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Control Methods and Influence Factors of Silt Liquefaction: Case of the Wangqingtuo Reservoir in the South-North Water Diversion project (Tianjin, China)

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Control Methods and Influence Factors of Silt Liquefaction: Case of the Wangqingtuo Reservoir in the South-North Water Diversion project (Tianjin, China)

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Abstract. Soil liquefaction is a major cause of site damage to an earth dam in the earthquake and geotechnical engineering. Wangqingtuo Reservoir is an integral part of China's South-North Water Transfer Project in Tianjin. Due to the weak geological engineering conditions of the reservoir area and the location belonging to regions with basic earthquake intensity of degree 7, there is a slight possibility of liquefaction of the dam foundation, when the reservoir is impounded. Therefore, liquefaction control measures need to be implemented. Mainly by improving soil properties and initial stress of the liquefiable soil, four liquefaction control measures were put forward; surface excavation and backfilling, setting pressure platforms, anti-seepage platform and strengthened drainage design. Based on high-density surface wave exploration, field tests, laboratory tests, liquefaction identification, and liquefaction classifications; influence factors of silt liquefaction are determined with results analyzed before and after liquefaction control measures of the dam structure. A dynamic numerical modeling analysis was used to evaluate the extent of the liquefaction control measures, with the aid of Geo-slope software.

1. Introduction

Earthquake liquefaction is one of the most important subjects to earth dams. Over last decades, the study on the soil liquefaction has focused on the assessment of liquefaction potential [1], evaluation of the deformations and settlement induced by the liquefaction [2], clay content influence on the liquefaction, the liquefaction-induced construction failure, and so on. From history, soil liquefaction caused by earthquakes is critical, and the anti-liquefaction safety methods should be given serious attention. The adequate safety of liquefaction resistance of foundations and buildings is of great significance to avoid heavy casualties and significant economic losses caused by earthquakes. A few research works approached the post-liquefaction behavior of soil [3] and post-liquefaction failure [4].
Although the strata are generally horizontal, the distribution of some layers in the local area is quite variable. The liquefaction possibility and liquefaction grade of each section were evaluated scientifically. Since the finite element method has been introduced to geotechnical engineering, the liquefaction problem has been focused on within the numerical analysis [5]. Nonlinear dynamic response analysis methods have aroused much interest to many researchers [6, 7]. To provide engineering guidance for the anti-liquefaction measures of the Wangqingtuo reservoir, comprehensive

evaluation and reliable analysis of the construction quality of the dam soil, dynamic response and safety against liquefaction of the dam under earthquake load is carried out.

Over the years, numerous anti-liquefaction and control methods have been researched yielding different results depending on the soil conditions.Naoyuk et al. (2006) explored anti-liquefaction performance by laying drainage ditches in the pile foundation [8]. The test shows that when the drainage pipe is relatively dense, it can effectively reduce the excess pore water pressure caused by the disturbance in the sandy soil between piles. Cao Youjie (2012) optimized the combination of different anti-liquefaction measures through experiments to achieve a better effect of anti-liquefaction [9]. SuWenji et al. (2004) evaluated the sand liquefaction measures by shear wave velocity discrimination and standard penetration test method[10]; consequently,they put forward reasonable measures for foundation liquefaction resistance. Anning (2007) selected the average particle size [11], clay content and seismic intensity of sand as the characteristic parameters; proposing a prediction method for liquefaction of roadbed sand based on BP neural network model.

This paper proposes to combine the calculation method through indoor and field tests with the finite element numerical analysis of the dynamic reservoir dam Wangqingtuo. This enables us to evaluate the effect of anti-liquefaction prevention measures, which are suitable for the soil characteristic and control index of the project design. Following this research, there will be improved safety during construction of the reservoir, and at the same time, these methods can be used to evaluate liquefaction potential in similar projects around the world.

