CONSTRUCTION OF UNDERGROUND HYDRAULIC STRUCTURES AND TBM TECHNOLOGY IN CHINA

Fu Bingjun[1]，Grasso P[2]，Xu Shulin[2]
([1]*Institute of Geology and Geophysics*，*The Chinese Academy of Sciences*， *Beijing* 100101 *China*)
([2]*Geodata SpA*， *Torino* 10129 *Italy*)

Abstract This paper deals with the construction of underground hydraulic structures and TBM technology in China—— past，present and future. China ranks number one in the world in water power. But，the ratio of developed to potential hydropower is only about 20%. The exploitable water power in West China，where is featured by high mountain and complex geology，accounts for 83% of the total for China. Most of the project structures have to be located underground. The projected length of hydraulic underground openings per year is about 180 km. Several underground projects completed，under execution and planned are highlighted in this paper. Finally，general information about the development of TBM technology in hydraulic construction in China is outlined.

Key words underground hydraulic structure，TBM technology，China
CLC number U 455 **Document code** A **Article ID** 1000-6915(2003)09-1521-06

1 BACKGROUND OF HYDRAULIC CONSTRUCTION

1.1 China is rich in hydropower

China ranks number one in the world in water power. The total theoretical hydropower potential in China is estimated to be 676 000 MW and the developable hydropower is 379 000 MW.

1.2 China is short in water resources

The total volume of water resources in China is 2 800 billion m^3，ranking sixth in the world. But the available water for every Chinese person only amounts to 1/4 of the average amount used elsewhere in the world. China is a country with a shortage of water although the hydropower potential ranks first in the world.

1.3 China has a long history in water conservancy and more than half of the large dams in the world

According to preliminary statistics from ICOLD (International Commission on Large Dams)，the total number of large dams (H ＞15 m) completed world wide is about 42 000. Of these，24 200，i.e. more than half are in China.

1.4 China has a good perspective for water power potential

The ratio of developed to potential hydropower in developed countries is usually between 50%～90%，while in China the ratio is only about 20%. Bring this ratio closer to the developed country average poses tremendous challenges to China and to Chinese engineers.

1.5 China has a good perspective for hydraulic underground construction

The water power potential is concentrated in Sou-

Received 16 Sep. 2002.
Fu Bingjun：Male，Professor，Institute of Geology and Geophysics，The Chinese Academy of Sciences，Beijing 100101 China.

thwest and Northwest China. The exploitable hydropower in this area accounts for 83% of the total for China. The area is featured by：(1) high mountains，(2) deep and narrow valleys，(3) large discharge of flood，and (4) complex geology with high level rock stress，high earthquake intensity，active faults，rock slides etc.

These constraints require that most of the project structures (intake，diversion and discharge tunnels，power houses) have to be located underground.

2 A BRIEF REVIEW OF PAST-DEVELOPMENT IN THE FIELD OF HYDRAULIC UNDERGROUND CONSTRUCTION IN CHINA

Although the Chinese people have a long history in hydraulic construction，sustained scientific research in this field was undertaken only after the forming of the People's Republic of China in 1949. Comprehensive systematic research did not start until 1958 when many units from all over China were concentrated in Wuhan to form the "Three Gorges Rock Mechanics Research Group" under the leadership of National Committee for Science and Technology. One of the major research topics was to solve the stability of the large underground cavern of the huge project on Yangtze River. Since then，a series of large project containing underground complex have been successfully constructed.

Before 1979，although China was isolated from the outside world，relying on the forces we ourselves organized，a series of large underground structures have been constructed，such as：

(1) The Liujiaxia Project on upper reaches of Yellow River was completed in 60's of the last century. The size of the underground power house with an installed capacity of $2\times 225=450$ MW is 23.9 m× 60.9 m×85.1 m (width×height×length). The size of the unlined diversion tunnel at left bank is 14 m×14 m (width×height).

