

Large deformation performance of the anti-seepage system connection part in earth core dam built on thick overburden

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Abstract. Dams are inevitably planned to be built on thick overburden with high permeability and deformability. The connection part between concrete cut-off wall in overburden and earth core in dam body is not only a key part of the anti-seepage system, but also a weak position. Large uneven settlement will be aroused at the connection part. However, the interaction behavior and the scope of the connection part cannot be determined effectively. In this paper, numerical analysis of a high earth core dam built on thick overburden was carried out with large deformation FE method. The mechanical behavior of the connection part was detail studied. It can be drawn that there is little differences in dam integral deformation for different analysis method, but big differences were found at the connection part. The large deformation analysis method can reasonably describe the process that concrete wall penetrates into soil. The high plasticity clay has stronger ability to adapt to large uneven deformation which can reduce stress level, and stress state of concrete wall is also improved. The scope of high plasticity clay zone in the connection part can be determined according to stress level of soils and penetration depth of concrete wall.

Keywords: connection part; earth core dam; large deformation numerical analysis; mechanical behavior; thick overburden

1. Introduction

Hydropower is an inexpensive, technologically mature renewable resource with a long-life cycle. China is rich in hydropower resource and the western region accounts for about 80% of the total hydropower resources with low exploitation level. However, the thick overburden is widely distributed in many rivers of Western China, particularly in the southwestern region (Wen *et al.* 2017). The overburden soil is characterized by looseness, lithological discontinuance and poor particle size distribution (Ito and Azam, 2013). Complex site conditions and load action can lead to poor performance, such as large settlements, severe cracking and excessive leakage (Xu *et al.* 2015, Karalar and Çavuşlu, 2018, Karalar and Çavuşlu 2021). Earth dam, which is well-adapted to different geological conditions and can make full use of locally excavated materials, are widely constructed in hydropower exploitation around the world. The seepage control and settlement are crucial important issues in the design of earth dams built on thick overburden (Wang *et al.* 2016).

The most famous method to control seepage in overburden foundation of earth dams is to adopt a concrete cut-off wall (Durgunoglu *et al.* 2012, Moharrami *et al.* 2015, Kazemian *et al.* 2016, Wen *et al.* 2019, Yu *et al.* 2021). Meanwhile, earth core is commonly used as the

diaphragm structure in dam body. For better seepage control, concrete cut-off wall is often designed to extend inside the earth core which is a widely employed method to connect concrete cut-off wall and earth core (Javanmard *et al.* 2018). The connection part connects the above two impermeable structures and ensures integrity and continuity of the anti-seepage system (Mahinroosta *et al.* 2012). It is a key position and should be studied with a great attention in order to ensure proper and suitable performance of the anti-seepage system for earth core dam built on thick overburden (Javanmard *et al.* 2018). The basic types of connection part are mainly divided into three kinds: insertion type, piston type and gallery type. Compared with others, the insertion type is most used in the construction of earth core dam because of simple construction, as presented in Table 1. The concrete cut-off wall with larger stiffness almost does not settle under the action of dam body, while large settlement will be aroused in the thick overburden foundation with strong deformability (Nayebzadeh and Mohammadi 2011, Baak *et al.* 2017). Therefore, deformation of the earth core with the effect of foundation settlement is so large that large uneven settlement is brought about in the connection part. This local uneven settlement is prominent for the inserted type and can be up to 2 to 4 times of thickness of concrete cut-off wall, and stress state of the connection part is very complex (Luo *et al.* 2013). Thus, the connection part is a weak part of anti-seepage system for earth core dam built on thick overburden.

Poor connection will lead to concrete cut-off wall being in an adverse stress state, causing cracks in earth core and seriously threatening safety of impermeable system and

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Table 1 Basic information of connection part of some earth core dams built on overburden

Dam name	Completion year	Overburden thickness (m)	Type of the connection part	H ₁ * (m)	H ₂ * (m)
Manick 3	1968	131.0	gallery	12.2	6.2
Maojiacun	1970	33.0	insertion	6.0	3.5
Bikou	1977	40.0	insertion	6.0	5.0
Xiaolangdi	2001	70.0	insertion	12.0	5.0
Karkh	2003	40.0	gallery	8.0	-
Taleghan	2006	65.0	insertion	8.0	3.0
Shuiniujia	2006	30.0	insertion	10.0	5.0
Quaiqi	2007	70.0	gallery	3.5	3.5
Pubugou	2009	78.0	insertion and gallery	15.0	5.0
Shiziping	2010	102.0	gallery	3.5	5.0
Maoergai	2012	50.0	insertion	10.0	5.0
Changhe Dam	2016	50.0	insertion and gallery	9.0	5.0

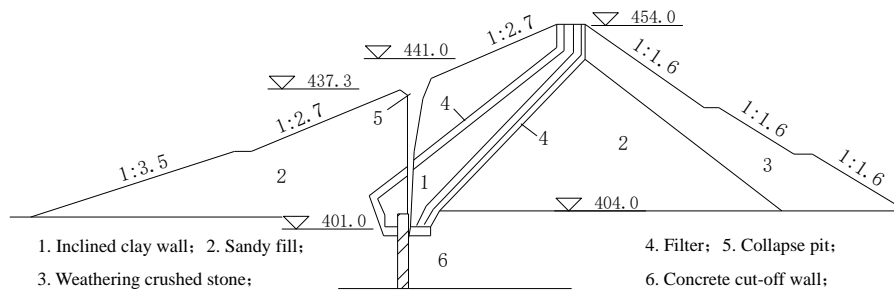


Fig. 1 The leakage illustration figure for Yuma dam

dam project (Shakouri and Mohammadi 2020). In the early stage of building dams on the thick overburden, not enough attention was paid to the design of the connection part, both the Yuma dam in Henan province and Xizhaitang dam in Beijing experienced infiltration damage caused by problems at the connection part (Niu 1998). The failure mode of Yuma dam is presented in Fig.1. The main reasons for this are summarized in the following two aspects (Cai and Wang 2012). Firstly, the soil of earth core has poor ability to adapt to large uneven deformation, and shear damage is aroused at the connection part. Secondly, the length of concrete cut-off wall inserted into earth core is not sufficient. Through summing up these experiences and lessons, China's code puts forward clear requirements for the design of the connection part in earth core dam built on overburden foundation, especially the height of concrete cut-off wall inserted into earth core. In order to improve working condition of the connection part, high plasticity clay with high deformability is often used instead of normal clay for earth core at the connection part between concrete cut-off wall and earth core (Bureau *et al.* 2007).