2. Case Study:Wangqintuo Reservoir

The reservoir is located in the western part of the town of Wangqingtuo in Tianjin, at 39º10'N and116º52'E (Fig. 1). It is a 24/7 regulating reservoir, accident reserve water source and local geology of the North China Plain (NCP) Quaternary silt. Although no seismotectonic zones cross the Wangqingtuo reservoir, the surrounding areas are very seismically active with seismotectonic zone (Tangshan– Cixian and Linqiu–Huailai) located east and west of the project site, respectively (Fig. 1) The location of the most critical recent earthquake disaster in China, the 1976 Tangshan Earthquake (Ms 7.8), is nearby the Tangshan–Cixian seismotectonic zone. The soil layers distributed under the dam body are mainly silty soil. Past surveys show that silty soils could liquefy during an earthquake. Following this, there is a reason to investigate the liquefaction potential of the dam foundation to ensure the safety of the South-North Water Diversion project. According to the correlative Chinese-Standard, the design maximum acceleration of the site is 0.15g, and seismic intensity VII is used for the liquefaction assessment.

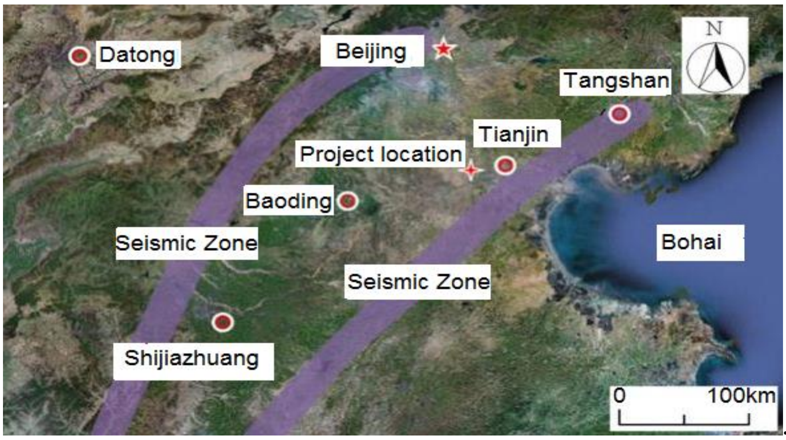


Figure 1. Map of Wangqingtuo reservoir

The soil properties of each soil layer are indicated in Table 1.Borehole data performed in 2005 was used to reveal the different soil layers that are compared with velocity structure map from high-density surface waves as shown in Fig 2.In the range of 0-5 m below the surface depth, the soil layer

(alQ_4^3)shown by the borehole data is mainly liquefiable soil, composed of silt. The silty soil in this top layer has relatively small permeability coefficient.

Table 1. Static Soil tests

Soil Layer	Main Soil Texture	Water Content %	Dry Density (kN/m^3)	Pore Ratio	Permeability Coefficient K_h (cm/s)	Cohesion (kPa)	Friction (°)
alQ_4^3	Loam(Untreated)	25.1	14.6	0.85	8.38×10^{-6}	15	22
	Loam(Treated)	21.1	19.4	0.681	4.29×10^{-5}	15.4	28.2
	Clay	22.2-26.7	14.6 - 15.7	0.74-0.86	1.2×10^{-6}-4.25×10^{-7}	18-22	18-19
$l+hQ_4^2$	Clay	23.9	15.6	0.75	4.36×10^{-7}	22	18
	Loam	27.2-32.5	14.5-15.4	0.77-0.88	1.35×10^{-6}-1.05×10^{-6}	18-23	17 -19
mQ_4^2	Loam	29.2-38.2	13.1-14.8	0.84-1.08	2.41×10^{-6}-8.73×10^{-7}	17-19	16 -21
alQ_4^1	Loam	23.4-26.5	15.5 -16.1	0.69-0.76	4.36×10^{-6}-1.19×10^{-6}	25-37	15 -16
	Silt	22.9	16.2	0.66	8.94×10^{-6}	7	30
alQ^3	Loam	14.7-27.8	15.8 -18	0.51-0.73	9.35×10^{-6}-4.96×10^{-6}	5-10	28-30
mQ^3	Clay	21.1-23.3	16.2-16.8	0.62-0.68	3.68×10^{-6}-6.11×10^{-7}	40-47	17-19

