Bull Eng Geol Environ
DOI 10.1007/s10064-010-0272-4

ORIGINAL PAPER

Jinping hydropower project: main technical issues on engineering geology and rock mechanics

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Received: 23 April 2009 / Accepted: 12 January 2010

Abstract In 1978, the Jinping Project was designed as an integrated hydroelectric power scheme on the Yalong River in Southwest China. Jinping I involves a 305 m high arch dam on the upstream side of the Great Jinping River Bend. Water is directed through the mountains in four 16.7 km long, c. 13 m diameter tunnels, beneath up to 2,525 m of overburden, to the Jinping II underground powerhouse where the head is 310 m. The combined schemes will produce 8,400 MW and an annual power generation of 40.8 TW.h.

Keywords Hydropower · Yalong River · Jinping Project · Geo-stresses · Arch dam · Deep underground caverns

Résumé En 1978, le projet Jinping a été conçu comme un dispositif intégré de production d'énergie hydroélectrique sur la rivière Yalong dans le sud-ouest de la Chine. Jinping I représente un barrage voûte de 305 m de hauteur, en amont du grand méandre de Jinping sur la rivière Yalong. L'eau est dirigée sous la montagne au travers de quatre galeries de 16,7 km de longueur et 13 m de diamètre, sous une couverture atteignant 2 525 m, vers l'usine hydro-électrique souterraine de Jinping II, après une chute de 310 m. Ce dispositif aura une puissance installée de 8 400 MW et produira annuellement 40,8 TW.h.

Mots clés Hydroélectricité · Rivière Yalong · Projet Jinping · Contraintes in situ · Barrage voûte · Cavités souterraines profondes

Introduction

The Yalong River, one of the tributaries of the Yangtze, originates in the southern foothills of Mt. Bayankala in Yushu Prefecture, Qinghai Province, China. The river enters Sichuan Province at Xiayisi. From its source to the confluence with the Yangtze, the Yalong River is 1,571 km long. It has a catchment area of 136,000 km^2, a drop in elevation of 3,830 m and an average annual flow of 1,910 m^3/s. The large flow and head of water mean that the river has a great potential as a source of hydropower. As a consequence, 21 cascade projects have been planned along the main reach of the river (Fig. 1), with a total capacity of 30,000 MW and an annual power generation of 150 TWh, making it the third largest of China's major hydropower bases, after the Yangtze River and the Jinsha River.

The first project on the Yalong River, the Ertan Project, was completed in 1999. The Jinping Hydropower Project is located on the Great Jinping River Bend in the lower reaches of the Yalong River (longitude East 101° to 102° and latitude North 28° to 29°) and is one of the largest hydropower projects under construction in China (Fig. 2). The Jinping Project, including Jinping I and Jinping II, will have a total installed capacity of 8,400 MW and an annual power generation of 40.8 TWh. In view of the very special topographical setting created by the Great Jinping River Bend, Jinping I and Jinping II, the so-called Hydropower Gemini, were investigated, designed and constructed contemporaneously. When the project is completed in 2013, the whole scheme will benefit from being operated under

This paper introduces the Jinping Project and the specific problems created by the topographic and geological setting.

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Published online: 30 March 2010

