Comparative study on settlement calculation of clay core rockfill dam by different constitutive models

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Abstract. The analysis and calculation of the settlement of the clay core rockfill dam is decided by the constitutive relation of the dam material. In this paper, the settlement of the clay core rockfill dam of Luding Hydropower Station under different working conditions is analyzed and calculated by using Duncan E-ν model and double yield surface elastic-plastic model. E-ν model is quite sensitive to Poisson's ratio, and the small changes of parameters G, D and F may lead to great differences in the deformation calculation results of the model, while the elastic-plastic model with double yield surface is not very sensitive, and its settlement calculation results under different working conditions are relatively stable.

1. Introduction

The research on the constitutive model of earth rock dam materials has been a special research field in China for many years. Many scholars have done fruitful research work in this field and put forward several constitutive models with distinctive characteristics [1,2]. Among them, Duncan E-ν model and double yield surface elastoplastic model which proposed by Shen Zhujiang who works in Nanjing water conservancy research institute that is known as "Nanshui" in Chinese pinyin (hereinafter referred to as "Nanshui" model) have more distinct characteristics. Duncan E-ν model is quite sensitive to e and v, while "Nanshui" model is sensitive to Cd, Nd and Rd [3,4]. In this paper, Duncan E-ν model and "Nanshui" model are used to calculate the settlement of typical clay core rockfill dam, and the difference of settlement calculation is analyzed.

2. Introduction of constitutive model

2.1. Duncan E-ν model [5,6]

With incremental stress-strain relationship of nonlinear, Duncan E-ν model conforms to the following generalized Hooke's law:

\[
\Delta \sigma = [D(\sigma)] \Delta \varepsilon
\]

(1)

The two basic variables of the model are tangent Young's modulus \(E_t\) and tangent Poisson's ratio \(\nu_t\), the expressions are as follows:

\[
E_t = KP(\frac{\sigma}{P})^\nu (1 - R_s S_t)^2
\]

(2)
\[ G - F \lg \left( \frac{\sigma_3}{P_a} \right) \]

\[ v_i = \left\{ 1 - \frac{D(\sigma_1 - \sigma_3)}{KP_a^2(\frac{\sigma_3}{P_a})(1 - R_i, S_i)} \right\} \]  \hspace{1cm} (3)

Where \( P_a \) is the atmospheric pressure; \( K \) is the young's modulus coefficient; \( n \) is the power of tangent Young's modulus \( E_t \) increasing with the increase of confining pressure \( \sigma_3 \); \( R_i \) is the failure ratio; \( S_i \) is the stress level, and its expression is

\[ S_i = \frac{(\sigma_1 - \sigma_3)(1 - \sin \varphi)}{2c \cos \varphi + 2\sigma_3 \sin \varphi} \]  \hspace{1cm} (4)

Where \( c, \varphi \) are shear strength indexes. Duncan \( E-v \) model has eight model parameters, namely \( K, n, R_f, G, F, D, c \) and \( \varphi \), that can be determined from the results of conventional triaxial tests.

For the unloading case, the resilient modulus is calculated by the following formula:

\[ E_u = K_{ur} P_a \left( \frac{\sigma_3}{P_a} \right)^n \]  \hspace{1cm} (5)

Where, \( K_{ur} \) is the coefficient of resilience modulus. The loading and unloading criteria of the model are as follows:

Set the loading function is

\[ F_i = S_i \left( \frac{\sigma_3}{P_a} \right)^n \]  \hspace{1cm} (6)

the historical maximum value of \( F_i \) is \( F_{i,\text{max}} \)

a. If \( F_i \geq F_{i,\text{max}} \) it is full loading, then \( E = E_t \)

b. If \( F_i \leq 0.75 F_{i,\text{max}} \), it is full unloading, then \( E = E_u \)

c. If \( 0.75 F_{i,\text{max}} < F_i < F_{i,\text{max}} \) it is partial unloading, then the young's modulus is calculated by interpolation formula:

\[ E = E_u + (E_i - E_u) \frac{F_i - 0.75 F_{i,\text{max}}}{0.25 F_{i,\text{max}}} \]  \hspace{1cm} (7)

For coarse-grained materials, \( c = 0, \varphi \) can be obtained as follows

\[ \varphi = \varphi_0 - \Delta \varphi \lg \left( \frac{\sigma_3}{P_a} \right) \]  \hspace{1cm} (8)

\( \varphi_0, \Delta \varphi \) are material parameters, which are determined by the results of triaxial test.

