地すべり　第36巻　第4号
Journal of Japan Landslide Society　36-4 (2000)

Numerical Analysis of the Residual Ratio of Groundwater in Reservoir Slopes

Shinjuro KOMATA*　Pucai YANG*

Yuuichi UENO*　Eisaku HAMASAKI**

Abstract

湛水に伴う地すべりは，ダム建設において重要なハザードであり，ダムの安全性に関わっている。貯水池周辺斜面の安定性は湛水の影響を大きく受けるため，斜面内の地下水挙動，特に残留間隙水圧の発生機構を明確にする必要がある。

間隙水圧の残留率は，貯水位低下速度，地すべり土塊の透水係数，有効間隙率及び斜面勾配，土層厚等の要因で決定される値と考えられるが，算出の基準が確定さていないのが現状である。本研究では，基礎研究として，残留間隙水圧の発生に占める要素（透水係数，地下水位上昇・降下速度，斜面勾配，土層厚）のそれぞれの影響度合いを有限要素法による飽和・不飽和浸透流解析によって明らかにし，残留間隙水圧の評価システムの構築を試みた。

Key Words: Reservoir-induced landslide, numerical analysis, and groundwater residual ratio.

1. INTRODUCTION

Reservoir-induced landslides in a reservoir slopes are major geotechnical hazards in dam construction and cause severe damage in many countries of the world. It is generally known that these landslides occur as a result of either filling or drawdown of reservoir. Filling a reservoir causes saturation of the soil or rock mass composing the slope, with a resultant reduction of shear strength related to increased buoyancy in the lower part of the slope. Rapid drawdown of reservoir water level can destabilize the slope by removing lateral confining pressure of the reservoir water on the lower slope, while the forming-slope soil or rock mass still has an reduced shear strength resulting from the high residual pore water and seepage pressures. Rapid drawdown appears to readily give rise to landslides, and most of the reservoir-induced landslides have occurred during the rapid drawdown of reservoir level due to the occurrence of residual pore water pressure (Fujita, 1985; Yoshimatsu, 1981). The reservoir-induced landslides, especially with respect to stability analysis and stabilization, have been the intensive research subject (e. g., Nakamura, 1981; Fujita et al, 1983, Fujita, 1985). However, few studies dealing with the occurrence mechanism of residual pore water pressure and its affecting factors have been made.

Actual measurements show that the groundwater residual ratio ranges from 0% to 40% when the reservoir level drawdown speed is 0.3 m/day to 0.5 m/day (National Land R & D Center, 1995). However, in analyzing the stability of a reservoir slope, the groundwater residual ratio is generally considered to be 50% on the safe side. Conventionally, empirical approaches proposed by Bishop (1954) and Morgenstern (1963) and flow net method have been adopted to estimate the magnitude and distribution of residual pore water pressure due to the rapid drawdown of reservoir water level. However, Bishop or Morgenstern approach is accepted to use only when groundwater level

* 日本工営株式会社・防災部
** 有限会社アドバンテクノロジー

abruptly drops at the initial stage of greatly rapid drawdown, by which the residual pore water pressure are usually overestimated, leading to excessive execution. Clearly, a better understanding of occurrence mechanism of residual pore water pressure due to the rapid drawdown and its affecting factors are essential for safe and economical design of prevention works of the unstable reservoir slopes.

In this paper, 2-dimensional saturated/unsaturated unsteady seepage flow analyses were performed, using the computer software AC-UNSAF 2 D, to understand the occurrence mechanism of residual pore water pressure due to the rapid drawdown and its affecting factors, and to investigate the sensitivity of the groundwater residual ratio to its affecting factors.

2. SLOPE MODELING AND ANALYTIC PROCEDUCES

2.1 Saturated/unsaturated unsteady seepage flow modeling

Darcy's law governs water flow through saturated or unsaturated soil masses. The major difference between water flow in saturated and unsaturated soil masses is that the coefficient of permeability for a saturated soil mass can usually be assumed to be a constant, but is a function of water content or pore water pressure head for unsaturated soil masses. Moreover, the pore water pressure has a negative and positive gauge value in unsaturated and saturated soil masses respectively. In unsaturated soil mass the pore water pressures occur as a result of changes in boundary conditions such as reservoir level fluctuation, or due to loading.

