The Adaptability to Fault Slip and Seismic Behavior of Exposed Steel Penstock Crossing Active Fault

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Abstract. By an exposed steel penstock crossing an active fault in high earthquake-intensity areas, the adaptability to fault slip and seismic behavior of the penstock is analyzed by the finite element method in this paper. The results show that it is effective to set several bellow-type expansion joints and arrange sliding and hinge supports at intervals for penstocks crossing active faults to adapt to fault slip. Most of the mass is concentrated on penstock, and each penstock section has a larger stiffness when there are bellow-type expansion joints at the two ends of the penstock section, so the penstock moved nearly rigidly under an earthquake and the stress is caused by internal water pressure mainly. However, as a result of the expansion joints, the axial displacement of the penstock is large and the supporting rings of hinge support bend seriously. Thus it is supposed to avoid excessive expansion joints to improve the axial seismic capacity. In addition, the sliding supports can work as base isolation supports, and excessive horizontal displacement can be restricted by hinge supports, and therefore it is of advantage not only to adaptability to inhomogeneous ground displacement but also to structural seismic behavior to arrange sliding supports and hinge supports at intervals. At the same time, the supports should have enough joint strength, and it is necessary to set restraining devices to avoid the penstock sliding off the supports.

Keywords: component; inverted siphon exposed penstock; fault slip; seismic behavior; bellow-type expansion joint; sliding support; hinge support.

1 Introduction

Water transfer is an effective measure to solve the contradiction between the supply and demand of water resources. For example, the South-to-North Water Diversion Project in China is a basic strategic project which aims to improve domestic water resources allocation and support economic and social development [1]. Southwest China is rich in water resources. However, the water transfer projects in this area are

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often subjected to complex geological conditions. In particular, the long-distance water transmission pipelines may cross the fault or even the active fault. For example, the Zhangjiu River diversion project in Yunnan Province crosses more than 60 faults with a width of more than 10m, of which the largest main fault is the Pudu River fault with a width of 150m [2-3]. For the deep active fault zone, the width often reaches above 100 m, and its activity law and deformation features have a great influence on the stability and safety of the project. Therefore, the ability of the structure to adapt to the potential sliding of active fault should be investigated carefully.

At the same time, due to the high seismic intensity in southwest China, the seismic safety problems faced by water diversion projects are very prominent. There are several examples of seismic damage in pipeline structures: urban water supply pipes with a diameter of 2m were severely bent into a "V" shape in the 7.6-magnitude Chi-Chi earthquake in Taiwan on September 21, 1999. The aqueduct collapsed and the inverted siphon was damaged in three sites in the 6.4-magnitude earthquake in Ning-'er, China, on June 3, 2007 [4]. The steel expansion joints ruptured at Shapai Hydropower Station, resulting in flooding of the plant, in the Wenchuan earthquake on May 12, 2008 [5]. For the water diversion and transfer project, once an important joint is damaged in the earthquake, water diversion across the line will be affected and even lead to serious secondary disasters [6].

At present, pipeline structures passing through faults at home and abroad mainly adopt the method of strengthening structural flexibility to adapt to the deformation of faults, and structural measures mainly include expansion joints, sliding supports, etc. For example, the supports of the trans-Alaska crude pipeline is set as sliding supports, and the pipeline can allow 0.512m lateral slip to adapt to fault dislocation deformation. The tunnel of Ximahe II Saizhu Hydropower Station is affected by an active fault, with a range of approximately 350 meters. The exposed steel pipe inside the tunnel, expansion joints, and alternatively arranged sliding supports and fixed supports have been applied in the tunnel. Having experienced the Wenchuan earthquake (8.0 magnitude) in 2008 and the Ludian earthquake (6.5 magnitude) in 2014, the tunnel has been operating well since then. However, as the flexibility of the structure increases, it may experience significant displacement when subjected to earthquake action. Especially for exposed steel pipes, duo to the large water quality within the pipe and the pipe supports with weak constraints, the exposed steel penstock is a typical top-heavy structure and disadvantageous to earthquake resistance.

Due to the action of active faults, pipelines may experience the axial and vertical displacement, leading to the significant strain and failure within the pipeline. Most studies on the adaptability of pipelines crossing faults are focused on buried pipelines [7], and there is relatively little research on exposed steel pipes. This paper will investigate the structural adaptation and seismic performance of steel penstocks under sliding displacements of active faults by combining an exposed steel penstock crossing an active fault with the finite element method.

