Research on the Influence of Material Permeability to Landslide Dam Seepage Stability

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Abstract

Landslide dams, often formed by quick deposits of landslide materials, are lack of sufficient consolidation, and loose in dam structure and material composition. Lacking of seepage control and flood drainage facilities, big water head difference can trigger seepage deformation of soil and influence landslide dam stability with the rise of landslide lake water level, which may lead to dam breach. The paper reports the experimental study on the seepage characteristics of landslide dam material, which takes the differences of grain grading into consideration. It was observed that piping and soil flow are the two seepage failure modes of landslide dam material. The experiments showed seepage deformation mode and permeability coefficient mainly depend on the condition of fine particles filling the pores between the coarse particle and the compactness. The paper provides a kind of critical hydraulic gradient equation of piping, which can be used in the critical hydraulic gradient calculation of the landslide dam materials with different densities.

Keywords: landslide dam, permeability, seepage stability, piping

1. Introduction

Landslide dams are natural dams, formed by quick deposits of landslide materials, which are lack of sufficient consolidation and loose in dam structure and material composition. Landslide dams can intercept upstream runoff to form landslide lakes, which lead to water head difference and make seepage in the dams. Because landslide dams are lacking of seepage control and flood drainage facilities, big water head difference can trigger seepage deformation of soil and influence landslide dam stability with the rise of landslide lake water level, which may lead to dam breach. Breach flood can cause huge losses of downstream life and property. Therefore, the seepage stability analysis of landslide dam is important.

Seepage problem study of landslide dams includes material permeability and seepage stability. Landslide dam material particle gradation has great influence on permeability. Casagli et al. (2003) divided landslide dam material structures into matrix-supported and grain-supported types. These materials have difference in permeability. Matrix-supported material, of which fine particles fill the pores between the coarse particle material and coarser particles are not in contact with each other, has low permeability. Grain-supported material, of which coarser particles are in contact with each other, has higher permeability. Wang and Yang (2003) and Hu et al. (2010) obtained the permeability coefficient of landslide dam materials by field tests. However, landslide dam sites are mostly complicated and it is difficult to do field tests.

In the study of landslide dam seepage stability, Meyer et al. (1994) concluded the modes of landslide dam seepage failure and provide methods to analyze the stability of landslide dams under seepage by using seepage stability criterion of soil. He et al. (2009) estimated the failure mode of Xiaojiaqiao Landslide Dam is piping and analyzed the seepage stability using critical hydraulic gradient. Hu et al. (2010) found that critical hydraulic gradient is different with different soil layers and seepage failure can occur in local region. However, critical hydraulic gradient in landslide dam seepage stability analysis is mainly calculated by the formula of general soil, and there are some differences between the grain gradation of landslide dam material and that of general soil.

The main objective of this research is to do typical landslide dam material seepage tests, of which result can be used to discuss the influence factors of the landslide dam material permeability and provide a formula of piping critical hydraulic gradient to analyze the seepage stability of landslide dam.

2. Experimental methods

Because the particle sizes of landslide dam material are great various, exiting testing apparatus do not apply to it. Referring to the principle of vertical seepage deformation apparatus in Code for geotechnical testing (Ministry of Water Resources , PRC, 1992), a testing apparatus for landslide dam material was developed (Fig. 1). It is composed of a permeameter, a water supply system, a suction system and a measurement system. Permeameter is designed to be 30 cm in diameter and 60 cm in height. If the landslide dam material contains sticky particles and the permeability is small, it can be saturated by suction method, which can reduce the use of time by water-head saturation method.