(2) The Baishan Project in Northeast China was completed in 70's of the last century. The size of underground power house with an installed capacity of $3\times 300=900$ MW is 25 m×54.3 m×121.5 m(width×height×length).

(3) The No.3 Yilihe diversion tunnel development in Southwest China was completed in 60's of last century. The length of diversion tunnel is 2 740 m，with diameter $\phi=3$ m. The available water head there is 723 m.

Since 1979，when China began to carry out open policy to the outside world，more and more hydraulic underground works have been built all over China，such as：

(1) The Lubuge Hydroelectric Power Station completed in 80's of last century in Yunnan Province is the first "window" opened to the world in Chinese hydroelectric system. Its influence，namely "Lubuge Impact" has spread over the country. The Lubuge station was constructed with financial support from World Bank and the governments of Norway and Australia. Many foreign specialists were involved as consultants. The station is a kind of diversion tunnel development with its installed capacity of 600 MW. Its intake tunnels have a total length of 9.38 km and mainly cut through limestones and dolomites. The Taisei Corp of Japan was awarded the contract to construct the tunnel. The project began in October，1984 and was finished in August，1988. The circular tunnel (ϕ 8.8 m) was excavated by using full section drilling and blasting method with a maximum monthly advance of 373.7 m and an average advance of 231 m which exceeded the world record of that time.

It should be mentioned that closely related to the Lubuge Project，in the 6^{th} five-year plan of the national economy(1980～1985)，a topic of "rapid excavation of underground works" had been included in the program of key research needs. It was consisted of (a) research on the stability of rock masses adjacent to large powerhouse caverns and associated support，(b) excavation machines and construction techniques for underground caverns，and (c) tunnel excavation by TBM(tunnel boring machine).

(2) The Yindaruqin Project completed in early 90's of last century is a kind of basin crossing development for transferring water from Datong River in Qinghai Province to Qinwangchuan River in Gansu

Province. The total length of the water transfer line is 86.9 km，in which 75.11 km，accounting 87% of the total is the cumulative length of 33 tunnels.

The longest tunnel Pandaoling，mainly passing through loosed sandstone，has a length of 15.72 km. The Kumagai Gumi Co. Ltd from Japan was awarded the contract to construct the tunnel with conventional method.

The tunnel Shuimogu(No.30A) with a total length of 11.65 km，mainly passing through muddy siltstone，sandstone of Tertiary system，and partly through crystalline limestone of Pre-Sinian system and loess of tertiary system. The CMC，SELI，TREV1 from Italy and No. 10 Hydraulic Construction Bureau of China were jointly awarded the contract. The project began in April and was finished in August 1992 with average monthly advance of 1 100 m，the maximum monthly advance of 1 408 m，the maximum daily advance of 75.2 m.

(3) The Wanjiazhai Yellow-River Diversion Project (WYRDP) is located in the Shanxi Province of China. The purpose of the project is to supply water from Wanjiazhai reservoir to the two important industrial cities of northern China，Datong and Taiyuan.

The project consists of General Main Line (GM)，South Main Line(SM)，Connecting Works(CW) and North Main Line(NW). The first stage of the project comprises GM，SM and CW. The second stage，NM.

The project involves a series of reservoirs，pumping stations，tunnels aqueducts，siphons and culverts.

The cumulative length of the 26 tunnels is 161.3 km，the longest one being 42.9 km in the first stage of construction.

The length of the longest tunnel in 2nd stage of construction is 44 km.

The tunnels No.6，7，8 of the General Main Line have a total length of 22 km and excavated diameter of 5.96 m. These tunnels mainly cut through limestones. The CMC and SEL1 Corp from Italy were awarded the contract to excavate the tunnels with double shield TBM. The project began in July，1994 and finished in September，1997.

The tunnels No.4，5，6，7 of South Main Line have a total length of 90 km，and mainly cut through limestone and mudstone. The CMC，Impregilo from Italy and No. 4 Hydraulic Construction Bureau of China were awarded the contract to excavate these tunnels. The project began in September，1997 and finished in May，2001. The circular tunnels (ϕ 4.82～4.94 m) were excavated by using double shield TBM.

