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Achievements and problems of geotechnical engineering investigation in China†

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Abstract: As an industry and a discipline, geotechnical investigation in China differs from that in the USA and European countries in its course of emergence and evolution. For over half a century, Chinese geotechnical investigation professionals witnessed continuous technical advances as they undertook independently almost all of China's large-scale construction projects. Based on projects that won the "National Outstanding Engineering Investigation" Gold Medal Awards since the year 2000, this paper discusses the achievements of geotechnical investigation in the context of comprehensive technical ability, project evaluation and analysis, hi-tech applications and engineering monitoring, and analyzes several factors that have hindered the industry's further development and alignment with international practice. Finally, some suggestions are given for future improvement.

Key words: Geotechnical engineering, Engineering investigation, Technical advance
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1 Introduction

In the first Spencer J. BUCHANAN Lecture, "The coming of age of soil mechanics: 1920–1970", Professor Ralph PECK pointed out that the publication of TERZAGHI's book "Erdbaumechanik auf Bodenphysikalischer Grundlage" (Earthwork mechanics based on soil physics) in March 1925, was recognized as the birth of modern soil mechanics. Since then, the framework of soil mechanics as a discipline has developed following the publication of another two important books, "Theoretical Soil Mechanics" and "Soil Mechanics in Engineering Practice" by TERZAGHI and his colleagues during his time as Professor of the Practice of Civil Engineering (a title established especially for him) at Harvard University. Thus, it is reasonable to say that soil mechanics and geotechnical engineering in the West has emerged and developed from academic and consulting activities within teaching and research institutions (Zhang, 2005).

In China, however, engineering investigation has inherited different genes. In the 1950s, in order to fulfill the requirements of many large-scale projects specified by the "Five-Year Plan", a team of engineering investigators was established and soon enlarged. The pioneers were trained by experts from the USSR and the organizational framework and direction of the team basically followed the USSR model which had been developed during the extensive reconstruction after World War II. The role of this industry was merely to match construction and design with geological conditions and data from the field and lab and almost no engineering analysis or judgment was reported. Under this direction, for the first twenty years or so, geotechnical investigation was confined to "boring-testing-information providing", an approach similar to that of a doctor examining a patient without giving a prescription. As a result, only a handful of universities and research institutions carried out research in this field, and almost no professional geotechnical consultant existed in China.

In the mid-late 1970s, experts realized the problems of this approach and its negative effects on

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infrastructure construction. They started to modify their work to align with international practice. In the 1980s, three events underlined this move. First, the State Planning Commission accepted experts' suggestions and issued a document calling for the introduction of a geotechnical engineering mechanism into site investigation organizations. Second, the term geotechnical engineering was for the first time included in the civil engineering volume of "The Encyclopedia of China" published in 1985. Last but not least, in 1986, the former State Planning Commission replaced the "Code for Geological Investigation of Industrial and Civil Building Engineering" with the "Code for Investigation of Geotechnical Engineering". According to the concept of greater geotechnical engineering, the code enlarged our professional scope from industrial and civil building construction to include underground construction, offshore engineering, pipeline engineering, tailing dam engineering, slope engineering, etc. Moreover, the code included much greater content on engineering calculation, analysis, and evaluation. The issuing and enforcement of the code represented a primary reorientation of the industry and a requirement for technical advances (Zhang, 2003).

In China, geotechnical engineering was defined as a new discipline that aims at solving or dealing with all the engineering problems related to rock and soil in the construction process, based on the understanding of engineering geology, soil mechanics, rock mechanics, and foundation engineering. With a strong emphasis on the combination of geology and engineering in its theory and practice, geotechnical engineering is a branch of civil engineering. Interestingly enough, 15 years later, a paper about the definition of geotechnical engineering published in the Journal of Ground Engineering closely resembled the Chinese definition "geotechnical engineering is the application of the science of soil mechanics and rock mechanics, engineering geology and other related disciplines to civil engineering construction, the extractive industries, and prevention and enhancement of the environment" (Anonymous, 1999).

Currently, many universities and research institutions are engaged in geotechnical engineering research and consultancy. However, the investigation sector, which does not play a technically dominant role in the western world, remains in China as an important branch of geotechnical engineering. This paper discusses the achievements and problems of Chinese geotechnical investigation.

2 Independent investigations of major construction projects in China

In 2000, Prof. MORGENSTERN listed important engineering projects of the 20th century at the GeoEng2000 Conference, jointly organized by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), the International Society for Rock Mechanics (ISRM), and the International Association for Engineering Geology (IAEG) (Morgenstern, 2000), which included: (1) tunnels (Holland Tunnel, 1927; Cascade Tunnel, 1928; Seikan Rail Tunnel, 1988; Channel Tunnel, 1994); (2) dams (Hoover Dam, 1935; Guri Dam, 1968; Aswan Dam, 1970; Snowy Mountains Project, 1974; Nurek Dam, 1977; James Bay Project, 1985; Itaipu Project, 1991); (3) highways (Alaskan Highway, 1942); (4) navigation projects (Mississippi River Locks and Dams, 1940; St. Lawrence Seaway, 1959); (5) bridges (Humber Bridge, 1981; Northumberland Straits Bridge, 1996); (6) pipelines (Trans Alaska Pipeline, 1977); (7) offshore structures (Statford B. Platform, 1981; Hibernia Platform, 1997); (8) subways (Washington, DC, 1976); and (9) airports (Chek Lap Kok, 1998).

Of a total of 21 projects from 9 categories, only one was in China: the Chek Lap Kok Airport project, of which the design and construction was conducted mainly by foreigners.

However, China does have many world-class projects on the basis of scale and difficulty.

China established an investigative team in the 1950s. From the first 156 projects in the first "Five-Year Plan" to projects in the new century, Chinese investigation professionals completed a great number of projects through an independent process of "boring, sampling, testing, trialing, monitoring, and analyzing". Taking bridge construction as an example, China has six of the world's ten longest cable-stayed bridges, two of the world's ten longest suspension bridges (with another two ongoing projects on the waiting list), and five of the world's ten longest large-span arch bridges. Another example is dam construction. In 1950, according to the International Commission of Large Dams (ICOLD), China had only 22 dams that measured over 15 m in height out of the world total of 5268, accounting for 0.4%. After twenty years' reform and opening up, China's dam construction skyrocketed both in the number of projects and their technical levels. According to ICOLD, between the years 1951 and 1977, when all other countries in the world built 335 dams per year on average, the Chinese built 420 dams per year, accounting for 55.6% of the world total. In 1982, there were 34 798 dams in the world measuring over 15 m in height, of which 18 595 (53.4%) were in China. At the end of 1986, there were 36 226 dams in the world, of which 18 820 (52%) were in China. By the end of 2005, China had over 22 000 dams measuring over 15 m out of the world total of around 50 000, accounting for 44%. Besides dams, China has three of the world's twenty super-tall buildings over 300 m, and two of the world's ten tallest TV towers.

