Construction of Concrete-Faced Rockfill Dams with Weak Rocks

Hao-Feng Xing[1]; Xiao-Nan Gong[2]; Xiao-Guang Zhou[3]; and Hai-Feng Fu[4]

Abstract: Constructing concrete-faced rockfill dams (CFRDs) with weak rocks has great advantages as a result of the use of local materials, cost-effectiveness, extensive adaptability, simple construction, and short construction period. However, the behaviors of CFRDs constructed with weak rocks are not well-understood. This paper reports the physical, mechanical, and hydraulic properties of weak rockfill during placement and compaction in three dam projects in China. These properties were obtained from laboratory and field tests. Important considerations, such as the control of crushing and crusting and the increase of the permeability of weak rocks, are discussed. Numerical studies on the settlements and slope stability of the dams were conducted and their results were compared with the field measurements. This study provides the opportunities for further understanding the behaviors of CFRDs with weak rocks.

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Introduction

A concrete-faced rockfill dam (CFRD) is a major type of earth-rock dam. It consists of cushion, transition, main rockfill, and secondary rockfill zones (see Fig. 1). Due to the advantages of CFRDs, including the use of local materials, cost-effectiveness, extensive adaptability, simple construction, and a short construction period, many concrete-faced rockfill dams have been and are being constructed, some being as high as 100 m. Weak rocks are potential sources of dam construction materials because they cover more than 50% of the Earth's surface. A number of CFRDs have been constructed with weak rocks, for example, weak rocks were used in the main body of the Cirata Dam and the Salvajina Dam (Pinkerton et al. 1985; Sierra et al. 1985); in the dry zones of the low part of the Winneke Dam, the Mangrove Dam, and the Zhushuqiao Dam (Casinader and Watt 1985; Mackenzie and McDonald 1985; Guo 1991); and in the middle part of the R. D. Bailey Dam (Beene and Pritchett 1985). Nevertheless, the behaviors of CFRDs constructed with weak rocks are not well-understood as explained in the next section. Extensive studies are needed in order to fully utilize the weak rocks as construction materials in CFRDs.

[1]Dept. of Geotechnical Engineering, Tongji Univ., Shanghai 200092, China; formerly, College of Civil Engineering, Zhejiang Univ., Hangzhou 310027, China. E-mail: hfxing@gmail.com

[2]Professor, Dept. of Civil Engineering, Zhejiang Univ., Hangzhou 310027, China.

[3]Professor, China Institute of Water Resources and Hydropower Research, Beijing 100044, China.

[4]Senior Engineer, China Institute of Water Resources and Hydropower Research, Beijing 100044, China.

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Problems of particular concern in CFRD construction are the measures to prevent weak rocks from further crushing during construction and the selection of different types of rocks in different zones of the dam. The objective of this study is to examine the properties of weak rocks, such as physical, mechanical, and hydraulic properties, thereby to find feasible ways to deal with the problems encountered during construction. This paper presents the studies on the weak rocks used in three dams at Yutiao, Da'ao, and Qiezishan in China. Slightly weathered sandy mudstone, weathered sandstone, and weathered granite, respectively, were used to construct these dams. Laboratory and field tests were conducted to determine their physical, mechanical, and hydraulic properties, the quality of placement, and the density of the compacted rocks. Stability analyses of these dams using Bishop's slice method were performed. Settlements were evaluated using the Duncan-Chang model (Duncan and Chang 1970). The numerical results were compared with the field measurements.

Descriptions of Dams

The three dams at Yutiao, Da'ao, and Qiezishan in China are located in Chongqing municipality, Jiangxi province, and Yunnan province, respectively, which have heights of 110, 90.2, and 106.1 m and crest lengths of 219.1, 423.75, and 237 m. The rock at Yutiao was stratified, slightly weathered sandy mudstone. The direction of the dip of its strata was NW30–50°. There were a few joints in the quarry zone. The rocks at Da'ao Dam were composed

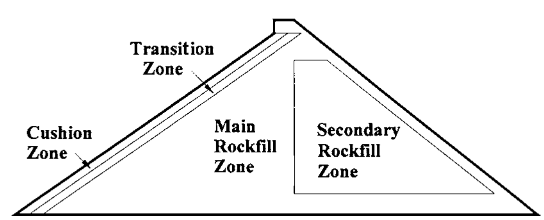

Fig. 1. Typical cross section of CFRD zones

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Table 1. Particle Size Gradation before and after Two Dry-Wet Cycle Tests

Dam name	Unconfined compressive strength (MPa)	State	Particle size distribution (%)				
			60–40 (mm)	40–20 (mm)	20–10 (mm)	10–5 (mm)	<5 (mm)
Yutiao Dam	18.8	Before	20	30	21	14	15
		After	17.8	27.6	16	17.9	20.7
Da'ao Dam	28.3	Before	26	23	22	10.5	18.5
		After	22.8	25.9	21.3	10.1	19.9

of weathered sandstone, conglomerate, and siltstone. There were four sets of joints at the dam site, and the inclinations of the joints were over 70°. The number of the joints was 1–3 per m and the lengths were 3–5 m. The rock at Qiezishan was weathered coarse granite with a specific gravity of 2.65.