Table 2. Dynamic soil tests

	Main Soil Texture	Depth(m)	Shear wave Velocity(m/s)	N	N_{30}	Seismic Shear Stress τav (kPa)
alQ_4^3	Loam(Untreated)	4.2	90-110	2-10	0.136-0.290	3.42-6.65
	Loam(treated)	4.2	140-200	3-13	-	3.42-6.65
	Clay	1.1	130-150	1-6	-	-
$l+hQ_4^2$	Clay	2.3	130-150	2-10	-	-
	Loam	3	110-130	3-14	0.245-0.40	1.73-3.42
mQ_4^2	Loam	8.9	150-170	2-18	-	-
alQ_4^1	Loam	11	160-180	3-31	-	-
	Silt	2	140-160	10-23	-	-
alQ^3	Loam	12.5	180-200	8-67	-	-
mQ^3	Clay	17	190-200	13-29	-	-

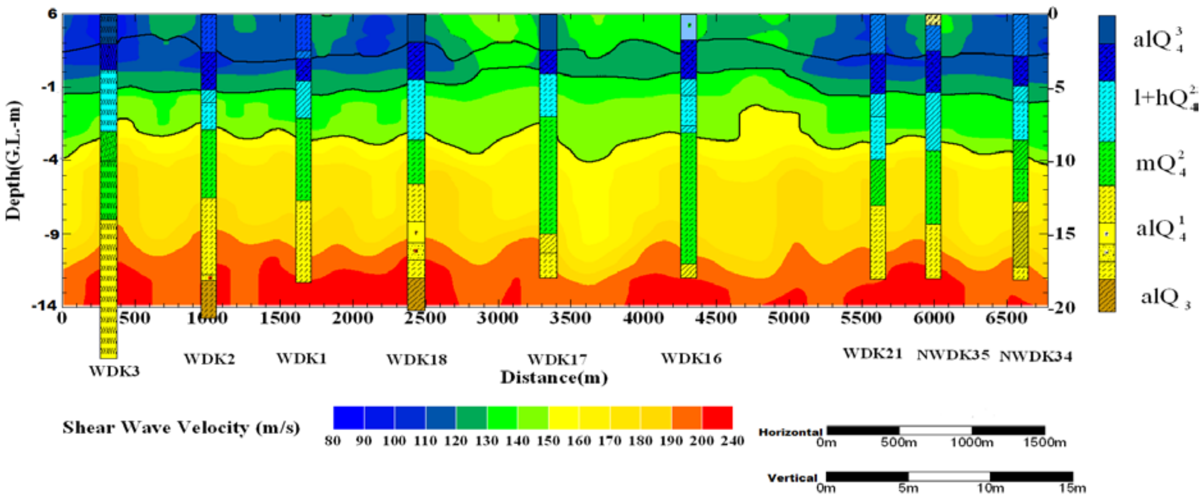


Figure 2. High-density surface wave and Borehole data in Wangqingtuo reservoir

3. Influence factors and Control methods

The dynamic triaxial tests were done at the Key Laboratory of Geotechnical and Underground Engineering, Tongji University.

3.1 Seismic Liquefaction mechanism of saturated silt and it's influencing factors

The liquefaction mechanism of soil and its influencing factors have always been a vital and challenging point in liquefaction research. The mechanism of liquefaction of soil is very controversial in history. Some factors that influence liquefaction were considered such as initial shear stress, consolidation pressure, particle composition, dry density, and soil structure.

3.2 Method of prediction based on dynamic triaxial test

According to the feasibility of on-site monitoring data acquisition, this paper uses dry densityasa control indicator for liquefaction silt foundation treatment. The Seed-Idriss method was used to analyze the relationship and how liquefaction is affected.

According to the Seed-Idriss simplified method provided by the geological engineering manual, the seismic shear stress can be calculated as:

$$\tau_{av} = 0.65\gamma_z \bullet r_d \bullet \alpha_{\max} / g \quad (1)$$
$$r_d = 1 - 0.0133z$$

where: τ_{av} is the equivalent of cyclic shear stress (kPa), γ is dry Density of Soil(kN/m^3),z is the depth of soil(m), r_d is the coefficient of stress reduction and $\alpha_{\max}$ refers to the maximum ground acceleration.