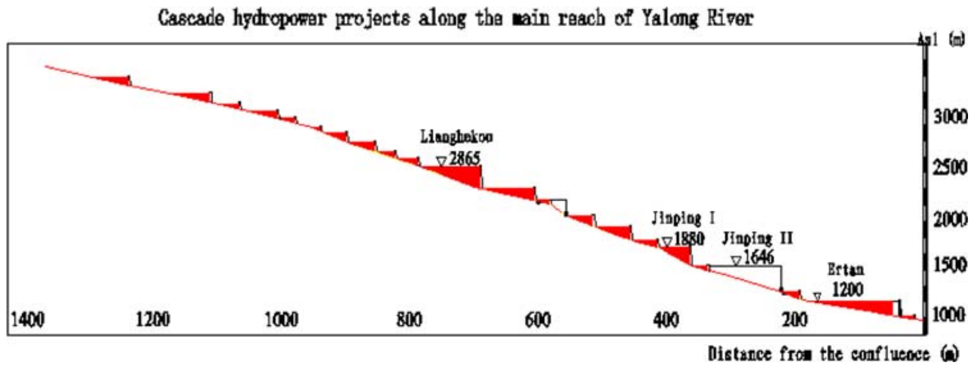

Fig. 1 Cascade hydropower projects along the main reach of Yalong River

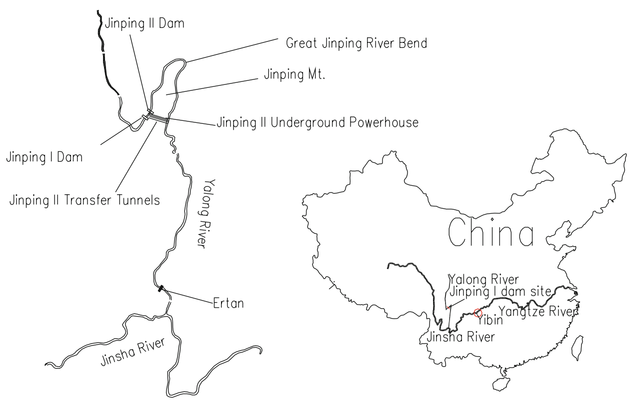

Fig. 2 Location of the Jinping Project

a unified management (Chengdu Hydropower Investigation & Design and Research Institute 2003).

Jinping I, located upstream of the Great Jinping River Bend, will have a capacity of 3,600 MW and annual power generation of 16.6 TWh. The 305 m high arch dam being constructed will be the highest in the world, creating a water head of 240 m for power generation.

Jinping II will consist of a sluice dam 7.5 km downstream of the Jinping I dam, with the tailrace water from Jinping I being diverted through the Jinping Mountain via four 16.7 km long tunnels with a gradient of 0.365%. A powerhouse is being constructed within the mountain on the downstream side of the 150 km long Great Jinping River Bend where a 310 m head of water will be used for power generation. Jinping II will have an installed capacity of 4,800 MW and an annual power generation of 24.2 TWh (East China Hydropower Investigation & Design and Research Institute, 2005).

In view of the topography and geological setting, the project team faced a series of huge technical issues related to engineering geology and rock mechanics, including:

1. The safety of the underground caverns, created in rocks with particular characteristics and under high geo-stress conditions.
2. Predicting and managing the groundwater which, because of the elevation, has a very high piezometric pressure;
3. Operation of the TBM under high geo-stresses and high groundwater pressures;
4. Constructing the dam foundations and abutments in strata where deep stress release fractures have developed and where the valley has been incised;
5. Managing the unloading and relaxation of the base excavation for the dam;
6. Stability of both the high cut slopes necessary for the arch dam and the natural steep mountain sides.

This paper discusses the background to the project and some of the initial challenges faced in its concept and construction.

Brief for the Jinping Projects

A computer simulated "bird's eye" view of the 305 m high arch dam is shown in Fig. 3. The Jinping I project will be equipped with six Francis turbines, each rated at 600 MW. The annual average flow at the dam site is 1,200 m^3/s. The normal water level of the reservoir will be 1,880 m asl and will fluctuate by 80 m such that the dead water level is 1800 m asl. The total reservoir storage will be 7.76×10^9 m^3; effective storage of 4.91×10^9 m^3 and dead storage of 2.85×10^9 m^3. After 100 years operation and sedimentation, the effective storage is computed to remain about 4.4×10^9 m^3.

The four tunnels linking the Yalong River at Jinping I to the powerhouse of Jinping II have a maximum overburden of 2,525 m. The 13 m diameter drill and blast and the 12.4 m diameter TBM tunnels will form the largest hydraulic tunnel complex in the world. A computer simulated "bird's eye" view of the sluice dam is shown in Fig. 4. Jinping II will be equipped with eight Francis turbines, each rated at 600 MW. The reservoir storage at the intake structure (indicated as Jinping II Dam in Fig. 4) will have a water level of 1,646 m asl, a total storage of 14.28×10^6 m^3 and an effective storage of 5.02×10^6 m^3. It will be regulated on a daily basis, although in operation with Jinping I it will be regulated annually to take account of the seasonal rainfall, river flow etc.

Fig. 3 Computer simulated "bird's eye" view of the Jinping I arch dam

Fig. 4 Computer simulated "bird's eye" view of the Jinping II sluice dam

Only 7,000 people needed to be resettled from the reservoir area: a very small number for such a large scheme. The total cost is estimated at RMB 54.4 billion Yuan (c. 8 billion US $). About 70% of the electricity generated from the project will be transmitted to the developed area in Eastern China through a circuit of ±800 kV DC electric power transmission lines, with the remaining 30% being transmitted to Sichuan and Chongqing.