Properties of Weak Rocks

Particle Gradation

Weak rocks can be easily crushed into smaller particles when compacted. Therefore their gradation varies during the construction. For example, the largest particle size of the quarried weak rock at the R. D. Bailey Dam (Beene and Pritchett 1985) was 813 mm. After compaction, the largest particle size decreased to 229 mm, the median diameters changed from 127–203 to 6–9 mm, and the amount of the particles smaller than 5 mm was about 40%.

The effect of direct crushing by roller compaction was investigated in this research. In addition, the wetting effects on the breakdown of weak rocks at the Yutiao and Da'ao Dams were investigated through the wet-dry tests. To examine the change of particle gradation, weak rock samples collected from the quarries were sieved first and then resieved after two wet-dry cycles. The changes of particle gradation after the wet-dry cycles are given in Table 1. Wetting effect causes the breakdown of weak rocks and increases the percentage of the particle size smaller than 5 mm. Particle breakdowns of the weak rocks at the Yutiao Dam were more obvious than those at the Da'ao Dam.

Density and Compressibility

Weak rocks are easily compacted to a high density due to breakdown of particles. The compacted weak rocks at the Yutiao Dam reached a maximum dry density of 2,280 kg/m^3 at the optimum moisture content of 6% using the standard Proctor compaction method provided in the Hydraulic Power Specification SL237 (WaterPower 1999) in China, which is similar to the ASTM D1557. This maximum dry density is close to that (2,260 kg/m^3) of the weak rock at Salvajina Dam (Hacelas et al. 1985). The results of the standard compaction tests for Da'ao and Yutiao Dams are given in Table 2. Data from Panshitou, Shuibuya, and Shisanling Dams in China are also listed in Table 2 for comparison. The maximum dry density of weak rocks is greater than 2,000 kg/m^3.

Oedometer tests were conducted to evaluate the compressibility of the weak rocks. The dimensions of the oedometer (300 mm in diameter; 180 mm in height) limited the maximum size of the particles in the specimens. The specimens were made of the modeled materials which were made by replacing the oversized particles with equivalent weight particles (diameter 50–60 mm) [Hydraulic Power Specifications SL237 (WaterPower 1999) and SL228 (WaterPower 1998) in China]. Based on the oedometer tests, the weak rocks have medium compressibility. Comparisons of the constrained modulus of compressibility of the weak rocks for Da'ao and Yutiao Dams and other dams are given in Table 2.

Table 2. Results of Compaction and Compressibility Tests

Dam name	Material	Optimum water content (%)	Maximum dry density (kg/m^3)	Modulus of compressibility (MPa)
Da'ao Dam	Weathered sandstone	—	—	21–62
Yutiao Dam	Mudstone	6	2,280	6.5–54.8
Panshitou Dam	Shale	3	2,060	13.8–40.1
Shuibuya Dam	Shale	8.4	2,000	—
Shisanling Dam	Weathered basalt	—	—	18.6–52.1

Strength and Stress-Strain Behavior

Compared with hard rocks, weak rocks deform more easily (Jiang and Fu 1997; Liu and Lin 2001). The unconfined compressive strengths of the weak rocks under a saturated condition determined for three dams range from 15 to 30 MPa. Their magnitudes were influenced by environmental factors, such as sunlight exposure and rainfall. The strengths of the weak rocks are lower than those of the hard rocks. Both weak rocks and hard rocks are

