IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Research on Key Problems of Seismic Design of Soft Foundation of Large Pumping Station

To cite this article: Liaojun Zhang and chen yajun 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **233** 032020

IOP Conf. Series: Earth and Environmental Science 233 (2019) 032020 doi:10.1088/1755-1315/233/3/032020

Research on Key Problems of Seismic Design of Soft Foundation of Large Pumping Station

Liaojun Zhang[1*], chen yajun[2]

[1]College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098, China

[2]Xuzhou Design Institute of Water Conservancy & Architecture, Xuzhou , Jiangsu , 221000, China

[*]Corresponding author's e-mail: ljzhang@hhu.edu.cn

Abstract. Based on the large-scale pumping station project of Suining Second Station, the seismic design theory of large-scale pumping stations on soft foundation is studied in this paper. A 3D fluid-structure interaction simulation model of pumping station- foundation- water is established. It can simulate the soil dynamic characteristics of the foundation and the contact nonlinearity of the opening and closing between different structures during strong earthquakes. A semi - underground structure integrated design scheme is finally proposed in this paper: the steel plates pressed together are used to connect the pumping station body, the maintenance room and the control room. The scheme with a combination of the underground continuous wall, bolts and bored piles for foundation reinforcement is proposed. And then a similar semi - underground structure is constituted. It turns out the design scheme has greatly improved the seismic performance of the Suining Pumping Station and solved the key technical problems of the seismic design of large pumping stations on soft foundation.

1. Introduction

As an important part in water conservancy projects, pumping stations bear the responsibility of regional flood control, waterlog elimination, irrigation, water transfer and water supply. They are also playing an important role in promoting the water conservancy modernization of urban water conservancy, environmental water conservancy, ecological water conservancy and livelihood water conservancy. Presently, a great deal of large pumping stations in China are built on soil foundations, and accordingly high requirements are put forward for the design of large pumping stations due to the weakness of the foundations. Especially in the high seismic intensity zone, the seismic response of buildings on soft soil is much larger than that on hard rock foundations. So the damage caused by earthquakes on soft foundation is much greater and thus the design difficulty is greatly increased. As for the East Route Project of South-to-North Water Diversion Project, it is pumping water from the Yangtze river in the south to the north by a series of large cascade pumping stations.If there is disastrous damage in one of the pumping stations, it will seriously affect the water supply of entire the East Route Project, or even lead to the breakdown of the entire lifeline engineering project [1-2].

Based on the large-scale pumping station project of Suining Second Station, the process of discussing a series of design problems of station building on soft foundation, repeatedly modifying the design scheme through scientific research, and ultimately solving the problems, is reproduced in this paper. In addition, the seismic design theory of large pumping stations on soft foundation is studied in detail, the engineering measures for seismic design are put forward and the effects after completion are discussed in this paper. The theory, method and application results of the seismic design of large pumping stations on soft foundation are summarized, which can provide a scientific reference for the construction of similar projects. It is worthy of mentioning that the research results of Suining Pumping Station has been interviewed and broadcasted on the Science and Education Channel of China Central Television(CCTV-10) [3] .

2. Main problems in design

The second station project of Suining Pumping Station is the fifth-level large-scale pumping station on the east route of the South-to-North Water Diversion Project. Its main function is to transfer water to the middle canal through Xuhong River. The engineering category of the newly-built Suining Second Station project is I and the seismic grade of the main building is Grade 1. The foundation of the pumping station site is a soft soil foundation. It is located in a strong earthquake zone with a basic seismic intensity of 8, with the peak acceleration of ground motion 0.30g. The main building is large in scale. During the initial design process, there are many difficulties encountered. And the main problems are as follows:

(1) The problem of structural size exceeding the standard

During the preliminary design of the main building of the pumping station, due to the need of hydraulic design flow channel arrangement, the length of the structural bottom plate in the direction of water flow exceeds the limit of 30m of the length specified in "Design code for pumping station" [4]. Therefore, the structure of the standing body is divided into The two parts of different sizes in the downstream, finite element simulation analysis shows that this design is very unfavorable for structural earthquake resistance.