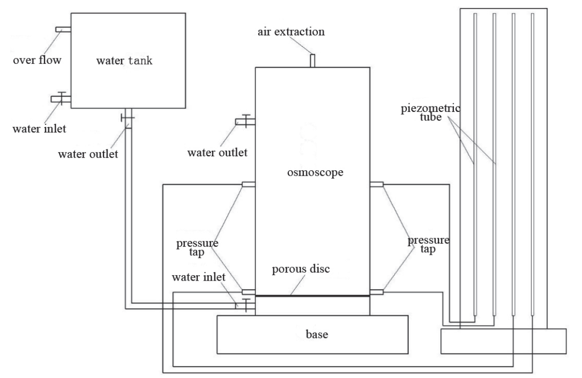

Fig. 1 Sketch of the testing apparatus

Four typical particle gradations were chosen to prepare specimens and the grading curves are shown in figure 2. The particle gradations of landslide dam material are influenced by the causes of the dams, which can be divided into three categories as high speed and long distance sturzstrom, large-scale collapse and bedding landslide. Donghekou landslide dam caused by high speed and long distance sturzstrom mainly composed of loose soil and rubble and the particle gradation was wide (Zhao, 2013), which was used to prepare specimens group 1 with continuous gradation. Collapse-caused Xiaogangjian Landslide Dam mainly composed of gravel (Qiu and Li, 2008), and specimens group 2 with coarse grain in majority was prepared according to it. The permeability of bedding landslide dam material, like Tangjiashan Landslide Dam, depends on the lithology of landslide (Hu, 2010). Specimens group 3 with fine grain in majority and Specimens group 4 gap-graded were prepared according to particle gradations of different soil layers of Tangjiashan Landslide Dam. Each group included four specimens with different dry densities, from 1.90 g/cm^3 to 1.78 g/cm^3, of which the parameters are shown in table 1.

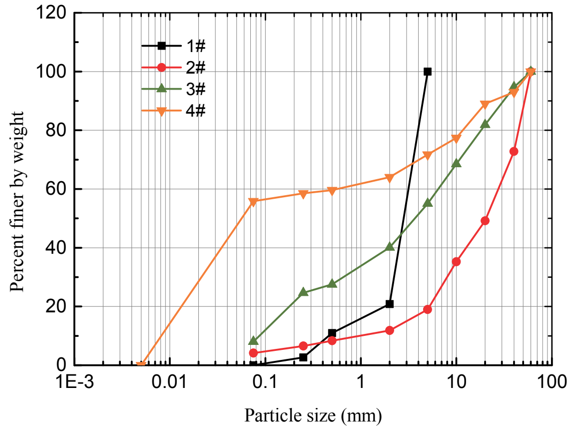

Fig. 2 Grading curves of landslide dam materials

Because Darcy's Law only can be applied to laminar flow conditions, the water head was loaded for multiple times in the tests, and the whole process of seepage from the beginning to failure can be observed. If the hydraulic gradient is nearly the critical hydraulic gradient, the horizontal fractures or springs may appear on the top surface of specimens, which can develop to the bottom, and the seepage flow can continually increase. When the fine particle move occurs on the two-thirds of the specimen top surface, the specimen can be considered to seepage failure and the test is stopped. The linear section of hydraulic gradient- flow velocity curve can be used to calculate permeability coefficient of the landslide dam material.

3. Results and analyses

3.1 Tests result

It was found from the tests result that the seepage failure mode of specimens group 3 was piping. When the hydraulic gradient rose to a certain value, fine particles of specimens' surfaces were washed away by water and concentrated seepage channels occurred in the specimens, which finally developed to the bottom (Fig. 3(a)). The piezometric level began decreasing, when hydraulic gradient exceed the critical hydraulic gradient. The *I-V* curves (Fig. 4) show that the hydraulic gradient remains stable, while the flow velocity increases significantly at that moment.

However, the seepage failure mode of specimens group 1 and 4 was soil flowing. With the rising of hydraulic gradient, there was slightly movement of fine particles on the specimens' surfaces, but no seepage channel. Finally, some horizontal fractures occurred in the specimens (Fig. 3(b)), the upper portions floated, flow velocity increased sharply and soil damaged.

Table 1 Characteristic indexes of landslide dam materials

Specimen number	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	Nonuniform coefficient C_u	Curvature coefficient C_c	Dry density ρ_d (g/cm^3)	Void ratio e	Porosity n
1-1	0.220	0.56	1.2	5.45454	1.18787	1.78	0.5168539	0.3407407
1-2	0.220	0.56	1.2	5.45454	1.18787	1.82	0.4835164	0.3259259
1-3	0.220	0.56	1.2	5.45454	1.18787	1.86	0.4516129	0.3111111
1-4	0.220	0.56	1.2	5.45454	1.18787	1.90	0.4210526	0.2962962
2-1	0.950	7.97	27.3	28.7368	2.44923	1.78	0.5168539	0.3407407
2-2	0.950	7.97	27.3	28.7368	2.44923	1.82	0.4835164	0.3259259
2-3	0.950	7.97	27.3	28.7368	2.44923	1.86	0.4516129	0.3111111
2-4	0.950	7.97	27.3	28.7368	2.44923	1.90	0.4210526	0.2962962
3-1	0.106	0.67	6.5	61.3207	0.65152	1.78	0.5168539	0.3407407
3-2	0.106	0.67	6.5	61.3207	0.65152	1.82	0.4835164	0.3259259
3-3	0.106	0.67	6.5	61.3207	0.65152	1.86	0.4516129	0.3111111
3-4	0.106	0.67	6.5	61.3207	0.65152	1.90	0.4210526	0.2962962
4-1	0.005	0.106	0.57	114	3.94245	1.78	0.5168539	0.3407407
4-2	0.005	0.106	0.57	114	3.94245	1.82	0.4835164	0.3259259
4-3	0.005	0.106	0.57	114	3.94245	1.86	0.4516129	0.3111111
4-4	0.005	0.106	0.57	114	3.94245	1.90	0.4210526	0.2962962