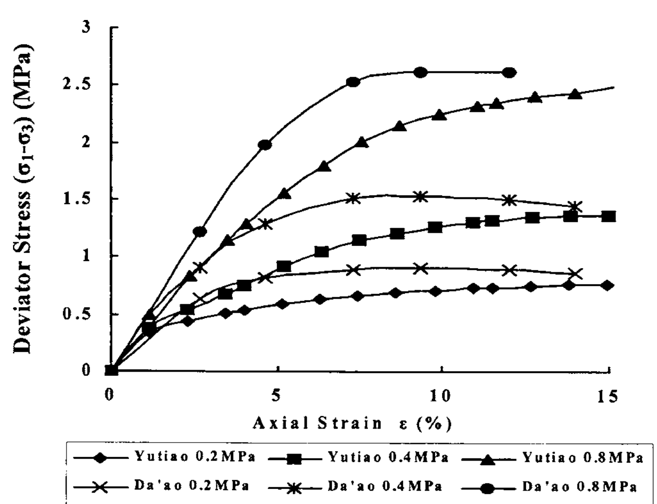

Fig. 2. Stress-strain relations of weak rocks at Yutiao and Da'ao Dams

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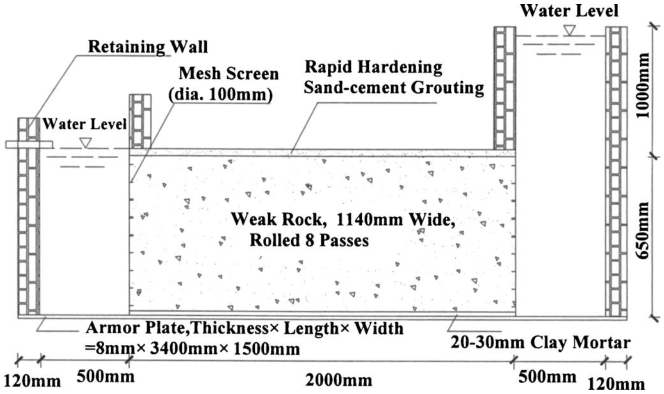

Fig. 3. Cross section of field horizontal permeability test

strain-hardening materials. Fig. 2 shows the stress-strain relationships of the weak rocks at Yutiao and Da'ao Dams.

Permeability and Deformation on Wetting

After compaction, the permeability of weak rocks can be significantly reduced. For example, the weak rocks of R. D. Bailey Dam (Beene and Pritchett 1985) were relatively impervious after compaction. The measured permeability after compaction was about 10^{-3}–10^{-5} m/s at Shisanling Dam (Dai 1994), 10^{-4}–10^{-5} m/s at Tianshengqiao1 Dam (Bai and Huang 2000), and 10^{-4}–10^{-6} m/s at Mangrove Dam (Mackenzie and McDonald 1985). The permeability of weak rocks depends on both the dry unit density and the small particle (<5 mm) content. Field permeability tests, both vertically and horizontally, were conducted at Da'ao Dam and Yutiao Dam. The setup of the horizontal permeability test is shown in Fig. 3. The vertical permeability test followed the procedures of double-ring, i.e.: (1) 0.8 m thick weak rock was rolled eight passes and then 0.2 m of its top was excavated, (2) an external steel ring (diameter 452 mm) and an inner steel ring (diameter 226 mm) were carefully placed at the test pit, (3) the inner steel ring and the gap of the external and inner steel rings were filled with pure water, and (4) the test instrument was installed. The measured horizontal and vertical permeability values are provided in Table 3.

Effect of Saturation

Saturation of weak rocks can reduce their strength. The reduction of strength can be represented by a softening coefficient, expressed as the ratio of compressive strength at saturation to that at the dry condition. The volume of weak rocks may decrease when soaked; this volume change is called the wet-deformation. The deformations of the compacted weak rocks at Da'ao Dam and

Table 3. Results of Permeability Tests

Dam name	Dry density (kg/m^3)	Coefficient of horizontal permeability ($\times 10^{-4}$ m/s)	Coefficient of vertical permeability ($\times 10^{-4}$ m/s)
Yutiao Dam	2,000	60	2.59
	2,110	2.11	0.139
Da'ao Dam	2,040	7.36	0.676
	2,100	2.07	0.439

Table 4. Results of Deformation upon Wetting

Dam name	Dry density (kg/m^3)	Lateral pressure (MPa)	Wetting deformation ratio (%)
Yutiao Dam	2,000	0.2	3.67
		0.4	4.38
		0.6	4.60
Da'ao Dam	2,040	0.2	2.24
		0.4	3.27
		0.6	3.67

Yutiao Dam under a saturated condition are listed in Table 4 at the stress level (defined as the ratio of the vertical pressure to lateral pressure) equal to 0.5.

Field Tests of Projects

Placement Tests of Weak Rocks at Yutiao Dam

Two test sites were selected at the left outlet of the spillway. A 2.18 m vibrating roller with a mass of 16,000 kg was used for compaction. The layout of the first test site is shown in Fig. 4. In order to observe the compaction, eight survey points were set up in every test panel. The symbols of A1–F3 represent the test panel number. Three layers were tested: the first two layers were mudstone with a thickness of 0.6 and 0.8 m; the third layer was a mixture of 60% mudstone and 40% argillaceous sandstone with a thickness of 1.0 m. The size of the second test site was 16 m×42 m. Within this site, all three layers have the same layer thickness of 0.8 m and the same material of mudstone with 10% water content.