All that aside, we have not yet taken into account the ongoing projects such as super-tall buildings, large-scale public facilities represented by the Olympic Stadium, the Three Gorges Dam, the Qinghai-Tibet Railway, the West-to-East Gas Pipeline, the South-to-North Water Diversion Project, and other highway, railway, and tunnel projects.

Therefore, it is justified to say that since the first "Five-Year Plan", all these investigation projects have been conducted independently by Chinese engineers, regardless of their scale and difficulty, and that in so doing, the level of technical competence has risen dramatically.

3 Technical advances in Chinese engineering investigation

Several projects that won the eighth, ninth or tenth "National Outstanding Engineering Investigation" Gold Medal Awards after the year 2000 are listed in Table 1, and the achievements and technical advances of Chinese engineering investigation are presented in four aspects. Note that projects nominated for these awards must be completed or checked and accepted for more than one year, so some key projects recently completed are not included.

3.1 Acquisition of the ability to conduct integrated investigations for all kinds of large-scale projects

Three projects are cited as evidence. The Qinling Mountain Tunnel of the Xi'an-Ankang Railway is presently China's longest and deepest railway tunnel. It consists of two parallel single-line tunnels each with a length of 18.456 km and a maximum embedding depth of 1600 m. By length it ranks 7th in the world. The tunnel passes the junction of the Yangtze Platform and the North China Platform, an area with complex geological formations, frequent formations, and highly developed faults. The tunnel cuts through extremely hard rocks such as compound gneiss and migmatitic granite. The thirteen faults that it cuts across have very complicated engineering properties, shapes, and distributions. Other geological difficulties include water gushing from faults, high geostress rock burst, high geotherm, high radiation, instability of the surrounding rock mass, and the pervasiveness of very hard rocks. On top of these natural challenges, the design requirements, such as ventilation of the dead ended long tunnel and draining of the reverse slope at the exit, have made the tunneling process difficult and critical for the whole project.

In the investigation stage, route selection work covered an area of 460 km^2, and gave rise to 17 comparable tunneling schemes going through the Qinling Mountains. Due to the difficulties mentioned above, the investigation had the following features: (1) During route selection, remote sensing techniques were applied over an extensive area for many schemes. (2) Comprehensive geophysical investigations, supplemented by boring methods, were used to improve greatly the geological route selection and investigation. (3) Numerical analysis and the absolute value determination technique were studied, and used to determine the formation stress field and earth pressure. (4) Multi-parameter hydro-geological investigations and new computing methods were adopted to visualize the reticular and vein-type distribution of groundwater and its movement. (5) Together with early-stage parallel pilot tunnel construction, comprehensive geological construction routing and forecasting of geohazards were conducted, which improved the accuracy of tunnel geological investigation and forecasting. (6) In combination with

Table 1 Projects that won the "National Outstanding Engineering Investigation" Gold Medal Awards since the year 2000

Area	Project name	Design unit
Hydraulic and hydropower engineering investigation	The Ertan Hydropower Station	Chengdu Hydroelectric Investigation and Design Institute of State Power Cooperation (CHIDI)
	The Tianshengqiao I Hydropower Station	Kunming Hydroelectric Investigation and Design Institute of State Power Cooperation (KHIDI)
	The Tianhuangping Pumped-Storage Power Station	East China Hydroelectric Investigation and Design Institute of State Power Cooperation (ECHIDI), etc.
	The Longyangxia Hydropower Station	Northwest Hydroelectric Investigation and Design Institute of State Power Cooperation
	The Minjiang River Zipingpu Hydraulic Complex in Sichuan Province	Chengdu Hydroelectric Investigation and Design Institute of China Hydropower Consulting Group
Thermal power station and nuclear power station investigation	The Ling'ao Nuclear Power Plant in Guangdong Province	Guangdong Electric Power Design Institute
	The Zhangjiakou Power Plant Phase II project	North China Power Engineering (Beijing) Co. Ltd.
	The Shuangliao Power Plant project	Northeast Hydroelectric Investigation and Design Institute of State Power Cooperation
Highway railway, bridge, tunnel, and airport engineering	The Qinling Tunnel of the Xi'an-Ankang Railway project	China Railway First Survey and Design Institute, etc.
	Retaining structures of the south anchor foundation pit of the Runyang Yangtze River Highway (Suspension) Bridge	Shanghai Shenyuan Geotechnical Engineering Co. Ltd. Shanghai Geotechnical Investigations and Design Institute Co. Ltd.
	Geological investigation for the route selection of the new Jiaozhou-Xinyi Railway project seated on Yi-Shu earthquake fault	China Railway Third Survey and Design Institute Group Co. Ltd.
	Airfield area of the Xiaoshan International Airport in Hangzhou	Zhejiang Engineering Investigation Institute
	Foundation stability evaluation of the terminal station of the New Baiyun International Airport, Guangzhou	Guilin Hydro-geological Investigation Institute in the Guangxi Autonomous Region, etc.
High-rise buildings and large-scale public facilities	Saige Square Building project in Shenzhen	Shenzhen Investigation Institute, etc.
	The Beijing International Center for Bamboo and Rattan (ICBR)	Beijing Geotechnical Institute (BGI)
	Zhongguancun Science and Technology Mansion	BGI
	China's National Center for the Performing Arts (NCPA)	BGI
Slope engineering under special conditions	Stability analysis of the Majiatian tailings fill dam for the Mining Company of Panzhihua Iron and Steel (Group) Co.	Kunming Prospecting Design Institute of China Nonferrous Metals Industry
	Baolongyu Rocket Engine Test Base of China Aerospace Corporation	Shaanxi Institute of Engineering Investigation and Design
Engineering monitoring	Deformation monitoring of high slopes in the Yangtze River Three Gorges Dam	Yangtze River Geotechnical Engineering Corporation
	Dam deformation monitoring of the Yellow River Xiaolangdi Hydraulic Complex	Huanghe Investigation, Planning and Design Co. Ltd.
Hydro-geological investigation	The hydro-geological investigation of the Yanhequan water source area, Yangchen Power Plant, Shanxi Province	North China Power Engineering Co. Ltd., etc.

engineering practice, five research programs were conducted. (7) The tunnel construction verified the quality of the engineering investigations.

Using tunnel boring machines (TBM), Line I of the Qinling Mountain Tunnel was finished in 29 months. In Line II, the boring and blasting method was used for the construction of a parallel pilot tunnel. Line II was started two years before Line I, and had an average construction speed of 220 m per month. After Line I was finished, enlargement excavation and liner installation were carried out (Fig. 1). The fulfillment of the Qinling Mountain Railway Tunnel investigation indicates that China's tunnel investigation techniques are already of world-class standard.