(a) (b)

Fig. 3 Piping and soil flowing

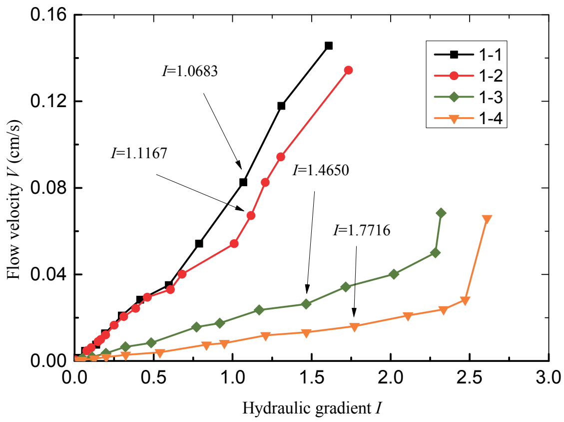

Fig. 5 The *I*-*V* curves for specimen group 1

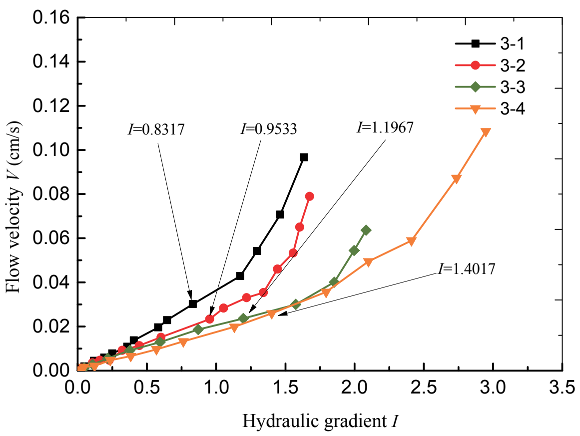

Fig.4 The *I*-*V* curves for specimen group 3

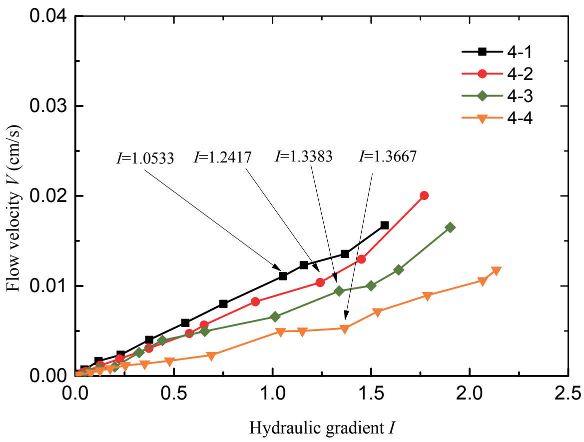

Fig. 6 The *I*-*V* curves for specimen group 4

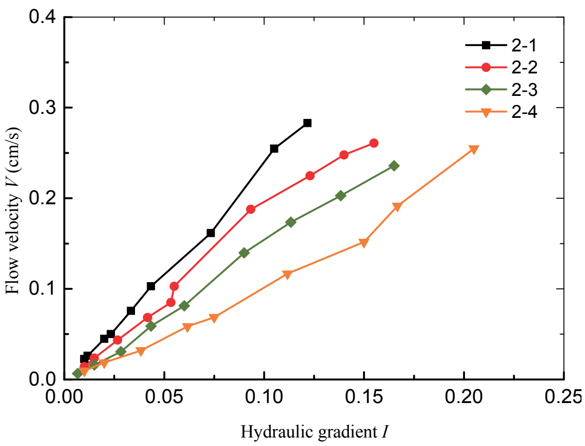

Fig. 7 The *I-V* curves for specimen group 2

The *I-V* curves are linear before the seepage deformation occurs. When hydraulic gradients exceed the critical hydraulic gradients, the slopes of the curves start to change and curves are nonlinear. The critical hydraulic gradient I_k can be calculated by the equation:

$$I_k = \frac{I_2 + I_1}{2} \tag{1}$$

Where I_2 is the hydraulic gradient that triggers piping and I_1 is the hydraulic gradient just before the piping occurs. Damage hydraulic gradient can be calculated by the same method.

