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A new concept for rockfill dams – protecting the surrounding environment

Un nouveau concept pour des barrages de “rockfill” - protection de l' environnement

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ABSTRACT

To meet the increasing demand for electric power and also preserve the environment, more and indeed new concepts for hydro-electric dams are been proposed. For pump-storage rockfill dams, the saturated-unsaturated hydraulic properties of construction materials are important considerations. This paper reports the results of a series of laboratory tests that were carried out on the hydraulic properties of coarse materials. A new method for determining the saturated-unsaturated coefficients of permeability of coarse materials in the laboratory and an evaluating system for rockfill dams under non-Darcy flow conditions due to rapid drawdown are proposed.

RÉSUMÉ

Pour satisfaire la demande croissante de l'énergie électrique et préserver également l'environnement, on propose des concepts plus et en effet nouveaux pour les barrages hydro-électriques. Pour des barrages de “rockfill” de pompe-stockage, les propriétés saturés-insaturées des matériaux de construction sont des considérations importantes. Cet article rapporte les résultats d'une série d'essais qui ont été effectués sur les propriétés hydrauliques des matériaux bruts dans le laboratoire. On propose une nouvelle méthode pour déterminer les coefficients saturés et insaturées de perméabilité des matériaux bruts dans le laboratoire et un système d'évaluation pour des barrages de “rockfill” dans des conditions d'écoulement de non-Darcy dues à l'abaissement du niveau rapide.

1 INTRODUCTION

In Japan, to meet the increasing demand, new hydro-electric dam projects continue to be developed. However, hydro-electric dams (HEDs) greatly modify their surroundings. Furthermore, with increasing land use and environmental concerns, the land area available for surface water storage is limited. To ensure adequate supply of electricity, new concepts for generating hydro-electricity, such as the pump-storage type, have been developed in Japan.The environment of the dam is inhabited by rare species of various trees and animals. However, the construction of the upstream dam may require a large area for water storage, with a consequent big effect on the environment. To produce equivalent amount of electricity but minimize adverse environmental impact of dams, a deeper reservoir over a small area is created for electric power generation.

Generally, environmental changes due to pump-storage dam are minimal. Relatively small land areas are used as reservoirs, both upstream and downstream. In most cases, the upstream drawdown is about 30 m. However if the area is small, then a drawdown of about 50 m may be needed to produce the equivalent amount of electricity. This rapid drawdown may sometimes cause environmental problems. Slope failure may occur and the core and the filter of the dam may all be affected.

Towards good environmental practice, this paper seeks to mention the problems that are most likely to occur and affect the environment when pump-storage rockfill dams are constructed; and suggest solutions to mitigate such problems. To preserve the environment as much as possible, it is important that studies are carried out on the stability of rockfill dams that are operated under pump-storage conditions. Within the context of saturated-unsaturated flow phenomenon, the following are important considerations in the design, construction and evaluation of pump-storage rockfill dams:

(a) How to determine the saturated coefficient of permeability (k_{sat}) of large particle size rock materials in the laboratory;
(b) The unsaturated hydraulic properties of the filter, such as the Water Characteristic Curve (WCC) and the coefficient of permeability under unsaturated conditions (k_{unsat}) for coarse materials (CMs) of shale; and
(c) The effects of drawdown - generally, flow of water in dams is assumed to be laminar. However, sometimes, non-Darcy (turbulent) flow is the case.

To gain insights into the above-mentioned considerations, a series of tests were carried out on the hydraulic properties of CMs in the laboratory. The objectives were to develop a new method for determining the saturated-unsaturated coefficients of permeability of CMs and also establish an evaluating system for rockfill dams under non-Darcy flow conditions due to rapid drawdown.