History of the project

The Jinping Project was conceived in the 1950s and was considered in three initial stages: planning, pre-feasibility and feasibility. In 1978, the Chengdu Hydropower Investigation & Design and Research Institute (CHIDI) completed "The study report of the development mode of the Great Jinping River Bend" which recommended that "two cascades be built, with a high dam, and then a sluice dam to divert the water through long tunnels for power generation, and the sluice dam be constructed first". In 1992, CHIDI completed "The study report of the planning of the lower reach of Yalong (from Kala to the confluence)."

Fig. 5 River closure at Jinping I in Dec. 2006

The pre-feasibility and feasibility study of Jinping I and Jinping II were carried out respectively by CHIDI and the East China Hydropower Investigation & Design Research Institute (ECIDI), including a comprehensive geological investigation and exploration. CHIDI completed the pre-feasibility report for Jinping I in 1998 and the feasibility report in 2003 while ECIDI completed the pre-feasibility report for Jinping II in 2003 and the feasibility report in 2005.

Over 23,000 km^2 of geological mapping as well as site investigation works were carried out in the feasibility study period. CHIDI focused on the selection of the dam type and the site for Jinping I, while ECIDI focused on the feasibility of constructing the long tunnels to the Jinping II powerhouse and excavated a 5 km long exploratory tunnel from the Jinping II side towards Jinping I. The area is considered to have a seismic intensity of VII hence a peak acceleration of 0.1 g was taken into account in the design. Researchers from other institutes and universities as well as international consultants contributed to the study.

Preparatory construction work on the Jinping Project began in 2003. The enabling works included c. 200 km of roads, often on sidelong slopes involving cut/fill, water and electricity supply, access tunnels etc. Construction of Jinping I formally started in November 2005 and the river was diverted in December 2006 (see Fig. 5). The construction of Jinping II formally started in January 2007, the two 17.5 km long access tunnels were excavated and completed in July 2008. As a consequence the river at Jinping II was diverted in November 2008. Commissioning of the first unit is scheduled for 2013 and the whole project will be operational in 2015.