Some scholars have studied the influence of different core materials on the deformation characteristics of dams (Mir Mohammad Hosseini 2002, Mirghasemi *et al.* 2005, Hosseini *et al.* 2012). The results noted that the dynamic performance of earth dams with mixed-clay core is more desirable than that of pure-clay core. Many scholars have also discussed the height of concrete cut-off wall inserted

into the earth core wall and the thickness of high plasticity clay at the connection part (Liu *et al.* 2016, Javanmard *et al.* 2018, Shakouri and Mohammadi 2020). In general, the insertion depth of concrete cut-off wall can be quantitatively determined with seepage analysis at present. However, impermeable effectiveness of the connection part is mostly depend on the scope of high plasticity clay, and this scope is often determined except working according to experience and the deformation and stress condition are hardly considered. The concrete cut-off wall located in the thick overburden is in a complex and three-dimensional stress conditions. In fact, concrete is a kind of the nonlinear material with multiaxial strength and strain softening behavior (Zoorasna *et al.* 2008, Karalar and Çavuşlu 2019, Karalar and Çavuşlu 2020). Moreover, the settlement of overburden soil will give rise to uneven deformation at the connection part, and significant soil-structure interaction problems is brought about. In current research, there are more results on shear characteristics of concrete structure-soil interface (Liu *et al.* 2006, Liu *et al.* 2014). But, there are fewer research results focusing on working condition of the connection part and interaction behavior between concrete cut-off wall and soil at the top of the wall (Luo *et al.* 2013). For real dam engineering construction, bottom of concrete cut-off wall is often inserted into the bedrock to control seepage more effectively. So that, the wall is not deformed when the dam body and overburden soil deform gradually, and uneven settlement with several times of the width of concrete cut-off wall will be aroused around top

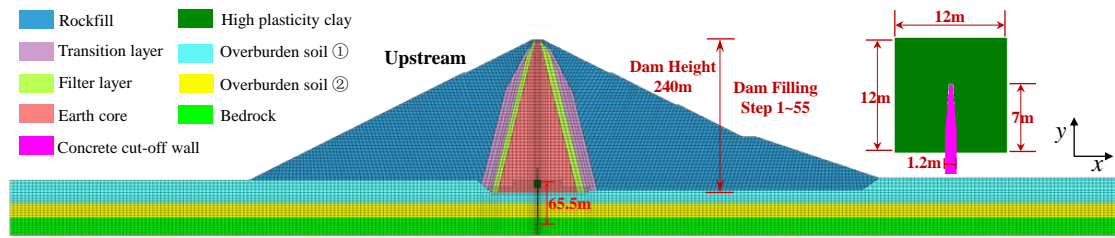


Fig. 2 FE mesh for earth core dam built on thick overburden

the wall at the connection part. In fact, the deformation process during dam body filling is more like a process that concrete cut-off wall penetrates into impervious soils at the connection part. The mesh for numerical analysis around the top of concrete cut-off wall will be severely deformed and distorted, which is a typical large deformation problems associated with soil-structure interaction (Yu *et al.* 2017). This issue has gained attention and some physical model tests have been carried out very early (Zhang *et al.* 1997), but most of them are mainly concerned with the deformation characteristics of concrete cut-off wall. Moreover, numerical simulation analysis is still limited to the small strain FE framework, which cannot describe the large and uneven settlement reasonably and is not conducive to the design and safety evaluation of connection part.

In this paper, RITSS (Remeshing and Interpolation Technique with Small Strain model) which is a large deformation FE analysis method was adopted to study the aforementioned large deformation problem at the connection part for a high earth dam built on thick overburden. Firstly, basic information of a real earth core dam engineering and research method adopted in this study are presented. Then, the large deformation behavior of the dam emphatically the connection part is studied in detail by compare results of RITSS and small strain FE analysis. The advantages of RITSS and necessity to conducted large deformation analysis are also presented. Finally, the effect mechanism of high plasticity clay at the connection part is researched and the optimization analysis is carried out for reasonably and effectively setting the scope of high plasticity clay. The results of this paper can provide theory and guidance for design and safety evaluation of the connection part between concrete cut-off wall and earth core wall for earth core dam built on thick overburden. Numerical analyses in this research were conducted with GEODYNA which is a high-performance calculation and analysis software that validated and utilized in many studies (Zou *et al.* 2013, Qu *et al.* 2017, Zou *et al.* 2018).

2. Basic information and research method

2.1 Numerical model of the researched dam

In this paper, an earth core dam designed to be built on thick overburden in western China is selected as the research object. Geometric parameters of this dam were listed as follows: maximum dam height is 240 m, dam crest width is 6.5 m, maximum overburden thickness is 58 m and

the overburden consists of two types of soil names clay gravel layer and gravel layer respectively. Both filter and transition layer are set on the upstream and downstream side of earth core wall to control dam body seepage and ensure the deformation coordination of rockfill and core wall. A fully enclosed concrete cut-off wall with a thickness of 1.2 m is constructed in the overburden to control dam foundation seepage. The maximum depth of concrete cut-off wall is 65.5 m, of which 11.5 m is embedded in the bedrock at the bottom of the overburden. In addition, a further 15 m is penetrated into the earth core wall in dam body. A 12 m × 12 m of high plasticity clay is set up at the connection part within a certain area at the top of concrete cut-off wall to ensure the impermeability. Fig. 2 shows the FE mesh utilized in numerical analysis, material names and detail information of the connection part are also marked.

There are 11313 elements in the finite element mesh, all of which are quadrilateral 4-node isoparametric elements except a few triangular elements at the boundary of dam slope and soil core wall. The high plastic clay area of joint has large uneven settlement and complex stress state, which is the part of stress concentration. Therefore, the high plastic clay area is simulated by dense grid in this study, and the specific size is $h_{\min}/Wt = 0.12$ (Yu *et al.* 2017). Where, h_{\min} is the minimum element size of the high plasticity clay region around the concrete cut-off wall and Wt is the maximum thickness of the wall. In order to ensure that the incremental deformation caused by each filling step is small enough, the filling thickness of each layer is not more than 5 m, and the dam body filling from the foundation surface to the dam crest layer by layer is simulate by 55 steps totally. In addition, to simulation boundary of the finite foundation more accurately, the lateral direction is more than 4 times of dam foundation thickness, which can well offset the boundary effect (Yu *et al.* 2015, Wen *et al.* 2019). The bottom of dam foundation is fixed in the x and y directions, and the lateral sides of the foundation are fixed in the x direction only.

