

# 西域砾岩砂砾料沥青混凝土心墙坝湿化变形数值分析

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**摘要:**我国新疆地区广泛使用西域砾岩砂砾料作为筑坝材料,由于西域砾岩砂砾料浸水后易软化、崩解,大坝蓄水后的湿化变形分析成为工程界广泛关注的问题.联合广义塑性模型和西域砾岩砂砾料湿化模型,对某沥青混凝土心墙坝进行了湿化变形有限元分析.结果表明:广义塑性模型和西域砾岩砂砾料湿化模型能够很好地反映大坝湿化变形及应力分布规律;上游蓄水湿化使坝体向上游方向的水平位移和沉降都增大,最大水平位移由竣工时的 1.5 cm 增至 22 cm 左右,最大竖向沉降由竣工时的 0.17% 坝高增至 0.53% 坝高,筑坝料的湿陷使心墙的变形也增大;西域砾岩砂砾料的湿化变形明显大于花岗岩堆石料,最大竖向沉降是花岗岩堆石料的近 3 倍,其湿化造成坝顶上游侧出现局部拉应力区,有可能导致坝顶出现裂缝.因此,在新疆干旱地区采用西域砾岩砂砾料筑坝时考虑蓄水时的湿化影响是十分必要的.

**关键词:**广义塑性模型;湿化变形;西域砾岩砂砾料;数值分析

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## 0 引言

目前,土石坝在水库初次蓄水时引起的湿化变形仍是大坝设计需要解决的一个难题.工程实践表明,湿化变形会引起坝体发生较大的变形并且在坝顶及坝坡引起纵向或水平裂缝,甚至引起溃坝<sup>[1-4]</sup>. Nobari 和 Duncan<sup>[5]</sup> 首先采用双线法测定湿化变形,并采用 Duncan 和 Chang<sup>[6]</sup> 的双曲线模型来分析大坝湿化变形.此后 Escuder 等<sup>[7]</sup> 提出一种改进的双曲线湿化模型并成功用于 100 m 高大坝的计算. Roosta 等<sup>[8]</sup> 通过引入应力释放因子来模拟湿化变形,结果与三轴试验结果吻合较好.国内的左元明和沈珠江<sup>[9]</sup> 通过单线法湿化试验提出了湿化模型.陈慧远等<sup>[10]</sup>、张芸芸等<sup>[11]</sup> 均采用邓肯-张 EB 模型来分析沥青心墙坝的湿化变形,董建筑等<sup>[12]</sup>、陆阳洋等<sup>[13]</sup> 和董龙根等<sup>[14]</sup> 则采用邓肯-张模型和沈珠江湿化模型对土质直心墙和斜心墙的蓄水湿化进行数值分析.李全明等<sup>[15]</sup> 引入了考虑小主应力的双曲线关系来反映

湿化体变的规律,联合双屈服面模型对公伯峡面板堆石坝进行了湿化分析.王富强等<sup>[16]</sup> 进一步修正了湿化模型,并对积石峡面板堆石坝的湿化变形进行了分析.张伟等<sup>[17]</sup> 对积石峡面板堆石坝在施工中减小湿化变形的工程措施进行了研究.岑威钧等<sup>[18]</sup> 采用考虑湿化效应的堆石料 Gudehus-Bauer 亚塑性模型对心墙坝进行数值分析.目前,已有文献中采用堆石料弹塑性本构模型来分析大坝湿化变形的研究并不多见.

我国新疆地区广泛使用当地的西域砾岩砂砾料作为筑坝料.西域砾岩是一种第四纪 Q1 时代的新近沉积岩<sup>[19]</sup>,泥沙质、钙质胶结或半胶结,抗外界变形能力差,遇水易软化、崩解,失水后易于缩开裂.此外,新疆地区常年干旱少雨,西域砾岩砂砾料作为筑坝材料在水库初次蓄水时的湿化变形分析就显得尤为重要.本文联合广义塑性模型<sup>[20]</sup> 和西域砾岩砂砾料湿化模型对某沥青混凝土心墙坝进行湿化变形分析,研究湿化变形对大坝应力和变形的影响.