The fundamental equation for water flow under the saturated/unsaturated conditions using a 2-dimensional saturated/unsaturated unsteady seepage flow model (Nishigaki, 1990) can be expressed as follows (see Fig. 1):

$$k\frac{\partial^2 h}{\partial x^2}+\frac{\partial}{\partial z}k\left(1+\frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial h}\cdot\frac{\partial h}{\partial t}+R \tag{1}$$

Where h is total pore water pressure head, k is the permeability coefficient, θ is the volumetric moisture content, R is the applied boundary flux (rainfall amount per unit length) and t is time. For the purpose of parametric study, the slope model was represented in Fig. 1

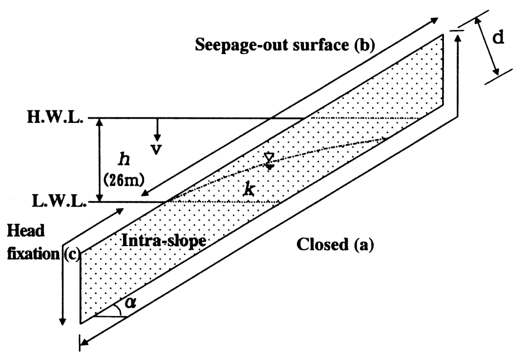


Fig. 1 Slope model

2.2 Setting of numerical model parameters

It has been pointed out that parameters such as soil layer thickness (d), permeability coefficient (k), reservoir level drawdown speed (v_1) and slope gradient (α) predominantly govern the behaviors of groundwater in reservoir slopes (Komata et al., 1998). Generally, these parameters are different for respective slopes and dams, thereby, the groundwater residual ratio (μ) will be also different respectively.

From the above-mentioned viewpoints, 2-dimensional saturated/unsaturated unsteady seepage flow analyses were performed to analyze the influences of changing of these parameters on the groundwater residual ratio. Table 1 shows the combination of these parameters used for the analyses. For these analyses slope moisture characteristics such as the volumetric moisture content, permeability and pore water pressure characteristic functions, are required and they should be obtained by direct measurements for a given slope as these properties vary from slope to slope. For the convenience of analysis, the volumetric moisture content, permeability and pore water pressure characteristic functions, as shown in Fig. 2, are used for the parametric analyses.

2.3 Analytical procedures

The following describes the procedures for obtaining

Table 1 Analytical conditions

Parameter	Symbol	Unit	Analytical condition
Slope gradient	α	deg	10, 20, 30, 40
Layer thickness	d	m	10, 20, 30
Permeability coefficient	k	cm/sec	10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}
Reservoir level drawdown speed	v_1	m/day	7.8×10^1, 5.2×10^0
Drawdown range	h	m	26

Reservoir level drawdown speed, 7.8×10^1 m/day and 5.2×10^0 m/day are examples of drawdown speed in pumped-storage hydropower projects and in multipurpose dams, respectively.

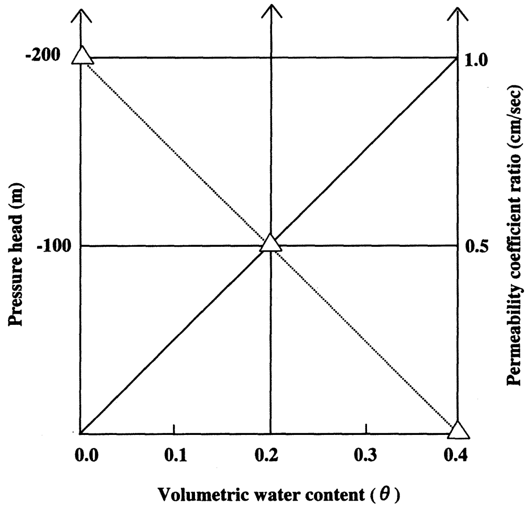


Fig. 2 Relationships of volumetric moisture contents, permeability and pore water pressure

the boundary conditions and groundwater residual ratio (μ).

(1) As the initial state, give the highest water level (H. W. L.) to the slope and perform the steady-state analysis thereby to make it an initial water surface form. In this case, as shown in Fig. 1, the boundary conditions should be made in such ways that the boundary (a) is made closed, the boundary (b) is defined as seepage-out surface and the boundary (c) is subject to head constant.

