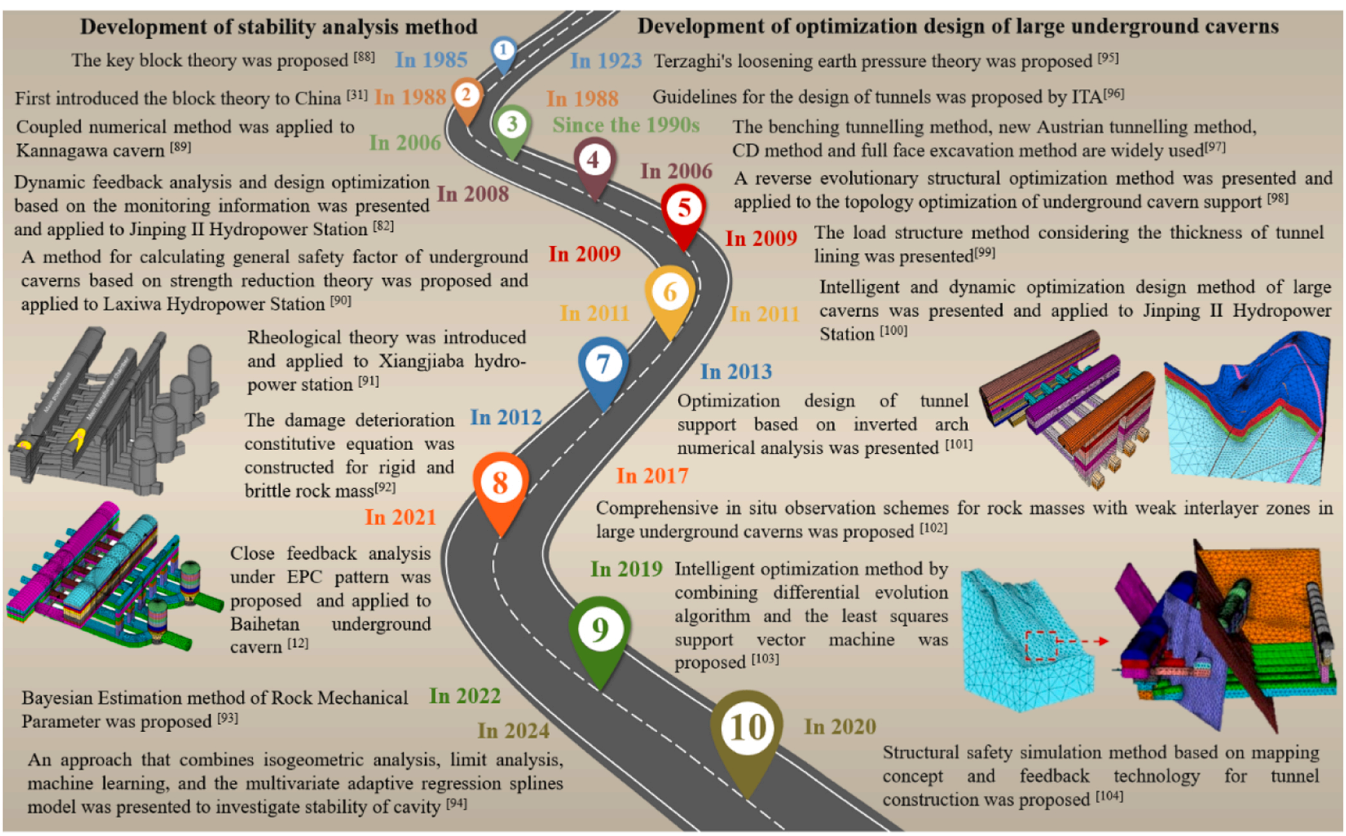

Fig. 18. Development skeleton of stability analysis method and optimization design of large underground caverns [88–103].

concept of intelligent dam construction based on the theory of closed-loop control and constructed the concept of dam construction oriented to the key construction processes and business processes (Fig. 19). Wang et al. [106] proposed the theory of intelligent arch dam progress simulation based on the Internet of Things and intelligent technology and the method of intelligent progress simulation analysis, which ensured that the construction of the project was completed in a safe and high-quality manner. Based on the theory, method and system of intelligent construction, a variety of high-quality and efficient intelligent construction technologies have been formed in the practice of hydropower project construction, including the application of digital twin technology such as BIM, intelligent design, intelligent monitoring, intelligent construction in the whole process, and real-time feedback and early warning automatic control system. It can be seen that the development of the field of large underground cavern project construction towards intelligence is a general trend.