Fig. 1 Entrance of the Qinling Tunnel of the Xi'an-Ankang Railway and the internal liner

The Ertan Hydropower Station is the largest hydropower station built in China, with advanced structural design and multiple internationally advanced technical applications. It has a total storage capacity of 5.8 billion m^3 and an installed gross capacity of 3300 MW. The double curved arch dam is 240 m high, making it the highest of its type in Asia and the third highest in the world. The maximum width of the arch dam base is 55.74 m. The length of the top is 774.65 m. The maximum flood discharge capacity is 23 900 m^3/s, of which the dam body contributes 16 300 m^3/s, ranking the highest in the world. The underground power station is the largest in China. The dimensions of the major power station are 280.2 m×25.55 m×65.7 m. The diversion capacity of the diversion tunnels is 13 500 m^3/s. The two tunnels have a section dimension of 17.5 m×23 m, and a length of 1087 and 1167 m, respectively, making them the two longest in the world (Fig. 2).

In the investigation stage, multiple advanced technical methods were used to tackle a series of key geotechnical problems, such as the surveying and selection of the site location in a complicated regional tectonic environment, geostress distribution testing and assessment, and the evaluation of the exploitability of joint rock weakened zones. A research framework for the evaluation and classification of engineering rock mass was set up to assess the stability of different kinds of structures in the hydraulic complex and provide reliable source information for the construction of the hydropower station. All of these activities not only facilitated the construction of the dam, but also provided valuable experience in the investigation which can be applied to future large-scale hydropower projects in China.

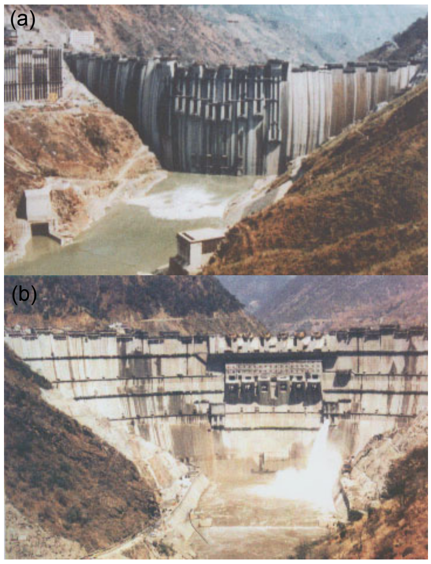


Fig. 2 Elevation views of the upstream (a) and downstream (b) of the Ertan Hydropower Station Arch Dam

The Tianshengqiao Hydropower Station was the first cascade of the series of Honghe cascade hydropower stations. With a total storage capacity of 10.257 billion m^3, a height of 178 m, a top length of 1104 m, a face area of 160 000 m^2, and a filling volume of 18 billion m^3, this reinforced concrete face rock-fill dam is the largest of its type in the world (built or being built). The spillway of the hydropower station is presently the largest bank spillway in China, with a diameter of 12.0 m and a total length of 2400 m for the four introduction tunnels. The installed gross capacity is 1.2 million kW.

In the investigation phase, 2D and 3D numerical and physical modeling, and stability analysis of the underground surrounding rock mass were carried out. In the construction phase, geological forecasting was conducted using advanced technology and interpretive methods. Together they solved the complex problems of stability of the high concrete face rock-fill dam and high slopes, the stability and design of the retaining structures of underground chambers, and karst leakage, etc.

3.2 In-depth geotechnical engineering analysis and evaluation of key projects

Chinese investigation organizations have evolved from providing merely hydro-geotechnical information to now performing in-depth analysis according to the requirements and geotechnical conditions of projects and working with structural engineers on problems of foundation engineering.

To illustrate this point, three projects in Beijing: the Beijing International Center for Bamboo and Rattan (ICBR), the Zhongguancun Science and Technology Mansion, and China's National Center for the Performing Arts (NCPA, also known as the National Grand Theater) are cited. The first two consist of high-rise buildings with medium-rise building groups and underground structures.

The NCPA is a huge multi-functional public facility and is made up of three parts (Fig. 3). The central part, which is called Zone 202, is the main structure formed by an elliptical dome with an east-west major axis of 212.2 m, a south-north minor axis of 143.6 m and a dome height of 46 m. Surrounded by a pool, the dome accommodates three independent buildings, an opera house, a drama house, and a music hall. On the south and north of Zone 202 are Zones 203 and 201, mainly underground structures. The whole NCPA project covers an area of more than 80000 m^2 with a total construction area of 190000 m^2.

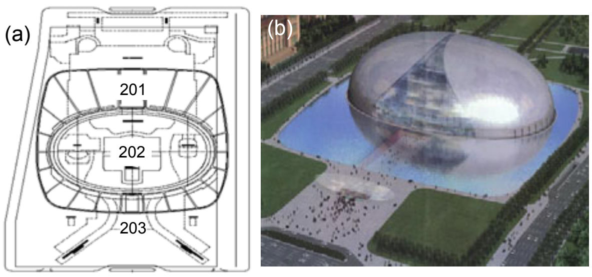


Fig. 3 Layout plan (a) and a bird's eye view (b) of NCPA

Although there are different types of structures, the three projects in Beijing faced similar problems in engineering analysis, some of which were new topics in foundation engineering:

1. Uneven load distribution caused by a complicated structural type with a contact pressure under the foundations ranging from an overcompensated state to near allowable bearing capacity. The estimation and control of uneven settlements within the same foundation slab became the key issue in deciding the foundation scheme.

2. Due to the existence of impermeable layers, multiple layers of groundwater were formed as the water level dropped. The multiple layers of groundwater and the unsaturated zones in between formed a complex occurrence and seepage system. Therefore, the evaluation of anti-buoyancy stability became a prominent issue, especially for the NCPA project.

3. For high-rise structures surrounded by basement or low-rise annexes, the lateral restraint of the foundation was provided by a hollow structure instead of soil. So, the estimation of bearing capacity became a new problem.

To predict and control the differential settlement, geotechnical consultants developed a compression-shear model with clear mechanics and simple parameters. Based on the model, a numerical subsoil and foundation interaction analysis (SFIA) program was developed to calculate foundation settlement and foundation stress distribution with an assumption of compatible deformation of the ground and foundations (Fig. 4). The principle of the model was to divide the stress state of a soil element into the compression part and the shear part, the parameters of which could be readily obtained through a compression test and a triaxial test. The parameters used in the model were obtained by comparing the computed and monitored data from hundreds of projects in Beijing and performing back analysis so that the predicted result would show good agreement with the real engineering behavior of the structures.