(2) Collision of adjacent structures on soft foundations during strong earthquakes

The preliminary design is as follows: the middle of the river course is the station body; the left side is the maintenance room; the right side is the control room; 2cm construction joint is left between the three buildings. Due to the long period and large amplitude of natural vibration of the buildings on the soft soil foundation, as well as the large difference in size and quality of the three buildings, the vibration frequencies of the three buildings are inconsistent during the earthquake, so it is easy to cause collision and damage of adjacent structures.

(3) Construction stability problem of deep foundation pits during excavation

The pumping station excavates a large deep foundation pit with a plane size exceeding 66m*33m and a depth of more than 17m, and constructs a pumping station, an inspection room and a control room in this pit. There are problems such as the stability of the deep foundation pit during construction and the influence of the earth pressure on the pumping station on the side of the foundation.

3. Theory analysis and model calculation

In order to simulate the real seismic response of the project when subjected to strong earthquakes and the temperature stress during construction, a reasonable calculation theory and analytical model are needed. Therefore, a three dimensional simulation calculation model for the dynamic interaction analysis of the structure-foundation-water system is established in this paper, which can simulate the dynamic characteristics of the foundation soil during strong earthquakes, the contact non-linearity of the opening and closing between different structures. And the whole optimization process of the Suining pumping station is reproduced and analyzed.

3.1. Theory of dynamic interaction analysis

Pump station structure-foundation-water dynamic interaction problems involve theories and methods of structural dynamics, hydrodynamics, and soil dynamics.

The basic equations of the dynamic finite element of structure and foundation:

$$\mathbf{L}^{\mathrm{T}}\boldsymbol{\tau}_{\mathrm{s}} + \rho_{\mathrm{s}}\mathbf{b} = \rho_{\mathrm{s}}\ddot{\mathbf{u}} \tag{1}$$

In this formula, $\boldsymbol{\tau}_s$ is the stress tensor, ρ_s is the density of the solid medium, $\mathbf{b}$ is the volume force, $\ddot{\mathbf{u}}$ is the acceleration array of the mass point, $\mathbf{L}^T$ is the differential operator.

The conservation equation of mass and momentum of continuous fluid medium motion are:

$$\nabla \cdot \mathbf{v} = \mathbf{0} \tag{2}$$

$$\rho_f \frac{\partial \mathbf{v}}{\partial t} + \rho_f \mathbf{v} \cdot \nabla \mathbf{v} - \nabla \cdot \boldsymbol{\tau}_f = \mathbf{f}_f \tag{3}$$

In these formulas, ρ_f is the fluid density, $\mathbf{v}$ is the velocity vector, $\mathbf{f}_f$ is the physical force vector of the fluid medium, $\boldsymbol{\tau}_f$ is the stress tensor.

Fluid-structure interaction boundary conditions are:

$$\begin{cases} \underline{\mathbf{d}}_f = \underline{\mathbf{d}}_s \\ \mathbf{n} \cdot \underline{\boldsymbol{\tau}}_f = \mathbf{n} \cdot \underline{\boldsymbol{\tau}}_s \end{cases} \tag{4}$$

In these equations, $\underline{\mathbf{d}}_f$ is the fluid displacement on the coupling surface, $\underline{\mathbf{d}}_s$ d is the solid displacement on the coupling surface, $\underline{\boldsymbol{\tau}}_f$ d is the fluid stress on the coupling surface, $\underline{\boldsymbol{\tau}}_s$ is the solid stress on the coupling surface, $\mathbf{n}$ t is the coupling plane normal vector.

The foundation soil material will undergo elastoplastic deformation during strong earthquakes, the generalized Mohr-Coulomb yield criterion is used:

$$f^s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi} = 0 \quad , \quad N_\varphi = \frac{1+\sin\varphi}{1-\sin\varphi} \tag{5}$$

In these formulas, c is the soil cohesion, φ is the internal friction angle, σ1 and σ3 are the first and third major stresses, respectively.

In the case of strong earthquakes, there are contact problems between opening, closing and sliding between adjacent structures. This paper uses the Constraint-Function dynamic contact algorithm, and the constraint function $w(g,\lambda)$ and $v(u,\tau)$ expression are as follows [6-7]:

$$w(g,\lambda) = \frac{g+\lambda}{2} - \sqrt{\left(\frac{g-\lambda}{2}\right)^2 + \varepsilon_N} \tag{6}$$

$$\tau + v - \frac{2}{\pi}\arctan\left(\frac{u-v}{\varepsilon_T}\right) = 0 \tag{7}$$

In these functions, g is the normal distance of the two contact faces, λ is the normal contact force between the contact faces, τ is the ratio of the tangential frictional force to the normal force between the contact faces. ε_N is a very small constant that is conducive to computational convergence. ε_T is an important parameter to measure the similarity between the regularized friction model and the Coulomb friction model, and the smaller the close.

