Study on compaction control standard of different contact clay areas for 300m high core rockfill dam

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Abstract. Based on several 300m high core rockfill dam in Southwest China, through studying the stress distribution, shear deformation and stress level of different gravel soil core walls, combined with the mechanical test results of contact clay under different compactness and moisture content, the compactness control standards for different contact clay areas of high core rockfill dam are proposed. The results show that for the contact clay area of dam slope on both banks, for the area where the stress level exceeds 0.9, the compaction degree should be increased, so as to improve the shear strength of the soil in the area; for the area with large shear deformation, the compaction degree should be reduced, so as to adapt to the larger shear deformation with larger allowable shear strain. During the filling of contact clay, the water content should not be too low or too high, and should be controlled in an interval near the optimal water content. Taking the test soil materials of the project as an example, it is suggested that the lower limit of filling water content should be controlled at 1% of the optimal water content, and the upper limit should be controlled at 3.5% of the optimal water content.

1. Introduction
Contact clay is widely used in earth-core rockfill dam. It is mainly located in the area where stress concentration is likely to occur at the joint part of concrete structure and dam material. It can release stress by relying on its strong plastic deformation ability to achieve the purpose of reducing local stress concentration [1]. Compared with the core wall soil, the contact clay has lower deformation modulus, can maintain good permeability under the condition of large deformation or crack formation, and has better crack self-healing ability compared with the core wall soil.

In the high earth core rockfill dam built on bedrock, the contact clay is mainly arranged at the connection between the core wall and the concrete cover plate, which plays a role of coordinating deformation. The properties and thickness of the clay are mainly studied in the design [2]. If the high core rockfill dam is built on the deep overburden, it is necessary to adopt engineering measures such as cut-off wall to prevent seepage of the dam foundation. The cut-off wall and the earth core wall generally adopt special connection mode. The corridor connection mode is to set up a corridor at the top of the cut-off wall, and the grouting hole is reserved in the middle of the wall, which can be reinforced grouting when the wall is partially failed. The plug-in connection mode relies on the effect of earth pressure on the outside of the wall of the insertion section, and the wall and the fill can be closely combined to avoid seepage contact and scouring [3,4]. A contact clay area is set at the top of the insertion section of the cut-off wall.
or around the corridor, which can effectively reduce the compressive stress of the cut-off wall, avoid the top crack of the core wall caused by the cut-off wall (or corridor), and also improve the impermeability of the connection part [5].

In the past design, the setting mode and scope of the contact clay area were usually determined according to the estimation or engineering analogy, considering the dam height, dam foundation material properties and other factors. Among them, the setting of thickness should be based on the settlement calculation value of the core wall or the top of the cut-off wall, a certain safety margin should be reserved, and combined with the construction requirements. Zhang Dan adopted the three-dimensional nonlinear finite element method based on the sub model method to study the different setting schemes of contact clay zone at the joint of Changhe dam cutoff wall and soil core wall, and obtained the influence of the range of clay zone on the stress and deformation of core wall, gallery and cutoff wall [5]. Zhang Kunyong used the two-dimensional static finite element method to calculate the influence of regional variation of different contact clay on the stress and deformation of high core rockfill dam body, cutoff wall and gallery [1]. Guo Qingguo studied the function and control conditions of high plastic zone of earth rock dam, and summarized the problems of concrete cutoff wall inserted into clay core wall [6].

With the development of dam height and the limitation of seepage gradient of cut-off wall, some high earth rockfill dams on deep overburden foundation also adopt two cut-off walls [7]. For example, relying on Pugou Hydropower Station, Wu Mengxi studied the design scheme for the connection of two cut-off walls and soil core wall, and analyzed the pore water pressure and seepage gradient at the bottom of the center wall in the two optimization schemes of the cut-off wall and gallery completely wrapped by contact clay and only the top wrapped by contact clay [8].

After the design index of contact clay is determined, it is necessary to review the rationality of the index and determine the appropriate rolling parameters to guide the construction according to the results of rolling test and indoor test. For example, Zhou Qiang carried out a series of field and laboratory tests on the contact clay of Guanyinyan Hydropower Station, including soil density, natural moisture content, maximum dry density, liquid limit index, plasticity index, particle composition, compactness and rolling technology [9]. Among these design indexes, the design and evaluation of compactness are mainly checked through comparative indoor test and field rolling test, but lack of corresponding control and evaluation standards. Therefore, based on a 300m high core rockfill dam project under construction in Southwest China, this paper studies the compaction control standards of different contact clay areas, in order to provide reference for the design of contact clay in the project.