Fig. 5a shows the predicted settlements of the ICBR, the Zhongguancun Science and Technology Mansion, and the NCPA, and Fig. 5b shows the monitored settlement distribution after these projects were finished. The two datasets show very good agreement. The results of the analysis indicate that the foundation settlement of the NCPA is within the design limits. As for the other two projects, based on soil and structure interactive analyses, the geotechnical consultants suggested important modifications of the structure designs.

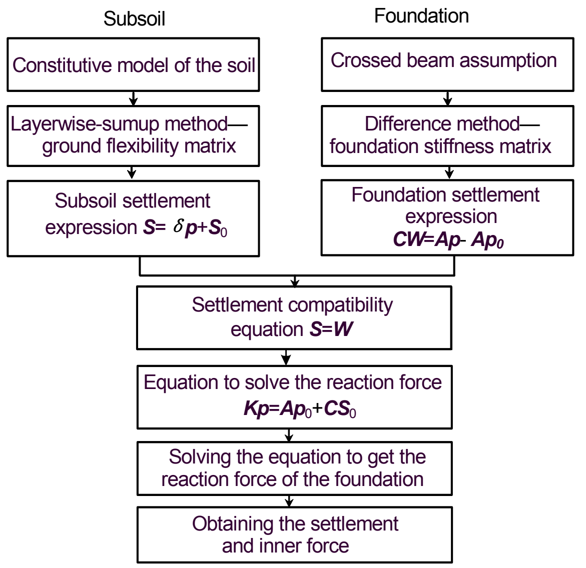


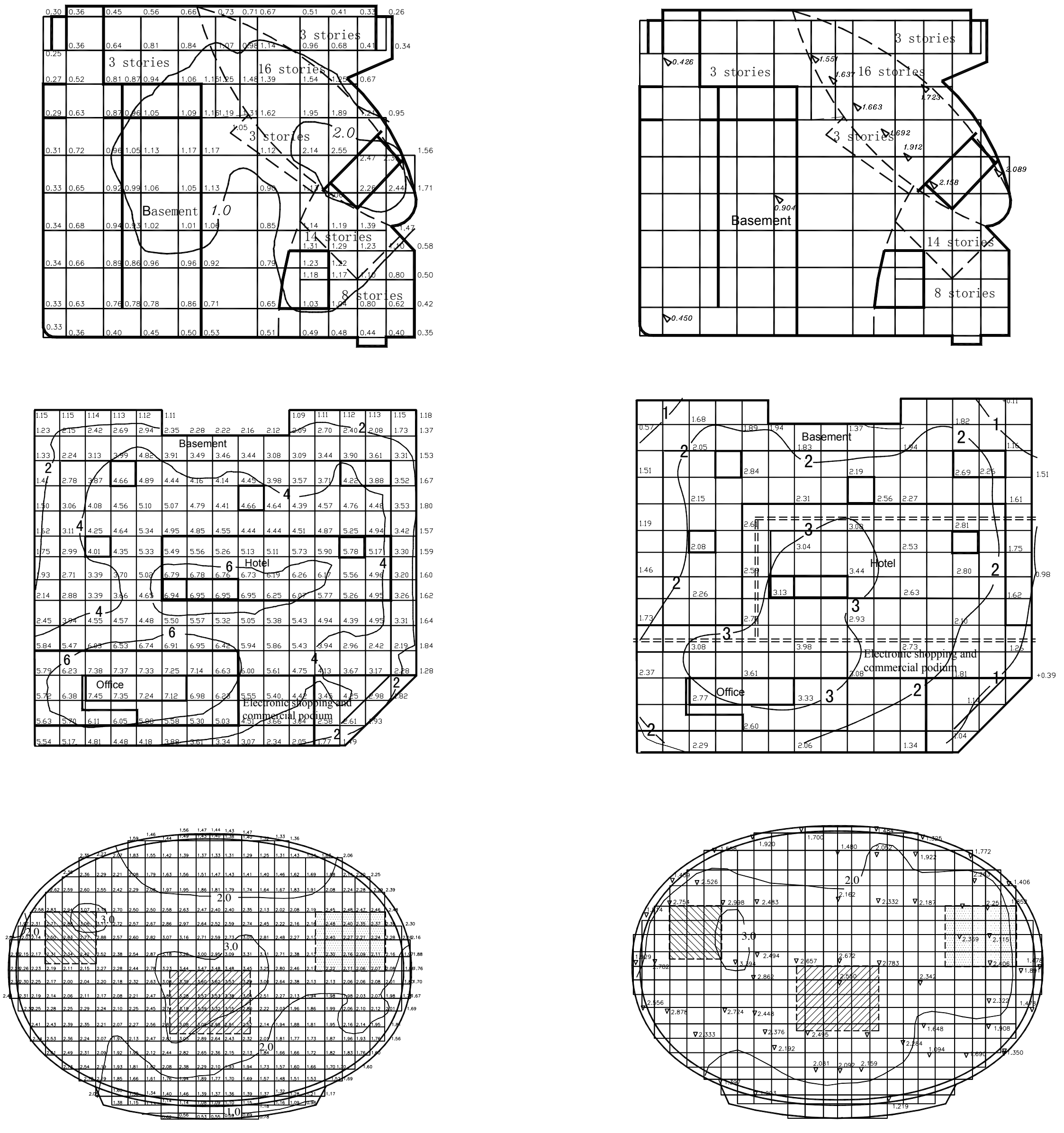
Fig. 4 Flowchart of subsoil-foundation interaction analysis
$\boldsymbol{S}$: vector of node settlement; $\boldsymbol{S}_0$: vector of external settlement; $\boldsymbol{\delta}$: ground flexibility matrix; $\boldsymbol{p}$: vector of average reaction force of the foundation; $\boldsymbol{p}_0$: load vector; $\boldsymbol{C}$: total stiffness matrix of foundation; $\boldsymbol{W}$: displacement vector; $\boldsymbol{A}$: basal area matrix; $\boldsymbol{K}$: coefficient of reaction force matrix

In the ICBR project, for the optimization of the foundation scheme and the convenience of construction following the SFIA analysis, it was suggested that one floor should be added under the basement part and some of the annex part, and that the post-pouring joint and pedestal-supported panel should be canceled. By so doing, expensive pile foundation could be avoided.

In the Zhongguancun Science and Technology Mansion project, the geotechnical engineer suggested that if the direct raft scheme was to be maintained instead of piling, as required by the owner, it would be necessary to lower the base load, adjust the elevation of the base, increase the size of the upstanding foundation beams, and control the process and proportion of loading before casting the construction joint. All these suggestions were accepted by the owner and the designer. In the end, four floors in the office and hotel buildings were canceled, while the elevation of the basement was lowered by 1.2 m at the middle column of the office building.