After compaction, two specimens were tested for each panel. The specimens were taken from the upper and lower parts of the panel layer. The particle size distribution, the water content, the dry density, and the coefficient of uniformity were determined. Table 5 lists these test results. Fig. 5 shows the comparison of the particle size distributions of the upper and lower parts, as well as the entire layer for the Test Panel C2. The relationship between

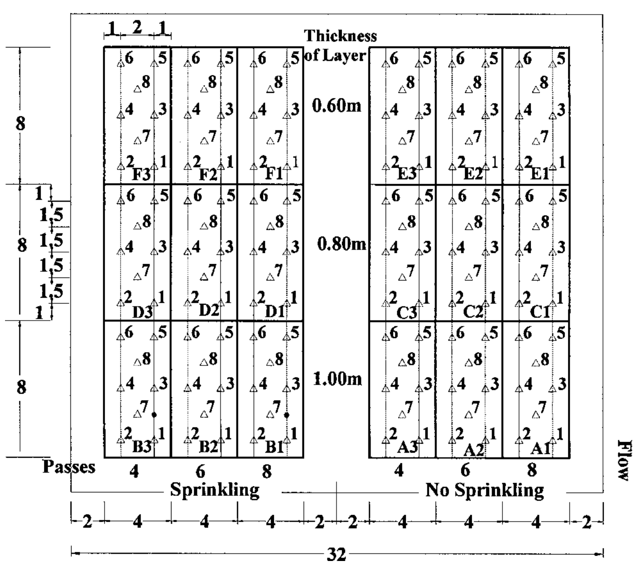

Fig. 4. Layout of placement and compaction test site of Yutiao

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Table 5. Results of Field Placement and Compaction Test at Yutiao Dam

Panel number	Layer thickness (m)	Number of passes of roller	Dry density (kg/m^3)	Porosity (%)	Water content (%)	Particle content (<5 mm) (%)	Particle content (<0.1 mm) (%)	Coefficient of uniformity	Coefficient of curvature
B1	1.0	8	2,270	16.2	4.5	8.1	0.3	61.5	0.9
B2	1.0	6	2,190	19.2	3.6	7.6	0.5	31.4	1.26
B3	1.0	4	2,180	19.5	3.8	8.7	0.4	58.3	1.07
C1	0.8	8	2,260	16.6	3.6	16.1	0.8	60.9	2.29
C2	0.8	6	2,210	18.5	3.5	12.0	0.9	46.7	1.21
C3	0.8	4	2,200	18.8	4.8	14.7	0.9	36.7	1.89
F1	0.6	8	2,160	20.3	5.8	13.8	1.2	32.3	1.86
F2	0.6	6	2,400	11.4	5.9	19.3	1.2	39.6	1.58
F3	0.6	4	2,280	15.9	4.6	17.3	0.9	46.1	2.00

the compaction ratio and the number of rolling passes is shown in Fig. 6 while the relationship between the dry density and the number of the rolling passes is shown in Fig. 7. The compaction ratio is defined as the ratio of the compression of the layer to its original thickness.

In order to study crushing and crusting of weak rocks, sprinkling tests of the weak rocks and permeability tests of the crusting layer were carried out. Sprinkling tests were performed by adding a certain amount of water to the weak rocks during the placement to achieve a specific water content and then testing its effect on the properties of the weak rocks. The results of the sprinkling tests are listed in Table 6. In addition, specimens were taken from the crusting layers to acquire the distribution of particles smaller than 5 mm. Tables 7 and 8 show the results of the sieve analysis and the permeability tests of the crust, respectively. The vertical permeability of the crusting layer was low and the thickness of the crusting layer after compaction was about 0.1 m.

Placement Tests of Weak Rocks at Da'ao Dam

The weathered sandstone was used as the test material at Da'ao Dam. The measured average unconfined compressive strength of this weathered sandstone at saturation was 28 MPa. A vibrating roller with a mass of 13,500 kg was used for five series of rolling compaction tests. The initial layer thicknesses ranged from 0.8 to 1.0 m with the average layer thickness of 0.93 m. After every two passes of rolling, the compression was measured and the specimens were sampled for tests. The average values of the rolling compaction test results are shown in Table 9. When the rolling compaction was over, the maximum particle size was determined at 580 mm and the average particle size was 90 mm. The coefficients of uniformity and curvature were 58.9 and 9.7, respectively.