Calculation of anti-liquefaction shear stress of soil layer:

$$\tau_d = C_r \left(\frac{\sigma_d}{2\sigma_c}\right)_{Nf} \sigma_v \quad (2)$$

Where; $\left(\frac{\sigma_d}{2\sigma_c}\right)_{Nf}$ refers to the soil liquefaction stress ratio determined by the vibration three-axis test, C_r is the correction of shear stress causing liquefaction and σ_v effective overburden pressure of soil.

3.3 Results of experiments and liquefaction assessment

3.3.1 Dry Density. Dry density is used in this research to investigate the influence on liquefaction potential of the soil. Soil with larger dry density tends to dilate during liquefaction generating negative pore pressure and higher resistance to shear stress. As shown in Fig 3, the liquefaction stress increases with the increase of dry density. When the dry density is increased by 10%-15%, the liquefaction strength of the surface soil is increased by 24%. According to the definition of compactness, compaction degree is equal to the ratio of dry density to maximum standard dry density after compaction.

Liquefaction control measures that can increase dry density are proposed.According to the maximum dry density of dug silt in the reservoir area, the design dry density should be no less than 1.65 g/cm3 with the soil moisture content being high enough.

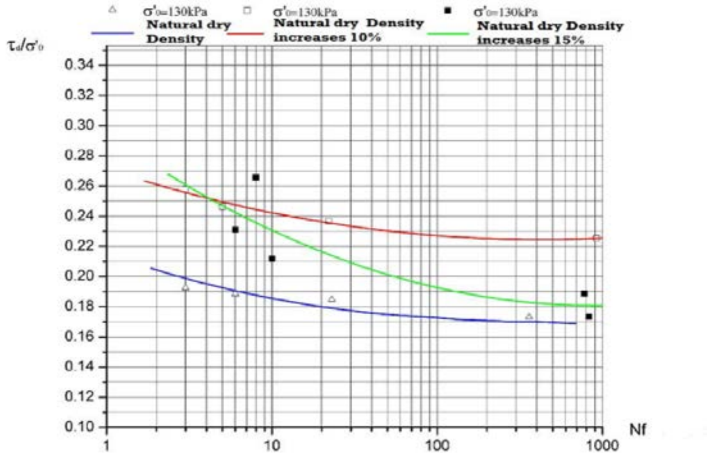


Figure 3. The relationship between liquefaction stress and dry density

3.4 Control Methods

According to a comparison from the previous conventional geotechnical tests and Seed's simplified method, the top damsoil(alQ_4^3) silt is susceptible to liquefaction. In view of the special geographical location and unfavorable geological conditions, fourmethods were implemented to control liquefaction. In particular; (I)surface excavation and backfilling, (II)setting of pressure platform on both sides of the dam, (III)Anti-seepage (IV)strengthening the drainage in front of the dam. Fig 4shows the dam cross section and anti-liquefaction methods used.