2.2 Constitutive model and calculation parameters

The constitutive model to describe stress-strain relationship is the basis of numerical analyses. At present, the research achievement on constitutive model is very mature. More than 200 models have been established, which can be roughly divided into nonlinear elastic model and elastic-plastic model (Duncan and Chang 1970, Kulhawy and Duncan, 1972, Clough and Woodward 1967, Wang *et al.* 2019, Wang *et al.* 2020, Wang *et al.* 2021). In dam engineering, plastic model would be better to simulate

Table 2 Parameters for soil of Duncan-Chang model

Material type	ρ_d (kg/m ³)	φ_0 (°)	$\Delta\varphi$ (°)	c (kPa)	R_f	K	n	K_b	m
Rockfill	2180	51.0	9.4	-	0.77	1335	0.24	480	0.21
Filter layer	2180	48.5	7.4	-	0.73	1078	0.23	377	0.21
Transition layer	2250	51.5	8.5	-	0.77	1319	0.24	494	0.22
Earth core clay	2140	25.5	-	66	0.85	358	0.33	165	0.35
High plasticity clay	1550	23.0	-	39	0.88	110	0.46	36	0.47
Overburden soil ①	1310	46.9	6.5	-	0.77	1075	0.33	343	0.27
Overburden soil ②	1450	48.0	7.0	-	0.8	1100	0.34	360	0.32

Table 3 Parameters for concrete-soil interface of Clough-Duncan model

Location	k_1	n	R_f	φ	c (kPa)
Concrete wall - overburden	757	0.8	0.89	11	10.5
Concrete wall - high plasticity clay	2000	0.5	0.80	15	1.0

the behavior of soils, but the lack of experience to determine model parameters and reliable testing data are obvious shortcomings. The hyperbolic model proposed by Duncan and Chang is normally used because of its good performance in predicting the deformation of soils and the results were consistent well with the in-situ measurements (Duncan and Chang 1970, Özkuzukiran *et al.* 2006, Zhou *et al.* 2011, Yu *et al.* 2015). In this paper, Duncan-Chang E-B model is employed to model the stress-strain characteristics of soils in the numerical analysis, and a detailed description of the hyperbolic model can be found in (Duncan and Chang 1970, Zou *et al.* 2013, Yu *et al.* 2017).

The Duncan-Chang model is presented according to the hyperbolic relationship as follows

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a + b\varepsilon_1} \quad (1)$$

where, $\sigma_1 - \sigma_3$ is the difference of principal stress; ε_1 is the axial strain corresponding to $\sigma_1 - \sigma_3$; a and b are test parameters determined by soil properties. In general triaxial tests, σ_3 remains unchanged. Thus, the incremental elastic module E_t can be obtained as follows

$$E_t = \frac{\partial(\sigma_1 - \sigma_3)}{\partial\varepsilon_1} \quad (2)$$

Based on the hyperbolic curve, E_t can be defined as follows

$$E_t = kp_a \left(\frac{\sigma_3}{p_a} \right)^n [1 - R_f S_t]^2 \quad (3)$$

$$S_t = \frac{(\sigma_1 - \sigma_3)(1 - \sin\varphi)}{2c \cos\varphi + 2\sigma_3 \sin\varphi} \quad (4)$$

The elastic module E_{ur} during unloading-loading is as follows

$$E_{ur} = k_{ur} p_a \left(\frac{\sigma_3}{p_a} \right)^n \quad (5)$$

In addition, the nonlinear behavior of strength is expressed as follows

$$\varphi = \varphi_0 - \Delta\varphi \log \left(\frac{\sigma_3}{p_a} \right) \quad (6)$$

In the finite element analysis of soil stress and deformation, a parameter reflecting the change of soil volume is needed. At first, tangent Poisson's ratio was used in Duncan-Chang model. Later, it was found that it was not ideal, and then the tangent bulk modulus B_t was used as the calculation parameter. The Poisson's ratio can be denoted by the elastic and bulk modulus as follows

$$\nu = \frac{3B - E}{6B} \quad (7)$$

$$B_t = k_b p_a \left(\frac{\sigma_3}{p_a} \right)^m \quad (8)$$

where k , k_{ur} , k_b , m and n are constants that can be obtained by the calibrating the test results, R_f is the failure ratio, S_t is the stress level that denotes the exerted degree of material shear strength, c and φ are the Mohr-Coulomb strength parameters and p_a is the atmospheric pressure expressed in the same units as σ_3 .

The parameters are listed in Table 2. In which, ρ is the dry density; c , φ and $\Delta\varphi$ are strength parameters; K and n are parameters of deformation modulus; R_f is the failure ratio; K_b and m are the parameters of bulk modulus.

The difference in deformation between concrete cut-off wall and soil including overburden and core wall is so pronounced that it is very necessary to set interface element between these two distinct materials (Karalar and Cavusli

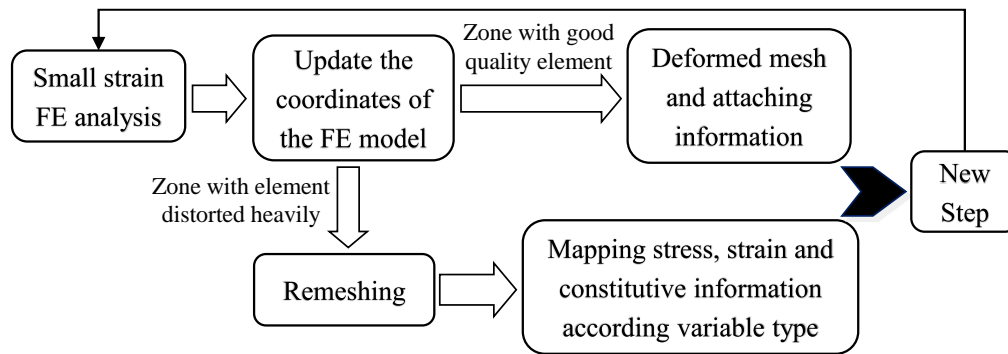


Fig. 3 Operational process of RITSS based on GEODYNA

Table 4 Parameters of linear elastic model

Material	ρ_a (kg/m ³)	E (GPa)	ν
Concrete	2400	30	0.17
Bedrock	2450	9	0.28

2019). In this study, Goodman interface element (Goodman *et al.* 1968) were added in these two locations. Meanwhile, the Clough-Duncan model was employed to describe the interaction characteristics of concrete structure and soil. The parameters are shown in Table 3, where k_1 and n are coefficient and index to calculate shear stiffness, c and ϕ are to describe interface strength, R_f is the failure ratio. The specific information about stiffness of this model can be found in (Yu *et al.* 2017). In addition, linear elastic model was used to simulate concrete cut-off wall and bedrock, corresponding parameters are shown in Table 4.

2.3 Large deformation FE analysis method

The problem of large-deformation has been one of the key concerns in the fields of geotechnical and hydraulic engineering. In the past decades, many efforts have been made to solve the large-deformation problem and some methods have been proposed (Huerta and Casadei 1994, Shen *et al.* 2009, Renon *et al.* 2005, Hu and Randolph 1998). The Remeshing and Interpolation Technique with Small Strain model (RITSS) method was proposed by Hu and Randolph under the framework of the ALE (Hu and Randolph 1998). When the RITSS method is employed, the large-deformation problems are solved through a series of small strain FE calculations combined with periodic remeshing, followed by mapping. This method is easy to be implemented using self-developed codes to couple the remeshing and mapping algorithms with any standard FE program. At present, most applications of the RITSS method are focused on marine engineering and the soils are usually assumed to be undrained, ideal elasto-plastic materials (Song *et al.* 2008, Wang *et al.* 2011, WangD. *et al.* 2013). However, there are significant differences between earth-rock dam engineering and marine engineering in terms of load types and soil material properties (Xu *et al.* 2012, Yu *et al.* 2017, Wang *et al.* 2020, Yu *et al.* 2021). The authors have extended the RITSS method to earth and rock dam projects successfully in previous research (Yu *et al.*

2017). The adaptability of Duncan-Chang model and the effect of grid size on the calculation were discussed in the course of RITSS being expanded to new area. This large deformation analysis method is verified to be stable and reliable in studying the engineering problems of earth and rock dams. Fig. 3 shows the procedure to operate RITSS method based on GEODYNA which is a high-performance calculation and analysis software. In this implementation and extension of RITSS, remeshing boundary is dynamic tracked. In addition, many mapping method can be chosen according to the complexity degree of mapped information. Moreover, large deformation analysis can be conducted coupling with many loadings condition, such as dam filling and gradually increased water pressure.