Buoyancy created a great problem in the NCPA project, especially in Zone 202. With a 26 m burial depth and a low average load, most of the 22500 m^2 elliptical slab was in an overcompensated state, like a boat sitting in a confined aquifer. Therefore, anti-buoyancy stability became the key problem to be solved. As multi-layered groundwater also exists elsewhere in the urban Beijing area and in other cities, geotechnical engineers carried out systematic research. They concluded that in cities with multiple layers of groundwater, due to the existence of unsaturated zones between saturated layers, relatively large vertical seepage vectors existed in the seepage field of the ground, and the pressure along the depth was lower than that of a traditional linear distribution. So the traditional method must have overestimated basement buoyancy. They suggested that in deciding the uplift forces, the overall occurrence and seepage regime and the overall seepage characteristics should be taken into account. Based on this understanding, a concept of effective anti-buoyancy design water level was proposed. Through an integrated study of historical water level data and the future supply and demand balance of water resources in urban Beijing, geotechnical engineers suggested that the slurry wall surrounding Zone 202 should be deepened and penetrate the clay layer under the foundation so as to change the seepage path. Field investigation and saturated-unsaturated seepage analysis indicated that with such a measure the effective anti-buoyancy design water level could be lowered from 43.3 to 38.0 m in elevation, and no other anti-buoyancy measures would be required. Fig. 6 shows one of the sections of the analysis model and the results obtained when the slurry walls penetrate 2 m down to the low permeability layer. Under the most adverse groundwater conditions, the base pressure head is 37.27 m in elevation near the upstream of the groundwater and 37.25 m near the downstream of the groundwater (Fig. 6).

To study the influence of weakened lateral restraint conditions on foundation bearing capacity and settlement behavior, besides checking the overall stability by the modified Bishop method, geotechnical engineers also performed numerical analysis using the commercial code fast Lagrangian analysis for continuum (FLAC). In the finite difference analysis, verification of the analysis model was achieved by comparing the computed and measured data of the foundation deformation (Fig. 7). Based on the verified model, influence mechanisms and computation



(a) (b)

Fig. 5 Comparison of the predicted (a) and monitored (b) settlements of the Beijing International Center for Bamboo and Rattan (ICBR), Zhongguancun Science and Technology Mansion, and China's National Center for the Performing Arts (NCPA) (unit: cm)

methods were studied. The methods suggested from this study have been included in the "Code for Geotechnical Investigation and Design of Building Foundations in Beijing Area" revised in 2007.

Different types of analyses were conducted in other award-winning projects, such as the Saige Square Building project in Shenzhen, the hydrogeological investigation of the Yanhequan water source area of the Yangchen Power Plant in Shanxi Province, the Tianshengqiao Hydropower Station project, and the Longyangxia Hydropower Station project. In these projects, engineering investigation transcended its traditional scope, showed new depth and influence, and progressed the industry in its transition to the "geotechnical engineering mechanism".

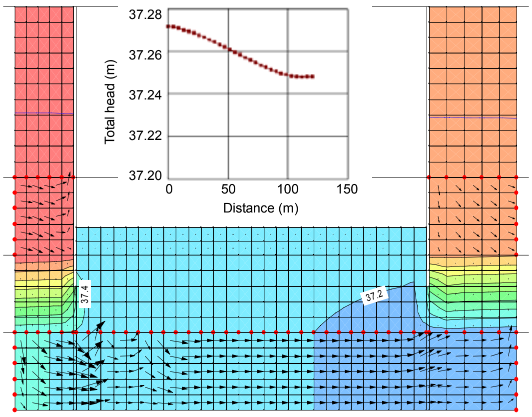


Fig. 6 Effects of the depth of the slurry wall penetrating into the low permeability layer on the seepage field, an example of the engineering approach to solve the groundwater problems

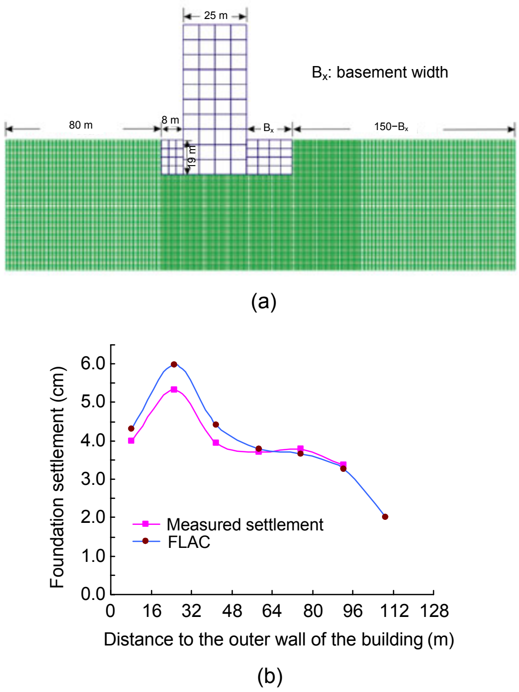


Fig. 7 (a) Model for numerical analysis on the influence of weakened lateral restraint on foundation bearing capacity in the Beijing Zhongguancun Science and Technology Mansion; (b) Comparison of computed and measured settlements

3.3 Application of advanced boring and testing techniques and other hi-tech methods

In many of the award-winning projects, advanced boring and testing techniques were used. Technical advances in process control and data acquisition have been witnessed in standard penetration test (SPT), cone penetration test (CPT), plate loading test (PLT), pressure meter test (PMT), and California bearing ratio (CBR) for the coefficient of subgrade modulus and resilient modulus, pumping tests, wave velocity tests, geological radar, seismic geophysical investigation, and all kinds of electro-magnetic methods. Conventional laboratory tests, cyclic and static triaxial tests, high pressure consolidation tests, permeability tests, compaction tests, CBR tests, and water quality and organic tests have become common testing measures.

In the field of in-situ tests, CPT and shear wave velocity tests performed in many projects have already reached a depth of over 100 m. Among them, the 120 m deep cross-hole wave velocity test and borehole elastic modulus test in the Ling'ao Nuclear Power Plant project in Guangdong Province is nationally pioneering.

In the Qinling Mountain Tunnel of the Xi'an-Ankang Railway project, a survey control net was established based on the global positioning system (GPS) system. For the first time, the direct projection method was used to establish a set of independent GPS construction coordinates. The precision of the survey was remarkable at both national and international levels. The vertical breakthrough error of the tunnel was 1 mm, and the horizontal breakthrough error was 12 mm.