2 Calculation models and methods

2.1 Project Overview

Fig.1 is a central longitudinal section of an inverted siphon pipeline in the water conveyance line, which is located in Yunnan Province, China. The seismic intensity of the site is up to 9 degrees. The steel pipe full-length 280m and across a fault zone with a width of 300m and about 80% of the pipe is located on the fault fracture zone. Due to poor foundation conditions and considering the adaptation to the fault creep and stick-slip deformation, and the safety of seismic resistance, the exposed steel penstock type is adopted. Four anchor blocks, eight expansion joints, nine hinge supports and nine sliding supports are arranged.

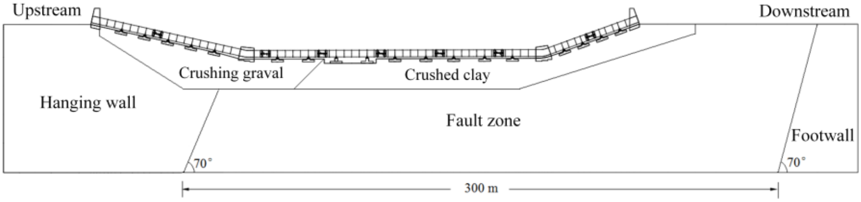


Fig. 1. Longitudinal profile of the pipeline

The inner diameter of the steel pipe is 3.4m and it bears the maximum internal pressure of 0.38MPa. Q345R was used for the penstocks, support rings, stiffeners and other structural steel, while C15 concrete was used for the anchor blocks and support piers. Corrugated pipe use compound reinforced U-shaped bellows with an inner diameter of 3400mm, an axial stiffness of 2.905 kN/mm and an axial and vertical allowable deformation of 100mm. The main material mechanics parameters are shown in Table 1.

Table 1. Material mechanics parameters

Material	Elasticity modulus /MPa	Poisson's ratio	Density /kN·m-3	Design tensile strength /MPa	Design compressive strength /MPa
Steel Q345R	2.06×10^5	0.30	78.5	290	290
Concrete C15	2.20×10^4	0.167	24.0	0.9	7.50
Crushed clay	6~9	0.40	17.0	—	—
Weakly weathered limestone	5000	0.27	26.0	—	—
Crushing gravel	100～300	0.20	22.0	—	—

2.2 Calculation model

The finite element mesh is shown in Fig.2. The model includes steel pipe, corrugated pipe, supporting rings, stiffener rings, anchor blocks, supports, and foundation. The numbers of each component are shown in Fig.3 and the supporting ring and its characteristic points are shown in Fig.4. The steel pipe, the supporting ring, and the stiffener ring are simulated by the shell element, and the concrete and the foundation are simulated by the eight-node solid element. The corrugated pipe is equated and simulated by the beam element, and the middle connecting pipe is simulated by the pipe element. The provision of surface-to-surface contact elements between the sliding plates of the sliding support allows relative sliding to occur. The left and right sides of the model foundation, the upper and lower sides and the bottom of the model are both subjected to normal constraints.

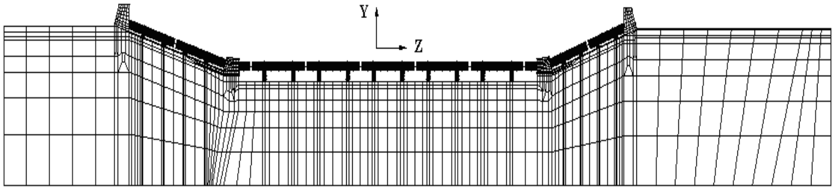
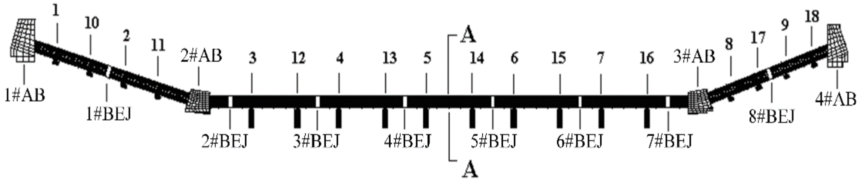


Fig. 2. Finite element meshes



Note: 1~9 sliding supports, 10~18 hinge supports, AB- concrete anchor block, BEJ- bellows expansion joint