1 计算模型与参数

1.1 堆石料本构模型

目前关于湿化变形的数值计算主要采用邓肯-张 EB 模型分析,然而土石坝在蓄水时堆石料的应力路径复杂,张宗亮等<sup>[21]</sup>指出邓肯-张 EB 模型不能很好地反映堆石料的剪胀、剪缩特性以及复杂应力路径下的加卸载过程.因此,本文采用理论上更为合理的广义塑性模型<sup>[20]</sup>来进行湿化变形分析,西域砾岩砂砾料风干样和饱和样的静力三轴试验及广义塑性模型的数值模拟结果如图 1 和 2 所示.

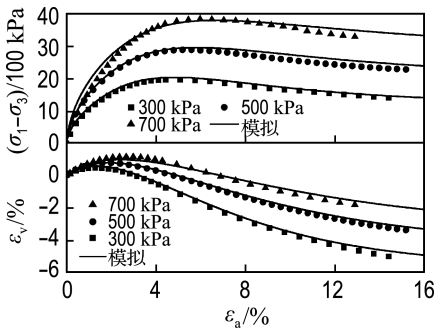


图 1 广义塑性模型模拟风干样试验结果  
Fig. 1 Prediction of the generalized plastic model for the results of dry samples

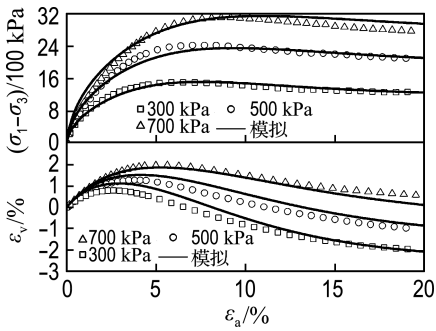


图 2 广义塑性模型模拟饱和样试验结果  
Fig. 2 Prediction of the generalized plastic model for the results of saturated samples

西域砾岩砂砾料的广义塑性模型参数见表 1 和 2. 由于沥青混凝土心墙对大坝变形影响很小,其模型仍采用了邓肯-张 EB 模型,参数见表 3.

1.2 湿化模型

作者对西域砾岩砂砾料开展了湿化试验,结果表明:湿化体应变与平均主应力和应力水平有

密切关系,而湿化剪应变主要受应力水平的影响.根据试验结果,提出如下湿化模型:

$$\frac{\Delta \epsilon_v}{1 - \Delta S_1} = \frac{\sigma_0 / p_a}{a_1 + b_1 (\sigma_0 / p_a)} \tag{1}$$

$$\Delta S_1 = \begin{cases} S_1 - S_{lc}; & S_1 \geq S_{lc} \\ 0; & S_1 < S_{lc} \end{cases}$$
$$\Delta \gamma_s = a_2 [S_1 / (1 - S_1)]^{b_2} \tag{2}$$

式中:  $\Delta \epsilon_v$  为湿化体应变;  $\sigma_0$  为平均主应力;  $p_a$  为工程大气压 ( $p_a = 100 \text{ kPa}$ );  $S_1$  为饱和样对应的应力水平;  $\Delta S_1$  为应力水平与临界应力水平的差值;  $S_{lc}$  为试样发生湿胀时的临界应力水平;  $a_1$ 、 $b_1$  为反映湿化体应变的参数;  $\Delta \gamma_s$  为湿化剪应变;  $a_2$ 、 $b_2$  为反映湿化剪应变的参数.