Engineering modeling and statistical analysis are gaining popularity due to their achievements in the areas of computation and numerical analysis. Besides the aforementioned settlement interaction analysis and seepage analysis, other examples include: hydrochemical fuzzy cluster analysis and 2D unsteady flow modeling applied in the hydro-geological investigation of the spring basin karst groundwater in the Yanhequan water source area for the Yangchen Power Plant in Shanxi Province, 2D and 3D numerical and physical modeling in the high slope stability analysis for the Tianshengqiao Hydropower Station project, and dam stability analysis using SHEN Zhujiang's elastoplastic constitutive model in the Majiatian tailings fill dam investigation commissioned by the Mining Company of Panzhihua Iron and Steel (Group) Co., China.

In recent years, remote sensing imaging and geographic information system (GIS)-based 3D visualization have been used more frequently and satisfactorily. Herein, two award-winning projects are mentioned.

The new Jiaozhou-Xinyi Railway project is an important part of the land-sea passage from north eastern China to the Yangtze River delta. Avoiding winding its way around the Shanhaiguan Pass of the Great Wall would shorten the traveling distance by from 400 to 1000 km. However, to do so the railway must pass the largest active earthquake fault in eastern China, the Yishu Fault. Active faults and regional stability thus became primary geological concerns in route selection. In the geological route selection, geotechnical engineers studied previous research and applied comprehensive investigation techniques, particularly remote sensing image interpretation techniques including aeromagnetic mapping, 1:100000 Thematic Mapper (TM) image interpretation, and 1:35000 panchromatic black and white aerial film. They also conducted indoor identification and outdoor extensive geological validation studies. Application of these advanced techniques guaranteed the outcome of an optimal route scheme that is short, economic, and geologically favored. The research of the site investigation played a key role in the route determination of this scheme and in the subsequent design and construction, yielding great economic and social benefits (Fig. 8).

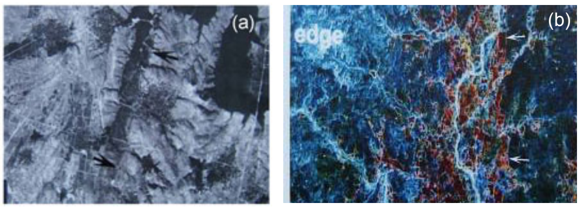


Fig. 8 Application of remote sensing image in the geological route selection of the Jiaozhou-Xinyi Railway
(a) Original fault image; (b) Fault image treated by edge filter. Arrows refer to the location of the fault

The new terminal of the Baiyun International Airport in Guangzhou had a construction area of 300000 m^2, ranking third among airports in China. The developed karst of the region, the hydrogeological complexity, and human mining activities aggravated the risk of ground settlement and foundation failure. The problem was unsolved even after 3735 boreholes were drilled and 5257 piles were installed in the early-stage investigation. In the late-stage investigation, besides a series of measures to obtain the characteristics of the karst distribution, TGO1.0 (Trimble Company, USA) was applied to generate 3D color images and contours of the bedrock surface to visualize the distribution and development of karrens, solution grooves, stone teeth, and rock pillars, as well as the distribution of soft soil (Fig. 9). In short, 3D image techniques enabled a clearer and more vivid foundation stability analysis.

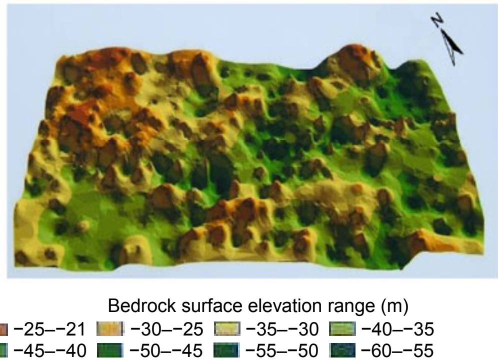


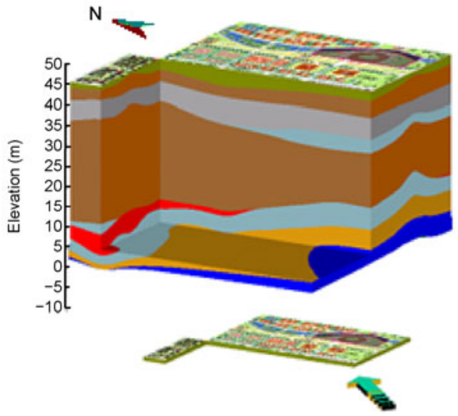
Fig. 9 3D image of the bedrock surface in the new terminal of the Baiyun International Airport project

Note that different kinds of 3D image visualization systems have been developed independently in China, some of which have been applied extensively in engineering. Fig. 10 shows the application of 3D image software based on the GIS technique in the central Olympic area and the risk management of the Beijing subway construction (Zhang, 2003).

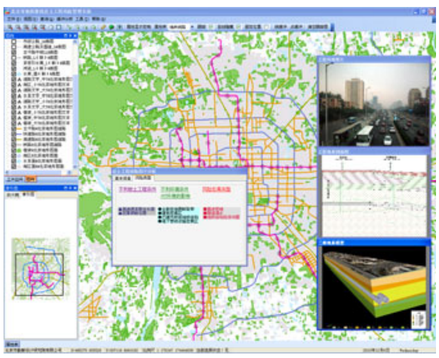
3.4 Advances in engineering monitoring

Engineering monitoring ensures the safety of a project, verifies design assumptions, and is important for accumulating engineering experience. The following examples serve to demonstrate the progress that China has made in this area.

A comprehensive program has been conducted for the deformation monitoring of high and steep slopes of permanent and temporary ship locks of the ship lift, one of the key projects in the Three Gorges Dam on the Yangtze River. There are steep slopes formed by the excavation of rock mass on both sides of the mountain, generally measuring 70 to 120 m high (with a maximum height of 170 m) and 2 km long. Such large artificial high slopes are rare both in China and abroad (Fig. 11). Excavation started in



(a)



(b)

Fig. 10 3D image of the geological condition in the central Olympic area (a) and application of the GIS technique and 3D visualization in the geotechnical engineering risk management system of the Beijing subway construction (Zhang *et al*., 2008) (b)

Fig. 11 High slopes of permanent and temporary ship locks of the ship lift in the Three Gorges Dam on the Yangtze River

1994, and was completed in 1999. In 1994, a network was set up for nonstop monitoring. The project was accuracy-demanding and difficult. The results of the deformation monitoring played a key role in ensuring the quality of the project. The main features of the monitoring included: (1) Theories on initial data error and on monitoring networks with different levels and irrespective of grades were proposed to guide the optimization of the deformation monitoring network. (2) Alongside the project, research was conducted, and new devices were developed. An automatic dam vertical displacement monitoring system and an automatic high-accuracy survey and monitoring system, which won the National Science and Technology Advance Award, were established. (3) The monitoring accuracy was ±1 mm, higher than the ±3–±5 mm specified by the code and the ±2 mm specified by the project.