(2) Perform the unsteady-case analysis by drawing down the reservoir level from the water level shown in the above paragraph (1) at two kinds of reservoir level drawdown speed, 7.8×10^{1}m/day and 5.0×10^{-1}m/day which are respectively examples of drawdown speed in pumped-storage hydropower projects and in multipurpose dams, and then calculate the groundwater residual ratio (μ) just after reaching the lowest water level (L. W. L.) of the reservoir. The calculations shall be made by combining the slope gradient (α), layer thickness (d), and permeability coefficient (k) with each others as parameters.

(3) When calculating the groundwater residual ratio (μ), the steady-state analysis shall be applied also to the lowest water level of L. W. L. thereby to make it the final water surface form.

(4) The groundwater residual ratio (μ) is, as shown in Fig. 3, defined as a percentage of the area surrounded by the groundwater level line obtained from the analysis in the paragraph (2) and the steady-stage groundwater level obtained from the analysis in the paragraph (3), with the area surrounded by the steady-state groundwater level at the highest water level (H. W. L.) within the slope obtained from the analysis in the paragraph (1) and the steady-state groundwater level at the lowest water level (L. W. L.) obtained by the paragraph (3) which is rated at 100%.

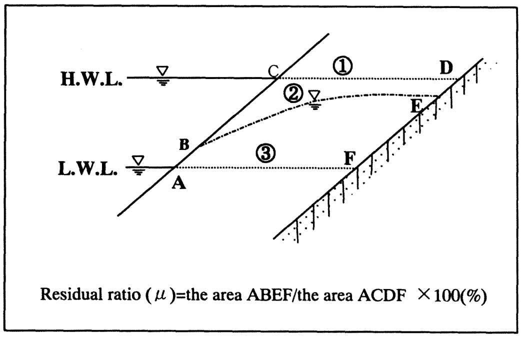


Fig. 3 Method of determining the groundwater residual ratio (μ)

3. RESULTS AND DISCUSSION

3.1 Factors affecting groundwater residual ratio

Groundwater residual ratio depends largely on reservoir level drawdown speed, permeability coefficient, slope gradient, layer thickness and so on. To investigate the influence of these factors on the groundwater residual ratio, a set of saturated/unsaturated unsteady seepage flow analyses are carried out using the computer software PC-UNSAF 2 D (see Table 1). These results are presented in Figures 4 and 5 where the groundwater residual ratio (μ) is plotted against the slope gradient (α) for different values of the permeability coefficient (k) and the layer thickness (d). It is seen from these figures that the groundwater residual ratio is smaller for steeper slope gradient, higher permeability coefficient and smaller layer thickness, however, it gradually increases as the slope gradient decrease, particularly in the case of the higher permeability coefficient. The difference in the groundwater residual ratio as the slope gradient changes is smaller when the slope is as gentle as 10° to 20° than when as steep as 30° to 40°. In addition, both Figs. 4 and 5 indicate that the layer thickness has little influence on the groundwater residual ratio when the permeability coefficient or the slope gradient is small.

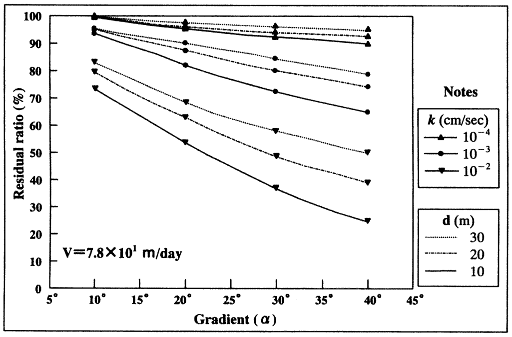


Fig. 4 Groundwater residual ratio versus slope gradient for different values of permeability coefficient and layer thickness at v=7.8×10^{1}m/day