2 SATURATED PERMEABILITY OF COARSE MATERIALS

2.1 *Estimation of saturated coefficient of permeability*

Constant head permeability tests were carried out in the laboratory on CMs samples of diameter 15,30,60,120cm. Samples of 53 different porous materials of 22 different particle size distributions (as shown in Fig. 1) were used (Kudou et al., 2002). k_{sat} of CMs was affected by the D_{10} and other fine particles. k_{sat} of CMs was also affected by the U_c and the D_{60}. Eq. (1) (shown in Fig. 2), modified from Terghazi’s equation, is thus proposed for the estimation of saturated coefficient of permeability (k_{est}).

Figure 2 shows the comparison of laboratory test results (k_{lab}) with reference data and k_{est}. It is obvious that the test results are in agreement with the k_{est}. Therefore, Eq. (1) could be applied to large CMs whose particle size distributions were shown in Fig. 1.

Figure 3 shows the laboratory test results of materials a, b, c, d and e, as shown in Fig. 1.As shown in Fig. 3, there is a strong correlation between k_{lab} and D_{10} for materials a, b, c, d, and e. Even for different porosities, there is no difference.

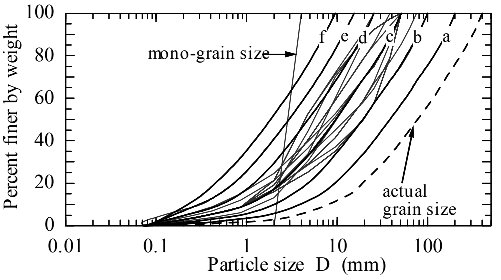
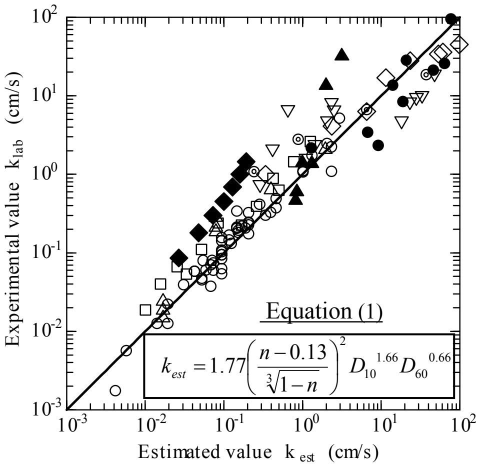


Figure 1. Grain size distribution of the materials used for saturated permeability tests (shale)



○	n=0.206～0.495	D_{10}=0.30～4.00mm	Uc=1.5～28	shale	This experiment
△	n=0.219	D_{10}=0.39～3.02mm	Uc=28	granite	
□	n=0.252～0.318	D_{10}=0.37～1.98mm	Uc=6.0	sandstone	Value referred to other research.
▽	n=0.294～0.405	D_{10}=1.20～8.20mm	Uc=3.2～3.4	schist/basalt	
◇	n=0.429	D_{10}=1.00～13.0mm	Uc=1.2～1.8	sandstone	
◆	n=0.286～0.500	D_{10}=0.56mm	Uc=2.7	crusher	
●	n=0.180～0.398	D_{10}=6.00～9.20mm	Uc=4.1～8.2	schist	
▲	n=0.309～0.456	D_{10}=1.66mm	Uc=13	rhyolite	
◎	n=0.360～0.510	D_{10}=0.88～10.8mm	Uc=1.3～1.7	siliceous amphibole	

(n : porosity)

Figure 2. Relationship between k_{lab} and k_{est} with Eq.(1) (Kudou et al., 2002)

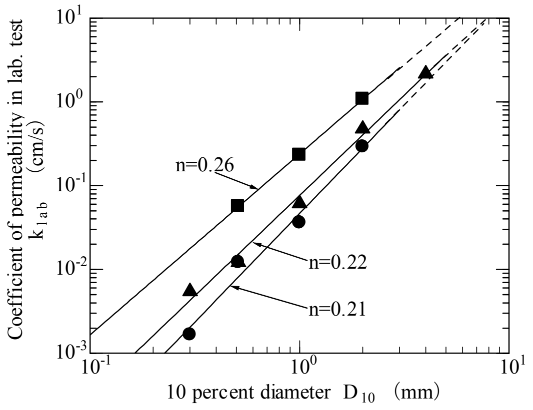


Figure 3. Relationship between k_{lab} and D_{10} (shale, n=0.22, U_c=14.3 , d/D_{max}=6, d: Diameter of test sample)

2.2 *Non-Darcy flow*

The relationship between k_{lab} and hydraulic gradient (i) for shale materials of n=0.22, U_c=14.3 is shown in Fig. 4.For materials a and b, k_{lab} decreased with increasing i, indicating non-Darcy flow phenomenon. As shown in Fig. 4, this is especially so when k_{lab} was more than 10^{-1} cm/s.