Dam deformation monitoring was also conducted in the construction and operation phases of the Xiaolangdi Hydraulic Complex constructed on the Yellow River (Fig. 12). The monitoring lasted for 10 years, including establishing data network (points), and deformation monitoring of the near-dam bank slope, the partition wall of the stilling pond, the high slopes in the mouth and the dam area. The monitoring network was well designed and scientifically advanced. Highly automated devices such as the survey robot digital leveling apparatus were used. The monitoring provided a wealth of data, complete source information, and a comprehensive analysis of high accuracy. The automatic monitoring software developed for this purpose was convenient and nationally advanced. The comprehensive analysis of monitored data accurately showed the deformation process of the dam and ensured its safe operation.

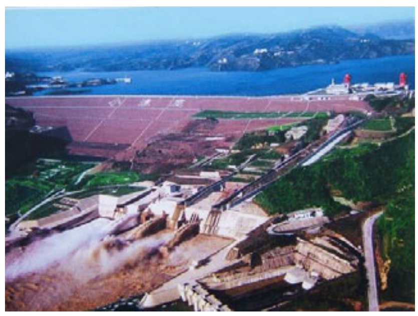


Fig. 12 Elevation view of the Xiaolangdi Hydraulic Complex on the Yellow River

The south anchor foundation pit of the Runyang Highway (Suspension) Bridge across the Yangtze River is 69 m long, 50 m wide, and 29 m deep. The retaining structure system consists of rows of bored soldier piles, a frozen thin soil wall as a watertight screen, and seven sets of reinforced concrete internal bracings. Such a retaining structure scheme posed a new challenge to Chinese engineers. Besides addressing difficulties such as the effect of frozen swelling stress on existing structures and the effect of raised temperatures during construction on frozen soil, information-enhanced construction monitoring was conducted. The monitoring system had the following features: (1) A large-scale automatic monitoring network for the retaining system with 760 sensors of different types yielded a maximum of over 4142 data points (Fig. 13). (2) An effective monitoring of frozen soil was established. Software was developed to enable nonstop monitoring of ten sections with high-quality sensors so that changes in the temperature field could be detected to avoid disasters. (3) The frozen swelling curve of the soil was drawn for the first time, and preliminary change characteristics of the temperature field and stress field were obtained. (4) The axial force of the internal bracings was monitored to guarantee safety. (5) A wealth of measured data was generated over an extensive period of time. In 540 d, 300000 monitored datasets were obtained. All this work has shown that engineering monitoring played an important role in ensuring the safety and optimal design of the retaining structure system for the deep excavation.

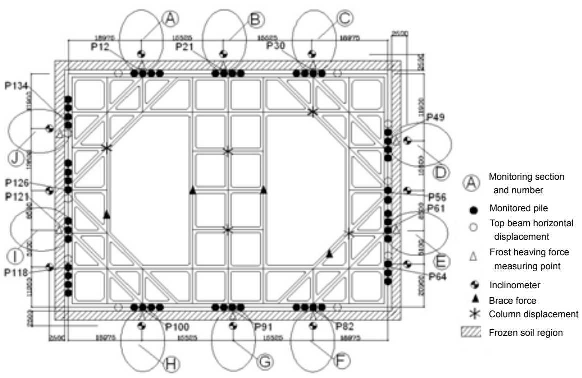


Fig. 13 Monitoring system of the south anchor foundation pit of the Runyang Yangtze River Highway (Suspension) Bridge (unit: mm)

4 Establishment of a large professional team and an extensive technical standard system

In achieving these technical advances, a standard system was formed gradually for the Chinese engineering investigation industry. Table 2 shows major Chinese national codes and industry codes in the geotechnical engineering discipline. Note that standards for the coal industry (MT/T), geological prospecting industry (DT or DZ), and forestry industry (LYJ) are not included. With another twenty regional standards yet to come, the standard system is very large. On one hand, it signals the establishment of a technical standard system with Chinese characteristics and wide applications. On the other hand, it exposes some problems which will be addressed later.

Meanwhile, China has established a huge team of site investigation professionals. Award-winning institutions in Table 1 include the State Power Cooperation, the China Hydropower Engineering Consulting Group Co., the Ministry of Railways, the China Nonferrous Metals Corporation, the Ministry of Construction, and local investigation institutions in Beijing, Shanghai, Shenzhen, Shaanxi, and Zhejiang. On a national level, there are still many other institutions and organizations not listed in Table 1. Member organizations registered at the investigation and geotechnical branch of the China Exploration and Design Association numbered over 306, making it perhaps the largest branch of its kind in the world.

5 Problems and disadvantages

From the above analysis, it can be seen that due to technical advances, we have lessened the disparity between the Chinese investigation industry and the international state-of-the-art. We have even achieved advantages in certain areas. However, as it is a large nation, there is imbalance in development among different regions, industries, and institutions in China. Overall, the major problem in the industry lies in the ongoing transition from the "engineering investigation mechanism" to the "geotechnical engineering mechanism". As a result, many organizations are still confined to providing source information, restricted by the following factors (Fig. 14).

Table 2 Summary of major Chinese national codes and industry codes in geotechnical engineering (after the national investigation master Zhao-qing BIAN)

Content	National code	Industry code							
	GB, GBJ, GB/T	Building construction (JGJ)	Urban construction (CJJ)	Thermal power (DL, DL/T, DLGJ)	Hydropower (SD, SL, DL, DL/T, DLJ)	Nonferrous metallurgy (YBJ, YS, YB/T)	Railway (TB, TBJ, TB/T)	Highway (JTJ)	Water transportation (JTJ, JTJ/T)
Soil classification	1				1		1		1
Soil-water test	2			2	5	2	3	4	
In-situ test	1	1			1	8	5	1	
Rock mass classification	1								
Rock mass test	1				2		1		
Engineering investigation	3*	5	3	11	9	14	9	3	2
Hydro-geological investigation			1		1	3	1		
Geophysical investigation			1	1	1	1	1		
Foundation design	1	4		1		3	3	6	4
Dynamic foundation	1					1			
Earthquake engineering	8**	2			1			1	1
Special soil	2	2					6		
Testing methods	1		1						
Ground improvement	1	3		2	2	5	3	1	3
Inspection and monitoring	1	3	1	1	2	1			
Geotechnical construction	4		1		4	4	6		
Subtotal***	28	20	8	18	29	42	39	16	11

* Including hydropower and railway engineering codes; ** including railway, thermal power, and nuclear power engineering codes; *** the total code is 211