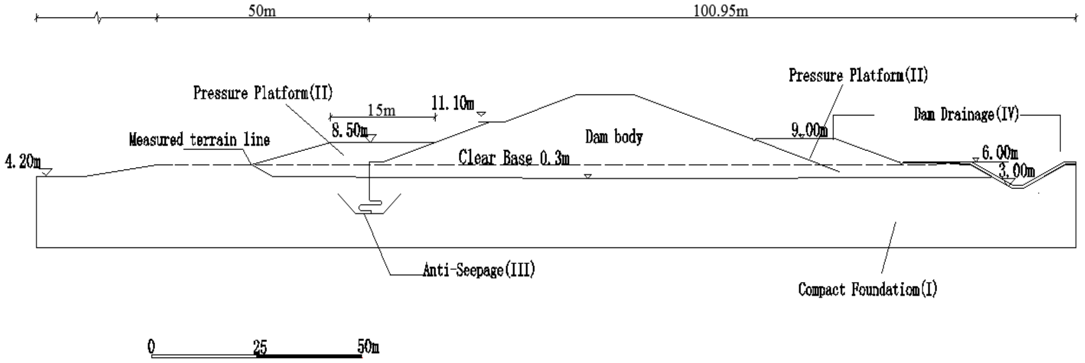


Figure 4. Cross section of the dam area

4. Field Tests

4.1 Shear Wave Velocity

The shear wave velocity of the soil Vs. is an important parameter to describe the engineering properties of soil analysis. It can be applied to evaluate earthquake resistance and other aspects. The magnitude of the shear wave directly reflects the degree of soft and hard strata, which is directly related to the elastic shear modulus of soil. The shear wave velocity of soil is also associated with the type of soil, the depth of the soil layer, the compactness of soil and the N value of standard penetration. The N value of the standard penetration number reflects the soft and hard segments of the soil as the shear wave velocity Vs. In general, the denser the soil layer (dry density), the higher the number of standard penetration and consequently the higher the shear wave velocity.

4.2 Application of high-density surface wave exploration in the evaluation of dam's treatment effect

High-density surface wave exploration equipment is composed of GEODE digital seismograph, single component geophone, exciter, and a data collector. A GEODE digital seismograph with 24 channel analog-to-digital converter is used for data recording. The maximum frequency is 500Hz, and the minimum frequency is 1. 75Hz.The single component detector for high-density surface wave exploration has a moving coil type velocity detector with an exciter 12lb hammer. For data acquisition, a laptop computer installed with surfstar software. Fig5 shows the setup of the apparatus used in high-density surface wave exploration.

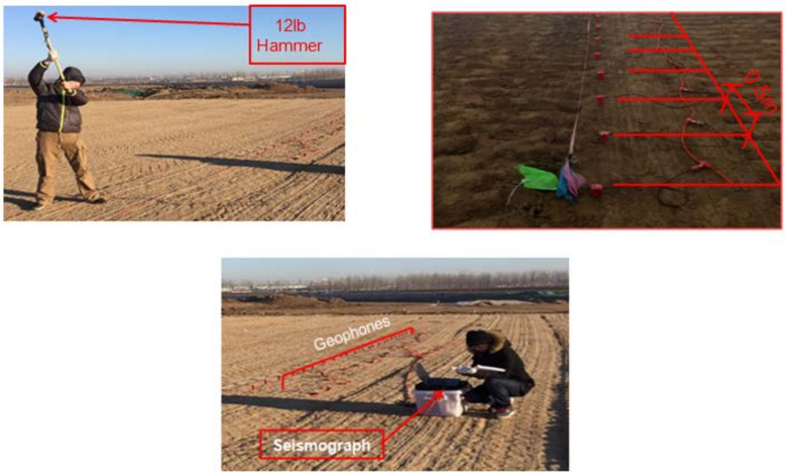


Figure 5. Equipment used for Surface Wave Exploration

4.3 Results of analysis of underground layer using surface waves

According to the results of field standard penetration test and high-density surface wave exploration after soil treatment as shown in Fig 6; it is proposed that the shear wave velocity of the earth dam and the platform of the compression platform is no less than 140m/s, which is the evaluation index of liquefaction measure. The test point shown in the range 1.15m to 4.15m has higher shear wave velocity after treatment, with the assessment indicating improved liquefaction resistance.

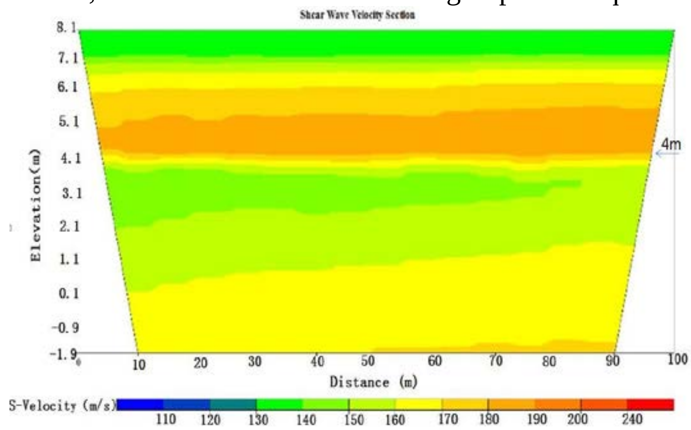


Figure 6. Velocity structure of underground transverse wave obtained by inversion analysis