2.2. “Nanshui” model\(^2\)

The two yield surfaces of “Nanshui” model are:

\[ f_1 = p^2 + r^2 q^2 \]

\[ f_2 = q^4 / p \]  \hspace{1cm} (9)

Where \( p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3), q = \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} \), \( r, s \) are model parameters, which can be taken as 2 for rockfill material. The expression of strain increment of double
yield surface model is:

$$\{\Delta \varepsilon\} = [D]^{-1}\{\Delta \sigma\} + A_1\{n_1\}^T\{\Delta \sigma\} + A_2\{n_2\}^T\{\Delta \sigma\}$$  \hspace{1cm} (10)$$

Where $[D]$ is the elastic matrix; $\{n_1\}$ and $\{n_2\}$ are cosines of normal direction of yield surface; $A_1$ and $A_2$ are plastic coefficients, which can be calculated according to the following formula:

$$A_1 = r^2 \left( \frac{\eta}{E_v} \right) \left( \frac{2\mu_1 - \frac{3\mu_2}{E_v} - \frac{3}{G_v} + \frac{3\mu_2}{E_v} - \frac{1}{B_v}}{(1 + \eta^2)(s + \eta^2 r^2)} \right)$$

$$A_2 = \left( \frac{2\mu_1 - \frac{3\mu_2}{E_v} - \frac{3}{G_v} - \frac{s\eta(3\mu_2 - 1)}{E_v} - \frac{1}{B_v}}{(s - \eta)(s + \eta^2 r^2)} \right)$$  \hspace{1cm} (11)$$

Where $\eta = q/p$, $G_v$ and $B_v$ are elastic shear modulus and bulk modulus respectively, which can be calculated according to the following formula:

$$G_v = E_v / 2(1 + \nu), \quad B_v = E_v / (3 - 2\nu)$$  \hspace{1cm} (12)$$

Where $\nu$ is the elastic Poisson's ratio, its value can be 0.3, $E_v$ is the unloading modulus of resilience. In equation (1), tangent Young's modulus $E_t$ and tangent volume ratio $\mu_t$ are the two basic variables of the model, and the expression of $E_t$ is consistent with the previous Duncan $E-v$ model, $\mu_t$ can be calculated by the following equation:

$$\mu_t = 2c_d \left( \frac{\sigma_3}{P_0} \right)^{n_d} \left( \frac{E_R}{\sigma_1 - \sigma_3} \right) \frac{1 - R_d}{R_d} \left( \frac{1 - R_{1u}}{1 - R_{1l}} \right)$$  \hspace{1cm} (13)$$

Where $R_s = R_f S_f$, $R_d$, $c_d$ and $n_d$ are calculation parameters, $c_d$ is the maximum shrinkage volumetric strain corresponding to $\sigma_1$ equal to unit atmospheric pressure; $n_d$ is the power of the shrinkage volume strain increasing with the increase of $\sigma_1$; $R_d$ is the ratio of $(\sigma_1 - \sigma_3)_{ult}$ at maximum shrinkage to the asymptotic value $(\sigma_1 - \sigma_3)_{ult}$ of deviatory stress. There are eight model parameters in the "Nanshui" model, which are $K$, $n$, $R_f$, $c$, $\varphi$, $R_d$, $c_d$ and $n_d$ respectively, that all can be concluded from the results of conventional triaxial tests. Compared with the parameters of Duncan $E-v$ model, "Nanshui" model has only three parameters $c_d$, $n_d$ and $R_d$, which are different from Duncan $E-v$ model. Duncan $E-v$ model has three corresponding parameters $G$, $F$ and $D$ for calculating tangent Poisson's ratio.