By solving the above equations in a simultaneous manner, it is possible to comprehensively reflect the complex dynamic nonlinear characteristics of the fluid-structure interaction of the structure-foundation-water body.

3.2. Three-dimensional simulation calculation model

The three-dimensional simulation model is based on the large-scale structural analysis software ADINA. It uses topological structure theory and Boolean operation technology to carry out accurate simulation of complex geometric shapes such as pump runners, inlet and outlet, middle piers, gate chest walls and pump chamber internal cavities and corridors, and the mathematical model is very complicated. The pumping station body structure, maintenance room, control room, underground continuous wall and foundation are all simulated by isoparametric hexahedral solid unit. The plate-like structure such as floor is simulated by shell unit, and the steel plates pressed together between maintenance room and control room and pumping station are simulated by shell unit, the pile and column structure are simulated by beam unit, the bolt is simulated by truss unit, and the water body is simulated by potential fluid FSI unit. Foundation range: The pumping station body takes 35m of the upstream and downstream, respectively, and the maintenance room and control room take 40m of the left and right banks, respectively, and the bottom plate takes 35m deep. Figure 1 shows the overall three-dimensional finite element mesh diagram of the structure-foundation-water body of the final design. Figure 2 shows the three-dimensional model of the pumping station body, the inspection room, the control room and the foundation reinforcement. The overall three-dimensional finite element model has 195,333 units and 283,460 nodes, of which 178,179 are solid elements, 974 are beam elements, 766 are shell units, 150 are rod units, and 15264 are potential fluid units. The constraint is taken as: the normal chain around the foundation is constrained, and the ground base is fixed. The coordinate system is selected as follows: the X axis is the vertical water flow direction pointing to the right bank, the Y axis is the forward flow direction, and the Z axis is the vertical direction.

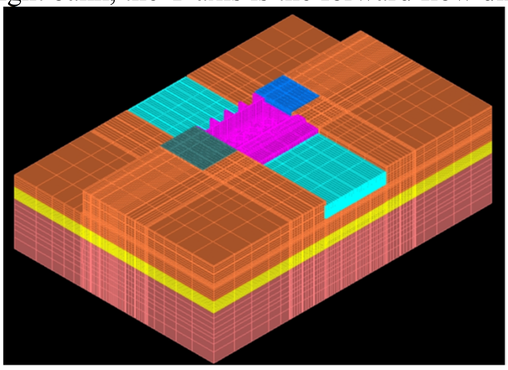

Fig.1 3D FEM model of the pumping station

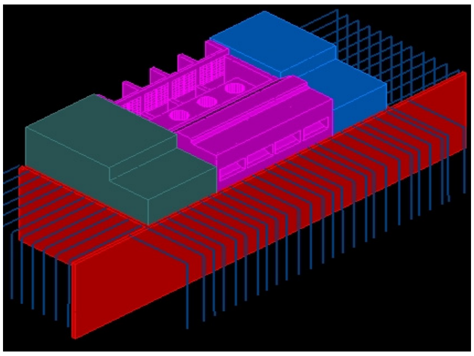

Fig.2 3D model of the pumping station and the foundation reinforcement

Structural and underground continuous wall concrete elastic modulus $E=2.8\times10^4$MPa, density $\rho=2500$kg/m^3, Poisson's ratio $\mu=0.167$; steel plates pressed together elastic modulus $E=2.07\times10^5$MPa, density $\rho=7800$kg/m^3, Poisson Ratio = 0.3. The foundation is divided into 5 layers from top to bottom, and Poisson's ratio is taken as 0.3, see Table 1. According to the " Specifications for seismic design of hydraulic structures " [5], the standard value of dynamic strength and dynamic elastic modulus of concrete is 30% of its static standard elastic modulus, and the standard value of dynamic tensile strength is taken as 8% of the dynamic compression strength standard value.