Placement Tests of Weak Rocks at Qiezishan Dam

The measured unconfined compressive strength of the weak rock at saturation was 20–30 MPa. The area of the test field was 15 m × 30 m. Two initial thicknesses of the two layers were 0.88 and 1.27 m, respectively. The rockfill was sprinkled with water to achieve a water content of 10–15% and then compacted with a vibrating roller with a mass of 17,000 kg. Sieve analysis showed that the percent of the medium size particles (5–80 mm) was less than 25% and small particle (<5 mm) contents were high after compaction. The densities of rockfill at the two test locations were both greater than 2,000 kg/m^3 after compaction.

In order to further study the crushing and crusting properties of the weak rocks, the sprinkling tests of the weak rocks and the permeability tests of the crusting layer were carried out with heavily weathered materials and the materials left in the process of construction. The test results of the weathered materials showed that the coefficient of the vertical permeability was in the order of 10^{-7} m/s. Rolling compaction apparently crushed the particles near the surface and formed a crusting layer with a thickness of 0.10–0.20 m. The test results of the left-over materials showed that the coefficient of the vertical permeability was in the

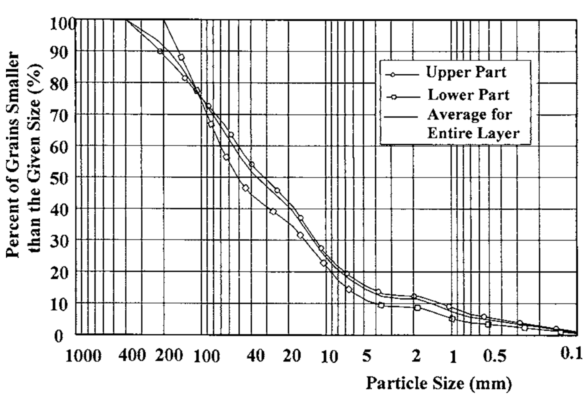

Fig. 5. Particle size distribution for Test Panel C2 at Yutiao Dam

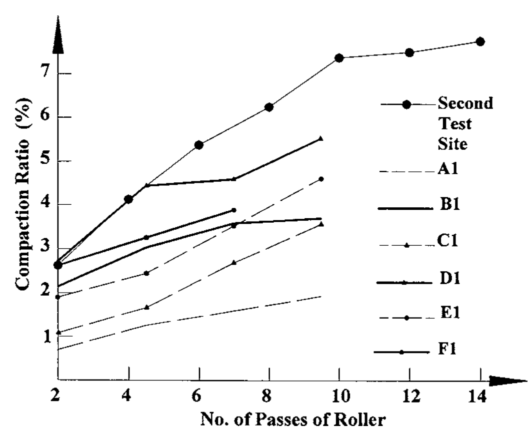

Fig. 6. Number of passes versus compaction ratio at Yutiao Dam

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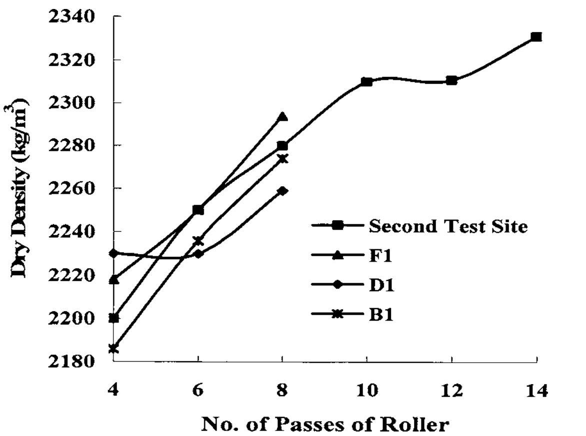

Fig. 7. Relation of pass number and dry density at Yutiao Dam

order of 10^{-5} m/s. Rolling compaction crushed about 30% surface and formed a crusting layer with a thickness of 0.05–0.10 m.

Summary of Weak Rock Placement Tests

Through the compaction tests at the three dams, the following summary can be made:

1. After compaction by a vibrating roller, the weak rocks generally exhibit well-graded, high density, and low porosity. The particles of the weak rocks become finer with an increase of the number of rolling passes. The number of rolling passes is recommended to be 6–8 in the compaction of weak rocks.
2. Proper sprinkling water content is useful for the compaction of the weak rocks, but the water content should be well-controlled. A suitable quantity of sprinkling water depends on the weak rock, which can be obtained from laboratory or field tests. The water content of the weak rocks was 5% for Yutiao Dam and 10% for Qiezishan Dam.
3. It is important to properly select the thickness of the weak rock for placement in the CFRD. The initial layer thicknesses used in these three dams were 0.8–1.0 m and the masses of the rollers were 13,500–17,000 kg. Under such conditions, the densities of the weak rocks after compaction met the requirements of the three projects.
4. The rolling compaction of weak rocks would create crust. The thickness of the crust is less than 0.20 m. Crusting significantly reduces the vertical permeability of weak rock fill. The following measures may be taken to deal with the crusting:
   a. Control the gradation of quarry materials during the placement of the weak rock;
   b. When the thickness of the crust is thinner than 0.1 m, the crust needs to be overturned and dislocated to enhance its vertical permeability. When the thickness of the crust is thicker than 0.1 m, the crust should be excavated, mixed with a certain amount of hard rocks, and then recompacted; and
   c. Adding a certain amount of hard rocks can increase the permeability of the crust. Since the thickness of the crust is generally less than 0.2 m, hard rocks should be added only to the upper part of each placement layer. Hard rocks were used in these three projects with the proportion of hard rocks at 60% at Yutiao Dam, 40% at Qiezishan Dam, and 25% at Da'ao Dam, respectively.

Stability and Deformation Analysis of Da'ao Dam

In order to ensure good drainage and maintain a relatively dry condition at the lower zone boundary to reduce the deformation

Table 6. Sprinkling Test Data on Weak Rocks at Yutiao Dam

Panel number	Layer thickness (m)	Number of passes of roller	Dry density (kg/m^3)	Water content (%)	Time of wetting[a] (h)	Particle content (<5 mm) (%)	Particle content (<0.1 mm) (%)
B1	1.0	8	2,170	6	0	13.55	0.84
B2	1.0	6	2,220	5	8	12.05	0.87
D1	0.8	8	2,160	6	0	13.72	0.69
D2	0.8	6	2,180	4	4	6.78	0.33
F1	0.6	8	2,180	4	4	7.37	0.35
F2	0.6	6	2,190	2	2	3.16	0.24

[a]"Time of wetting" is the interval time from the end of sprinkling water to the beginning of compaction.

Table 7. Percentage of Retained Grains of Crusted Layers at Yutiao Dam

Panel number	Layer thickness (m)	Number of passes	Percent of retained grains (%)						
			>5 (mm)	5 (mm)	2 (mm)	1 (mm)	0.5 (mm)	0.25 (mm)	<0.1 (mm)
B1	1.0	8	0.2	29.8	17.2	12.8	11.2	21	7.8
B2	1.0	6	0.2	32.2	19.4	11.6	7	18.8	10.8
D1	0.8	8	0.2	29.4	20.2	12.8	9.8	19.8	7.8
D2	0.8	6	0.2	21.8	22.2	18.6	12.8	18.6	5.8
F1	0.6	8	0.2	13.8	11	12.6	17.4	32.4	12.6
F2	0.6	6	0.2	23.2	24.8	15.4	8	20	8.4

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Table 8. Permeability Test Results on Crusted Layer of Weak Rocks at Yutiao Dam

Panel number	Layer thickness (m)	Number of passes	Depth of test (m)	Coefficient of vertical permeability ($\times 10^{-7}$ m/s)
B1	1.0	8	0.045	1.22
B2	1.0	6	0.02	5.93
B2	1.0	6	0.06	35.3
B2	1.0	6	0.10	3,010
B2	1.0	6	0.12	4,890
D1	0.8	8	0.04	7.41
D2	0.8	6	0.03	3.78
D2	0.8	6	0.065	39.0

of the weak rocks upon wetting, a number of measures were taken at Da'ao Dam, which include the upper boundary of the weak rock zone covered with 5 m fresh hard rocks; the downstream boundary line positioned in a way to ensure the slope stability; and 2 m fresh hard rocks placed on the outer layer to prevent weak rocks from further weathering. The upper boundary of the weak rock zone was determined based on numerical analysis as discussed later.

Slope stability of Da'ao Dam was analyzed using Bishop's simplified slice method. The strength parameters (cohesion c and angle of internal friction φ) were obtained from drained triaxial tests on the samples of 300 mm in diameter and 600 mm in length. The test data shows that the internal friction angle of rock fill has a nonlinear relationship with the confining stress, σ_3, which can be expressed using Eq. (1) (Bai and Cui 1997).

$$\varphi = \varphi_0 - \Delta\varphi \lg\left(\frac{\sigma_3}{Pa}\right) \tag{1}$$

where φ_0=internal friction angle when σ_3 is equal to 0.1 MPa; $\Delta\varphi$=linear slope; and Pa=atmospheric pressure expressed in the same unit as σ_3. The parameters of materials used in the stability analyses for Da'ao Dam are provided in Table 10.