2. Project profile

A gravel soil core rockfill dam is located in Southwest China. Its maximum dam height is 295m. The normal water level of the reservoir is 2865m. The total storage capacity is 10.767 billion m³, and the regulating storage capacity is 6.56 billion m³. The installed capacity of the power station is 3000MW and the annual average power generation is 11 billion kw·H. The top elevation of gravel core wall is 2873m, the width of dam top is 6m, and the upstream and downstream slopes are 1:0.2. Contact clay with a horizontal thickness of 4m is laid at the joint between the cover plate and the core wall. The upstream of the core wall is provided with two layers of filter with a horizontal thickness of 4m, and the downstream is provided with two layers of filter with a horizontal thickness of 6m. A transition layer is set between the upstream and downstream filter layers and the dam rockfill, and the upstream and downstream slopes are 1:0.4. The foundation of upstream and downstream rockfill area is provided with shore transition material with horizontal width of 3M. The upstream side of the dam is set with rockfill zone I above the elevation of 2658m and rockfill zone II below the elevation of 2658m. The downstream dam shell is filled with rockfill zone I materials. A typical section is shown in Figure 1.
3. Analysis of soil test
Under 604kJ/m³ compaction work, the maximum dry density of contact clay is 1.75g/cm³, the optimal moisture content is about 17%, the control test condition is compaction D=100%~106% (JHD-1 is 100% compaction condition, JHD-4 is 106% compaction condition). The direct shear test was carried out under the condition of W_op+1%=18%. The test results under normal stress of 100kPa~400kPa are shown in Figure 2.

The test results show that with the increase of normal stress, the shear strength of contact clay is hardening; Under the same normal stress, the shear modulus of contact clay increases with the increase of compactness; When the shear stress level of soil sample is less than 1, under the same shear stress condition, the shear deformation of high pressure compaction soil sample is smaller than that of low pressure compaction soil sample, that is, the contact clay under low pressure compaction condition can better adapt to larger shear displacement. Therefore, the shear and deformation characteristics of clay material should be considered in the zonal compaction of high plasticity clay

(1) When large shear deformation occurs in the region, under the condition that the shear stress does not reach the shear strength, the compaction degree can be appropriately reduced to adapt to the larger shear deformation with larger allowable shear strain.

(2) When the shear stress in the area exceeds the shear strength, or for the area with larger shear stress level (such as greater than 0.8), the compaction degree should be increased to improve the shear strength. According to the above principles, combined with the stress level and deformation characteristics of dam body and contact clay, the control standard of compaction degree is studied.
4. Study on compaction control standard

![Image of stress contour maps](image-url)

Figure 3. Contour map of stress level of dam during impoundment period.

The stress level is defined as the ratio of the existing shear stress to the corresponding failure shear stress, which reflects the exertion degree of dam material strength. When the stress level is greater than or equal to 1, the shear failure occurs. As can be seen from Fig. 3, there are mainly two areas with high stress level in the dam body:

1. Near the interface between dam shell and soil core wall. It is characterized by large area, high stress level and a few elements close to 1. The reasons are as follows: first, the large difference between the core wall and the rockfill body modulus leads to the large uneven settlement in this area, which leads to the large shear deformation; The second is that the core wall moves downstream under the effect of the dam storage pressure, resulting in a significant decrease of the small principal stress in this area.

2. The contact part between soil core wall and bank slope on both banks. It is characterized by steep bank slopes on both sides and relatively high stress levels. The stress levels in some areas where the core wall contacts the bank slope exceed 0.7. During the construction period, due to the steep bank slope, the dam body and core wall have the tendency of cross cutting deformation along the bank slope. Under the action of water pressure during the impoundment period, the shear deformation of the core wall further occurs to the downstream.