表 1 风干样广义塑性模型参数 ( $\rho_d = 2.18 \text{ g/cm}^3$ )  
Tab. 1 Parameters of the generalized plastic model for the dry samples ( $\rho_d = 2.18 \text{ g/cm}^3$ )

| $G_0$ | $K_0$ | $M_g$ | $M_f$      | $\alpha_f$    | $\alpha_g$ | $H_0$     | $H_{u0}$  | $m_s$ |
|-------|-------|-------|------------|---------------|------------|-----------|-----------|-------|
| 1 500 | 2 000 | 1.75  | 0.95       | 0.34          | 0.48       | 1 500     | 3 000     | 0.5   |
| $m_v$ | $m_l$ | $m_u$ | $\gamma_d$ | $\gamma_{dm}$ | $\gamma_u$ | $\beta_0$ | $\beta_1$ |       |
| 0.5   | 0.4   | 0.5   | 0          | 10            | 15         | 40        | 0.035     |       |

表 2 饱和样广义塑性模型参数 ( $\rho_d = 2.18 \text{ g/cm}^3$ )  
Tab. 2 Parameters of the generalized plastic model for the saturated samples ( $\rho_d = 2.18 \text{ g/cm}^3$ )

| $G_0$ | $K_0$ | $M_g$ | $M_f$      | $\alpha_f$    | $\alpha_g$ | $H_0$     | $H_{u0}$  | $m_s$ |
|-------|-------|-------|------------|---------------|------------|-----------|-----------|-------|
| 1 000 | 1 400 | 1.7   | 0.9        | 0.28          | 0.45       | 1 050     | 3 000     | 0.5   |
| $m_v$ | $m_l$ | $m_u$ | $\gamma_d$ | $\gamma_{dm}$ | $\gamma_u$ | $\beta_0$ | $\beta_1$ |       |
| 0.5   | 0.45  | 0.5   | 0          | 10            | 15         | 20        | 0.023     |       |

表 3 沥青混凝土邓肯-张 EB 模型参数  
( $\rho_d = 2.41 \text{ g/cm}^3$ )  
Tab. 3 Parameters of the Duncan-Chang EB model for the asphalt concrete ( $\rho_d = 2.41 \text{ g/cm}^3$ )

| 材料    | $c/\text{kPa}$ | $\varphi/(^\circ)$ | $K$   | $n$ | $R_f$ | $K_b$ | $m$  |
|-------|----------------|--------------------|-------|-----|-------|-------|------|
| 沥青混凝土 | 250            | 26.9               | 397.5 | 0.5 | 0.91  | 920   | 0.48 |

该模型对西域砾岩砂砾料及两种花岗岩堆石料<sup>[22-23]</sup>的湿化试验结果的模拟情况见图 3,可以看出作者建议的湿化模型能很好地模拟不同材料的湿化变形特性,且西域砾岩砂砾料的湿化变形明显大于其他两种堆石料. 3 种筑坝材料的湿化模型参数见表 4.

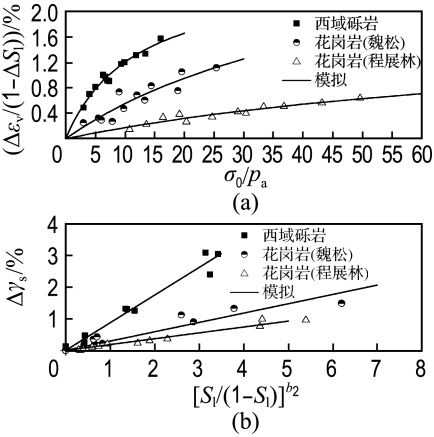


图 3 不同筑坝材料的湿化模型模拟结果

Fig. 3 Wetting model prediction results with different dam materials

表 4 湿化模型参数

Tab. 4 Parameters of the wetting model

| 试验材料     | $a_1/100$ | $b_1/100$ | $a_2/\%$ | $b_2$ | $S_{lc}$ |
|----------|-----------|-----------|----------|-------|----------|
| 西域砾岩     | 4.49      | 0.38      | 0.87     | 0.66  | 0.66     |
| 花岗岩(魏松)  | 15.18     | 0.29      | 0.29     | 0.96  | 0.50     |
| 花岗岩(程展林) | 51.50     | 0.55      | 0.18     | 0.93  | 1.00     |

2 坝体湿化变形分析

对新疆某地区的西域砾岩砂砾料沥青混凝土心墙坝进行施工和蓄水模拟,填筑和满蓄时分别为 54 步和 38 步.蓄水过程中分别采用西域砾岩砂砾料湿化参数和魏松<sup>[22]</sup>花岗岩堆石料湿化参数计算,坝体最大横剖面如图 4 所示.