The tunnel No. 7 of the Connecting Works has a length of 13.52km， and mainly cut through limestone and marly dolomite. The CMC of Italy was awarded the contract. The circular tunnel(ϕ 4.8 m) was excavated by using also double shield TBM. The project began in December 2000 and finished in September，2001.

There are 6 TBMs put into operation for rapid excavation of these tunnels. The maximum monthly advance is 1821.5 m. The maximum daily advance is 99.4 m.

(4) Underground works at Ertan Hydropower Project

Ertan Hydropower Station is located in Sichuan province on the upper reaches of Yalongjiang River. The maximum height of the double curvature arch dam is 240 m founded on basalt and syenite. The dimension of the main power house with installed capacity of $6\times 550 = 3\ 300$ MW is 25.5 m×65.7 m×242.9 m (width×height×length). The underground caverns are deep buried under the ground surface of 250～350 m at the left bank where the maximum geostresses of the surrounding rock masses are 20～38 MPa.

Two diversion tunnels with each cross section of 17.5 m×23 m are located at left and right bank，respectively. The design discharge of the tunnels is 13 500 m^3/s. The scale of the tunnel is considered as largest one in the world.

(5) Underground structures of Xiaolangdi Project

The Xiaolangdi Multipurpose Project on the Yellow River is located in Henan Province. The earth and rock fill dam is 154 m high，founded on sandstone，siltstone，and claystone.

At the left bank，a series of underground structures were provided，such as 3 free flow tunnels with rectangular cross section of 10.5 m×13 m，10 m×

12 m and 10 m×11.5 m，3 pressure tunnels with circular section of 6.5 m diameter，6 power tunnels with circular cross section of 7.8 m diameter，and 3 underground chambers of power house system. The dimension of the main power house is 25 m×57.9 m×251.5 m(width×height×length). The installed capacity of the power station is 1 800 MW.

There are also access tunnels，grouting tunnels，construction galleries，drainage tunnels，cable shafts，ventilation shafts etc. The total number of the underground works is 109.

The project was constructed with the finacial support from World Blank. Many foreign contractors and specialists worked for this project，such as Zublin from Germany，CIPM from Canada，Prof. W. Wittke from German，Dr. N. Barton from Norway，Dr. P. Grasso from Italy and so on.

There are more than 500 km tunnels and more than 100 underground hydro power stations completed in China. Among them，there are 17 pressure tunnels with a length longer than 5 km，in which the longest one is the diversion tunnel in Taipingyi Project in Sichuan Province，mainly passing through granite with heavily rockburst，with a length of 10.6km and a diameter of 9 m；27 free flow tunnels with a length longer than 5 km，in which the longest one is No. 7 diversion tunnel in South Main Line of Wanjiazhai Yellow River Diversion Project (WYRDP)，with a length of 42.9 m，and a diameter of 4.82～4.94 m；and 12 underground power houses with the installed capacity more than 100 MW，in which the maximum width of underground main power house is 25.5 m at Ertan Project，and at Dachaoshan Project，is 26.4 m.

3 FUTURE OUTLOOK

3.1 Large hydroelectric districts

China is planning to establish 12 large hydroelectric districts. The name of the district and its installed cpacity are as follows.

(1) Jinshajiang River 58 200 MW，

(2) Yalongjiang River 19 400 MW，

(3) Daduhe River 17 720 MW，

(4) Wujiang River 8 680 MW，

(5) Upper Yangtze River 28 900 MW，

(6) Nanpanjiang River & Hongshuihe River 13 290 MW，

(7) Middle Lancangjiang River 22 250 MW，

(8) Upper Yellow River 16 080 MW，

(9) Middle Yellow River 6 150 MW，

(10) West Hunan(Xiangxi) Region 9 120 MW，

(11) Fujian，Zhejiang，Jiangxi Region 14 870 MW，and

(12) Northeast China 11 980 MW.