(2) Mechanized construction

With the continuous improvement of labour costs, the number of

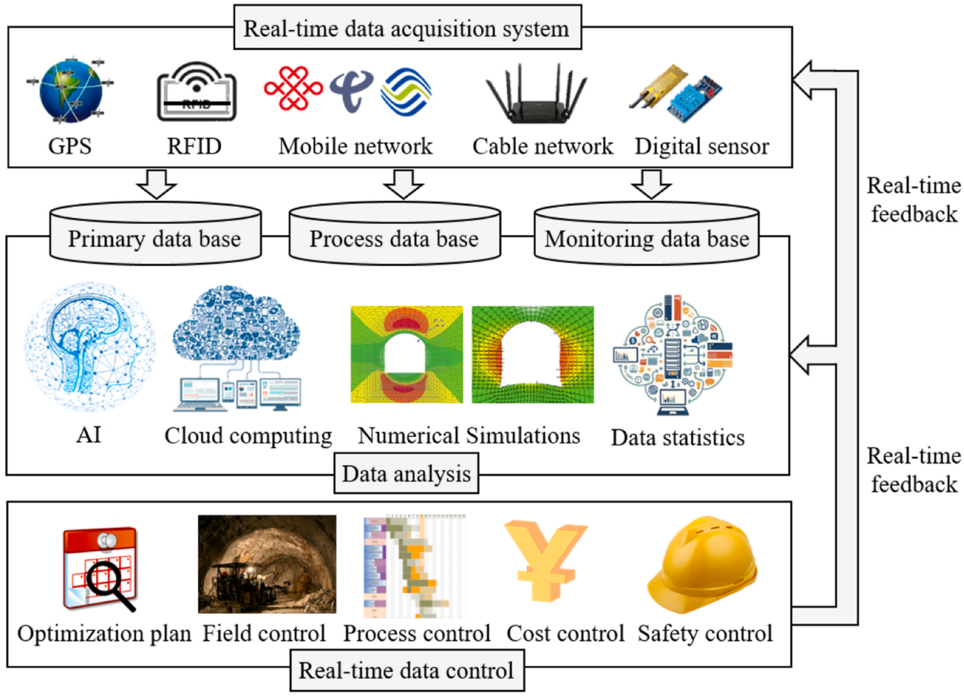

Fig. 19. Intelligent design and its control system [107].

experienced construction technicians on underground cave construction sites is decreasing year by year. Underground engineering construction "machine instead of man" has become a real demand, and less manpower (or even unmanned) is the inevitable trend of the future development of underground engineering construction. Based on the high integration of mechanization, data, informationization and artificial intelligence, the development of intelligent machines with the functions of self-perception, self-learning, self-decision and self-implementation to carry out intelligent operation of the main processes of underground cave construction is of great significance to improve construction efficiency, ensure construction safety and enhance construction quality.

At the same time, it is particularly important to develop the theory and method of intelligent design of underground cavern support compatible with it. Considering the current demand for underground cavern construction in China, the current technology level and the development status, the development trend of Mechanized construction in underground cavern stability and support structure optimization design theories and methods can be expressed as follows:

a. Realize the integration of design and construction.

b. Develop comprehensive remote sensing technology that can accurately detect potential hazards in inaccessible areas, and integrate various investigation techniques to improve the accuracy and efficiency of geological investigation.

c. Continuously accumulate and perfect the parameters and design methods of underground cavern support structures under various geological conditions, and eventually break through to the intelligent design of caverns based on deep learning.

d. Develop intelligent construction machinery and equipment with the functions of self-perception, self-learning, self-decision making and self-implementation to carry out intelligent operations in the main processes of cave chamber construction, improve construction efficiency, ensure construction safety, improve construction quality and perceive the status of surrounding rocks and supporting structures in real time.

e. Establish a comprehensive platform that integrates design, construction and management to realize intelligent design and construction of cave chambers.

(3) Greening construction

Faced with the serious situation of increasing resource shortage, severe environmental pollution and ecosystem degradation, advocating and practicing green construction under the guidance of the “dual-carbon” goal has become an inevitable choice for realizing the sustainable development of geotechnical engineering. The concept of green construction is implemented throughout the planning, investigation, design, calculation, construction, monitoring, materials, equipment, maintenance and disposal of underground cavern projects, etc. By adopting environmentally friendly, low-carbon and sustainable engineering and technology methods and materials, we can effectively protect the environment, conserve resources, reduce energy consumption and achieve sustainable development. In the future, industries are expected to emerge in the research and development of new materials and technologies with lower life-cycle carbon footprints and the substitution of existing energy-intensive materials and technologies. For example, the research, development and application of environmentally friendly and renewable new green geotechnical engineering materials, high-risk environment operation drones, gas recluse, intelligent operation and maintenance robots, the development of virtual tunnel construction site systems, and the use of 3D printing technology instead of traditional rock materials for scientific research, etc., to explore the green design and construction technology has become an effective way to promote the greening of the construction of large-scale underground cavern clusters.

8. Conclusions

According to our bibliometric research, China continues to lead the globe in this area. The country with the highest number of articles is China, the United States ranked second, and Canada ranked third. The scholarly institutions with the most impact in this area include the Institute of Rock and Soil Mechanics, Wuhan, Wuhan University and Shandong University. The author with the most published SCI articles is Academician Feng from Northeastern University, China. Jiang from Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China and Xu from Sichuan University, China ranked second. Stability analysis and optimization design comprise the future research directions and potential topic hot spots for large underground caverns.

By using bibliometric analysis, the typical deformation and break modes of large underground caverns under high geostress include rockburst, spalling and falling, time-dependent deformation of rock mass, relaxation failure behavior of surrounding jointed / fractured rock, shear deformation of weak fault / interlayer / dislocation zone, the expansion and relaxation of rock fractures and collapse failure. At present, the common stability analysis methods of the surrounding rock include engineering analogy method, theoretical analysis methods, numerical analysis methods and physics simulation experiment methodology. Relevant theory of optimization design of large underground caverns includes engineering analogy and empirical method, quantitative computational analysis and integrated design approach. Design method for dynamic feedback analysis and optimization is a new cracking-restraint design method for caverns' stability optimization, which provides a new idea for design optimization of underground engineering. Intelligent design, mechanized construction and greening construction are development trends in this field.

These results assist the researcher in better grasping the methods and trends of stability analysis and optimization design of large underground caverns under high geostress. We appeal to the relevant researchers of large underground caverns, hoping to strengthen the research of stability analysis and design optimization methods of surrounding rock by considering the high geostress, and communicate to promote the development and application of relevant technology.

CRediT authorship contribution statement

Long Li: Resources, Investigation, Formal analysis, Data curation. **Quan Jiang:** Methodology, Conceptualization. **Qingfu Huang**: Supervision, Investigation. **Tianbing Xiang**: Supervision. **Jian Liu**: Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Quan Jiang reports financial support and administrative support were provided by State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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