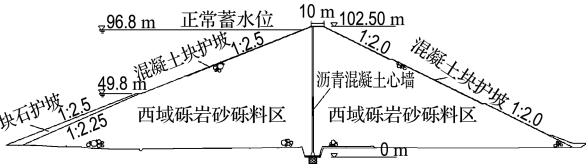


图 4 大坝最大横剖面示意图

Fig. 4 Sketch map of the maximum cross section of the dam

湿化变形在数值中的实现过程如下:

- (1)坝体填筑过程中采用风干样的广义塑性模型参数和沥青混凝土的邓肯-张 EB 模型参数模拟大坝变形,并得到蓄水前状态;
- (2)蓄水后,根据湿化模型计算上游侧水位以下砂砾料的湿化变形(水位以下砂砾料认为饱和

度为 100%),按初应变法考虑湿化引起的应变势,根据本构模型计算单元的等价节点力,进行迭代计算;

(3)水位增加,重复(2),直到满蓄.

2.1 坝体位移分析

竣工时位移分布如图 5 所示.坝体水平位移很小(仅 1.5 cm 左右)且大致对称;竖向沉降最大位移发生在中轴线的 1/2 坝高附近,最大值为 17 cm 左右,占最大坝高的 0.17%.心墙的水平位移也很小,竖向沉降沿坝高大致呈抛物线分布,如图 6 所示.这与 Naylor 等<sup>[24]</sup>对 Beliche 坝和陈慧远等<sup>[10]</sup>对碧流河沥青混凝土心墙坝的分析相吻合.

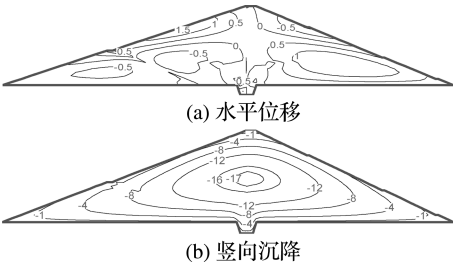


图 5 竣工时坝体位移(单位:cm)

Fig. 5 Displacements of the dam when construction is completed (unit:cm)

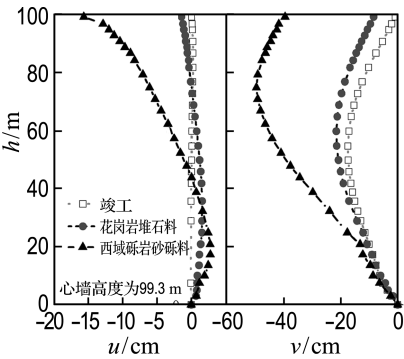


图 6 心墙的位移

Fig. 6 Displacements of the core

满蓄时,上游侧西域砾岩砂砾料产生湿陷,使得坝体向上游方向水平位移和竖向沉降明显增加,分别达到 22 cm 和 55 cm 左右,最大沉陷发生在心墙上游侧 2/3 坝高处,占最大坝高的0.53%,是竣工沉降的 3.2 倍,如图 7 所示.心墙上游侧西域砾岩砂砾料的湿陷引起心墙向上游侧水平位移和竖向沉降也较大,如图 6 所示.西域砾岩砂砾料

和花岗岩堆石料的湿化变形规律大致相同,但西域砾岩砂砾料在蓄水时的湿化变形明显大于花岗岩堆石料,竖向沉降达到花岗岩堆石料的近 3 倍.