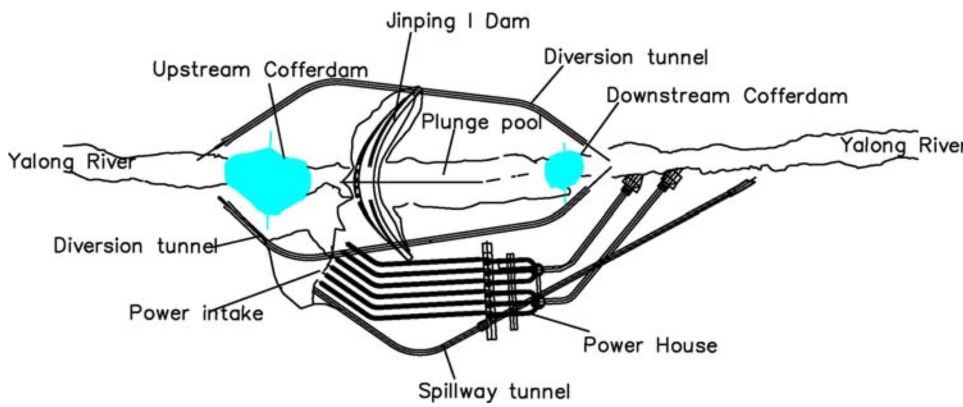

Fig. 6 Layout of the main features of Jinping I

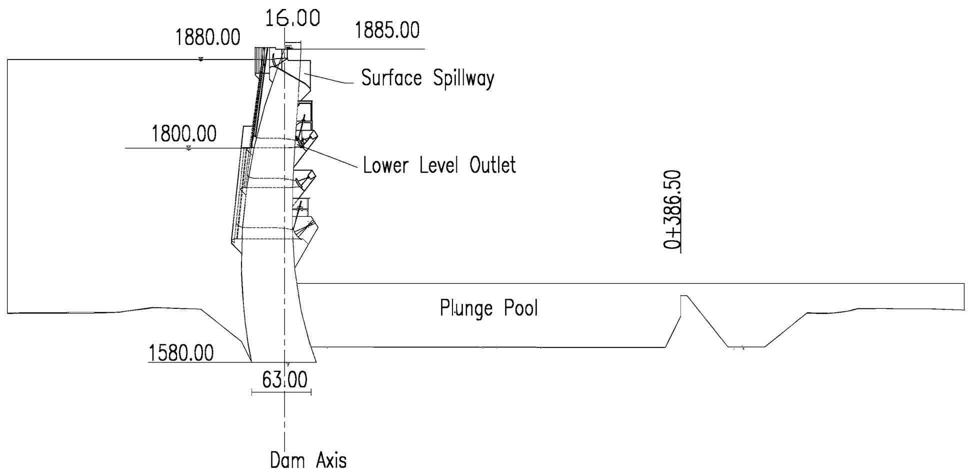

Fig. 7 Cross section of the arch dam of Jinping I

Layout of the project

Jinping I consists mainly of a high arch dam, a power generation complex on the right bank, flood release structures and diversion tunnels.

1. The 305 m high concrete double-curvature thin arch dam will be the highest arch dam in the world when completed and require 4.737×10^6 m^3 of concrete. The aggregate is produced locally using metamorphosed sandstone and slate and marble. At the crown cantilever, the thickness will be 16 m at the crest and 63 m at the base. The arc at the crest is 552 m long.
2. The power generation complex, located on the right bank of the Yalong River, consists of a concrete intake structure, six 9.5 m diameter penstocks, an underground powerhouse 277 m long × 29.2 m wide × 68.83 m high, a surge chamber downstream of the powerhouse, and two 15 m × 16.5 m inverted U-shaped tailrace tunnels.
3. The designed discharge capacity is 12,109 m^3/s, via four surface spillways (2,992 m^3/s), five lower level outlets (5,466 m^3/s) and a 1,400 m long spillway tunnel on the right bank (3,651 m^3/s).
4. Two 15 × 19 m inverted U-shaped 1,200 m long diversion tunnels.

The general layout and dam cross section for Jinping I are given in Figs. 6 and 7.

Jinping II consists mainly of a diversion tunnel and a sluice dam on the west side of the Jinping Mountain, four headrace tunnels through the mountain and an underground powerhouse complex on the east side of the mountain.

1. The 14 m × 15 m inverted U-shaped, 604 m long diversion tunnel will accommodate the normal river flow after commissioning of the project.
2. The 165 m long concrete sluice dam is 34 m high.
3. Four headrace tunnels, with an average length of 16.7 km, will pass through the Jinping Mountain beneath up to 2,525 m of overburden.
4. The two access tunnels (with designed Sections 5.5 m × 5.7 m and 6 m × 6.3 m, respectively) through the Jinping Mountain to connect the two projects have an average length of 17.5 km. In addition, there will be a 17.68 km long, 7.2 m diameter drainage tunnel.
5. The underground powerhouse complex includes a surge chamber upstream and eight tailrace tunnels.

Fig. 8 Computer simulated view of the Jinping II underground powerhouse

The powerhouse itself is 352.4 m long × 28.3 m wide × 68.7 m high (see Fig. 8).

Main geological and rock mechanics challenges

The safety of the underground caverns, created in rocks with particular characteristics and under high geo-stress conditions

The Jinping Project, with its large underground caverns, is located in an area of high geo-stress in Southwest China (Gong et al. 2009; Jiang et al. 2009; Shan 2009; Wu et al. 2009). As a consequence, the behaviour of the rock mass requires special consideration. Figure 9 shows the cross section of the headrace tunnels of Jinping II, which will be excavated by both drill and blast and TBM. Most of the tunnel sections have an overburden of >1,500 m, hence rock bursts are likely to occur during the construction period (see Fig. 10)—an important issue for the safety of personnel.

Fig. 10 Area of rock burst in the headrace tunnels of Jinping II

Predicting and managing the groundwater, which, because of the elevation has a very high overburden pressure

The geological exploration showed that in the mountains in which the long tunnels of Jinping II would be constructed, the groundwater flow is mainly along the discontinuities; some opened by karstic dissolution although there is no obvious exposed structural anomaly. As a consequence, underground water at high pressure burst into the drives during the excavation of the access tunnels (see Fig. 11). It was very difficult to predict the location and distribution of the water flows using the usual hydrogeological forecasting methods, hence pre-drilling was necessary to predict the location and quantity of the groundwater more accurately. Once assessed, pre-grouting in advance of the excavation was carried out in an attempt to seal the main water flows. If this was not done, groundwater could burst into the tunnel with pressures of up to 12 MPa, which would have to be sealed with high pressure grouting.