The total installed capacity for projects in these districts will be 226 700 MW. By the end the 2010，the total installed hydropower capacity will be 125 000 MW.

3.2 Large dams

Some major projects with the maximum dam height ＞200 m planned to be under design or construction by the year of 2010 are listed in Table 1.

As mentioned above a series of the structures have to be located underground. We can take Xiluodu

Table 1 Large dams

No.	Name of project	Max. dam height/m	Installed capacity/MW	Type of dam
1	Xiluodu	273	12 600	Double culvature arch dam
2	Nuezhadu	258	5 500	Rock-fill dam
3	Longtan	192～216.5	4200/5400	RCC gravity dam
4	Xiaowan	292	4 200	Double culvature arch dam
5	Laxiwa	254	3 720	Double culvature arch dam
6	No.1 Jinping	305	3 000	Double culvature arch dam
7	Goupitan	225	2 000	Double culvature arch dam
8	Shuibuya	227	1 500	CFRD(Concrete faced rock-fill dam)

Project on Jinshajiang River as an example. The project has 2 power house systems located at left and right bank，respectively，with total installed capacity of 18× 70 = 12 600 MW. The dimension of each power house is 30 m×75 m×333 m(width×height×length). The underground installed capacity will be the largest one in the world after completion. At each bank，there are also 3 flood discharge tunnels with a cross section of 13 m×15m，9 diversion tunnels with a diameter of 10 m，and 3 tailrace tunnels with a diameter of 20 m.

In the 2nd construction stage of Three Gorges Project，6 power houses with a dimension of 30 m× 88.6 m×280 m(width×height×length) at the right bank will be constructed. The dimension will be the largest in the world after completion.

3.3 Long tunnels

Several case histories are as follows.

(1) Western Route Project(WRP) for transferring water from southern to northern China

The WRP will transfer water from the upper reach of the Yangtze River to the Yellow River in Qinghai Plateau —— the source region of the two rivers mentioned above. Bayankala mountain is the watershed between the Yangtze River and Yellow River. The bed elevation of the Yellow River is higher than the Yangtze by 80～450 m. For the water supply in the first stage of the WRP，5 large dams，7 tunnels and 1 channel will be constructed. The total length of the diversion line is 260.3 km，while the cumulative length of 7 tunnels is 244.1 km.

In addition to the complicated geology，earthquake and high geostress，there still exist the problems of high elevation，harsh weather and oxygen shortage，which will influence the efficiency of men and machines and induce some special difficulties during construction.

(2) No. 2 Jinping Project

No. 2 Jinping Hydropower Project on Yalong River is located in Sichuan Province. The installed capacity of the project is 1 600 MW. 6 intake tunnels with a diameter of 8.5 m and a total length of 20 km are to be excavated. The maximum depth of the tunnels is 2 600 m which is 100 m deeper than the Mont Blanc Tunnel in Apls. The tunnels will mainly go through limestone(60%) and marble. In construction，there will exist a series of difficulties，such as high geostress(max = 50 MPa) high rock temperature(up to 45℃～50℃)，rock burst，karst，waterinflow，and instability of the surrounding rock masses. Experience in dealing with some of these problems is lacking.

(3) Muoto Hydropower Project

Muoto Hydropewer Scheme on Yarlung Zangbo River is located in Tibet plateau. The project has an installed capacity of 43 800 MW，a maximum hydraulic head of 2 420 m，an intake discharge of 2 280 m^3/s，and a dam of 180～200 m height. Three pressure tunnels are designed with each one being 33.9 km in length and 13 m in diameter.

4 TBM TECHNOLOGY IN HYDRAULIC CONSTRUCTION IN CHINA

Several open full face TBMs for hard rock were developed under the leadership of National Committee of Science and Technology in 60’s of last century. Generally speaking，the beneficial result was not very satisfactory. In 80’s of last century，8 hard rock TBMs were manufactured and used in Xierhe Hydropower Project in Yunnan Province and Yinluanrujin Water Diversion Project near Tianjin City and so on. The average monthly advance was approximately 100 m at that time，amounting 1/5～1/10 of the international level.