In the aspect of engineering measures, the partition of filter material and transition material between dam shell and soil core wall is set to improve the stress level and protect the core wall; A contact clay with a horizontal thickness of 4m and a concrete cover plate with a thickness of 1m are laid between the soil core wall, the bank slopes on both banks and the bedrock of the dam foundation to solve the problem of deformation coordination. The contour map of the stress level of the high plastic soil during the impoundment period is obtained, as shown in Figure 4. Some parameters of the soil material are shown in Table 1.

| Material Type                  | $R_f$ | $K$ | $n$ | $G$ | $F$ | $D$ | $K_m$ | $\phi$ (°) | $c$ (kPa) | $\rho$ (g/cm³) | $\phi_i$ | $A$ | $\phi$ | $K_b$ | $n$ |
|--------------------------------|-------|-----|-----|-----|-----|-----|-------|------------|----------|---------------|----------|-----|--------|-------|-----|
| Core material (area A)         | 0.72  | 650 | 0.36| 0.36| 0.02| 3   | 1300  | 31         | 40       | 2.16          | 43       | 11  | 500    | 0.20  |
| Core material (area B)         | 0.76  | 600 | 0.30| 0.38| 0.015|2   | 1100  | 30         | 45       | 2.13          | 42       | 10  | 450    | 0.16  |
| Core material (area C)         | 0.90  | 500 | 0.28| 0.44| 0.01| 0.8 | 900   | 23         | 50       | 2.07          | 37       | 13  | 470    | 0.15  |
| Blending                       | 0.92  | 200 | 0.32| 0.36| 0.01| 1.0 | 300   | 16         | 50       | 1.95          | 33       | 15  | 100    | 0.35  |
Figure 4. Stress level contour of contact clay during dam impoundment period.

It can be seen that the stress level of contact clay in the dam slope area on both banks is mostly above 0.8, especially in the left bank (0.15h-0.5h dam height interval) and the right bank (0.23h-0.75h dam height interval), the stress level of contact clay in some areas exceeds 0.88, and in some areas reaches 0.93 or even higher. The stress level of the valley section at the bottom of the core wall is lower than that of the dam slope area, but it is mainly distributed in the range of 0.73-0.78.

(1) For the contact clay in the dam slope area on both banks

The deformation and stress distribution of the dam during the impoundment period are shown in Fig. 4 and Fig. 5.

Figure 5. Displacement contour map of longitudinal section during impoundment period (cm).

Figure 6. Contour of small principal stress in longitudinal section during impoundment period (MPa).

Figure 4 shows the deformation of the dam body: along the axial direction of the dam, the deformation mainly shrinks to the inner part of the dam body, mainly in tension; Along the river, the connection of bank slopes on both banks is mainly shear, which is caused by the displacement of core wall along the river; Along the vertical direction, the shear of the bank slopes on both sides is affected by the settlement of the core wall. According to the contour of small principal stress in the longitudinal section of the dam during the impoundment period shown in Fig. 5, it can be seen that the small principal stress in the longitudinal section of the dam body is greater than 0, indicating that the core wall does not produce tensile stress, that is, the bank slope action on both banks is mainly shear action. Since the horizontal displacement along the river is less than 5cm (see Fig. 4 (b)), the shear effect in this direction can be ignored, and the whole bank slope on both banks has a shear deformation of about 20cm (Fig. 4 (c)), which is the area where the shear effect is prominent. Therefore, the compactness of contact clay should not exceed 100% in the local area of left bank dam slope (0.1h-0.4h dam height) and right bank dam slope (0.08h-0.6h dam height) to adapt to large shear deformation.

For the left bank dam slope, due to the setting of two slope ratios, the stress concentration occurs at the turning point (see Fig. 5), resulting in a large contraction towards the dam body, and the maximum displacement reaches 25cm (see Fig. 4 (a)). Therefore, in the range of this section, the compactness of contact clay should be appropriately increased (106% according to the soil test) to improve its shear modulus.
(2) Contact clay area at the bottom of core wall (valley section)
Considering that the contact clay in this area mainly plays two roles: the arch effect of the contact clay reduces the stress of the concrete cover plate; The vertical displacement of the core wall can be reduced by increasing the degree of compaction and the compression modulus, so as to improve the relative dislocation of the joint between the core wall and the bank slope. Therefore, there is no upper limit for the compactness of contact clay in this area.