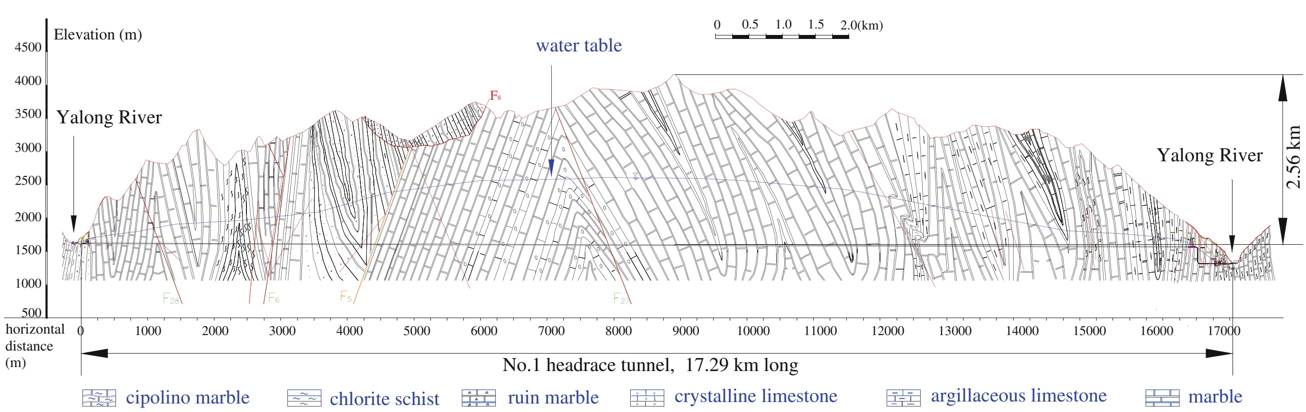

Fig. 9 Cross section of the No.1 headrace tunnel (After Shan Zhigang 2009)

Fig. 11 High pressure ground water bursting in the access tunnels

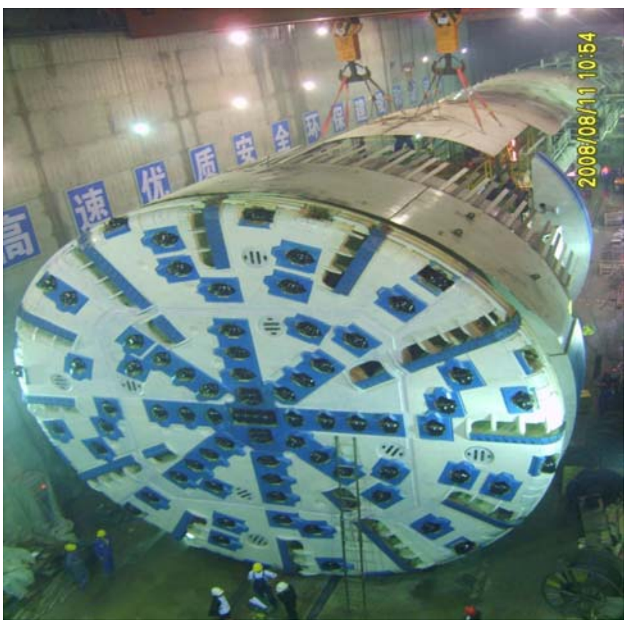

Fig. 12 TBM used to excavated the headrace tunnels of Jinping II

Operation of the TBM under high geo-stresses and high groundwater pressures

A decision was taken to excavate part of two headrace tunnels and the Jinping II drainage tunnel using a TBM (Fig. 12), after considering safety and the construction progress. It was only practical to use the TBM on the Jinping II side where the slopes were moderate and the drainage constructed meant that the machine would not be flooded. The use of a TBM in conditions of high geo-stresses and high pressure groundwater is very rare. Excavation speed under normal conditions and maintenance of the TBM after rock burst or high pressure

Fig. 13 Zone of crushed weak rock in the left dam abutment of Jinping I

Fig. 14 Deep buried fissure in the left dam abutment of Jinping I

groundwater ingress were the main issues. However, a maximum rate of advance of 515 m per month was achieved, compared to 300 m just for the upper half-range using drill and blast.