The dynamic boundary of the computational model takes the equivalent uniform viscoelastic artificial boundary [6]. The damping ratio of the pump house structure is 5%, and the damping ratio of the foundation soil is 15%. Ground motion uses artificially generated seismic waves. According to the ground motion peak acceleration of 0.30g, the response spectrum characteristic period T_g=0.35s, etc., the standard design response spectrum is obtained, and then the design response spectrum is used as the target spectrum to fit the seismic acceleration time history. Figure 3 shows one horizontal fitting artificial Seismic waves and seismic responses are calculated using dynamic time history analysis.

4. Structural seismic design

4.1. Separation scheme

During the preliminary design, due to the need of the flow channel arrangement of the pumping station, the length of the main pumping house structure of the pumping station exceeds the “Design code for pumping station” [4], so the bottom plate is 26.70m along the Yanshun River. The vertical construction joint is set up, and the whole pumping station structure is divided into two parts: the station and the station. The total length of the design in the direction of the river is 39.16m and the height is 21.5m. The pumping station is designed to be separated. Due to the large length of the river, the soil below the pumping station structure remains (see in Figure 4).

Table1.Mechanic parameters of soil layer of the foundation

soil layer	unit weight γ /(kN • m^{-3})	compression modulus E /MPa	cohesion C/kPa	internal friction angle φ /(°)
4	20.1	7.75	34	20
5	19.6	11.7	15	28
6	19.5	7.21	42	19
7	19.9	6.42	39	19
8	20.0	12.8	77	18

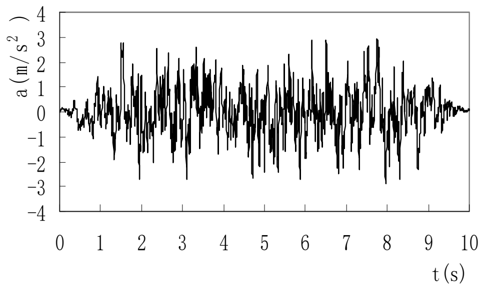

Fig. 3 Artificial horizontal seismic wave

The three-dimensional seismic simulation analysis model is established by using the calculation theory and method in Section 3. The calculation results show that the design scheme has the following problems: (1) The soil behind the wall in the lower part of the station needs grouting reinforcement, but the grouting effect is not easy to control. (2) The construction of ribbed underground continuous wall is more complicated; (3) The structure and weight of the pumping station on the station and the station are different, the different heights of the structural floor are difficult to control, and the uneven settlement of the foundation is difficult to control; (4) On the station, The two structures in the lower part of the station have a large difference in frequency, and there is only 2cm of construction joints in the middle. The soft foundation has a greater amplification effect on the earthquake, and there is a hidden danger of damage caused by the collision in strong earthquakes. Therefore, the seismic design must be redesigned.

4.2. Improved separation scheme

The problems existing in the above scheme were improved. The modified scheme is: the total length of the pumping house is 33.4m, the total length of the river is 44.20m, and the vertical construction joint is set at 26.70m along the river. The whole pump house structure is divided into two parts, upstream and downstream, and the length of the river is 26.7m and 17.5m respectively. The empty box of the structure is filled with soil for weight gain. A permanent ribbed diaphragm wall is provided in the outlet of the downstream pump house and the sides of the river, the right and downstream sides of the control room, and the left and downstream sides of the service room. The height of the continuous wall is 15.8m ~ 17.2m. The gap between the continuous wall and the structure is 3 cm, and the longitudinal section is shown in Figure 5.