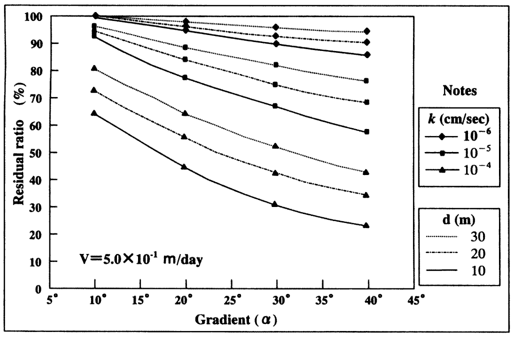


Fig. 5 Groundwater residual ratio versus slope gradient for different values of permeability coefficient and layer thickness at v=5.0×10^{-1}m/day

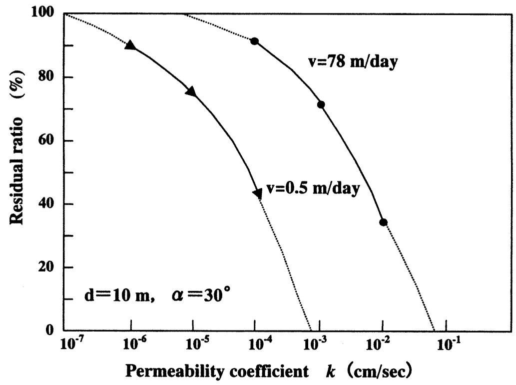


Fig. 6 Groundwater residual ratio versus permeability coefficient for different values of reservoir level drawdown speed

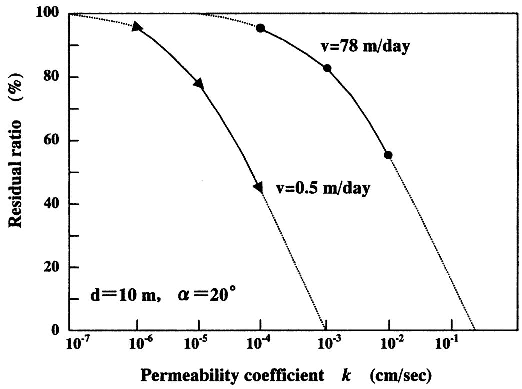
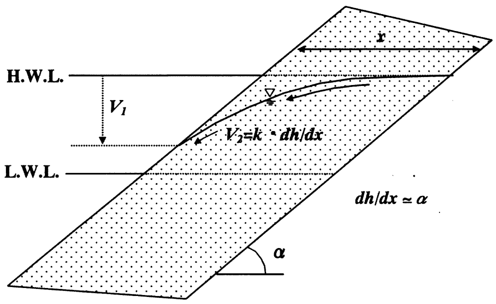


Fig. 7 Groundwater residual ratio versus permeability coefficient for different values of reservoir level drawdown speed

A historical survey of reservoir-induced landslides suggests that landslides due to the reservoir level drawdown, occur mostly in detritus or highly weathered rocks, possibly related to its small permeability coefficient (Komata, et al, 1998). The influence of the permeability coefficient on the groundwater residual ratio for a given slope geometry is clearly seen from Figs. 6 and 7 where the groundwater residual ratio is plotted against the permeability coefficient with the reservoir level drawdown speed v_1=7.8×10^{1}m/day and v_2=5.0×10^{-1}m/day. It seems that a higher drawdown speed permeability coefficient corresponds to a higher permeability coefficient when the slope becomes non-residual water condition. For example, when the groundwater residual ratio becomes zero, the permeability coefficient is close to 10^{-1}cm/s for v_1=7.8×10^{1}m/day, and it is close to 10^{-3}cm/s for v_2=5.0×10^{-1}m/day. Comparing Fig. 6 with Fig. 7, the slope gradient has a considerable influence on the groundwater residual ratio, particularly when the reservoir level drawdown speed is large. From Figs. 6 and 7, it can be seen that for a given slope geometry the groundwater residual ratio is not only controlled by the permeability coefficient, but is also controlled by the reservoir level drawdown speed. These results also shows the possibility to exactly predict and to effectively prevent the unstable slope of reservoir rim by determining the groundwater residual ratio with respect to the reservoir level drawdown speed and the reservoir slope conditions in planning and operating a dam.