Constructing the dam foundations and abutments in strata where deep stress release fractures have developed and where the valley has been incised

The geological condition of the dam abutment on the left bank at Jinping I is very complicated. Lamprophyre dykes and crush zones of soft rock (Fig. 13) are present as well as stress release fractures which can be found as far as 330 m (max horizontal depth) from the face; see Fig. 14 Qi et al. 2004). The dam abutments have been reinforced to support the 305 m high dam (1,580-1,885 m asl) and the huge pressure of the stored water. Such work as high-pressure consolidation grouting and a concrete grid replacement of the near surface rocks has also been undertaken (Qi et al. 2009; Gong Manfu et al. 2009; Huang et al. 2009).

Fig. 15 Deformation of unloading and relaxation of the dam foundation surface

Fig. 16 The natural high slope of the *V-shaped* canyon (After Qi Shengwen et al. 2009)

Managing the unloading and relaxation of the base excavation for the dam

The river slopes in the dam area of Jinping I are high (c. 530 m) and steep (c. 40 to 70°), hence the geo-stresses are high under natural conditions, especially at the toe of the slope. The major principle stress has been measured as >40 MPa (Gong et al. 2009). In order to construct the dam, the final surface has to be stabilized to produce a firm abutment. During these works, some of the high geo-stresses will be released (Fig. 15). Controlling the deformation of the abutments and strengthening the dam foundation surface has been a major issue.

Fig. 17 Excavation of the left dam abutment of Jinping I

Stability of both the high cut slopes necessary for the arch dam and the natural steep mountain sides

The project area of Jinping I is a typical deep V-shaped canyon (Fig. 16). The slopes on the left bank have an excavation height of 530 m and required the removal of some 5.50 million m^3 of material (Fig. 17). About 8,000 anchors amounting to a total length of c. 400 km were required. This is one of the highest project slopes and presented the most difficult stability problems of all the hydropower projects currently being constructed in China.

Conclusions

The paper introduces the Jinping Project in Southwest China, which will provide significant social and economic benefits. The huge amount of electricity generated from the project, designed to be 40.8 TWh per annum, will be transmitted to the developed area in Eastern China and Sichuan and Chongqing.

The project will set a number of world records: the world's highest arch dam will be constructed for Jinping I and the world's largest hydraulic tunnel complex will be constructed for Jinping II. In the meantime, there are a huge number of technical challenges to be overcome.

1. V-shaped deep valley, high geostresses, and development of cracks due to stress release.

2. Particular characteristics of the deep rock mass and very high pressure groundwater caused by 2,525 m of overburden.
3. TBM used in the long tunnel excavation under the complicated hydrogeological conditions.
4. Associated remediation to ensure the safety of the long tunnels, abutments and foundations in the light of the rapid rate of construction included optimizing the excavation, quick provision of strong supports, grouting, concrete replacement etc. At the end of the project, some of the access tunnels will be filled with reinforced concrete.

The successful construction of the Jinping Project will provide important experiences for the design and construction of large scale hydropower projects with high dams and large underground caverns.

References

Chengdu Hydropower Investigation & Design and Research Institute (2003) The feasibility Report of Jinping I Hydropower Project, Chengdu, China

East China Hydropower Investigation & Design and Research Institute (2005) The feasibility Report of Jinping II Hydropower Project, Hangzhou, China

Gong M, Qi S, Liu J (2009) Engineering geological problems related to high geo-stresses at the Jinping I Hydropower Station, Southwest China. Bull Eng Geol Environ (submitted)

Huang R, Lin F, Yan M (2009) Deformation mechanism and stability evaluation for the left abutment slope of Jinping I Hydropower Station. Bull Eng Geol Environ (submitted)

Jiang Q, Feng X, Xiang T (2009) Rockburst characteristics and numerical simulation based on a new energy index: a case study of a tunnel at 2500 m depth. Bull Eng Geol Environ (submitted)

Qi S, Wu F, Yan F, Lan H (2004) Mechanism of deep cracks in the left bank slope of Jinping first stage hydropower station. Eng Geol 73(1–2):129–144

Qi S, Wu F, Zhou Y, Song Y, Gong M (2009) Influence of deep seated discontinuities on the left slope of Jinping I Hydropower Station and its stability analysis. Bull Eng Geol Environ (submitted)

Shan Z (2009) High in situ stress break and controlling during excavation of deep-lying tunnel in Jinping II Hydropower Station. Bull Eng Geol Environ (submitted)

Wu F, Hu X, Gong M, Liu J, Ren A (2009) Unloading deformation during layered excavation for the underground powerhouse of Jinping I Hydropower Station, southwest China. Bull Eng Geol Environ (submitted)