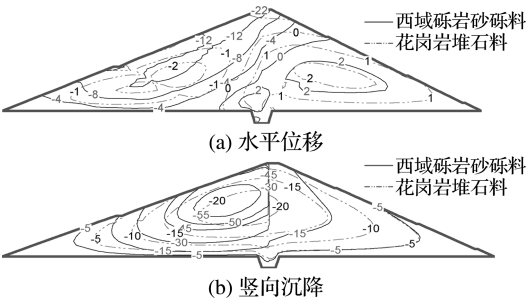


图 7 满蓄时坝体位移(单位:cm)  
Fig. 7 Displacements of the dam at normal water level (unit:cm)

蓄水后,上游西域砾岩砂砾料的湿化引起心墙的水平 and 竖向沉降的变形规律(如图 6 所示)与 Infiernillo 坝<sup>[4]</sup>和 Beliche 坝<sup>[25]</sup>蓄水后的位移分布规律基本一致,即填筑时心墙沉降沿高度方向大致呈抛物线分布,蓄水后心墙顶部沉降逐渐增大,最大沉降位置在心墙偏中上部位,同时向上游的水平位移增大,如图 8 和 9 所示. 这表明联合广义塑性模型与反映西域砾岩砂砾料湿化特性的模型能较好地分析大坝的湿化变形.

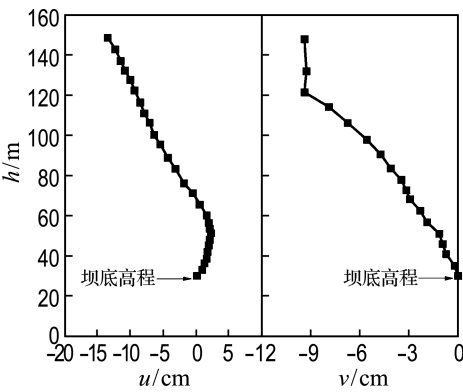


图 8 Infiernillo 坝实测的蓄水期心墙位移  
Fig. 8 Measured displacements of the core of Infiernillo dam during reservoir filling

2.2 坝体应力分析

竣工时坝体的主应力分布见图 10(a)和图 11(a),大小主应力分布基本与坝坡平行. 心墙处应力小于两侧筑坝料,表明存在一定的拱效应作用.

满蓄时坝体主应力分布见图 10(b)和图 11(b),上游侧的主应力都有所减小. 特别要注意的是西域砾岩砂砾料填筑蓄水后,上游侧坝顶附近出现了小范围拉应力区,这主要因为西域砾岩砂砾料湿化变形较大导致了大坝顶部不均匀变形,有可能在坝顶出现裂缝,这与 Ataturk 坝<sup>[3]</sup>和密云水库走马庄 II 号<sup>[2]</sup>等工程一致. 当采用花岗岩堆石料参数时,蓄水湿化变形较小,则没有出现拉应力.

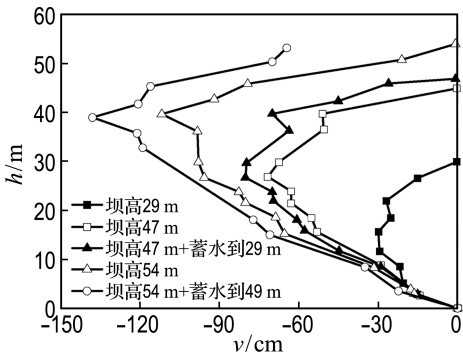


图 9 Beliche 坝实测的施工期和蓄水期心墙位移  
Fig. 9 Measured displacements of the core of Beliche dam during construction and reservoir filling

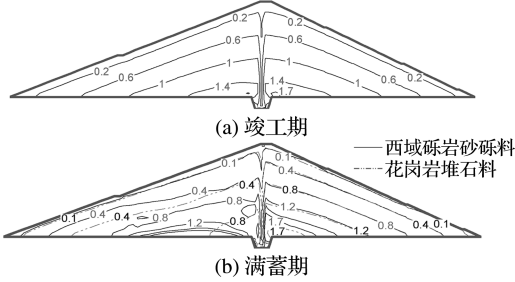


图 10 坝体大主应力分布(单位:MPa)  
Fig. 10 Major principal stress distribution of the dam (unit:MPa)