5. Silty Soil Liquefaction Prevention and Control Measures

5.1 Finite element model

To reduce the computational error caused by artificial boundaries, a sufficient range of soil is needed for modeling. The total width of the model is 320m as shown in Fig7.Boundary conditions:

when carrying out the static calculation, the horizontal constraint is applied at the bottom of the model, while the horizontal constraint is applied on both sides. When the dynamic calculation is carried out, the fixed boundary is applied at the bottom, and the vertical constraint is applied on both sides, and the seismic wave is input from the bottom of the model.
Percolation boundary: the seepage boundary of the soil and the dam body is determined according to the seepage analysis, and the above seepage boundary part of the dam body is calculated.

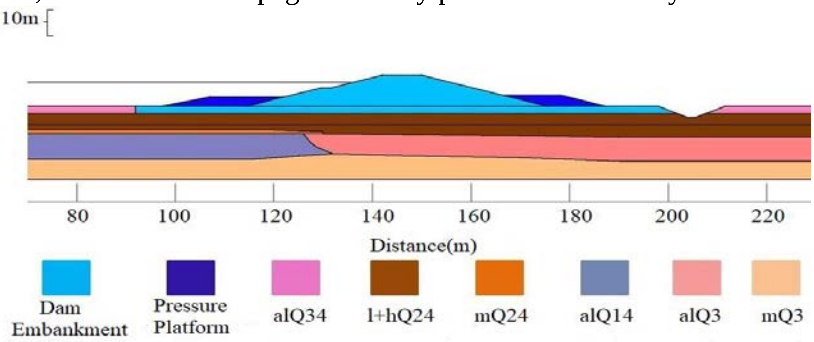


Figure 7.FEM model

5.2 Value of material parameters

The value of the material parameters of the numerical calculation of the seismic response of the dam in natural conditions(untreated)and during construction of the dam(treated)are shown in Table 1. Routine geotechnical tests obtain soil parameters of the surrounding dam soil and heavy load platforms during construction. The reservoir section contains soil parameters of the soil layer, which are obtained from the routine geotechnical test and the dynamic triaxial test. The embankment filling is constructed to maintain a 98% degree of compaction with a measured dry density of at least 1.65 g/cm^3.The pressure platform, on the other hand, maintains a 90% degree of compaction with a measure dry density of 1.56g/cm^3.According to the concept of compactness, the degree of compaction is the ratio of dry density to the maximum standard dry density after the compaction of soil.

5.3 Load Cases

This paper uses the synthetic seismic waveform from the National Seismological Bureau's analysis and Prediction Center as shown in Fig 8. The synthetic method of ground motion is used to simulate the time course of ground motion according to the input seismic response spectrum. Two cases are compared where the untreated and treated soil have different material properties in the top layer as shown in Table 1.

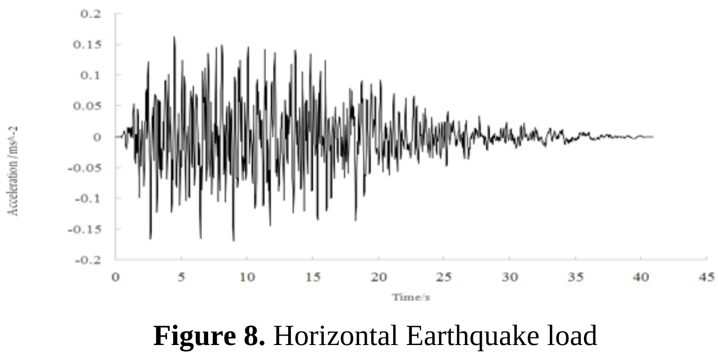
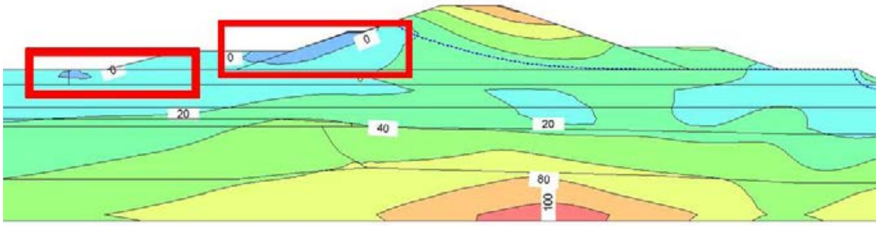