Fig. 3. Supports and bellow-type expansion joints

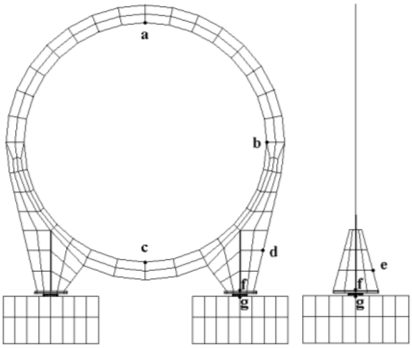


Fig. 4. Supporting rings and feature points

2.3 Fault creep dispalcement

This article only discusses the displacement caused by fault creep. The horizontal and vertical displacement of this fault respectively accumulated about 1.63 ± 0.67m and 0.99 ± 0.45m in 100 years. The designed service life of the steel pipe is 30 years, and in service life, the horizontal and vertical displacement of the fault are up to 0.690m and 0.432m respectively.

The creep movement of the fault is slow. This paper assumes that the geomaterials are continuous, and the creep displacement is the relative displacement between the hang wall and footwall. The footwall of the fault is fixed and the hang wall is shifted relative to the footwall. The fault is perpendicular to the pipe axis. As shown in Fig.5, the uplifted displacement is applied to the bottom of the foundation. The bottom of the hanging wall is uniformly lifted by 0.432m. The displacement applied to the fault fracture zone is linearly distributed. The horizontal compression displacement of the hang wall to the downstream is 0.69m.

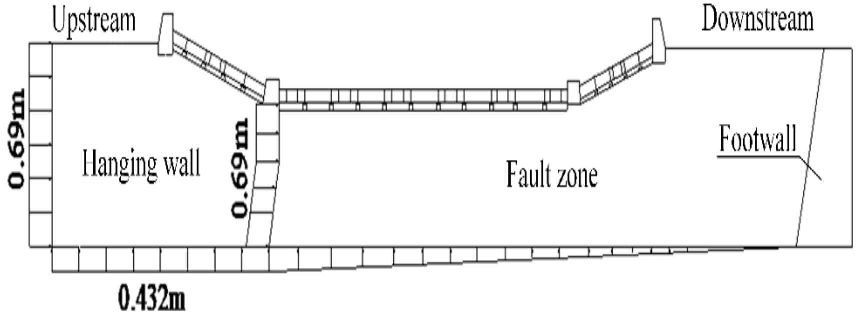


Fig. 5. vertical lifting and horizontal compression displacement

3 Adaptability of pipeline structure to fault dislocation

In order to adapt to the dislocation displacement of the fault, there are 8 expansion joints along the pipeline. Also, one hinge support and one sliding support are arranged between the adjacent expansion joints. Fig.6 shows a typical pipeline layout. One anchor block(or hinge support), one expansion joint, one sliding support and one hinge support are arranged from left to right in sequence. Table 2 shows the axial displacement of the key points shown in Fig.6, where point a1~ e1 are on the pipeline axis, f1 and g1 are at the center of the support base plate. Point c1, d1, e1 and g1 have the same displacement. The right end of the expansion joint is moved with the hinge support. The compression displacement between the anchor block and the hinge support is absorbed by the expansion joint. The slip amount of the sliding support is basically equal to the compression of the foundation between the sliding support and the hinge support.

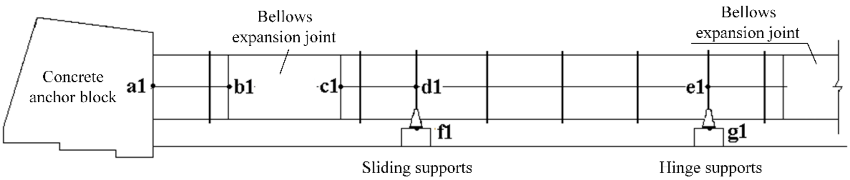


Fig. 6. Compensator layout

Table 2. Axial displacement of feature points

Key points	a1	b1	c1	d1
Displacement/ mm	686.2	685.8	634.8	634.4
Key points	e1	f1	g1	Sliding support slip
Displacement/ mm	633.4	655.5	631.4	19.3

Table 3 lists the axial deformation of the expansion joints. The expansion joints No. 2 ~ No. 7 shared a total amount of 428.1mm compression, and the total compression displacement between No. 2 and No. 3 anchor blocks is 438.0mm. It can be seen that the displacement is mainly borne by the expansion joints, while the steel pipe carries very little displacement. Therefore, the pipe will not be seriously deformed, and the stress of the pipe is still mainly generated by the internal water pressure and gravity.