The stresses and the strains in the dam were evaluated using a two-dimensional finite element software. The nonlinear hyperbolic model (Duncan and Chang 1970) for stress-strain relations was used in the analysis. The tangent modulus E_t and the bulk modulus B can be expressed by

$$E_t = K \cdot Pa\left(\frac{\sigma_3}{Pa}\right)^n \left[1 - \frac{R_f(1-\sin\phi)(\sigma_1-\sigma_3)}{2\cos\phi + 2\sigma_3 \sin\phi}\right]^2 \tag{2}$$

Table 9. Results of Field Compaction Test at Da'ao Dam

Number of passes	Compaction ratio (%)	Dry density (kg/m^3)	Porosity (%)
0	0	1,968	26.41
2	3.31	2,042	23.77
4	4.88	2,074	22.53
6	6.01	2,096	21.74
8	6.47	2,110	21.26
10	6.84	2,118	20.99

$$B = K_b \cdot Pa\left(\frac{\sigma_3}{Pa}\right)^m \tag{3}$$

The unloading-reloading modulus E_{ur} is expressed by

$$E_{ur} = K_{ur} \cdot Pa\left(\frac{\sigma_3}{Pa}\right)^n \tag{4}$$

where σ_1 and σ_3=major and minor principal stresses, respectively; φ=internal friction angle; R_f=failure ratio; K=modulus number; n=exponent determining the rate of variation of the initial tangent modulus with σ_3; K_b=bulk modulus number; m=bulk modulus exponent; and K_{ur}=unloading-reloading modulus number.

The above parameters were obtained from the drained triaxial compression tests and provided in Table 11.

The maximum height of the Da'ao Dam was 90.2 m (the top elevation at 220.2 m) and the length of the crest was 423.75 m. The upstream slope was 1:1.4 (v:h) and the downstream slope was 1:1.3 (v:h) above elevation 165 m and 1:1.4 (v:h) between elevation 165 and 145 m.

Two cases were analyzed for slope stability: weak rocks used partially and completely in the cross section of the dam. The stability analysis of these two cases shows that the safety factors against circular slip failure are greater than 1.55 and the critical slip surfaces are at shallow depths.

To investigate the effect of the weak rock zone on the stresses and strains of the dam body and the deflection of the face slab, four finite element analyses of this dam were performed. The cross-sectional areas of the weak rocks for these four analyses are ABCH, ABDH, ABEH, and ABFG as shown in Fig. 8. The effect of the location of the weak rock upstream boundary on the stresses and strains in this dam was also studied.

The calculated maximum values of stresses and displacements in the dam are provided in Table 12. The analyses based on these four models show that the distribution of stresses and displacements in the dam are almost identical. The maximum settlements occur near the dam axis and at about one-half of the dam height. The maximum settlements during water storage are 1.07, 1.20, 1.23, and 1.31 m, corresponding to 1.18, 1.33, 1.36, and 1.45% of the dam height, respectively. The settlements of the dam increase with an increase of the weak rock zone. These settlements are found to be acceptable to this project. The calculated maximum tensile stress in the face slabs is 0.56 MPa, which is lower than the allowable tensile strength (2.55 MPa) of the concrete.

Field Observations at Da'ao Dam

Weak rocks were used at both the main rockfill and the secondary rockfill zones at Da'ao Dam. Deformations and seepage within Da'ao Dam were monitored. At the crest and downstream slope of the dam, six collimation lines and 26 surface benchmarks were established to observe horizontal displacements and settlements of the dam. At elevations of 161, 178.5, and 191 m, 11 settlement gauges were installed to monitor its internal settlements of the dam and six displacement gauges were installed along the concrete slab and the dam axis to monitor the horizontal displacements. Eleven bidirectional and 2 four-directional strain gauges were installed on the concrete slab to measure the strains in the slab.

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Table 10. Material Parameters in Stability Analyses at Da'ao Dam

Material	Dry density (kg/m^3)	Porosity (%)	Cohesion (MPa)	φ (degrees)	φ_0 (degrees)	$\Delta\varphi$ (degrees)
Cushion material	2,175	19	0	40.0	53.8	11.2
Transition material	2,144	20	0	40.0	54.4	10.2
Hard rockfill	2,120	21	0	38.0	47.8	6.2
Weak rockfill	2,100	22	0	36.0	45.0	7.6

Table 11. Material Parameters in Duncan-Chang Model at Da'ao Dam

Material	Dry density (kg/m^3)	Cohesion (MPa)	φ_0 (degrees)	$\Delta\varphi$ (degrees)	R_f	K	K_{ur}	n	K_b	m
Cushion	2,175	0	53.8	11.2	0.73	800	1,000	0.46	136	0.40
Transition	2,144	0	54.4	10.2	0.72	800	1,000	0.42	136	0.30
Hard rockfill	2,120	0	47.8	6.2	0.71	630	800	0.40	120	0.30
Weak rockfill	2,100	0	45.0	7.6	0.72	307	368	0.39	134	0.30

Displacements Prior to Water Filling

The field measurements indicated that the deformation patterns of Da'ao Dam were similar to those of hard rock dams during construction, i.e., the maximum settlement exists at the dam axis of about one-half of dam height. The measured maximum settlement in the field was 0.920 m, which is equal to 1.02% of the dam height. Most of the deformation occurred during the construction. The horizontal displacements were nearly symmetric along the dam axis. The maximum horizontal displacement occurred at the dam bottom.