Certainly, the parameters of Duncan $E-v$ model can also be used to calculate the "Nanshui" model, and the tangent volume ratio can be obtained from the tangent Poisson's ratio as follows:

$$\mu_t = 1 - 2\nu$$  \hspace{1cm} (14)$$

For unloading, the modulus of resilience is still calculated according to formula (5), and the loading and unloading criteria of "Nanshai" model are as follows:

a. If $F_1 > F_{1max}$, $F_2 > F_{2max}$, it is full loading, then $A_1 > 0$, $A_2 > 0$

b. If $F_1 > F_{1max}$, $F_2 \leq F_{2max}$ or $F_1 \leq F_{1max}$, $F_2 > F_{2max}$, it is partial unloading, then $A_2 = 0$ or $A_1 = 0$

c. If $F_1 \leq F_{1max}$, $F_2 \leq F_{2max}$, it is full unloading, then $A_1 = A_2 = 0$

3. Analysis examples

3.1. Project overview

Luding Hydropower Station is located in Luding County, Sichuan Province. The normal water level of the reservoir is 1378.00 m, the total storage capacity is 219.5 million m$^3$, and the regulating storage capacity is 22 million m$^3$. It is the 12th level of Dadu River basin development, with daily regulation
performance and installed capacity of 920 MW.

Luding Hydropower Station is mainly composed of the river dam and the water diversion and power generation system on the right bank. The flood discharge facilities of the project are four spillway tunnels, which are respectively arranged on the left and right bank of the dam. The dam is a clay core rockfill dam with a maximum height of 84m and a crest length of 537m.

The clay core rockfill dam is composed of clay core, filter layer, transition zone and rockfill zone. A suspended concrete cutoff wall which is 1.0m in thickness and maximum 70.0m in depth is adopted for dam foundation seepage control. Three grouting curtains are connected under the wall. A 5.0 m thick horizontal clay blanket is set at the bottom of the dam shell on the upstream side of the core wall to connect with the core wall of the upstream cofferdam. Combined with the upstream cofferdam cutoff wall which 45.0m in depth, a row of curtain grouting pipes is embedded in the dam foundation cutoff wall. A 6m×6m grouting gallery is set at the dam foundation, and a row of curtain grouting holes are arranged on both sides of the cutoff wall. The curtain grouting is carried out on the overburden layer of the dam foundation, which starting from the elevation of 1245m. The overlapping length of the curtain and the cutoff wall is 15.0m, and the lower part of the curtain is 2.0m deep into the bedrock. The middle row carries out curtain grouting on the overburden through the embedded grouting pipe in the wall, and the curtain goes deep into the weak weathered layer of bedrock.

The cross section of the river valley in the dam site area is asymmetric wide "U" shape, and the mountains on both sides are thick and solid. The river valley in the dam site area has deep overburden and complex hierarchical structure. The modern riverbed and high floodplain are mainly composed of alluvial drift gravel (alQ4), the first terrace is composed of alluvial and proluvial mixed accumulation of drift gravel (al+plQ4), the second terrace is composed of periglacial debris flow and alluvial mixed accumulation of gravel (prgl+alQ3), and the bottom of the valley is composed of drift gravel (fglQ3).

According to the drilling exploration results, the maximum thickness of riverbed overburden is 148.6m (SZK6). According to the material composition, distribution, genesis and formation age, the overburden of the river valley and bank slope can be divided into four layers and seven sub layers from bottom, the older to top, the newer. The riverbed section is shown in figure 1.