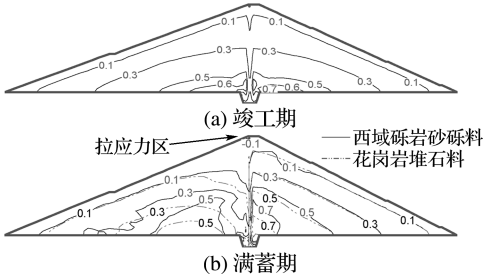


图 11 坝体小主应力分布(单位:MPa)  
Fig. 11 Minor principal stress distribution of the dam (unit:MPa)

心墙竣工和满蓄时的应力分布如图 12 所示。蓄水后导致心墙中下部的应力增大。西域砾岩砂砾料产生较大的湿陷导致心墙底部的附加应力比花岗岩堆石料大。

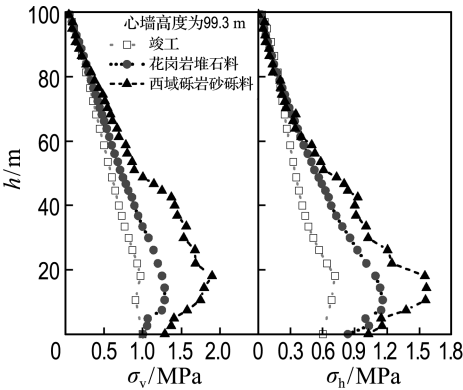


图 12 心墙应力分布

Fig. 12 Stress distribution of the core

3 结 论

- (1)联合广义塑性模型和湿化模型能较好地模拟心墙坝的湿化变形及应力分布规律。
- (2)上游筑坝料蓄水湿化会导致坝体向上游方向水平位移和竖向沉降都明显增大,西域砾岩砂砾料湿化导致最大竖向沉降由竣工时的0.17%坝高增大至0.53%坝高,而最大水平位移则由竣工时的1.5 cm增大至22 cm。上游筑坝料湿陷致使心墙的水平位移和竖向沉降也变大,并且西域砾岩砂砾料的湿化竖向沉降为花岗岩堆石料的近3倍。
- (3)蓄水湿化后坝体上游侧主应力明显减小,西域砾岩砂砾料较大的湿化变形导致上游侧坝顶附近出现0.1 MPa左右的拉应力区,有可能引起坝顶裂缝。
- (4)采用西域砾岩砂砾料作为筑坝材料时,应密切注意坝体在蓄水过程中的湿化变形。

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Numerical analysis of wetting-induced deformation  
of Xiyu conglomerate gravel dam with asphalt concrete core

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**Abstract:** Gravel from Xiyu conglomerate, which is easily softened and disintegrated when inundated, is widely used as filling materials of dam in Xinjiang region of China. Therefore, the wetting deformation problem of earth dams during the reservoir filling is a serious concern in engineering field. The generalized plastic model and wetting model based on the wetting tests of Xiyu conglomerate gravel are incorporated into procedure, and numerical analyses of wetting-induced collapse of an asphalt concrete core dam are performed. Analytical results show that the generalized plastic model combined with the wetting model can well reflect the wetting deformation and stress distribution of the dam. Wetting collapse that happened in the upstream shell increases the horizontal displacement toward the upstream direction and settlement significantly, the maximum horizontal displacement increases from 1.5 cm to as much as 22 cm and the maximum settlement increases from 0.17% to 0.53% of the dam height, which leads to the significant deformation of the asphalt concrete core. Wetting deformation of Xiyu conglomerate gravel is apparently larger than the granite rockfill, for the maximum settlement is nearly 3 times of that of the granite rockfill. Particularly, small tensile stress is observed around the dam crest, which may result in cracks nearby. Therefore, close attention should be paid to the wetting deformation during reservoir impoundment for dams filled with Xiyu conglomerate gravel in Xinjiang arid region.

**Key words:** generalized plastic model; wetting-induced deformation; Xiyu conglomerate gravel; numerical analysis