3. Large deformation numerical study and the results analysis

In this part, large deformation analysis with RITSS method improved by authors and small strain FE analysis are carried out in parallel. When large deformation analysis is conducted, the RITSS progress is invoked and operated when stepped dam filling completed and remeshing zone is high plasticity clay zone in the connection part maintained unchanged where large uneven deformation often appearance. And, the figures about stress state of the connection part is also presented with high plasticity zone representatively.

3.1 Global deformation of the dam

Fig. 4 shows the deformation distribution of the dam engineering. The color cloud result is got by small strain FE method. The attunements line result is got by RITSS method. The maximum deformation with different methods are presented in Table 5. It can be seen that the results with these two analysis methods are in good agreement in distribution rule and deformation value. In addition, the distance of location with maximum deformation is far from the connection part where dramatic interaction aroused. And, the dam deformation is controlled by overburden according the distribution of horizontal displacement. Therefore, it is effective to employ small strain FE method to study the global deformation rules of earth core dam built on overburden.

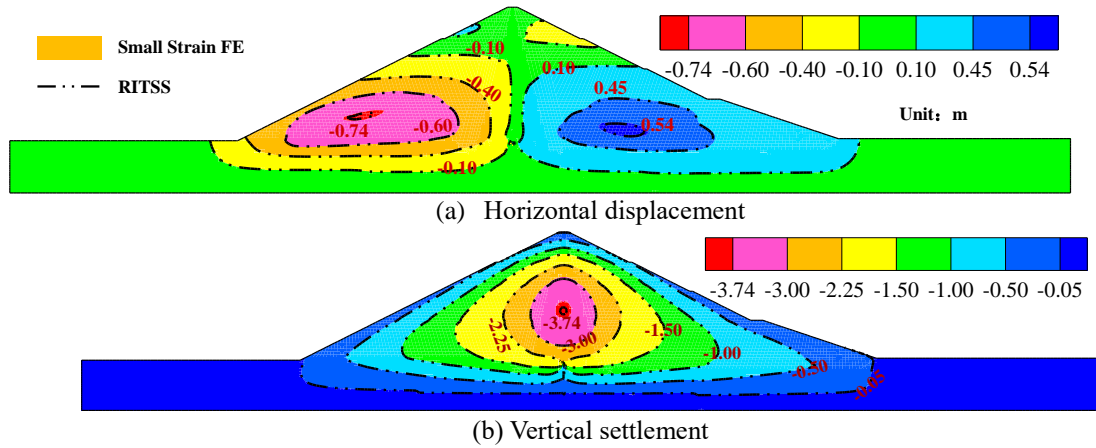


Fig.4 Deformation distribution of the holed dam with different analysis method when dam filling completed

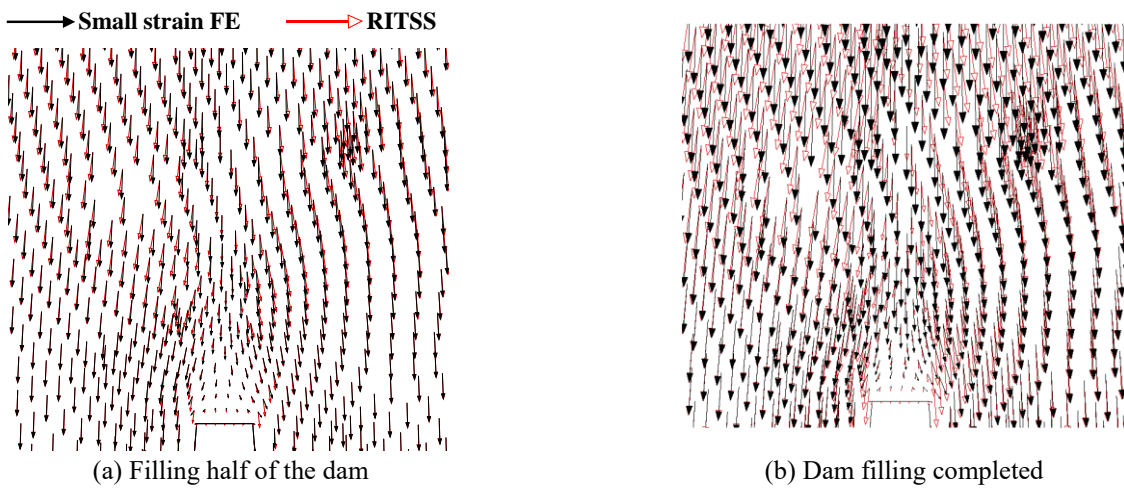


Fig. 5 Deformation vector of the high plasticity clay zone

Table 5 Maximum deformation with different analysis methods

Analysis method	Vertical settlement (m)	Upstream horizontal displacement (m)	Downstream horizontal displacement (m)
Small Strain FE	3.790	0.75	0.546
RITSS	3.749	0.74	0.543

3.2 Locally deformation of the connection part

Fig. 5 presents the deformation vector of the connection part with high plasticity clay at top of concrete cut-off wall with small strain FE method and large-deformation FE method respectively. In order to compare results of these two methods, the mesh information of RITSS method is mapped to the corresponding mesh of small deformation FE method. Under the action of dam body, the high plasticity clay zone presents strong vertical deformation ability. Moreover, it can be seen that when large deformation FE analysis is conducted, the soil mass presents a moving trend to the side of the concrete wall more obvious in a certain range at top of connect cut-off wall. With the progress of dam filling, the difference of deformation vectors between the two methods is more noticeable.

Fig. 6 shows the horizontal deformation of the high

plasticity clay zone when dam filling completed. The figure shows the difference of horizontal deformation between in above two analysis methods more intuitively. In fact, in order to avoid the penetration of concrete cut-off wall, soil such as high plasticity clay and normal clay with limited compression capacity at the connection part will present strong horizontal flow characteristics. However, this horizontal deformation is underestimated with small strain FE method. In addition, the large deformation behavior such as the penetration of concrete cut-off wall and the horizontal deformation at top of the wall have big effect on stress behavior of the connection part and the concrete wall according early research. The results of small strain FE analysis method have an overly optimistic view of stress state in the connection part. And, there is a deviation of more than 25% in principle stress of concrete cut-off wall with small strain FE analysis (Yu *et al.* 2017). These phenomenonses are also presented in flowing context.