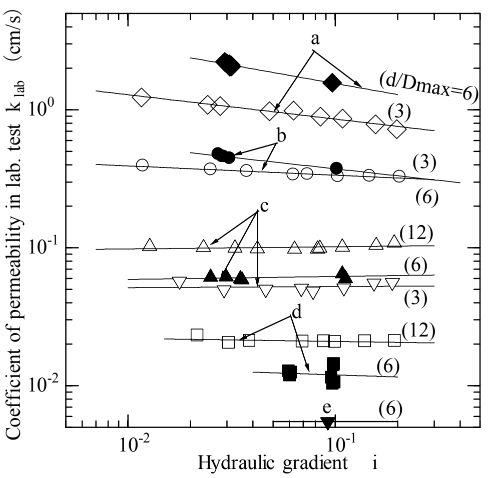
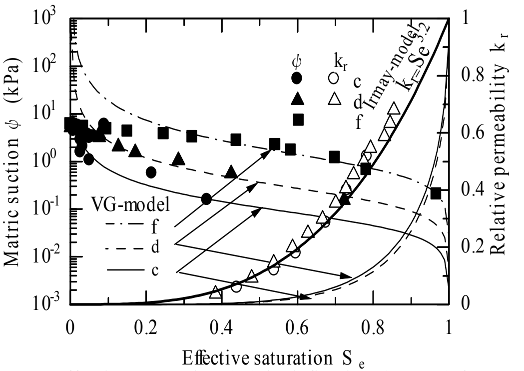


Figure 4. Relationship between k_{lab} and i (shale , n=0.22 , U_c=14.3)



Effective saturation (S_e) is defined as (θ - θ_{res}) / (θ_{sat} – θ_{res}), where θ is the volumetric moisture content, θ_{res} is the residual volumetric moisture content, θ_{sat} is the saturated volumetric moisture content.

Figure 5. Unsaturated hydraulic properties of coarse materials (shale , n=0.22 , U_c=14.3)

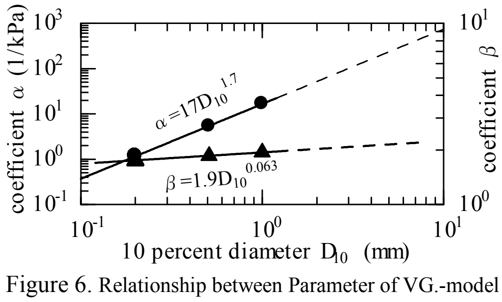


Figure 6. Relationship between Parameter of VG.-model and D_{10} (shale , n=0.22 , U_c=14.3)

3 UNSATURATED HYDRAULIC CHARACTERISTIC OF COARSE MATERIALS

3.1 *Water characteristic curve*

The WCC for CMs c, d and f, whose particle size distributions were shown in Fig. 1, were obtained from column tests (Kudou et al., 2003a). Figure 5 shows that as matric suction decreased, particle size increased. The curves were further compared with Van Genuchten (VG) model (Van Genuchten, 1980), as expressed by Eq. (2). The test results fits well with the VG model.

$$S_e = \left[\frac{1}{1+(\alpha\psi)^{\beta}}\right]^m \quad , \quad m = (1-1/\beta) \qquad (2)$$