In the end of 80’s of the last century，2 second hand TBMs for hard rock (ϕ 10.8 m)，manufactured by Robbins Co. were used in the No. 2 Tianshengqiao Hydropower Station to excavate the 3 long tunnels. The length of each tunnel is 9.8 km. A series of difficulties，such as karst，unqualified working staff，occurred during construction.

Finally，instead of TBM，conventional drilling and blasting method was used.

Since 90’s of last century，some successful case histories in using TBM by foreign contractors and Chinese partners in Yindaruqin Project，Wanjiazhai Yellow River Diversion Project(WYRDP) exerted a great influence in China. Some basic data related to the excavation are shown in Table 2.

In 2001，a well organized international workshop

Table 2　Some case histories

Project name	Diameter of tunnel/m	Max. monthly advance/m	
		by TBM	by D&B
Yindaruqin	5.5	1 408	70
WYRDP，general main line	4.8	1 200	70～100
WYRDP，south main line	4.8	1 821	100～120

on TBM and related engineering practice in conjunction with ISRM 2001-2nd ARMS，chaired by Prof. J. Reilly，former president，American Underground Construction Association(AUCA) and Prof. Qian Qihu，Member of Chinese Academy of Engineering，and helped by other experts，Chinese and international，exerted also a great influence in China.

The main topics of the workshop are

(1) advance in the field of TBM technology and related underground woks in China，

(2) advances in the field of TBM technology and related underground works international，

(3) discussion on approaches to set up a TBM industry in China，and

(4) to bring together the international cooperation of engineers，scientists，consultants，government officials etc. in the field of TBM development and underground works in China.

Additionally，a small exhibition of TBM technology was held.

The International TBM Workshop was held in Beijing in 2001 and was well attended.

Before that，a high level report “Joint Cooperation—Technology Development for Chinese Tunnel and Hydro Projects” compiled by Prof. J. Reilly，Dr. G. Arrigoni，Dr. Shulin Xu，Dr. P. Grasso was presented and translated into Chinese. A Chinese version of the report and a special issue related to the International TBM Workshop have been published in China.

Recently，a special Working Group related to TBM technology in China，headed by Prof. Qian Qihu，was organized. Some comments and suggestions have been submitted to top Chinese authorities.

APPENDIX

Name list of some foreign contractors，consulting Co.，research institutes，manufacturers involved in the Chinese underground works.

1. ITALY

(1) CMC
(2) CMC + SELI
(3) Geodata SpA
(4) Rodio
(5) Electroconsult
(6) Impregilo
(7) ISMES

2. JAPAN

(1) Aoki Corporation
(2) Taisei Corporation
(3) Kumagai Gumi Co.
(4) Shimizu Corp.
(5) Mitzubishi Co.
(6) Komatzu Ltd.

3. U.S.A.

(1) Robbins
(2) Bachtel Civil & Minerals Inc.
(3) Harza Engineering Co.
(4) Morrison-Knudsen Engineers，Inc.
(5) MTS-System.
(6) TerraTek Inc.

4. CANADA

(1) CIPM-Canadian International Program Management
(2) Golder Associates
(3) Graham Rawlings Consulting Ltd.
(4) Hydro-Quebec International

5. SWEDEN

(1) ATLAS COPCO
(2) Vattenfall Swedish State Power Board

6. NORWAY

(1) NGI
(2) Advisory Group of Norway(AGN)
(3) NOCON GROUP
(4) Statkraft(State Power Board)

7. FRENCH

(1) Coyne et Bellier
(2) Spie-Batignolles
(3) Electricite de France

8. AUSTRALIA

SMEC-Snowy Mountain Engineering Corp.

9. Switzerland

Amberg Consulting Engineer