Nonlinear Finite Element Analysis of CSGR Dyke Engineering on Soft Foundation

Sha Wang¹, ²*, Jinsheng Jia¹, ², Huichen Yang¹, ² and Cuiying Zheng¹, ²

¹China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
²State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing, 100038, China
*Corresponding author’s e-mail: wangsha.smx@163.com

Abstract: In order to obtain the optimal section of the cemented sand, gravel and rock (CSGR) dyke on the soft foundation of sand and gravel, this paper designs three different plans to analyze the vertical normal stress of the foundation, comprehensive stability, settlement, maximum and minimum principal stresses, and the foundation stress by adopting the finite element method and the finite element equivalent stress method. Based on the finite element calculation results of the optimal plan, this paper analyzes the safety situation of various parts of the dyke and proposes engineering measures accordingly. Sensitivity analysis of the soft foundation parameters shows that the foundation parameters have a great influence on the stress and deformation of the fending groyne and the seepage proof wall. The analysis in this paper can provide some reference for the design of similar projects.

1. Introduction
As environmental protection draws more attention, more and more are aware of the burden that construction waste imposes on the environment, and that is why the idea of CSGR dam is proposed. This new idea of damming uses the mixture of a small amount of cementing materials (cement, fly ash, etc.) and the waste material excavated using the river channel for excavation without the need to sieve as the damming material, and reasonably chooses the body shape of the dam based on material characteristics. The CSGR dam has been promoted in China in recent years and applied in the cofferdam and dam-building projects [2]. The project described in this paper is the first application example of CSGR in the dyke project. Due to the conditions of the soft foundation, it is necessary to carry out special research on the CSGR dyke and the foundation [3] to ensure project safety.

2. Project overview
The dyke project is located on the right upstream bank of the permanent work of the downstream section of the main stream of the Minjiang River in Sichuan Province, China. It is 2.755km long, with a top elevation of 336.10m, and a maximum height of 14.1m. The city level of the protection zone is Grade IV, and its dyke engineering level is Grade 4. According to the previous geological survey, the site is composed of the silt and the pebble layer as well as the liquefiable soil layer. The Code for Seismic Design of Buildings specifies that the site with the liquefied soil is unfavorable for earthquake resistance. Therefore, this paper takes the foundation into consideration to conduct the sensitivity analysis of the ground parameters.
3. Study on reasonable section of dyke

3.1. Design of grid and body shape

The section design of the dyke and the finite element grid in this paper are shown in Figure 1. The material zone includes the covering layer foundation, the seepage prevention wall, the junction plate, and the fending groyne. The finite element model includes a total of 4,130 nodes and 1990 hexahedral units. The calculation analysis and the result presentation adopt the Cartesian coordinate system, with the direction from the left to the right bank along the axis of the fending groyne as the positive x-coordinate, the direction from the upstream to the downstream along the river channel as the positive y-coordinate, and the vertical direction from the low altitude to the high altitude as the positive z-coordinate.

Table 1. 3 different slope ratios

| No. | Top width(m) | Upstream slope ratio 1:m | Downstream slope ratio 1:n | Comprehensive slope ratio m+n | Bottom width(m) | Cross-sectional area(m²) |
|-----|--------------|--------------------------|---------------------------|------------------------------|-----------------|--------------------------|
| 1   | 6            | 1:0.5                    | 1:0.7                     | 1.2                          | 22.92           | 203.89                   |
| 2   | 6            | 1:0.55                   | 1:0.65                    | 1.2                          | 22.92           | 203.89                   |
| 3   | 6            | 1:0.6                    | 1:0.6                     | 1.2                          | 22.92           | 203.89                   |

The construction simulation of the fending groyne is determined based on the design scheme, and is carried out by means of horizontal filling [4]. The reservoir simulation is divided into ten levels from the minimum water level of 321.5 m to the normal water storage level of 335.12 m.

3.2. Material parameters

The parameters of the CSGR material used in the finite element calculation are determined according to the test and relevant engineering empirical values. The parameters of the cover material adopt those of similar projects. The parameters of the concrete material are determined based on relevant specifications and the data of similar projects. For specific parameters, see Tables 2 and 3.