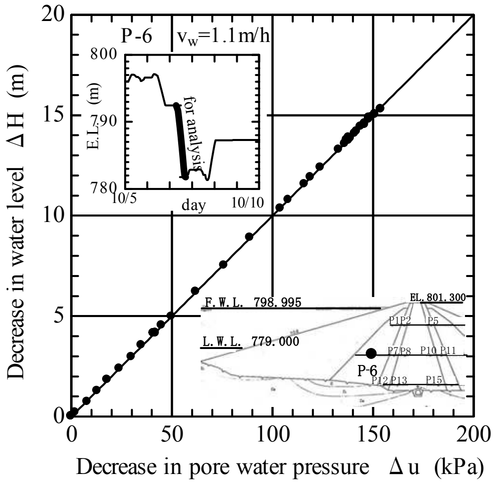


Figure 7. Relationship between ΔH and Δu (Ohta 2nd dam at P-6 , 1993.10 , started storage of water from 1992.6) (Kudou et al., 2003b)

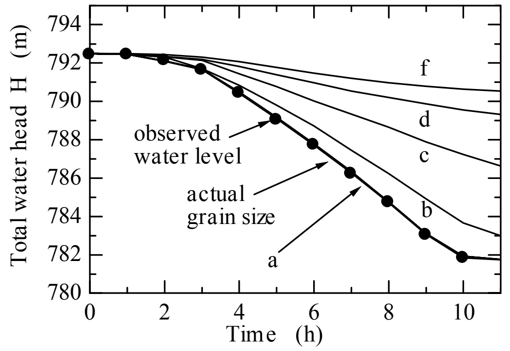


Figure 8. Changes in total water head over times at P-6

where α and β are coefficients obtained by fitting the WCC. The relationship between α and β in Eq. (2) and D_{10} is shown in Fig. 6. This is a linear relation and using this relationship, the trend that was shown in Fig. 5 can be estimated for large CMs in the field.

3.2 *Relative permeability*

Relative permeability (k_r) is defined as k_{unsat}/k_{sat}. The relationship between k_r and S_e were determined from laboratory tests. Pieces of large diameter permeability equipments (d=20cm) were used for CMs c and d. The results are also shown in Fig. 5. The relationship between k_r and S_e showed approximately the same trend. Therefore, in using this relationship, the effect of particle size distribution is not very important. A comparison of VG and Irmay's models are also shown in Fig. 5. It is evident that, for the estimation of k_r, the Irmay's (Irmay, 1954) model ($k_r = S_e^{3.2}$) fits better. If the VG model is used, a low estimation of k_r is obtained.

4 NUMERICAL ANALYSIS IN ROCK-FILL DAMS

The relationship between drawdown (ΔH) and pore water pressure (Δu) at Point 6 (see Fig. 7) in the upper rock zone of the 2nd Ohta Dam was numerically studied. As shown in Fig. 7, the decreasing behavior of Δu is almost the same phenomenon as the drawdown. That is, as the permeability is large, residual pore water pressure dose not occur. The drawdown velocity (V_w) of the reservoir water level was 1.1 m/h.

Figure 8 shows the results of numerical analysis of changes in water head with time at Point 6 in the 2nd Ohta Dam, at the same drawdown condition as in Fig. 7. The unsaturated hydraulic properties and non-Darcy relationship used in this analysis are shown in Figs. 9 and 10. These estimated from Figs. 4, 5 and 6, based on laboratory tests. In Fig. 8, a, b, c, d and f are particle size distributions of CMs, as shown in Fig. 1. The D_{max} of the actual grain size is 350 mm, which is the real size of material of the 2nd Ohta Dam. The D_{max} of the filter of the dam is 160 mm.