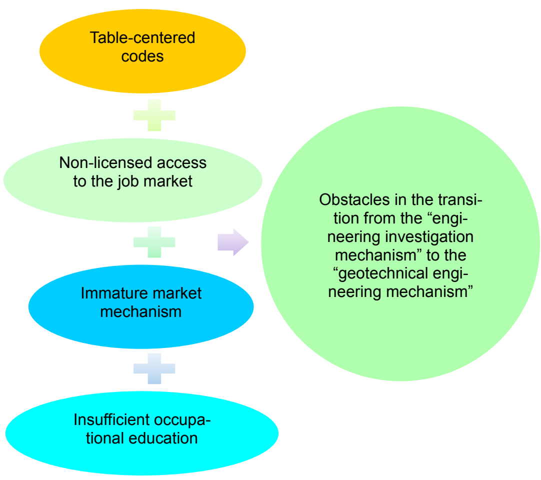


Fig. 14 Factors hindering the further transition of the investigation industry to the "geotechnical engineering mechanism"

5.1 Problems in the national standard regime (Chen, 2003)

Geotechnical standards have covered almost every aspect of construction engineering to guarantee safety and quality. However, while great benefits have been brought about by the existing standard regime, limitations should never be overlooked.

Generally, a code on geotechnical engineering consists of three parts: fundamental principles, application rules, and engineering parameters. Codes in developed countries and economic unions usually emphasize a grasp of fundamental principles, and treat application rules as no more than guidance on applying the principles. A detailed list of specific design parameters is rarely seen. A good example is the Euro Code 7, "Code for Geotechnical Design".

However, the development of the Chinese standard system has been strongly influenced by two factors. One is the changes to the administrative system. The other is the practical constraints stemming from the constitution of the investigation team in the old days, making the standard system heterogeneous, and undermining technical advances. For example, most of our codes are table-centered. By giving the physical or mechanical properties of soil and rock, engineering parameters can be obtained directly from tables without exception. These table-centered codes functioned in the past when nationwide construction projects were pressing and when investigation professionals did not have much background knowledge. Also, at the expense of efficiency, this methodology worked effectively because elementary safety could be guaranteed when people applied almost the same method to obtain the design parameters, wherever they were. However, as geotechnical engineering properties vary from site to site, scholars and engineers from developed countries are strongly opposed to the table-centered methodology. As Canadian experts GREEN and BECKER said, "Data for geotechnical design are site specified. Any statistics tend to pertain to one site or to one engineered material. There is not a material history from which various statistics can easily be developed". Their perception of and emphasis on engineering judgment reflected the objective principles of geotechnical engineering (Becker, 2001).

Although the current code regime is convenient, it neglects basic characteristics of geotechnical engineering, discourages research activities, and hinders the transition to the "geotechnical engineering mechanism".

5.2 Professional licensing system yet to be installed and insufficient occupational education

The discipline of geotechnical engineering emerged and grew in developed countries during the 1960s and 1970s. As an educational discipline, geotechnical engineering is clearly defined and identified. With continuous efforts, the concept of geotechnical engineering has been instilled among engineers, and related technical codes have been written. It seems that the time has come for a national licensing examination and a professional certification system to be installed.

Following the establishment of architecture and structural engineering disciplines, the preparation and operation of a professional licensing examination for geotechnical engineers started in 1998. In June 1998, a panel of geotechnical experts from related industries and universities were established to design and mark the examination papers. The national professional licensing examination was then administered. In the past ten years, six national examinations were organized from which more than 6000 professionals were awarded the title of "national registered geotechnical engineer". But a system that proves to be effective internationally is yet to be formally installed in China.

Associated with this issue is the problem of the engineers' lifelong learning.

At the 1st International Conference on Geotechnical Engineering Education and Training, 2000, Gibbos and Fairweather (1998) made a very relevant statement on the strategic significance of occupational education for engineers. They cited the book "Human Capital Investment" written by a group of famous experts from different countries in which it was claimed that about two thirds of all the prosperity the world had achieved was based on human intellectual capital, while the physical capital (such as engines, buildings, and infrastructure) and the material resources accounted for only one sixth. So the development of a country relies increasingly on its human resource and the education of citizens. Recently a Swedish social scientist asserted the concept of "more heads than hands", a biased but strong acknowledgement of the importance of human intelligence.

The quality of continuing education depends on many aspects, including the job requirements and the career development plan, but the requirements of a professional certification system are fixed and rigid. Prof. TOWNSEND from the University of Florida, USA stated that, currently, maintaining one's license is dependent upon demonstrated professional development hours (PDHs) (Townsend, 2005). Or simply, a licensee must demonstrate to the licensing board the satisfactory completion of specified activities. Admittedly, such a rigid requirement has certain limitations, but it does motivate geotechnical engineers to continuously update their knowledge.

In China, however, there is not yet a strong trend of lifelong learning among engineers nor any rigid rules or requirements in that regard.

5.3 Immature market mechanism

In a socialist market economy, a mature market mechanism is characterized by many features in this context including: (1) an admission mechanism that is consistent with the requirements of the market; (2) a mechanism for quality management and an environment that fosters technical advance; (3) a healthy competition mechanism; and (4) a mature and rational client group. In China's civil engineering market, low-price bidding, vicious competition, and other unregulated behaviors work together to bring about many low-quality projects, and geotechnical engineering likewise.

In summary, the above factors have hindered the transition of the site investigation organizations to the "geotechnical engineering mechanism".

6 Conclusions and prospects

A large investigative professional team characterizes Chinese geotechnical engineering. However, this team has little communication with the research and education teams. This paper describes the present situation in Chinese engineering investigation, in the hope of promoting communication and exchange with our colleagues in academia.

Several conclusions can be drawn:

1. For over half a century, the Chinese engineering investigation industry has emerged and grown. It has accomplished all kinds of investigations for key projects successfully and independently, some of which are world-class in terms of scale and difficulty. Since the 1970s, the industry started a transition to the "geotechnical engineering mechanism" and made great strides in geotechnical investigation, design, construction, and monitoring. The technical disparity with developed countries has been lessened.

2. China is a country with a large area and imbalanced development. In general, there are several deeply-rooted factors hindering the development and technical advances of the industry, such as problems in the technical standards system, market mechanism and professional certification system. All these should be addressed in line with the development of the industry and the country.

3. The practice of strategic "people-oriented" and "scientific development" concepts provides a new opportunity for the development of geotechnical engineering. Engineers will be increasingly engaged in geoenvironmental engineering, geotechnical earthquake engineering, forecast and management of geohazards, and implementation of the soft-engineering concept. By improving communication between scholars and engineers, an effective integration of industry, education and research will be achieved in geotechnical engineering.

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