Table 2. Parameters of EB model for sandy gravel strata of Qianwei dyke

| Materials        | γ  | k  | n  | k_b | M  | R_f | c  | φ_0 | Δφ |
|------------------|----|----|----|-----|----|-----|----|-----|-----|
| Sandy gravel     | 21 | 500| 0.38| 300 | 0.22| 0.85| 0  | 30  | 5.0 |

Table 3. Mechanical parameters of CSGRR and concrete

| Materials                | Volume-weight(kN/m³) | Elasticity modulus (Gpa) | Poisson’s ratio |
|--------------------------|----------------------|-------------------------|-----------------|
| Rich motor CSGRR         | 23.8                 | 25.0                    | 0.19            |
| CSGRR                    | 23.6                 | 13.0                    | 0.15            |
| Seepage proof wall       | 24.0                 | 18.0                    | 0.125           |
| C20concrete              | 24.0                 | 25.5                    | 0.167           |
| Junction plate           | 24.0                 | 25.5                    | 0.167           |
3.3. Comparison of results

When the dyke is completed and has normal water storage, the settlement and maximum and minimum principal stresses of different body types are shown in Table 4. For the vertical positive stress of the sand pebble foundation calculated using the finite element method and the finite element equivalent stress method [5], see Figure 2.

| No. | Maximum settlement (cm) | Maximum principal stress (Kpa) | Minimum principal stress (Kpa) |
|-----|-------------------------|-------------------------------|-----------------------------|
|     | Construction completed  | Impoundment completed         | Construction completed       | Impoundment completed |
| 1   | 4.99                    | 5.30                          | 897.0                       | 829.8                 | -507.5                | -438.1                |
| 2   | 4.62                    | 5.02                          | 903.3                       | 883.9                 | -536.0                | -429.9                |
| 3   | 4.41                    | 4.84                          | 906.1                       | 942.5                 | -559.2                | -402.4                |

(a) Situation 1

(b) Situation 2
4. Analysis of finite element results of the optimal plan

Based on the above analysis, this paper takes section of Plan 1 for finite element analysis. The positive and negative values indicate the direction of the displacement, and the positive direction is consistent with the coordinate system of the finite element calculation grid. The positive stress represents tensile stress, while the negative stress represents the compressive stress.

The large principal stress distribution (Figures 3 to 5) of the fending groyne, the rich-in-slurry CSGR, and the CSGR in the completion and full storage periods is similar, while the corresponding values of the full storage period are larger than those of the completion period. The maximum principal stress values of both periods appear in the C20 concrete precast block at the heel of the upstream dam and the toe of the downstream dam of the fending groyne. The maximum principal stress of the construction period is 6 MPa, while that of the full storage period is 7.5 MPa, smaller than 10 MPa, the design value of the axial compressive strength of C20 concrete. Large principal stress also appears at the heel of the rich-in-slurry CSGR seepage proof body, with the maximum value of the completion period of 3.8 MPa and that of the full storage period of 4.6 MPa. According to the design requirements, this paper adopts the 4 times of the safety factor against pressure, so the allowable compressive strength of the rich-in-slurry CSGR is 4.75 MPa, which is larger than its maximum stress. Under the two working conditions, the large principal stress values of other areas of the dyke are lower, generally less than 1 MPa and the allowable compressive stress of the dam body of 1.5 MPa. The large principal stress value of the fending groyne meets the specification requiring that “the maximum principal compressive stress of the CSGR dam should be lower than the allowable compressive stress of the material under any working conditions”. The distribution of the large principal stresses (Figure 6) of the seepage proof wall and the junction plate during the completion and the full storage periods are similar with the maximum values appearing in the junction plate area.