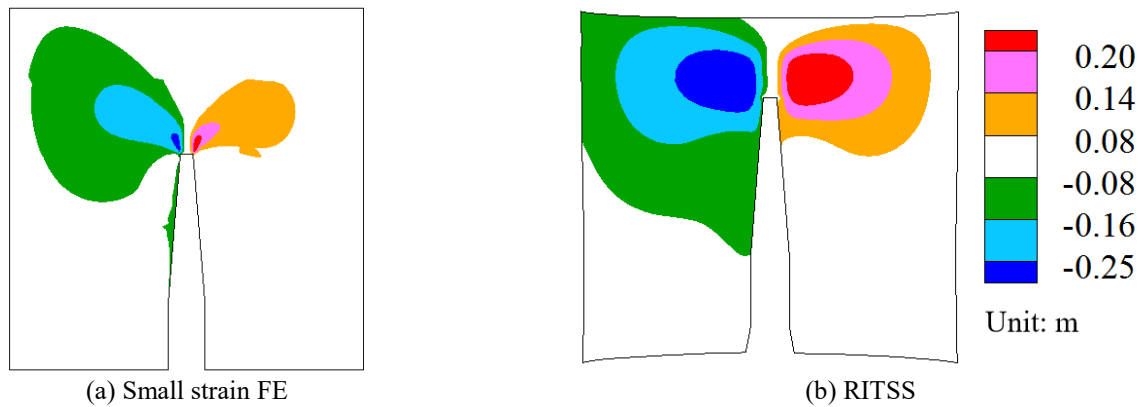


Fig. 6 Horizontal displacement of the high plasticity clay zone (Unit: m)

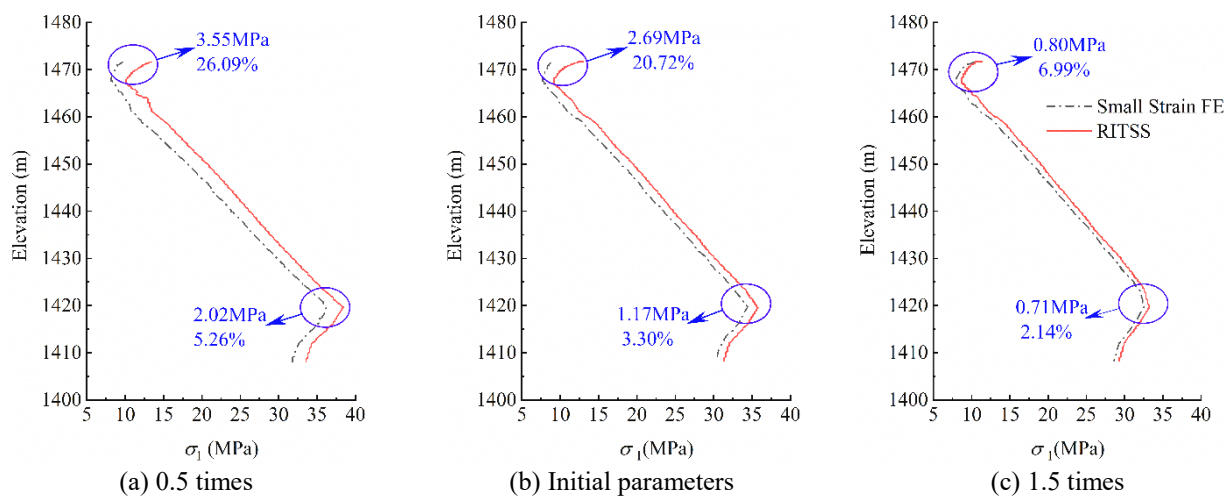


Fig. 7 Major principal stress of concrete wall with different deformation modulus of overburde

Therefore, large deformation FE analysis should be conducted when the connection part of anti-seepage system is the study focus.

3.3 Effects of locally uneven deformation

The interaction between concrete cut-off wall and anti-seepage which is particularly pronounced at the connection part is mainly caused by locally uneven deformation because of the disparate differences in deformation behavior between the concrete wall and the soil. In addition, the foundation deformation directly affects the connection part settlement due to the dam directly built on overburden, thus soil-structure interaction strength at top of concrete cut-off wall is changed with overburden deformability. In order to analyses the effect of locally uneven deformation on stress state of the connection part and stress distribution behavior of concrete cut-off wall, the modulus coefficients, K and K_b , of overburden in Table 1 are reduced and enlarged to 0.5 times and 1.5 times respectively to carry out numerical analysis.

Fig. 7 shows the major principal stress distribution along the height of concrete cut-off wall when RITSS analysis and small strain FE analysis are conducted respectively. It can be seen that the distribution rule is same

for these two analysis method. However, there is a significant difference in value. Moreover, the difference between the stresses in concrete cut-off wall obtained from these two analysis is small when the deformation modulus of the overburden soil is larger, which is basically less than 0.80 MPa at top of the wall and 0.71 MPa at location with maximum value along the wall. In addition, when the overburden deformation modulus parameter is taken as half of original parameters, the larger overburden deformation causes locally uneven deformation bigger and stronger interaction between soil and structure at the connection part is aroused. In this condition, the results of small strain FE analysis is significantly smaller than RITSS analysis. And the deviation is up to 3.55 MPa at top of the wall and 2.02 MPa at the position with the maximum value, which is 20.09% and 5.26% lower than RITSS result respectively. Therefore, the interaction between soil at the connection part and concrete cut-off wall is seriously affected by the degree of locally uneven deformation. The reliability of results with small strain FE analysis decrease with the increase of locally uneven deformation. Large deformation analysis with RITSS method should be employed when studying the stress behavior of concrete cut-off wall in earth core dam built on overburden, especially that the overburden foundation is thick or with large deformability.