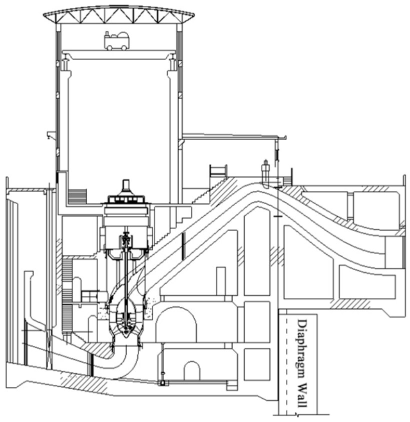

Fig.4 the longitudinal plan of the separate scheme

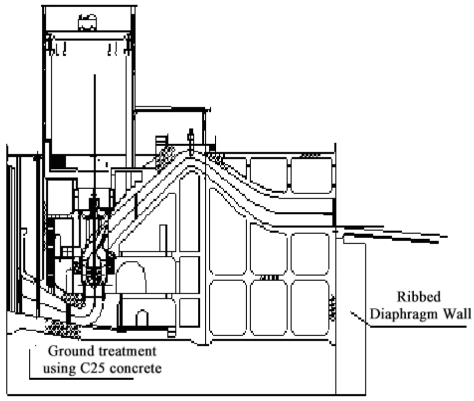

Fig.5 the longitudinal plan of the improved separate scheme

The 3D seismic simulation model is established by using the calculation theory of Section 3. The calculation results show that: (1) The improved scheme has greater improvement in the uneven settlement control of the bottom plate and the stability of the foundation than the separate scheme; (2) The length of the water flow direction reaches 44.2m, the length of the vertical water flow reaches 33.4m, the structure volume is large, and the concrete engineering volume is large; (3) Due to the different natural vibration frequencies of the two sections of the pumping station, there is still a hidden danger of damage caused by the collision the two sections of the station when strong earthquakes rarely occur.

4.3. Semi - underground integrated scheme

In view of the deficiencies of the separate scheme, the good seismic performance of the underground structures and the integral structures are taken into consideration. A semi - underground integrated design scheme and the corresponding engineering measures are proposed. And the design problems of Suining Pumping Station have been solved through the research in this paper. The semi - underground integrated design scheme is:

The main pump room adopts a block-based structure and a complete bottom plate. The flow length is 33.50m, the vertical water flow is 31.80m, the total height is 21.4m, and the 1m thick concrete cushion is arranged under the bottom plate. The total length of pump house structure, overhaul room and control room is 65.44m, and 2cm construction joints are reserved for each structure. The concrete structures on both sides of the joint surface are arranged with dozens of rectangular steel plates pressed together with a thickness of 1cm. The pressure of filling soil on both banks keeps the three adjacent structures tightly pressed to greatly enhance the transverse integrity, and the steel plates pressed together are pressed tightly to avoid brittle failure of the concrete. In the excavation of deep foundation pits, the reinforcement scheme of continuous wall, cast-in-place pile and anchor rod combination is adopted, and the horizontal displacement of the continuous wall is controlled by the pre-stressed anchor to ensure the stability of the deep foundation pit. Figure 6 shows the cross section layout. Figure 7 is a ground reinforcing view, and Figure 8 is a longitudinal section of the pump house.