Table 3. Axial displacement of feature points

Number	1	2	3	4
Compensation /mm	0.3	51.0	62.6	71.9
Number	5	6	7	8
Compensation /mm	73.6	72.0	97.0	37.27

The results show that by installing multiple expansion joints between the anchor blocks, and spacing arranging sliding support and hinge support, the steel pipe can perform well during the service life under the fault creep. If there is a strong earthquake, and a sudden surface rupture occurred, the expansion joints can control the extent of the damage without damaging the entire pipeline.

4 Seismic behavior of steel pipe

The dynamic time history analysis is carried out. The horizontal seismic wave is shown in Fig.7, and the vertical seismic acceleration is taken as two-thirds of the horizontal. The foundation is massless and the damping ratio is 0.05. Only the inertial effect of the water inside the pipe is taken into account, and the water is simplified to the additional mass of the pipe wall. Before dynamic analysis, the static analysis of normal operating conditions is carried out to obtain the initial state of dynamic analysis.

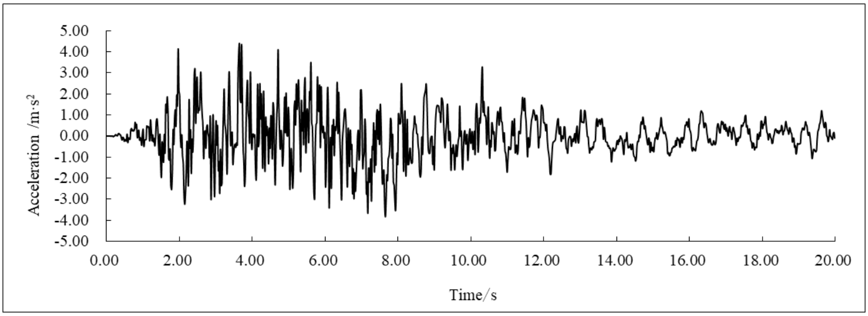
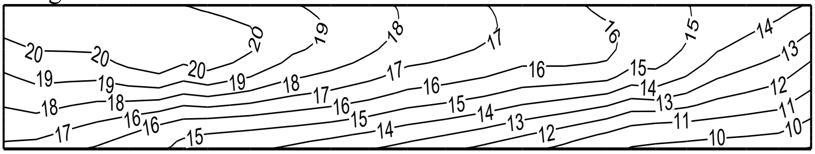


Fig. 7. Horizontal acceleration time history

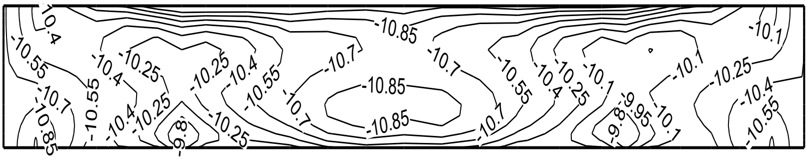
The straight segment has a total length of 150m. There are only two anchor blocks at the two ends and 6 expansion joints in the middle. The pipe between the two adjacent expansion joints, the sliding support and the hinge support form a relatively independent structural unit. Because the constraints are relatively small, the earthquake response is relatively large. Moreover, the seismic response of each structural unit is similar, and the following will take the pipe section between the expansion joints No.4 and No.5 as an example to illustrate.

4.1 Displacement analysis

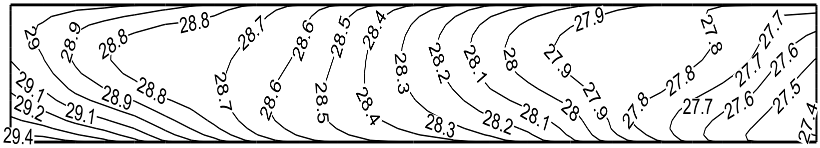
Fig.8 is an envelope diagram of the displacement components of the steel pipe. For long-span and multi-span structures, the main deformation and damage usually occur in the horizontal direction. The sliding support and the superstructure can slide relatively in the horizontal direction, and the horizontal displacement changes suddenly above and below the contact surface of the sliding plate. Because the constraint on the pipe in X-direction at the sliding support is smaller than that at the hinge support, the X- direction displacement decreases gradually from left to right. The axial rigidity of the steel pipe is relatively large than that of the support ring of hinge support, thus, the steel pipe exhibits rigid motion in the axial direction, and the axial displacement is approximately equal and large. The Z-direction displacement varies little on the pipe and is larger than those in other directions.