### 3.2. Determination of calculation parameters

The calculation parameters are based on the laboratory test results. See Table 1

| Name of samples                          | P (g/cm³) | Φ (°) | ΔΦ (°) | C (kPa) | φ | K   | n   | Rf | G  | F  | D  |
|-----------------------------------------|-----------|-------|--------|---------|----|-----|-----|----|----|----|----|
| Core material                           | 1.68      | /     | /      | 39.54   | 26.77 | 108.6 | 0.354 | 0.686 | 0.39 | 0.3 | 2.7 |
| Filter layer                            | 2.08      | 46.08 | 8.90   | /       | /   | 1308.9 | 0.476 | 0.703 | 0.49 | 0.16 | 8.8 |
| Rockfill                                | 2.08      | 48.04 | 11.03  | /       | /   | 1245.5 | 0.552 | 0.698 | 0.45 | 0.22 | 9   |
| Dam foundation material 1               | 2.22      | 43.07 | 3.51   | /       | /   | 1491.3 | 0.287 | 0.73  | 0.5  | 0.26 | 3.9 |
| Dam foundation material 2-2             | 2.05      | 43.38 | 15.86  | /       | /   | 241.5  | 0.278 | 0.738 | 0.22 | 0.1  | 3.7 |
| Dam foundation material 2-3             | 1.68      | 42.5  | 9.5    | /       | /   | 452.7  | 0.788 | 0.802 | 0.37 | 0.12 | 5.1 |
| Dam foundation material 3-1(With gradation of drilling sample) | 2.06      | 41.3  | 5.44   | /       | /   | 184.3  | 0.701 | 0.801 | 0.25 | 0.1  | 3.4 |
| Dam foundation material 3-1(With average gradation of 35 group samples) | 2.06      | 41.46 | 4.09   | /       | /   | 373.02 | 0.308 | 0.81  | 0.32 | 0.12 | 3.08 |
3.3. Mesh generation and loading process simulation

Both the Duncan E-ν model and the "Nanshui" model adopt the same discrete element and the same loading process. In the calculation, the dam construction process is simulated by the method of step-by-step loading, and the water storage process of the reservoir is simulated by step loading. The specific simulation sequence is as follows: natural dam foundation overburden → dam cutoff wall, gallery and upstream cofferdam cutoff wall pouring → upstream cofferdam filling construction, which lasting 120 days → upstream cofferdam water retaining (water level rises to 1339.8m), which lasting 30 days → dam body and waste slag weighting. The filling construction intensity is 6m per month, the water level is from 1339.8m to the normal water level 1378.00m, which takes 40 days, and the dam operates at the normal water level for 1460 days (4 years), one step every half a year. Figure 2 shows the mesh generation.

![Figure 1. River bed section](image1)

![Figure 2. Mesh generation graph](image2)

3.4. Calculation results

![Figure 3. Calculation results](image3)

- a. Duncan E-ν Model
Figure 3. Isoline map of riverbed section settlement during the completion period

Figure 4. Isoline map of riverbed section settlement during the reservoir storage period

The figure above shows the comparison of the calculation results of the two models. It can be seen that the calculation result of the maximum settlement of the dam body in the completion period is that Duncan E-v model is 180.3cm, and "Nanshui" model is 197.9cm, which is not much different, but "Nanshui" model is larger than Duncan E-v model; the calculation result of the maximum settlement of the dam body in the reservoir storage period is: Duncan E-v model is 171.8cm, which is slightly upward, and "Nanshui" model is 198.0cm, which basically remains unchanged.

4. Conclusions
The clay core rockfill dam is different from the reinforced concrete face rockfill dam, so the "Nanshui" model is more suitable in its settlement analysis and calculation.
A large number of numerical calculations also show that Duncan E-ν model is quite sensitive to Poisson's ratio, and small changes of parameters G, D and F may lead to great differences in the deformation calculation results of the model, while "Nanshui" model is not very sensitive, which is the main reason why the settlement calculated by "south water" model is slightly larger than Duncan E-ν model.

Reference

[1] Duncan JM and Chang CY 1970 Non-linear analysis of stresses and strain in soils J. Journal of the Soil Mechanics and Foundations Division. 1970, 96(5):1629-1652

[2] Shen Zhujiang 2005 A new model for soil stress-strain analysis [C]. Shen Zhujiang: Selected Papers on soil mechanics (in Chinese). Beijing: Tsinghua University Press, 2005:290-302

[3] Li Shaolin et al. 2018 High core rockfill dam transient rheological parameter decoupling back analysis method and deformation prediction J. Journal of the Yangtze River academy of Sciences (in Chinese), Sept. 2018

[4] Dong Weixin et al. 2012 Dynamic back analysis of model parameters of Nuozhadu high core rockfill dam J. Journal of hydropower (in Chinese), No.05, 2012

[5] Zhang Yali et al. 2016 Experimental study on Duncan E-B and E-μ model parameters of upstream earth rock cofferdam of Songta hydropower station J. Hydropower project (in Chinese), No.02, 2016

[6] Li Guangxin. 1998 Mistakes in parameter determination of Duncan hyperbolic model J. Chinese Journal of geotechnical engineering, No.05, 1998