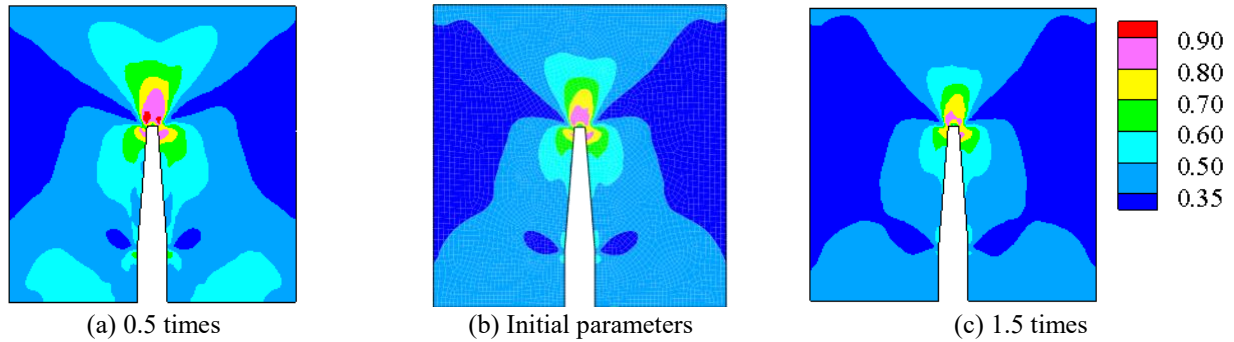


Fig. 8 Stress level of the connection part with different modulus of overburden for small strain FE analysis

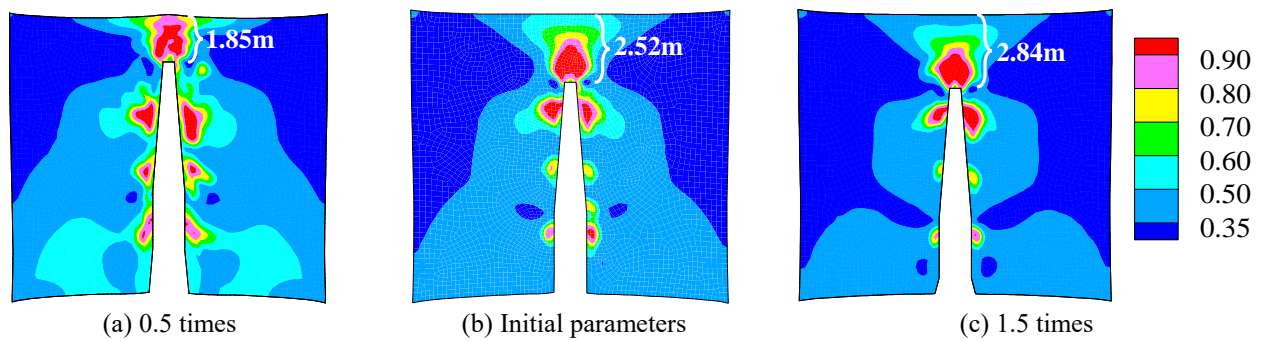


Fig. 9 Stress level of the connection part with different modulus of overburden for RITSS analysis

Figs. 8 and 9 present the stress level distribution in the connection part of high plasticity clay zone for the small strain FE method and RITSS method analysis respectively. The higher the stress level is, the failure is more likely to happen at this zone. As the deformation modulus of overburden decreasing, the strength of soil-structure interaction increases, and the range of stress level which no less than 0.5 in the connection part increases significantly. However, the small strain analysis obtains a safer stress state, which is an overestimation of impermeability of the connection part. The design with these result will make the anti-seepage system under an unsafe state. The large deformation analysis with RITSS method not only obtains the trend of stress state, but also directly presents the change in the effective thickness of the high plasticity clay at top of concrete cut-off wall. The large deformation analysis method is a good method to capture the penetration behavior of the concrete wall. When the deformation modulus of overburden decrease to half of initial, the effective thickness decreases to 1.85m from designed 5.00m. Moreover, the stress state at this zone is very high which is harmful to working ability of the connection part. Therefore, it is necessary to conduct large deformation FE analysis to obtain a more reasonable deformation-stress state of the connection part for earth core wall dams built on overburden, so as to provide a basis for impermeability safety evaluation and impermeability design of the connection part.

4. Optimization study on the connection part with RITSS analysis

4.1 Effect mechanism of high plasticity clay

According to the above analyses, there is strong interaction between concrete cut-off wall and soil at the connection part because of locally uneven deformation. This can lead to unfavorable stress state in the connection part. And, it is unfriendly to the performance of the anti-seepage system. Therefore, the connection part should be designed to be able to adapt to the locally uneven deformation. The high plasticity clay is often used to replace the common clay for the earth core within certain limits at the connection part to wrap top of concrete cut-off wall as shown in Fig. 2. However, there is few research about the effect mechanism of high plasticity clay at the connection part of anti-seepage system. In order to express the role of high plasticity clay more clearly, the large-deformation FE analysis with RITSS method was conducted to study the working condition of the connection part with or without high plasticity clay. Fig. 10 presents the stress level of the connection part when common clay and high plasticity clay is installed at this region respectively. The maximum principle stress of concrete cut-off wall for these two conditions is shown in Fig. 11.

The regional boundary in Fig. 10 represents the boundary between common clay and high plasticity clay at the connection part. The soil below this line is different for these two research conditions. If common clay is used at the connection part, the stress state level is very high and with a wide range. When the soil at the connection part is high plasticity clay with a higher deformability than common clay as presented in Table 2, the stress state is improved greatly by comparing with the common clay condition. The

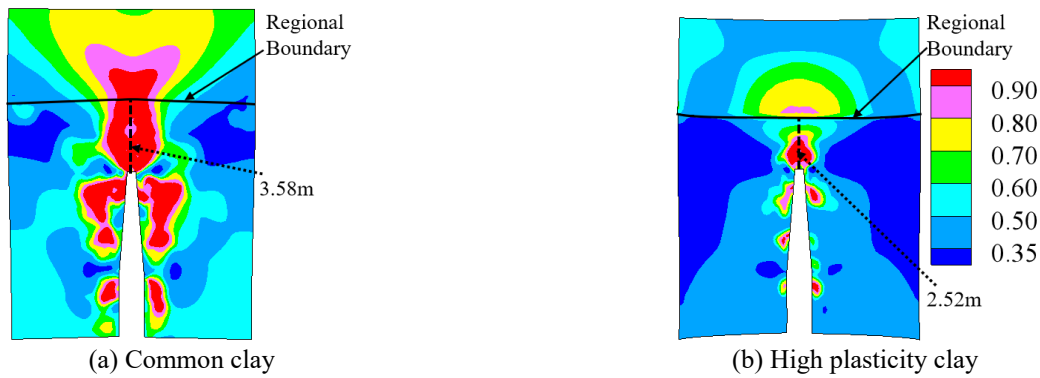


Fig. 10 Stress level of the connection part with different clay

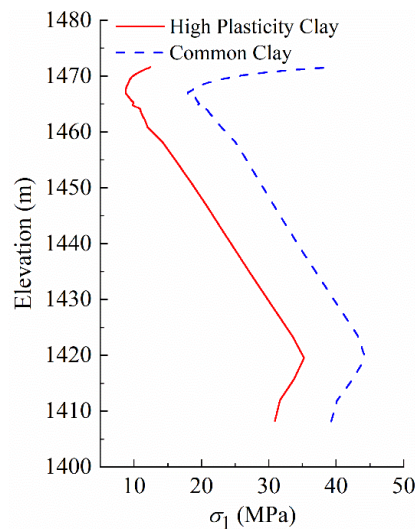


Fig. 11 Maximum principle stress of concrete cut-off wall with different clay at the connection part

stress state value around the concrete wall decreases seriously with a large penetration depth. The effective thickness is reduced to 2.52 m for high plasticity clay condition from 3.58 m for normal clay condition. The final deformation state of the regional boundary is convex when the soil at the connection part is common clay, while it is concave when the high plasticity clay is used. The common clay eventually leads to a stronger interaction between soil and the concrete wall at the connection part, and a large area of higher stress level in the soil will be aroused. It is very likely to form a shear damage penetration region and is not conducive to the impermeability of the connection part. In addition, the stress concentration problem at top of the concrete wall relieves outstanding, the major principal stress value decreases 26.35 MPa. And, the stress along concrete cut-off wall is reduced, resulting in 10.54 MPa reduction at the location with maximum major principal stress.