3.2 Mechanism of residual groundwater

In order to understand the above mentioned analysis further, the authors consider a conceptual model as shown in Fig. 8, where a drawdown speed of reservoir level is denoted by v_1 and a mean seepage flow velocity within the slope, by v_2. According to the Darcy's law, v_2 is proportional to the permeability coefficient and hydraulic gradient (dh/dx), and is thus expressed



V_1/V_1	Large	Small
Residual ratio	Easily renained	Hardly remained

Fig. 8 Conceptual diagram of seepage flow model

as $v_2=k \cdot dh/dx$. Besides, dh/dx has a positive correlation with the slope gradient ($\tan\alpha$). Namely, it can be expected that v_2 becomes larger as slope gradient (α) increases. In this case, the fact that the groundwater does not remain within the slope (μ=0%) and the groundwater level within the slope perfectly responds to the reservoir level drawdown when v_1 is sufficiently smaller than v_2. This implies that if v_1 is constant, v_2 should be large, that is, the permeability coefficient or slope gradient should be large.

On the contrary, if v_1/v_2 is large, the groundwater readily remains within the slope when either permeability coefficient or slope gradient is small. If permeability coefficient or slope gradient is extremely small, the groundwater within the slope cannot entirely follow the reservoir level drawdown, resulting in remaining at 100%. Obviously, if v_1 is large, v_1/v_2 becomes large; the groundwater is thus easy to remain within the slope.

In case that the layer thickness is large, the intra-slope horizontal distance (x) becomes large (see Fig. 8). In such case, there exists a trend that the hydraulic gradient (dh/dx) becomes small. As a result, v_1/v_2 becomes relatively large and the groundwater may easily remain within the slope. In this study, since the upstream end of the slope is made closed (the water head is not fixed, and there is no recharge from the upstream), the hydraulic gradient (dh/dx) becomes extremely independent of the intra-slope horizontal distance (x). Therefore, the layer thickness (d) has a relatively smaller influence on the groundwater residual ratio than the other factors such as permeability coefficient and slope gradient.

4. CONCLUSIONS

A series of saturated/unsaturated unsteady seepage flow analyses were performed to investigate the mechanism of residual groundwater and its affecting factors. The analyses and evaluation of the obtained results has led to the following conclusions:

(1) Mainly permeability coefficient, reservoir level drawdown speed, slope gradient, and layer thickness govern the groundwater residual ratio. The groundwater residual ratio becomes smaller with a higher permeability coefficient, a smaller reservoir level drawdown speed, a larger slope gradient and/or a thinner layer thickness. There appears a whole tendency that the groundwater residual ratio depends largely on the slope gradient and the permeability coefficient, and it depends less on the layer thickness in some cases such that there is no recharge from the upstream.

(2) Parametric study can establish a good correlation of the groundwater residual ratio and its affecting factors. By using the correlation, safety and economic design of preventive measures for the unstable reservoir slope will be made possible.

REFERENCE

1) Fujita H: Landslides and their preventive works in reservoir slopes, Engineering for Dams, Vol. 3, No. 1, pp. 12-26, 1985.
2) Yoshimatsu H: Studies on slope stability of landslides along the reservoir, Landslide, Vol. 18, No. 2, pp. 22-30, 1981.
3) Nakamura H: Stability analysis of reservoir slopes by the simplified slice method, Landslide Control Techniques, Vol. 8, No. 4, pp. 43-48, 1981.
4) Fujita H・Yoshimatsu H・Sakamoto Y: Stability analysis of slopes submerged by reservoir water, Civil Engineering Jour., Vol. 25, No. 9, pp. 570-575, 1983.
5) National Land R & D center (eds.): Landslides survey peripherally of reservoirs and their countermeasures, pp. 171, 1995.
6) Bishop A. W: The use of pressure coefficients in practices, Geotechnique 4-4, pp. 148-152, 1954.
7) Morgenstern N. R: Stability charts for earth slope during rapid drawdown, Geotechnique, 3-2, pp. 121-131, 1963
8) Nishigaki, Numerical analysis of groundwater (4), Jour. Groundwater Hydrology, Vol. 32, No. 3, pp. 163-171, 1990.
9) Komata S・Hamasaki E・Tanaka H; Slope instability induced by dam reservoir operations and their mechanisms, Jour. Japanese National Committee on Large Dams, No. 163, pp. 42-47, 1998.

(原稿受理日 平成 11 年 9 月 21 日)