Figure 3. The major principal stress distribution of the dyke body of the construction and impoundment completed periods (Pa)
Figure 4. The major principal stress distribution of the rich motor CSGRR impervious layer of the construction and impoundment completed periods (Pa)

Figure 5. The major principal stress distribution of the CSGRR of the construction and impoundment completed periods (Pa)

Figure 6. The major principal stress distribution of the seepage proof wall and junction wall of the construction and impoundment completed periods (Pa)

The maximum principal stress of the construction period is 5.4 MPa, and that of the full storage period is 6.3 MPa. The large principal stress of the seepage proof wall is generally small, which is about 1 MPa in most areas. The stress of the top of the seepage proof wall connected to the junction plate is relatively large, which is 2~3 MPa. The large principal stress of the seepage proof wall is lower than the allowable compressive stress of C20 concrete.

The large principal stress distribution of the fending groyne, rich-in-slurry CSGR, and the CSGR during the construction period and the full storage period can be seen in Figures 7 to 9. In the two working conditions, the tensile stress zone of the fending groyne appears in the C20 concrete precast block area of the rich-in-slurry CSGR seepage proof body and the heel of the upstream dam and the toe of the downstream dam near the foundation surface. The maximum tensile stress occurs in the C20 concrete prefabrication zone, and that of the completion period is about 1.79 MPa, and that of the full storage period is 2.3 MPa, greater than the design value of C20 concrete tensile strength. It is recommended to add rebars into the concrete precast block at the heel and the toe of the dam to enhance tensile strength.

The maximum tensile stress at the bottom of the rich-in-slurry CSGR of the completion period is about 1.7 MPa, and that of the full storage period is 1.8 MPa. A certain tensile stress also exists at the bottom of the CSGR partition, with the maximum value of the completion period of 0.24 MPa and that of the full storage period of 0.33 MPa. The tensile stress zone is mainly caused by the settlement of sand pebble foundation, therefore, it is recommended to further improve the performance of the
rich-in-slurry CSGR near the base surface, or to increase the thickness of the bottom rich-in-slurry CSGR to 3-2.5 m.

For the tensile stress distribution of the seepage proof wall and the junction plate during the construction and the full storage periods, see Figure 10. It can be seen that the tensile stress of the seepage proof wall and the junction plate mainly appears at the top of the seepage proof wall near the junction plate. The maximum tensile stress of the construction period is about 3.1 MPa, and that of the full storage period is about 2.98 MPa, larger than the design value of the tensile strength of C20 concrete. In order to avoid the tensile failure and enhance the tensile properties, it is recommended to add steel bars into the concrete of the top of the seepage proof wall and of the junction plate.

Figure 7. The minor principal stress distribution of the dyke body of the construction and impoundment completed periods (Pa)

Figure 8. The minor principal stress distribution of the rich motor CSGRR impervious layer of the construction and impoundment completed periods (Pa)

Figure 9. The minor principal stress distribution of the CSGRR of the construction and impoundment completed periods (Pa)

Figure 10. The minor principal stress distribution of the seepage proof wall and junction wall of the construction and impoundment completed periods (Pa)
5. Sensitivity analysis of parameters of the covering layer

This paper conducts sensitivity analysis on the parameters of the covering layer, so as to discuss the influence of the changing deformation parameters of the covering layer on the stress and deformation of the fending groyne and the seepage proof wall. In the basic calculation scheme, based on the relatively conservative estimation of the parameters of the overburden foundation, this paper adopts deformation parameters that are relatively lower. However, the in-situ structural properties of the actual overburden foundation will make the actual deformation parameters higher than the estimated values. Therefore, this paper designs three sets of sensitivity analysis plans in addition to the basic calculation scheme. For the calculation parameters of each plan, see Table 5.

Table 5. Sensitivity analysis scheme of sand gravel foundation

| Schemes   | $\gamma$ (KN/m$^3$) | $k$  | n   | $k_b$ | m   | $R_f$ | c   | $\varphi_0$ (°) | $\Delta \varphi$ (°) |
|-----------|---------------------|------|-----|-------|-----|-------|-----|----------------|-----------------|
| 2D-L-FG1  | 21                  | 500  | 0.38| 300   | 0.22| 0.85  | 30  | 5              |                 |
| 2D-L-FG2  | 21                  | 750  | 0.38| 400   | 0.22| 0.85  | 30  | 5              |                 |
| 2D-L-FG3  | 21                  | 1000 | 0.38| 600   | 0.22| 0.85  | 30  | 5              |                 |
| 2D-L-FG4  | 21                  | 1500 | 0.38| 750   | 0.22| 0.85  | 30  | 5              |                 |