(3) Discussion on compaction control standard
Combined with the stress and deformation analysis of the dam, the contact clay may have stress states such as compression, tension and shear in a certain range of dam height.
In the compressive stress area, it is impossible to produce tensile cracks. With the increase of compactness, the modulus increases, which helps to reduce the vertical deformation of contact clay, improve the cooperative deformation ability of the contact part with the core material, and reduce the tensile stress area, so that the tensile stress area appears at a higher elevation. Therefore, the compaction standard can be appropriately improved in the compression area of contact clay.
On the other hand, according to the stress-strain analysis of the dam body, the tensile stress zone and the shear deformation zone of the contact part between the contact clay and the concrete cover plate are inevitable. In these two areas prone to tensile cracks or shear deformation, the deformation adaptability of the contact clay itself should be emphasized. The lower the compression modulus is, the lower the possibility of tensile cracks or shear cracks is. Therefore, it is suggested to reduce the compaction standard in the tensile stress area.
In conclusion, it is considered that the control of compactness should comprehensively consider the stress level and stress deformation characteristics of contact clay zone. For the area where the stress level exceeds 0.9, although the soil is not damaged by shear, but it is close to the critical area of failure, we can consider improving its compactness, so as to improve the shear strength of the soil in this area. For the area with large shear deformation, the compaction degree can be reduced to improve the adaptability of shear deformation.

5. Influence of water content on contact clay filling
Filling moisture content is an important index to control the deformation of high plastic clay during construction. When the water content is controlled near the optimal water content (wop), it is relatively easy to compact and has good mechanical properties. In order to better guide the compaction and filling of high plastic clay, it is necessary to refine the control range of water content of high plastic clay filling. Therefore, high plastic clay shear tests within different water content ranges are carried out. The results are shown in Figure 7 (the optimal water content wop is 17%).
It is known from the test that when the water content of high plastic clay increases gradually, the matrix suction of soil decreases gradually, and the water film between soil particles thickens. With the lubrication of water, the friction decreases and the shear strength index of soil decreases. In addition, the super wet soil is easy to produce super static pore water pressure in the soil, the strength is reduced, and the filling is easy to form "rubber soil", so the strength value is greatly attenuated.

When the moisture content is low, the thickness of water film surrounding soil particles is thin. Under the action of external load, it is not easy to shear movement between soil particles. At this time, the ability of soil to adapt to shear deformation is weak. When the water content gradually increases, the water film around the soil particles becomes thicker, the lubrication effect gradually increases, and the soil particles are easy to move with each other, resulting in shear movement. When the water content increases greatly, the lubrication effect between the particles reaches the most sufficient effect. At this time, the shear displacement increases sharply, and the ability of the soil to adapt to shear deformation is greatly improved.

Therefore, it is necessary to comprehensively consider the engineering characteristics of soil strength and ability to adapt to shear deformation. When the moisture content is low, the ability of soil material to adapt to shear deformation is weak. When the moisture content is high, the shear strength of soil material is low. Therefore, when filling high plastic clay, the water content should not be too low or too high, and should be controlled in an interval near the optimal water content. Taking the test soil materials of the project as an example, it is suggested that the lower limit of filling water content should be controlled at 1% of the optimal water content, and the upper limit should be controlled at 3.5% of the optimal water content.

If the filling moisture content is not within this range and is dry or wet, the rolling effect of contacting clay is poor, and the on-site rolling effect is shown in Figure 8.

**Figure 7.** Relationship between internal friction angle, shear displacement and water content of contact clay.
6. Conclusion

The contact clay area is a very small point on the cross section of earth rock dam, but it has good plastic flow performance, which can slow down the uneven deformation, eliminate stress concentration and prevent crack damage. It is a safety device to ensure the connection effect between concrete structure and earth core wall [6]. In this paper, based on the properties of contact clay, considering the stress level and stress deformation characteristics of dam body and contact clay area, the control standard of compaction degree is proposed. The main conclusions are as follows:

1. In the area where large shear displacement may occur, the compactness of contact clay should be controlled not more than 100%, so as to improve the shear deformation adaptability of the soil in this area.
2. For the areas prone to stress concentration and the areas where the stress level exceeds 0.9, the compaction degree should be appropriately increased to improve the shear capacity.
3. The contact clay area at the bottom of the core wall (valley section) should be compacted to improve the relative dislocation at the junction of the core wall and the bank slopes.
4. The sensitivity of comprehensive confined compression modulus of contact clay with moisture content is higher than that with compactness. Controlling moisture content of contact clay can improve its deformation adaptability.

7. References

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