（a）X-direction



（b）Y-direction



（c）Z-direction

Fig. 8. Displacement envelope diagram of steel penstock

The sliding distance time histories of sliding support are shown in Fig.9. The maximum sliding distance in the X-direction and Z-direction are 18.3mm and 21.1mm respectively, which are less than the allowable value of 100mm. The maximum deformations of the expansion joints are listed in Table 4. The vertical deformation of the expansion joints are small, and the horizontal deformations are relatively large. The maximum deformation of the expansion joints does not exceed 20mm, indicating that the relative motion between adjacent pipe sections is small. Therefore, the damage caused by a mutual collision can be avoided.

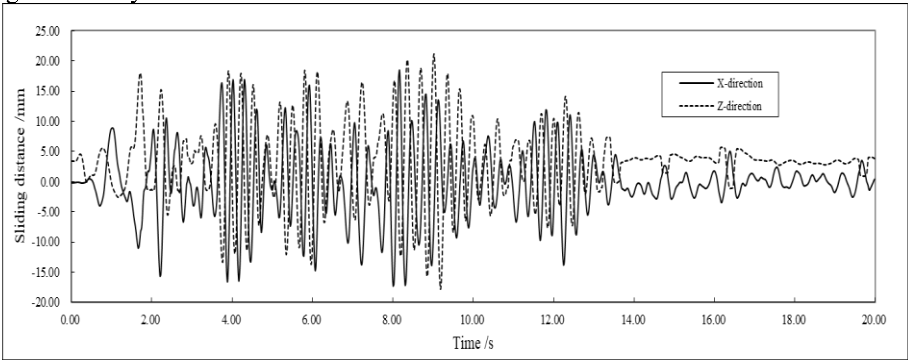


Fig. 9. Sliding distance time history of sliding support

Table 4. Maximum deformation of expansion joint /mm

Expansion joints number	X-direction		Y-direction		Z-direction	
	MIN	MAX	MIN	MAX	MIN	MAX
4	-16.22	15.79	-0.65	0.38	-14.65	15.61
5	-15.97	16.05	-0.71	0.32	14.26	15.12

4.2 Stress Analysis

Fig.10 shows the Mises stress envelope of the pipe during the earthquake. The pipe stress is essentially below 60MPa. The stress of the pipe is still caused by the internal water pressure mainly.

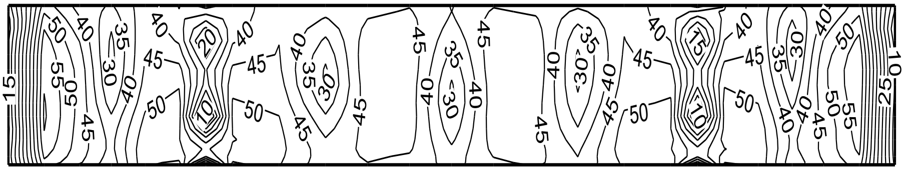


Fig. 10. Mises stress envelope diagram of the steel penstock under earthquake /MPa

Table 5 shows the Mises stresses at the key points (see Fig.4) of the support ring for normal operation and seismic operation. In normal operation, the stress of the supporting ring above the waist is very small, and the stress at the bottom is larger because of the weight of the steel pipe and water. Under the action of earthquake, the stresses of all the support rings are increased compared to normal operation. As the support ring of the sliding support can move with the pipe, the increase in stress is small. While, under the earthquake, the displacement difference between the basement of the hinge support and the steel pipe is large. This part of the displacement difference is borne by the support ring, resulting in a serious bending of the support ring. Also, the bending direction changes continuously during the earthquake. The stress of point e is only 30.47MPa under the normal operation, and the maximum stress can reach 190.30MPa under earthquake as shown in Fig.11.