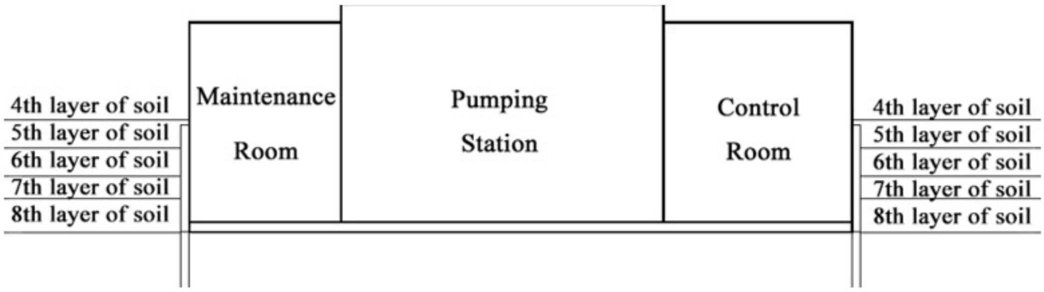

Fig6. Cross section layout diagram

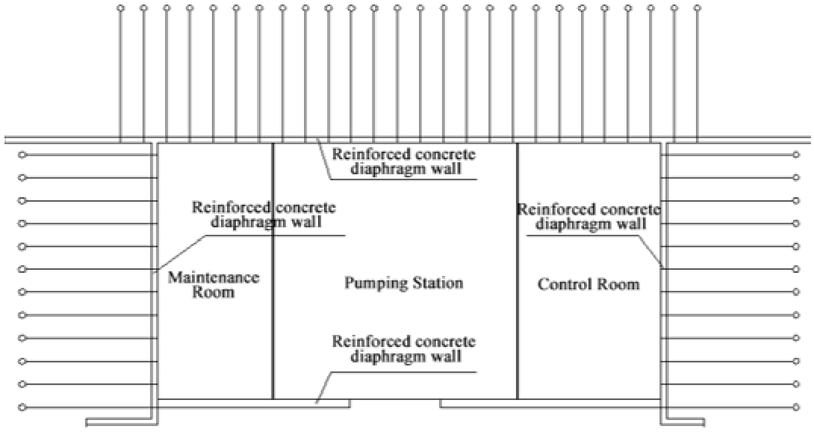

Fig7. Layout diagram of underground continuous wall and bored

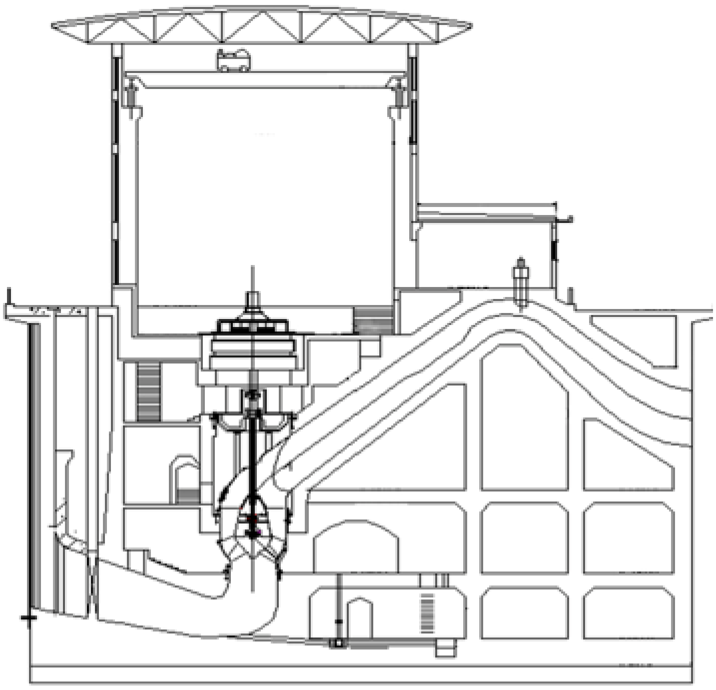

Fig8. Longitudinal section of Integral Scheme

By using the simulation model in Section 3.2, the calculation and analysis show that: (1) The uneven settlement of the pumping house structure is small, which greatly improves the seismic performance of the structure; (2) The foundation reinforcement scheme of the underground continuous wall with cast-in-place pile and anchor The stability of the deep excavation of the construction excavation is guaranteed; (3) After the construction is completed, the release of anchor prestress makes the underground continuous wall, maintenance room, pump house and control room in a tight state in the transverse direction through the steel plates pressed together. It forms a semi - underground structure, and the overall stability of the pumping station is greatly improved; (4) the strength, rigidity and stability of the whole pumping station are greatly improved, and the seismic capacity of the project is greatly enhanced, which solves the Suining Pumping Station. The key anti-seismic safety issues are effective and feasible.

5. Strength, stiffness and seismic safety of the integrated scheme

This section mainly introduces the results of simulation analysis of the overall scheme of Suining Pumping Station to illustrate the effectiveness of the research method and the implementation of engineering measures.

5.1. The reinforcement scheme with a combination of underground wall, bolts and bored piles

The three-dimensional finite element simulation model is in Section 3.2. The finite element calculation of the overall pumping station are carried out, respectively under the completion condition, the normal pumping condition and the condition where an earthquake with a seismic intensity of 8 occurs. And the release and relaxation of the pre-stress of the bolts and the situation of being unreleased are considered respectively. The main results are as follows:

(1) Deformation and prestressing effect of underground continuous wall

In the foundation reinforcement scheme, the completion condition is the control condition. When the prestressing of the anchor is laid during construction, the relative displacement of the upstream and downstream underground continuous walls is 1.44cm, and the relative displacement of the horizontal and vertical sides of the underground continuous wall on both sides is about 2.38cm; the prestress of the anchor is not When the sheet is released, the horizontal displacement of the underground continuous wall and the pumping station are basically kept in the same direction, and the gap between them is close to about 2 cm, so the effect of prestressing is obvious.