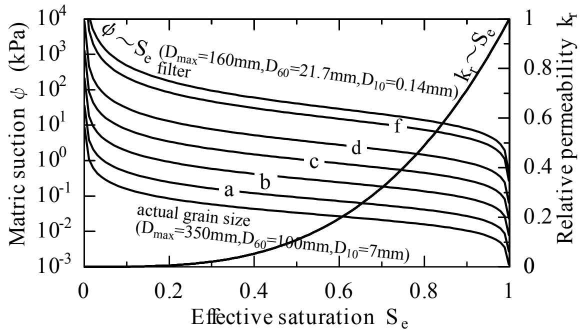


Figure 9. Unsaturated hydraulic properties used for analysis

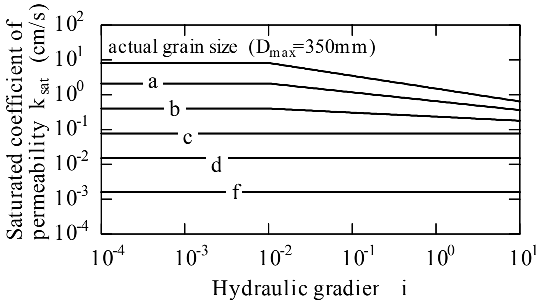


Figure 10. Relationship between k_{sat} and i used for analysis

As shown in Fig. 8, there is a good fit for the measured value and material a, whereas b, c, d and f deviate upwards. The saturated coefficient of permeability used to design (k_{dsn}) is 0.1 cm/s. For coarse material c, k_{sat} is 0.08 cm/s. These are almost equal to each other. Selecting this permeability, the residual water head is large and does not fit the measured data. From this result, k_{dsn} is a bit small compared with the real permeability.

It must be stressed that it is important to estimate k_{sat}, taking into consideration the actual particle size.

5 THE EFFECT OF NON-DARCY FLOW AND UNSATURATED CONDITIONS ON RESIDUAL PORE WATER PRESSURE

The effect of non-Darcy flow and unsaturated conditions on residual pore water pressure resulting from rapid drawdown was evaluated. Under non-Darcy flow, k_{sat} depends on the hydraulic gradient of the media. By using saturated-unsaturated flow analysis for a model dam, the sensitivity of drawdown to residual pore water pressure was evaluated.

Non-Darcy flow and unsaturated conditions all have strong effects on residual pore water pressure. Figure 11 shows the effect of non-Darcy flow on the total water head at Point 6. Two drawdown velocities are shown in Fig. 11 and they have different consequences on residual pore water pressure. These are: (1) V_w is 1.1 m/h: there is no effect of hydraulic gradient; and (2) V_w is 4 m/h: there is large effect of hydraulic gradient, this is about 4 times higher.

For pump-storage rockfill dams in Japan, Vw_{max} is about 3 ~ 5 m/h. In this practical situation, the flow in the dam follows the non-Darcy flow when Vw_{max} is 4 m/h, which is the maximum effect expected. The temporal variation of total water head at Point 6 is shown in Fig. 12. A k_{sat} of 0.4 cm/s and V_w of 1.1 m/h

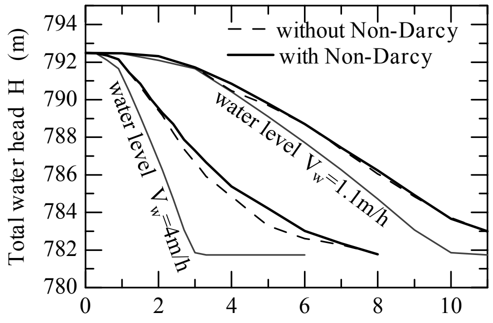


Figure 11. Influence of Non-Darcy flow on total water head at P-6 (material b, k_{sat}=0.4cm/s)

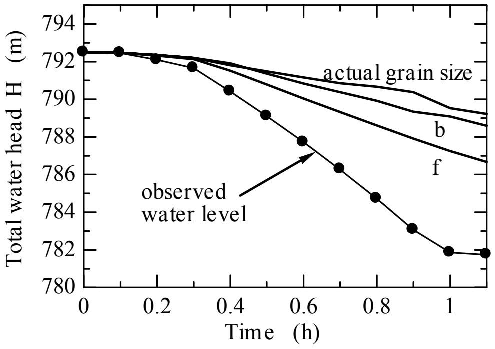


Figure 12. Changes in total water head over time at P-6 (k_{sat}=0.4 m/s, V_w=1.1 m/h)