The results of the sensitivity analysis of the overburden foundation of the two periods (Table 6) show that as the parameters of the covering layer increase, the horizontal displacement and settlement of the dyke foundation and the fending groyne decrease, and the tensile stress and compressive stress of the fending groyne, the seepage proof wall, and the junction plate all decrease, with the maximum reduction being about 40%. Therefore, the deformation characteristics of the covering layer have a great impact on the stress of the fending groyne and the seepage proof wall. Since the basic scheme considers that the overburden foundation is relatively weak, it might overestimate the stress of the fending groyne and the seepage wall, which makes it relatively conservative. It is suggested to conduct experimental research on the deformation parameters of the sand pebble dam foundation and determine the true deformation parameters of the overburden foundation, so as to provide support for the reasonable determination of the parameters of the fending groyne and the covering layer.

Table 6. Statistical table of characteristic values of the full storage period of each sensitivity analysis scheme

| Schemes   | Horizontal displacement (cm) | Settlement (cm) | Compressive stress (MPa) | Tensile stress (MPa) |
|-----------|------------------------------|----------------|--------------------------|---------------------|
|           | Toward upstream               | Toward downstream | Dyke body | Impermeable wall and junction slab | Dyke body | Impermeable wall and junction slab |
| 2D-L-FG1  | 0.88                         | 7.47            | 7.50                    | 6.30                | 2.31           | 2.98                        |
| 2D-L-FG2  | 1.08                         | 2.57            | 7.64                    | 6.59                | 2.28           | 3.00                        |
| 2D-L-FG3  | 0.51                         | 2.69            | 5.56                    | 4.78                | 1.72           | 2.24                        |
| 2D-L-FG4  | 0.42                         | 1.78            | 4.21                    | 3.59                | 1.26           | 1.74                        |

6. Conclusion

(1) This paper conducts calculation on a CSGR dyke project on the soft foundation using the finite element method and the finite element equivalent stress method. By combining the calculation results of the comprehensive stability, dam body stress, and foundation stress, this paper selects the optimal section of the dyke on the soft foundation, namely, upstream slope ratio, 1:0.5 and the downstream slope ratio, 1:0.7. Therefore, it is concluded that a CSGR dyke with an upstream slope steeper than the downstream slope is feasible to be built on the soft foundation.

(2) This paper analyzes the calculation results of finite element stress of each part in the optimal plan, and makes corresponding reinforcement measures for the parts whose stress is larger than the allowable value, including adding steel bars and increasing the thickness of the rich-in-slurry CSGR.
(3) The sensitivity analysis of the parameters of the soft foundation shows that the improvement of the parameters of the overburden foundation will greatly reduce the displacement and stress of the dyke body, the seepage proof wall, and the junction plate.

(4) This paper provides some reference for the construction of CSGR dykes on soft foundations.

Acknowledgments
This research was funded by the National Key R&D Program of China (No.2018YFC0406800)

References
[1] Jia JS, Liu N, Zheng CY, et al.. Studies on cemented material dams and its applications[J]. Journal of Hydraulic Engineering, 2016, 47(3):315-323.
[2] Feng W, Jia JS, Ma FL.. Study on design parameters of mix proportion for cemented sand and gravel[J]. Water Resources and Hydropower Engineering, 2013, 44(2):55-58.
[3] Zheng CB. Interpretation of the main points of Technical guidelines for cemented material dam construction [J]. Zhejiang Hydrotechnics, 2016(3):058-60.
[4] Yang HC. Structural design research on cemented sand and gravel dam and engineering application [D]. China Institute of Water Resources and Hydropower Research, 2013.
[5] Yang HC, Jia JS, Zheng CY. Study and application of the improved finite element equivalent stress method to analyze the strength of gravity dams[J]. Journal of China Institute of Water Resources and Hydropower Research, 2013, 11(2):112-116.