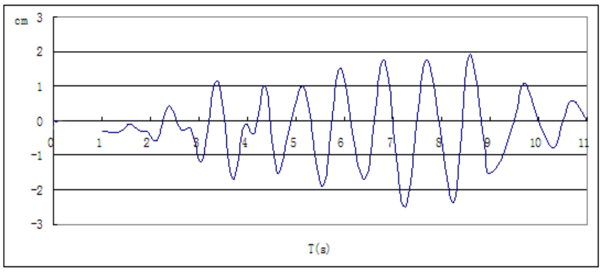

Fig9. the relative displacement along the river between the bottom and top of the underground continuous wall

The seismic response caused by horizontal earthquakes is relatively large. The results of the time history analysis method show that the maximum horizontal displacement of the underground continuous wall is 5.71, and the maximum relative displacement of the top and bottom is about 2.5 cm (Figure 9).The vertical displacement is not large , no control role.

(2) Stress of the underground continuous wall

When the construction is completed, the maximum tensile stress of the underground continuous wall is located at the contact of the bottom surface of the side cushion of the inspection room, which is 3.1 MPa, which belongs to stress concentration. The maximum tensile stress in normal pumping conditions is 1.78 MPa, and the maximum compressive stress is 6.6 MPa. Therefore, the underground continuous wall needs to be reinforced. During the earthquake, the dynamic stress of the underground continuous wall is not large , and no control role.

(3) Deformation and bearing capacity of the foundation

The maximum settlement of the foundation is 10.5 cm, which appears at the top of the foundation on the lower side of the pumping station. The maximum compressive stress is 0.25 MPa, and the maximum value appears at the junction of the bottom of the underground wall and the foundation, which is stress concentration. The main compressive stress of the foundation under the structural floor is 0.05MPa~0.15MPa. Within the allowable range of foundation bearing capacity, the degree of unevenness meets the requirements of medium compact and special soft soil.

The comprehensive research shows that the bolt-supported underground continuous wall scheme can help reduce earthwork excavation, save concrete consumption, and thus effectively reduce the amount of work, which helps shorten the construction period and reduce the cost. In addition, it can help ensure the stability of the support and the deep foundation pit during the construction period of the pumping station. After the construction is completed, the bolts become slack, and the underground continuous wall and the structure of the pumping station are compacted, so that the pump house, the maintenance room, the control room, the underground continuous wall and the side soil are integrated to bear loads as a whole, and consequently the seismic performance of the pumping station is greatly improved, with its safety guaranteed.

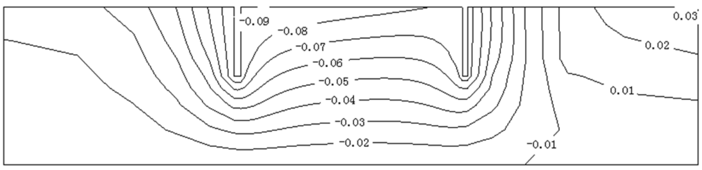

Fig.10 vertical displacement contours of the foundation of the pumping station structure（m）

5.2. Displacement, stress and seismic response of the integrated pumping station scheme

Through the comparison of the results obtained, respectively under completion condition and normal pumping condition, it shows that the completion condition is the control one, and the main results obtained are as follows:

(1) Strength and stiffness analysis: The completed construction condition shows the overall settlement of the pumping station is biased towards the station and the side of the control room. The maximum settlement is 10.33cm, and the maximum uneven settlement of the bottom plate is 1.14cm. Under normal operating conditions, the maximum settlement is 8.33cm. The uneven settlement was 1.86 cm. The horizontal deformation of the pump station is small. The deformation meets the design requirements. The maximum tensile stress of the structure occurs near the door opening of the left pier. The maximum value is 2.52 MPa, which is the stress concentration. The maximum compressive stress occurs at the steel plates pressed together of the right pier near the station, which is 5.81 MPa, which meets the strength requirement.

(2) Stability analysis: When the pumping station is in normal operation, the stability coefficient of the anti-sliding stability of the pumping room, the maintenance room and the control room is greater than 1.35, which meets the anti-sliding stability requirements specified in the specification. The maintenance room, the pump house structure and the control room are tightly contacted by the cross plate of the steel plates pressed together, and the stability of the three combinations is very high.

(3) Analysis of natural vibration characteristics: The fundamental frequency of the integrated pumping station in the completed construction condition and the normal pumping condition is 1.136 Hz and 1.120 Hz respectively, and the corresponding periods are 0.880 s and 0.893 s. The completion condition of the pump house structure is basically the same as the main vibration direction of the normal pumping condition. The main direction of the first order vibration is along the river, and the main direction of the second order vibration is the transverse direction. The third order is vertical.