4.2 Influences of the scope of high plasticity clay zone

As presented before, the high plasticity clay can make the anti-seepage system including the connection part and

concrete cut-off wall at a good working condition. While, there has been no according way to determine the scope of high plasticity clay zone. And, stress state of the connection part is often ignored in previous designing study. In addition, small strain FE analysis is usually adopted. However, the small strain FE analysis cannot capture the deformation-stress behavior aroused by locally large uneven deformation. And, the stress level of the connection part and stress in concrete cut-off wall are generally small with small strain FE analysis. The working ability of the anti-seepage system will be overrated, which may be the hidden trouble to dam safety. Hence, the scope of high plasticity zone showed be large than determined by small strain FE analysis. On the other hand, high plasticity clay should be used sparingly from an investment perspective, because high plasticity clay often needs to be transported over long distances. Therefore, it is very necessary to conduct large deformation analysis to design the connection part more precisely.

For the studying case presents in 2.1 of this research, the thickness of high plasticity clay at top of the concrete wall is reduced from the designed 5.00 m to 2.52 m and the stress level is still high. At the same time, it is connected with the high stress level area in the common clay zone

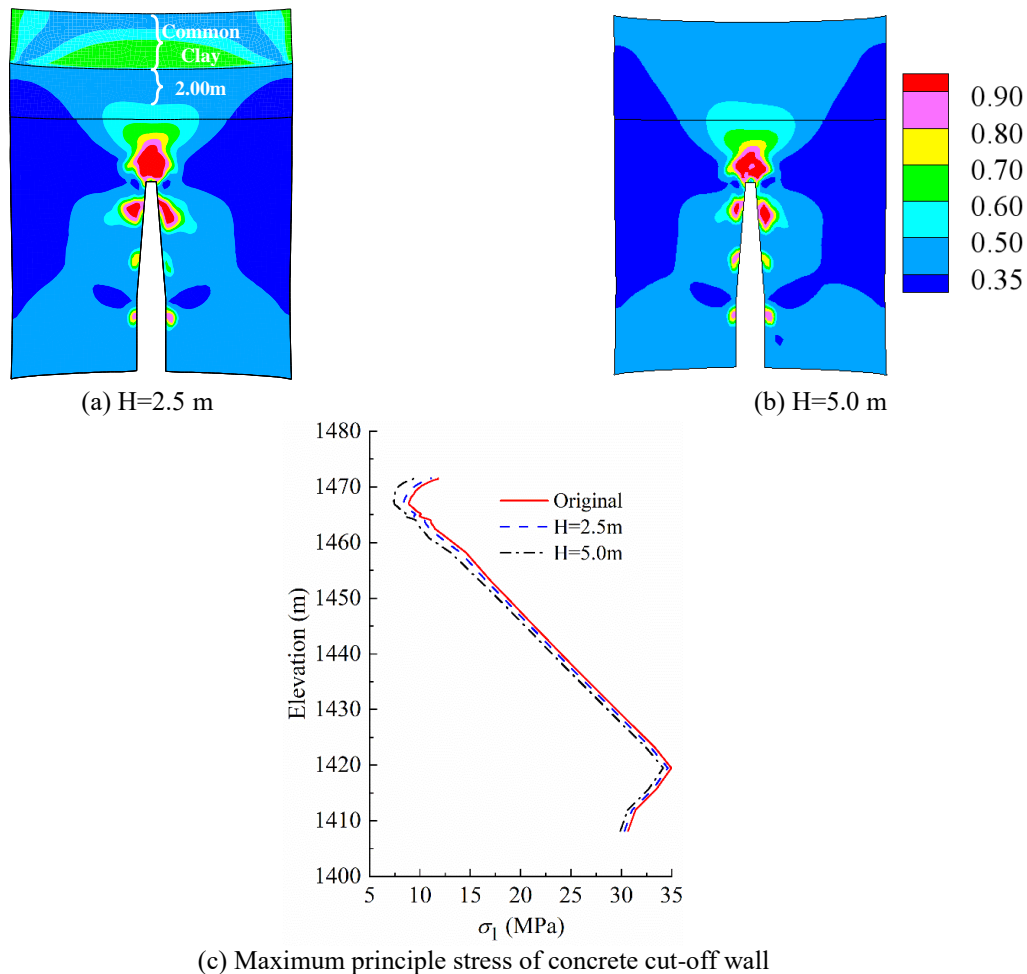


Fig. 12 Influences of the scope of high plasticity clay with different thickness in height direction

as shown in Fig. 10(b), which is a big potential safety hazard. In addition, a large range of high plasticity clay at both sides of the concrete wall is small. Therefore, optimization study is needed to determine a reasonable scope of high plasticity clay zone.

Fig. 12 shows the stress state in concrete cut-off wall and high plasticity clay region when the original high plasticity clay region is increased by 2.50 m and 5.00 m ($H=2.50$ and 5.00) in the height direction respectively. When the thickness of high plasticity clay is increased, the deformation of the soil at the connection part increases and the interaction between the soil and the concrete wall is relieved. The major principal stress in the concrete cut-off wall are reduced slightly. When the thickness of the high plasticity clay is increased by 2.50 m, a low stress level region which is less than 0.50 with 2.00m thickness approximately exists at top of high plasticity clay region and the stress level in normal clay region is significantly reduced by comparing Figs. 10(b) and 11(a). When the thickness is increased by 5.00 m, the stress level in the original high plasticity clay region does not change much, but the thickness of low stress level region at the top increases obviously. Because of the high anti-seepage properties, a small amount of high plasticity clay is sufficient to meet the permeability requirements. Therefore,

for economic reasons, the thickness in the height direction of the high plasticity clay region should be increased by at least 2.50 m to 7.50 m for this study case.

It can be seen that the range of low stress level in high plasticity clay region on both sides of concrete cut-off wall is large from the above analyses. The concrete cut-off wall has a strong ability to reduce the water head in the horizontal direction. And, when the contact between the soil and the concrete wall at the connection part is in a closed state, it can even be designed without high plasticity clay. Therefore, it is sufficient to ensure that there are no seepage channels between the soil and concrete cut-off wall, and the range of high plasticity clay in the horizontal direction could be as small as possible. Fig. 13 shows the maximum principle stress of concrete cut-off wall and stress level of high plasticity clay region when the thickness above top of the concrete wall in height direction is 7.50m, and the thickness in the horizontal direction is 1, 2 and 3 times the thickness of concrete cut-off wall respectively (Case T=1, 2, 3 respectively).