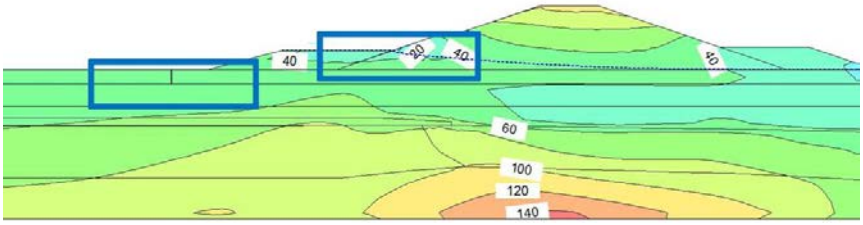
Figure 8. Horizontal Earthquake load

5.4 Results and discussion

According to the liquefaction characteristics of the sandy soil, when the effective stress is zero, the soil loses the shear strength and presents the state of similar liquid. The liquefaction result is defined according to the effective stress distribution map of the dam at the end of the earthquake. The area with effective stress equal to or less than zero is the liquefied area. The effective stress distribution before and after the compaction of the dam foundation under different working conditions is shown in fig 9.



(a)Before Anti-Liquefaction measures



(b)After Anti-liquefaction measures

Figure 9. Effective Stress Distribution

The design water level is 11.9m, the earthquake intensity is VII, and the peak value of the earthquake acceleration is 0.15g.

(1) **Calculation results of the working condition without anti-liquefaction measures(Untreated)**

Without liquefaction prevention measures the liquefaction range extended to a larger range of the pressure platform, the front pressure platform and the foundation below the upstream. The red boxes in Fig 9 show relatively large liquefaction of the front pressure platform and some liquefaction the foundation below the upstream. For the damage situation, the dam is very likely to have serious accidents such as collapse or a landslide.

(2) **Calculation results of working condition with anti-liquefaction measures(Treated)**

There is little or no liquefaction in front of the dam foundation liquefaction area as shown in the blue boxes. The pressure platform in front of the dam has some minimal liquefaction. Overall the dam body has no liquefaction and is more stable. The whole dam under compaction degree is not liquefied. The liquefied area only appears on the surface silt area in the reservoir.

6. Conclusion

Wangqingtuo reservoir is responsible for the storage function of the South to North Water Diversion Project and is used as an accident reserve reservoir in Tianjin. The whole engineering geological condition of the reservoir area is weak, and the surface layer is easily liquefied within a certain depth below the surface layer. In this work, we explored the dams anti-liquefaction methods used and how it affects the dam safety which is very important for the construction of the reservoir.According to experiments and results, three key conclusions can be drawn.

1.According to the investigation results, four liquefaction prevention and control measures are suggested. Soil replacement and backfill, Pressure platforms, Anti-seepage, and a drainage system. The standard compaction degree of the earth material should be not less than 98% for the dam body and not less than 90% for the pressure platform.

2. Combination of shear velocity and dry density were used to control the liquefaction of the earth dam**.** High-density surface wave exploration is proposed to use shear wave velocity to master the distribution and thickness of the liquefiable soil layer and the aquifers to provide a basis for liquefaction grade zoning in the reservoir area.

3.For the two control factors, Firstly the shearwave velocity of the dam and pressure platform should not be less than 140m/s. Secondly, the dry density of the earth material should not be less than 1.65g/ cm^3.

Further investigations are needed to determine more influence factors and use a suitable combination of measures to control liquefaction potential of foundation soil to allow optimum safety during construction.

Acknowledgments

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