(4) Seismic response: The time history analysis results show that the maximum displacement of the pump house is 4.72cm, the maximum relative displacement of the top and bottom is 2.07cm, and the maximum displacement of the pump house is 3.20cm. The maximum relative displacement of the top and bottom is 0.81 cm. It can be seen that the cross-river stiffness of the pump station is

significantly greater than that along the river. During the earthquake, the maximum tensile stress at the top of the bottom plate is 1.43 MPa and the compressive stress is 4.49 MPa. The stresses in the rest are not large, and the structural stress meets the strength requirements. The maximum dynamic stress of the steel plates is 8.78 MPa, which is much smaller than the compressive strength of the steel.

The calculation results obtained through the three-dimensional simulation method show that: the pumping station is designed by the integrated scheme with a combination of the underground continuous wall, bolts and bored piles for foundation reinforcement. After completion of the construction, the stress of the bolts is released so that the adjacent structures are in close contact with each other to bear loads as a whole. As a result of which the seismic performance of the pumping station is greatly improved and it fully meets the requirements of strength, stiffness and seismic safety.

6. Conclusion

(1) Based on the large-scale pumping station project of Suining Second Station, the seismic design theory of large-scale pumping stations on soft foundation is studied on in this paper. A 3D fluid-structure interaction simulation model of pumping station- foundation- water is established. It can simulate the dynamic characteristics of the foundation soil and the contact non-linearity of the opening and closing between different structures during strong earthquakes.

(2) A semi - underground integrated design scheme is proposed in this paper: the steel plates pressed together are used to connect the pumping station body, the maintenance room and the control room, and then a similar semi - underground structure with the underground continuous wall is constituted; the scheme with a combination of the underground continuous wall, bolts and bored piles for foundation reinforcement is proposed, and the stability of the deep foundation pit is ensured by the prestressing of the tension bolts during the construction process.

(3) In regard to the integrated design scheme proposed in this paper, the simulation model for dynamic interaction analysis of the structure-foundation-water system established in this paper is utilized to calculate. The strength, stiffness and stability of the integrated pumping station and the foundation reinforcement scheme are analyzed in detail, with the seismic reinforcement effects are evaluated emphatically. And it turns out that the seismic performance of Suining Pumping Station is greatly improved upon.

(4) The theory, method and application results of the seismic design of large pumping stations on soft foundation are summarized in this paper, which can provide scientific reference for the construction of similar projects.

Acknowledgments

This research was financially supported by National Key Research and Development Plan of Ministry of Science and Technology of the People's Republic of China (2017YFC0404903) and Key fund of National Natural Science Foundation of China (90510017).

Reference

[1] Chen H. (2003)Seismic safety of the South-to-North water transfer project.J. Journal of China Institute of Water Conservancy and Hydropower Research, 1:17-21.
[2] Chen H. (2008)Review and prospect of aseismic study on concrete hydraulic structure.J. Journal of China Institute of Water Conservancy and Hydropower Research, 6:245-257.
[3] China central television.(2013)Approaching Science-The water thing on the eastern line(1): Water flows upward. http://tv.cntv.cn/video/C14122/d38516d349b341cf9f1b8d257684d438
[4] Ministry of Water Resources the People's Republic of China. (1997)Design code for pumping station.S.China Waterpower Press.
[5] China Institute of Water Resources and Hydropower Research. (1997)Specifications for seismic design of hydraulic structures.S.China Water & Power Press.
[6] Cheng H., Zhang L. (2009)Zhang H.Application of 3D consistent equivalent viscous-spring boundary element to seismic analysis of arch dams.J.Journal of Hydroelectric

Engineering,28:169-173.
[7] Bathe K., Chaudhary A. (1985)A solution method for planar and axisymmetric contact problems.J. Int. J. Num. Meth. in Eng., 21:65-88.
[8] Bathe K., Bouzinov P. (1997)On the constraint function method for contact problems.J. Computers and Structures, 64: 1069-1085.
[9] Zhang L J, Wen R. (2013)Numerical simulation of temperature field and stress field of large pump station during construction period.J. Water Resources and Power,31:92-95