Table 5. Mises stress of supporting rings' feature points /MPa

Support	Working condition	a	b	c	d	e
No.5 sliding support	Normal operation	24.06	17.69	7.05	93.88	17.78
	Earthquake + Normal operation	32.02	24.20	19.37	138.20	24.19
No.14 Hinged support	Normal operation	23.81	16.93	10.12	103.51	30.47
	Earthquake + Normal operation	31.56	23.07	29.74	128.54	190.30

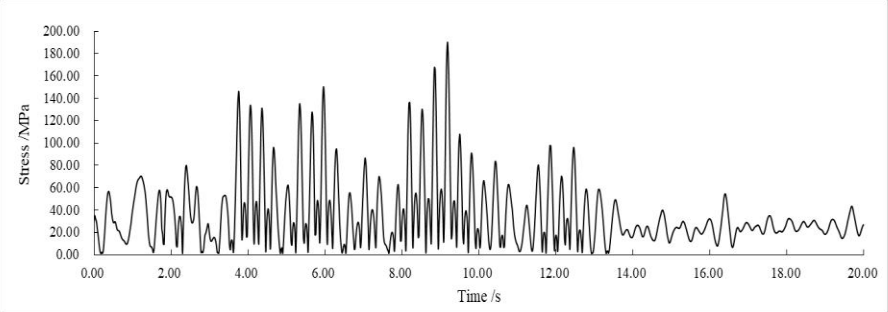


Fig. 11. Mises stress time history of poin

In order to adapt to the large deformation of the active fault, the steel pipe is provided with multiple expansion joints between two adjacent anchor blocks, while only one expansion joint is set in general. Under the earthquake, the steel pipe moves integrally and the stresses will not increase significantly. However, the arrangement of expansion joints makes the steel pipe less constrained in the horizontal directions, especially in the axial direction. Under the earthquake, the axial displacement response is great, and the stress state of the supporting ring of the hinged support is deteriorated, which is unfavorable to the earthquake resistance.

In order to cooperate with the setting of the expansion joints, the sliding support and the hinge support are arranged at intervals. Sliding support separate the upper steel pipe and the lower support pier to make the seismic force transmitted upwards reduce significantly due to the friction and energy dissipation of the support. However, this kind of support lacks the constraint on the steel pipe. Nevertheless, the hinged support has some restrictions on the pipeline, and the horizontal displacement can be reduced. Therefore, the spacing arrangement of sliding support and hinge support is beneficial for earthquake resistance.

5 Conclusion

(1) Installing several expansion joints between anchor blocks, spacing arranging sliding and hinged supports can effectively adapt to the long-term creep of active fault for exposed steel penstock crossing fault.

(2) The steel penstock concentrates most of the quality of the structure. In addition the axial restraint on the pipe is small because of the expansion joints, each steel penstock segment move integrally under the earthquake. The stress of the pipe generated by the earthquake is small, and still mainly caused by internal water pressure.

(3) There are multiple expansion joints between the anchor blocks, which caused the axial displacement of the steel penstock under the earthquake. As a result, the support ring of the hinged support is severely bent and becomes a weaknesses during the earthquake. Therefore, if there is no special need, it is necessary to avoid setting excessive expansion joints to enhance the structural integrity and earthquake resistance.

(4) The sliding support can play a role in seismic reduction and isolation, but it lacks the constraint on the horizontal displacement of the superstructure. However, the hinge support can limit the structural displacement. Therefore, the spacing arrangement of sliding support and hinge support is beneficial to the earthquake resistance. But it is necessary to ensure the strength of the connection of the support and to provide a limiting device to prevent the pipe from slipping off.

Acknowledgments

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References

1. C.M. Liu, H.X. Zheng, “South-to-north water transfer schemes for China,” International Journal of Water Resources Development 18.3 (2002): 453-471.
2. G.M. Huang, Y. Li, “Study on key technical issues encountered in the Zhangjiuhe water transfer project”, Water power, 2006, 32(11): 12-13. (in Chinese).
3. O. Norio, T. Y, "The 2011 eastern Japan great earthquake disaster: Overview and comments." International Journal of Disaster Risk Science 2 (2011): 34-42.
4. Y.K. Lu, Y.Q. Zeng, G.Q. Zhou, et al., “Summarization of the 2007 Ning-er, Yunnan MS6.4 earthquake disaster”, Journal of seismological research, 2007, 30(4): 364-372. (in Chinese).
5. S.A. Zheng, R.K. Wang, J.Y. Zhang, et al., “Influence analysis of Wenchuan earthquake on the hydropower projects in the upstream of the Minjiang River”, Water power, 2008, 34(11): 5-9. (in Chinese).
6. H.Q. Chen, “Seismic safety of the South2to2North Water Transfer Project”, Journal of China institute of water resources and hydropower research, 2003, 1(1): 17-22. (in Chinese).
7. H.Y. Li, W.D. Tian, H.X. Yan, “Inverted siphon”, Beijing: China Waterpower Press, 2006. (in Chinese).

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