The results of specimens group 2 tests were not ideal. Even the water head reached the maximum that the water supply system can offer, there was no seepage failure been observed. The Piezometric level difference remained a low value as the whole seepage process, which meant the hydraulic gradients in the specimens were lower. The phenomenon may be result from the grain gradation of specimens group 2. The pores of coarse particles are so large that water can easily flow away. As a result, when the water head goes up, the hydraulic gradients increases slightly.

3.2 Influencing factors

It can be found from the tests results that the seepage failure modes and permeability coefficients of landslide dam material mainly depend on the condition of fine particles filling the pores between the coarse particle and the compactness. When the pores between the coarse particle are large and the content of the fine particles is less, fine particles cannot fill the pores, the water can easily wash them away and piping occurs (as specimens group 3). However, when the content of the fine particles is lager, they can be constrained in the pores and the soil flowing occurs (as specimens group 1 and 4).

The compaction of landslide dam material has influence on the seepage stability and permeability coefficient. The critical hydraulic gradients I_k increase and the permeability coefficients K reduce with the increasing of compaction. Comparing the results of specimens group 1 and 4tests, the I_k and K change of the former is larger significantly than those of latter combining with the dry density ρ_d rising from 1.78 g/cm^3 to 1.90 g/cm^3. Because the content of the fine particles of the specimens group 1 is larger, the rising of dry density ρ_d makes the arrangement of fine particles closer, the anti-permeability strength increases, and then the changes of I_k and K are clear. However, because the shortage of intermediate grain diameter, the dry density ρ_d rising of specimens group 4 just changes the arrangement of coarse particles structure and the fine particles are still easily washed away by water, and then the changes of I_k and K are not significant.

3.3 The discrimination method of seepage failure modes

As the results of tests, the content of the fine particles decides the seepage failure modes. Liu and Xie (2012) studied the seepage stability of gravelly soil and put forward a discrimination method of seepage failure modes according to the optimal fine particles content:

$$\left.\begin{array}{ll} P \le 0.9P_{op}, & \text{Piping type} \\ P > 1.1P_{op}, & \text{Soil flow type} \\ P = (0.9 \sim 1.1)P_{op}, & \text{Transitional type} \end{array}\right\} \tag{2}$$

Where P is the fine particles content (%). Specially, the geometry mean particle size $d_q = \sqrt{d_{70}d_{10}}$ is used as the particle size to distinguish the fine and coarse particles (Liu, 2012). P_{op} is optimal fine particles content, which can be calculated as the following equation:

$$P_{op} = \frac{n_c + 3n^2 - n}{1 - n} \tag{3}$$

Where n is the soil porosity and n_c porosity without the fine particles, which relates to the uniformity coefficient of coarse particles.

The method was used to analyze the seepage failure modes of the four landslide dam materials types. It is found that the analyze results basically equates with the tests results (table 6). Therefore, the method applies to landslide dam material and using the geometry mean particle size d_q to distinguish the fine and coarse particles is reasonable.

Table 2 Test results for specimen group 3

Specimen number	Nonuniform coefficient C_u	Curvature coefficient C_c	Dry density ρ_d (g/cm^3)	Porosity n	Critical hydraulic gradient I_k	Failure hydraulic gradient I_F	Permeability coefficient k(m/s)
3-1	61.320	0.651	1.78	0.340	0.738	1.548	3.331E-04
3-2	61.320	0.651	1.82	0.325	1.003	1.624	2.734E-04
3-3	61.320	0.651	1.86	0.311	1.033	1.925	2.498E-04
3-4	61.320	0.651	1.90	0.296	1.267	2.843	2.203E-04

Table 3 Test results for specimen group 1

Specimen number	Nonuniform coefficient C_u	Curvature coefficient C_c	Dry density ρ_d (g/cm^3)	Porosity n	Critical hydraulic gradient I_k	Failure hydraulic gradient I_F	Permeability coefficient k(m/s)
1-1	5.454	1.187	1.78	0.340	0.928	1.458	8.724E-04
1-2	5.454	1.187	1.82	0.325	1.063	1.519	6.295E-04
1-3	5.454	1.187	1.86	0.311	1.32	2.291	2.073E-04
1-4	5.454	1.187	1.90	0.296	1.619	2.541	1.031E-04

Table 4 Test results for specimen group 4

Specimen number	Nonuniform coefficient C_u	Curvature coefficient C_c	Dry density ρ_d (g/cm^3)	Porosity n	Critical hydraulic gradient I_k	Failure hydraulic gradient I_F	Permeability coefficient k(m/s)
4-1	114	3.942	1.78	0.340	0.903	1.468	1.289E-04
4-2	114	3.942	1.82	0.325	1.078	1.611	9.942E-05
4-3	114	3.942	1.86	0.311	1.176	1.771	7.845E-05
4-4	114	3.942	1.90	0.296	1.204	2.101	6.080E-05