As the thickness in the horizontal direction of high plasticity clay region decreases, the major principal stress at top of concrete cut-off wall gradually decreases and increases at the bottom, but the effect is very small. When the thickness on both sides of the wall is same with the

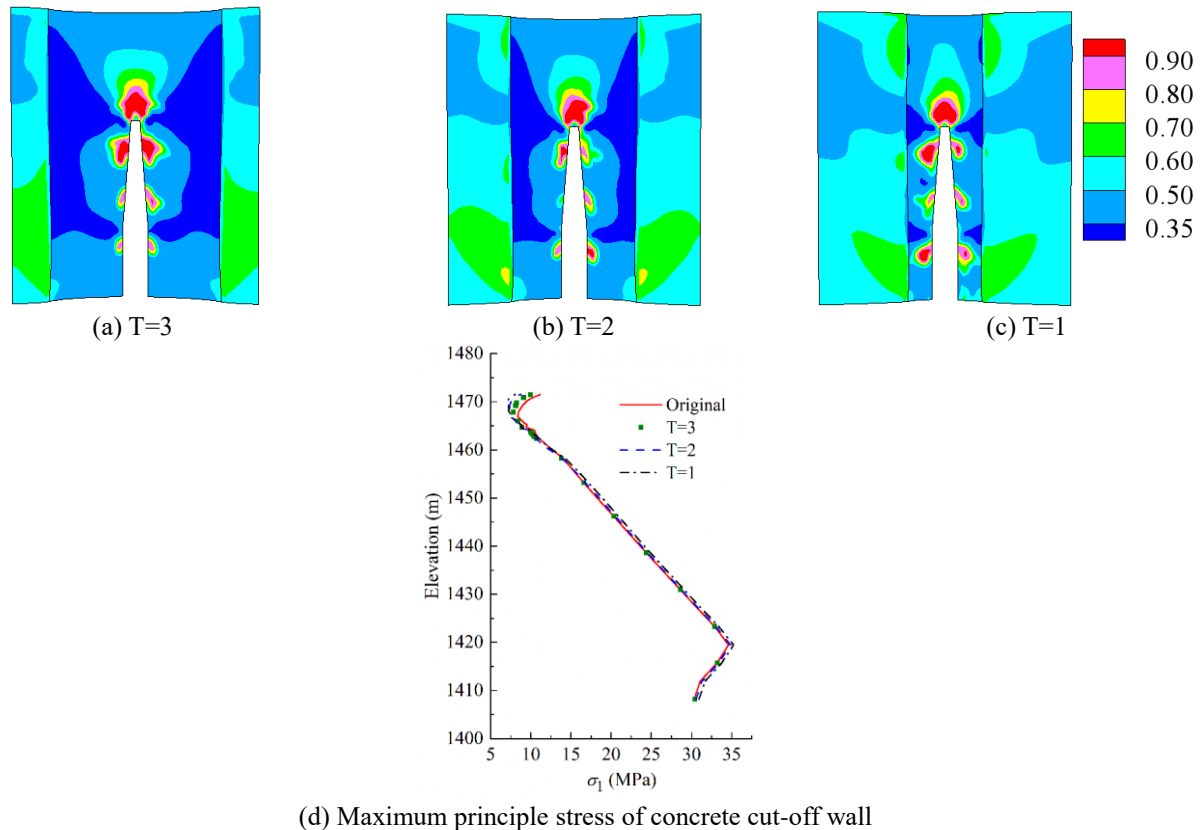


Fig. 13 Influences of the scope of high plasticity clay with different thickness in horizontal direction

thickness of concrete cut-off wall, the interaction between the concrete wall and the soil makes the stress level in local range of the wall higher and develops to common clay region. That, seepage channels is very easy to be formed and the safety of the anti-seepage system is affected. When the thickness in the horizontal direction is 2 times the thickness of the concrete wall, the high stress level region at both sides of concrete cut-off wall is surrounded by a relatively thick high plasticity clay with low stress level state, which ensures seepage resistance in the horizontal direction. When the thickness is increased to 3 times, the region of high plasticity clay with low stress level in the horizontal direction is further expanded. Therefore, thickness with 2 times of wall thickness in horizontal direction is enough to the case in this study. According these research, the deformation and stress state of the connection part can be obtained straightforward with large deformation FE analysis. Then, the connection part can be optimal designed according the range of high stress level and requirement for thickness of protective layer conveniently.

5. Conclusions

This paper focuses on the key issues in revealing the locally working behavior and designing of the connection part for anti-seepage system of earth dam built on thick overburden. An advanced large deformation FE analysis method, RITSS, is introduced, and a series large

deformation numerical analysis and compared analysis are carried out based on a dam engineering case. The locally soil-structure interaction behavior and influences of uneven deformation is analyzed. Then, the effect mechanism of high plasticity clay at the connection part is researched. Finally, the optimization analysis is carried out with RITSS method for reasonably and effectively designing the scope of high plasticity clay.

- The global deformation rule and the maximum deformation value are in good agreement for large deformation analysis and small strain analysis. However, small strain analysis is failing to capture the phenomenon that the soil mass at top of concrete cut-off wall present a more obvious moving trend to both side of the wall because of the progressed penetration. So that, the results of small strain analysis method make an overly optimistic view of the connection part, which may be a hidden trouble to anti-seepage safety. While large deformation analysis with RITSS method have described and modeled the key points caused by locally uneven deformation preferable, such as wall penetration and soil lateral deformation.
- The degree of locally uneven deformation has a prominent effect on the reliability of results with small strain FE analysis. When the deformation modulus of overburden decrease to half of initial parameters, the stress in concrete cut-off wall with small strain analysis is significantly smaller than RITSS analysis, and is up to 20.09% at top of the wall. The large deformation analysis with RITSS method not only

obtains the trend of stress state, but also directly presents the change in the effective thickness of the high plasticity clay at top of concrete cut-off wall. The effective thickness decreases to 1.85m from designed 5.00m when the deformation modulus of overburden decrease to half of initial. Therefore, it is necessary to conduct large deformation FE analysis to obtain a more reasonable deformation-stress state of the connection part for earth core wall dams built on overburden.

- The high plasticity clay surrounded top of concrete cut-off wall can greatly improves the stress state of soils and the concrete wall by comparing with common clay condition. The effective thickness at top of the wall is reduced to 2.52 m only when high plasticity clay is employed at the connection part because of the strong deformation ability, and 3.58 m for common clay condition. The approximate additional 1.00 m deformation greatly alleviates the stress level in soils and the range with high stress level reduces. For the studying dam engineering case in this paper, to make sure the effective thickness is big enough and stress level is small enough, the height above top of concrete cut-off wall should increase 2.50 m to 7.50 m in total at least. Moreover, thickness in horizontal direction could be reduced to 2 times of concrete cut-off wall thickness.

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