are used under unsaturated conditions, for the actual material (D_{max} = 350 mm), for coarse material b and fine material f. As shown in Fig. 12, some differences in behavior of residual pore water pressure between the coarse and fine grains are evident. Material f showed the water head become low and the residual pore water pressure become small. From the above results, even if selected k_{sat} depends on particle size, and if we miss the WCC is chose, as such as material f, the result become small residual pore water pressure. Generally, fine materials have low permeability and higher water retention characteristic and also show high residual pore water pressure. However, Fig. 12 showed the opposite case. It is important therefore to make a good selection of permeability and the WCC.

6 THE STABILITY OF DAM UNDER DRAWDOWN

To evaluate the safety factor (F_s) analysis of the upstream slope stability of the rockfill dam, the circular slip method was used. Table 1 shows the results of the stability analysis. k_{dsn} was 0.1 cm/s and the field k_{sat} was 1.0 cm/s. The WCC for the coarse material c, actual material and fine material f were as shown in Fig. 9.The results showed that:

(a) When V_w is large and k_{sat} is small, F_s is small, especially k_{sat} has a strong effect on F_s. These were obtained by comparing (5) and (9), and (1) and (4) in the WCC column in Table 1.

(b) Comparing the actual grain size and fine materials for WCC, the actual grain size showed a small and dangerous F_s. This trend depends on V_w, especially when V_w = 11 m/h. The WCC column in Table 1 showed a big change in F_s values in columns (9) and (15). The Japanese standard is F_s more or equal to 1.2.

(c) The effect of non-Darcy flow conditions is not so strong, comparing to the effect of unsaturated hydraulic properties but F_s under non-Darcy condition still appears; the value of F_s becomes small when non-Darcy flow is considered; and

Table 1. Stability analysis conditions and safety factor (at earthquake: k_h=0.15)

Water level condition		Non-Darcy flow	k_{dsn} = 0.1cm/s	field k_{sat} = 1.0 cm/s	
Draw-down velocity (m/h)	Decrease in water level (m)		WCC		
			c	actual grain size	f
1.1	11	×	(1) 1.289	(4) 1.523	(10) 1.505
		○	—	(5) 1.493	(11) 1.503
3.2	19	×	(2) 1.247	(6) 1.549	(12) 1.588
		○	—	(7) 1.490	(13) 1.573
11	11	×	(3) 1.091	(8) 1.232	(14) 1.375
		○	—	(9) 1.148	(15) 1.331

(d) The determination of k_{sat} depends on particle size distribution and this is also important in the evaluation of stability of rockfill dams. Even if a good value of k_{sat} is estimated from particle size distribution, design could be inadequate and dangerous if the effect of non-Darcy flow and unsaturated hydraulic properties of the material are not considered. It is therefore important that the unsaturated hydraulic properties under non-Darcy flow conditions are evaluated.

7 CONCLUSIONS

The conclusions of this paper are follows:

(1) The value of D_{10} and fine particles greatly affects the value of permeability of coarse materials. U_c also has an effect on k_{sat} and proposed a new equation to estimate the value of permeability of CMs.

(2) It is shown that there is effect of hydraulic gradient on k_{sat} which is greater or equal to 10^{-1} cm/s.

(3) The Van Genuchten model for WCC fits very well, and for α and β the relationships of D_{10} are proposed:

(4) For coarse materials, the Irmay's model is better than the Van Genuchten model of the relationship between k_r and S_e.

(5) Inappropriate selection of hydraulic properties of CMs in the design process may lead to failures of the dam and environmental disasters, especially under rapid drawdown situations.

(6) In saturated-unsaturated seepage analysis and studies on residual pore water pressure distribution in rockfill dams during rapid drawdown in reservoirs, the effect of non-Darcy flow conditions should be taken into account.

(7) Finally, in this paper, it is concluded that if the saturated-unsaturated hydraulic properties of CMs are properly considered, good rockfill dams, which preserve the environmental conditions could be constructed.

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