Displacement during Water Filling and Storage

The field observation showed that the rate of the settlement of the dam depended on the water level during water filling. The settlement rate was larger when the water level rose rapidly during the first 2 months of water filling. From September 1999 to February 2000 the settlement rate decreased as a result of slower rise of the water level. During the flood season from March to May 2000, the water level reached 216.66 m (the highest elevation ever) and the deformation rate increased again. The settlement of the dam became stable within 1 year after the water level had reached a normal elevation of 208 m. The corresponding maximum settlement was 0.198 m. The maximum horizontal displacements observed from the inner part and from the surface of the dam were 0.110 and 0.121 m, respectively.

The measured maximum total settlement and horizontal displacement during the construction, water filling, and storage were 1.118 and 0.232 m, which are less than the calculated values of 1.31 and 0.45 m, respectively.

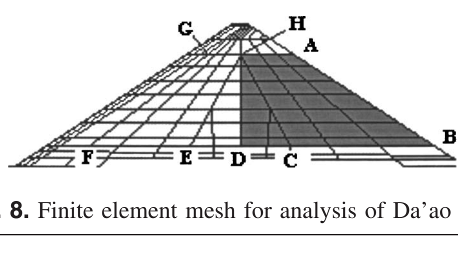

Fig. 8. Finite element mesh for analysis of Da'ao Dam

Deflections of Face Slabs during Water Storage

The measured maximum deflection of the face slabs was 0.2253 m, which is less than the calculated value of 0.2733 m. The horizontal strains in the concrete face slabs were all compressive. Most of the strains in the slope direction were also compressive except at the border and at the corner where the strains were tensile. The observed maximum compressive and tensile strains were -421.77×10^{-6} and 61.65×10^{-6}, respectively, which are within the acceptable range. No damage of the face slabs by water filling is expected.

Seepage Observations

The measured pore water pressure in Da'ao Dam changed with the water level. The highest water level within the dam was observed in the cushion of the dam, which was only 0.99–3.23 m higher than the water level of the downstream from October 1999 to October 2000. In the same period, the water level difference between the upstream and downstream was 66–77 m. This observation showed that the concrete face slab functioned well in waterproofing and the dam had a good drainage system. The rate of the seepage discharge also changed with the water level. The rate of the total seepage discharge prior to January 2000 was slightly higher than 0.030 m^3/s. The seepage rate increased continuously from 0.030 to 0.160 m^3/s with the rising of the water level and then dropped to 0.061 m^3/s with the lowering of the water level

Table 12. Numerical Results on Da'ao Dam

Model number	Maximum settlement (m)	Maximum deflection (m)	Maximum compressive stress (MPa)	Maximum tensile stress (MPa)
ABCH	1.07	0.1464	1.26	0.05
ABDH	1.20	0.1512	1.41	0.05
ABEH	1.23	0.1615	1.38	0.07
ABFG	1.31	0.2733	1.33	0.56

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until the end of October 2000. When the rate of the total seepage discharge reached 0.160 m^3/s, the height of the saturation line in the dam was only slightly higher than the riverbed.

Conclusions

The following conclusions may be drawn from this study:

1. The unconfined compressive strength of the weak rocks in this study ranges from 15 to 30 MPa, which includes soft and weathered rocks;
2. As compared with hard rocks, weak rocks are easily crushed and sensitive to water content variations in addition to their low permeability. However, they have medium compressibility, well-graded particle-size distribution, and easy compaction so that they can be used as construction materials in CFRDs;
3. The three projects discussed in this paper showed that it is critical to avoid crushing and crusting of weak rocks and to ensure the density of compacted fill during the construction;
4. The numerical analyses showed that the deformations of the weak rock dams are larger than those of hard rock dams. The maximum settlement of the dam increases with the percentage of the weak rock used in the dam. The upper boundary of the weak rock zone has a significant effect on the deformation of the dam. Both slope stability and deformation analyses showed that the CFRD performed well by using proper rock materials in different zones; and
5. Field monitoring confirmed the performance of CFRDs and the feasibility of using weak rocks as construction materials for dams.

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