Table 5 Test results for specimen group 2

Specimen number	Nonuniform coefficient C_u	Curvature coefficient C_c	Dry density ρ_d (g/cm^3)	Porosity n	Critical hydraulic gradient I_k	Failure hydraulic gradient I_F	Permeability coefficient k(m/s)
2-1	28.736	2.449	1.78	0.340	/	/	2.482E-02
2-2	28.736	2.449	1.82	0.325			2.024E-02
2-3	28.736	2.449	1.86	0.311			1.556E-02
2-4	28.736	2.449	1.90	0.296			9.846E-03

3.4 Critical hydraulic gradient equation of piping

Costa and Schuster (1988) found that overtopping, landslide failure and piping failure are the three breaching modes of landslide dam. Therefore, it is important to provide a critical hydraulic gradient equation of piping for landslide dam materials. The phenomenon that fine particles are washed away through the pores of coarse particles is piping, which relates to the problem of particle move starting. Referring to Chen and Ming (2001), this paper provides a new critical hydraulic gradient equation for piping:

Table 6 Analysis results and the tests results of seepage failure modes

Specimen number	Geometry mean particle size d_q (mm)	Porosity n	Optimal fine particles content P_{op}			Fine particles content P (%)	Seepage failure modes	
			0.9 P_{op}	P_{op}	1.1 P_{op}		Analysis results	Tests results
3-1	1.08	0.3407	0.3817	0.4241	0.4665	0.3583	Piping	Piping
3-2	1.08	0.3259	0.3535	0.3928	0.4321			
3-3	1.08	0.3111	0.3283	0.3648	0.4013		Transitional	
3-4	1.08	0.2963	0.3058	0.3398	0.3738			Transitional
4-1	0.14	0.3407	0.3403	0.3781	0.4159	0.5725	Soil flow	Soil flow
4-2	0.14	0.3259	0.3131	0.3479	0.3827			
4-3	0.14	0.3111	0.2887	0.3208	0.3529			
4-4	0.14	0.2963	0.2670	0.2967	0.3264			

Table 7 Tests results and calculation results of critical hydraulic gradient of piping

Specimen number	Porosity n	Fine content P_f	Critical hydraulic gradient I_k			
			Tests result	Calculation result by author	Calculation result by Liu	Calculation result by Mao
3-1	0.3407407	0.3583	0.738	0.806	0.783	0.398
3-2	0.3259259		1.003	0.870	0.819	0.416
3-3	0.3111111		1.033	0.937	0.855	0.434
3-4	0.2962962		1.267	1.006	0.892	0.453

$$I_k = (0.721 \sim 1.30)\left(\frac{\gamma_s}{\gamma_w} - 1\right)\frac{\alpha_1 d}{2D_0} \qquad (4)$$

Where α_1 is drag coefficient, d is particle size that is washed away by the water and D_0 is average porous diameter of particles, which can be calculated as the following equation:

$$D_0 = d_q\left[\frac{n_c + 3n^2 - n}{p_{po}(1-n)}\right] \qquad (5)$$

Where d_q is the particle size of grain boundary, and α_1=4.24, γ_s=2.7, γ_w=1, $d = 0.20$ in this paper. The equation (5) can be changed to:

$$I_k = (2.60 \sim 4.68)\cdot\frac{d}{d_q}\left[\frac{p_f(1-n)}{B + 3n^2 - n}\right] \qquad (6)$$

The equation was used to calculate the critical hydraulic gradient I_k of landslide dam materials and the results were compared with tests results and calculation results of other equations (Liu, 1992; Mao, 2005) shown in table 7. The calculation results of equation provided in this paper and tests results are quite consistent.

4. Conclusions

Seepage characteristics of landslide dam materials are experimentally studied. The tests measurements can be used to study the influence of the characteristics on the seepage stability of landslide dams.

Piping and soil flowing are the two seepage failure modes of landslide dam material. Before the seepage deformation occurs, the *I-V* curves are linear. The seepage failure modes and permeability coefficients of landslide dam material mainly depend on the condition of fine particles filling the pores between the coarse particle and the compactness.

Using the geometry mean particle size d_q to distinguish the fine and coarse particles of landslide dam materials is reasonable. A new critical hydraulic gradient equation for piping is provided in this paper and its calculation results are quite consistent with the tests results.

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