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Scaling effects of g-level and fluid viscosity on flow velocity through transverse cracks in embankments

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ABSTRACT: Flow through transverse cracks in embankments is a potential failure mode that can lead to concentrated leak erosion (CLE) and embankment failure. Current practice to assess whether CLE will propagate compares the hydraulic shear stress imparted by the fluid on the crack walls to the critical shear stress of the soil. Hydraulic shear stress, and by relation, fluid velocity through the crack, depends on factors including crack geometry, change in head, and fluid viscosity. An experimental parametric study was conducted to evaluate the scaling factors associated with g-level and fluid viscosity on flow velocity through a known crack geometry. Centrifuge models comprising homogenous embankments with 1.5H:1V slopes were constructed using low plasticity clay compacted to 95% standard Proctor maximum dry density. Tests were performed at 1g, 20g, and 40g, using 1 cPs, 7 cPs, and 40 cPs fluid. For each test, a 4.7 mm nominal width transverse crack was cut into the embankment, and a reservoir maintained constant head on the upstream side of the crack. The scaling relationships for flow velocity through the cracks with respect to g-level and fluid viscosity are discussed. The study finds that free-surface flow velocity through the cracks is generally governed by Froude number similitude and not Reynolds number similitude. This supports scaling the velocity of surface flows through cracks by a factor of 1 between model scale and prototype scale.

1 INTRODUCTION

Concentrated leak erosion (CLE), where fluid flow concentrates through a crack or other defect and erodes the surrounding soil, is one of the most challenging potential failure modes of dams and levees to design against. This is because transverse cracks, which can be caused by fault rupture, differential settlement, other means (Fell et al., 2014), can create paths for fluid flow and can occur in otherwise well-constructed embankments.

In CLE, the hydraulic shear stress imparted by the fluid on the crack wall is a key variable in whether erosion will initiate and propagate. The hydraulic shear stress is a function of the fluid velocity. Therefore, accurate centrifuge modelling of erosion conditions requires an understanding of how velocity scales for different fluid viscosities under different g-levels. A centrifuge testing program was thus performed to test the model-to-model performance of surface flow scaling laws, to assess the applicability of the scaling laws for traditional model-to-prototype scaling.

2 SCALING LAWS

Flows through transverse cracks in embankments can be considered free-surface flows. Dimensional analysis suggests that flow is driven by the Euler number, which is a function of Reynolds number and Froude number (Potter et al., 2010). Velocity can be estimated between experimental models if similitude is maintained, i.e. by setting a constant dimensionless parameter between tests. If a constant Froude number is set, the ratio of velocities between models should scale by $\sqrt{N}$, meanwhile if a constant Reynolds number is set, the ratio of velocities should scale by X

(Equation 1). To maintain Euler number similitude between tests, the velocity ratios would be required to equal one another. However, it may be acceptable to not maintain Euler number similitude should one dimensionless parameter control flow velocity to a greater extent than the other, as is examined herein.

$$\frac{V_{m@Ng,X\ cPs}}{V_{m@1g,1\ cPs}} = \sqrt{N}\ or\ X \tag{1}$$

where $V_{m@N\mathrm{g},\mathrm{X}\ cPs}$ is the velocity of a model tested at Ng with a X cPs fluid, $V_{m@1\mathrm{g},1\ cPs}$ is the velocity of a model tested at 1g with a 1 cPs fluid, N is the gravitational scaling factor and X is the viscosity scaling factor.

3 TEST DESIGN

Centrifuge tests were conducted using the 9-m radius centrifuge at the UC Davis Center for Geotechnical Modeling. Eleven tests were constructed across three models. Centrifugal acceleration was varied between 1g, 20g, and 40g, and target dynamic viscosities were varied between 1, 7, and 40 cPs. The testing matrix was bounded by the embankment modelled in parallel testing (Ko et al., 2026). The models were a homogeneous lean clay embankment constructed with a height of 25 cm, crest width of 5 cm, and 1.5H:1V side slopes (Figure 1). Prior to each test, a vertical cut with a nominal width of 4.7 mm and nominal depth of 9.6 cm was made in the embankment using a circular saw (Figure 2). After each test the crack was filled with epoxy to prevent flow through the tested cracks and so that multiple tests could be performed on each model.

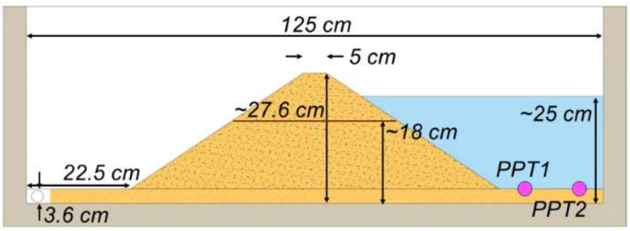

Figure 1. Centrifuge model cross-section.

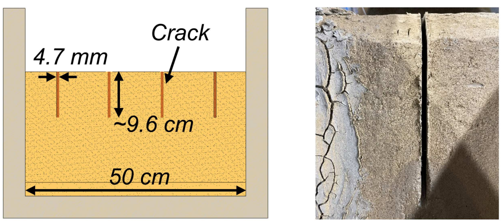

Figure 2. Cracks cut in embankment: (left) section of the upstream face showing the location of each of the cuts, and (right) photograph of a saw cut through the embankment.

4 RESULTS

The steady-state flow velocities through the cracks are shown in Figure 3. Velocity increases with g-level and can be fit well by the $\sqrt{N}$ trendline from Froude number similitude (Equation 1). Conversely, velocity decreases with viscosity, suggesting that Reynolds number similitude (Equation 2) is not met. Froude number similitude therefore governs velocity scaling. Consequently, free-surface flow scales by unity between model-scale and prototype-scale in traditional centrifuge modelling applications.

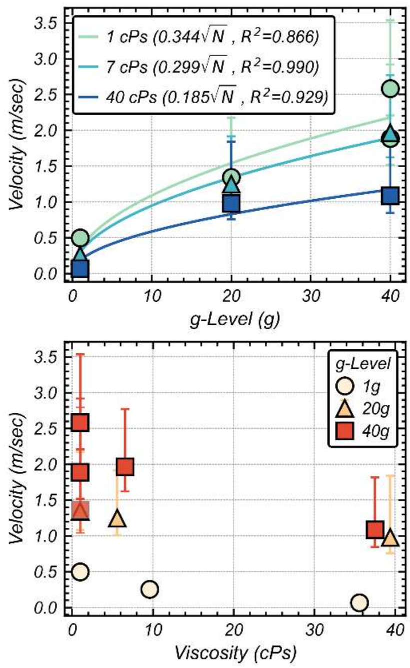

Figure 3. Velocity through the crack by: g-level (top); and viscosity (bottom).

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REFERENCES

Fell, R., MacGregor, P., Stapledon, D., Bell, G. and Foster, M. (2014). *Geotechnical Engineering of Dams*. 2nd ed. CRC Press

Ko, KW, Bancroft, M.J., DeJong, J.T., Wilson, D., Boulanger, R.W. Montgomery, J., Chen, G. and Friesen, S. (2026) "Crack propagation mechanisms in dams and levees caused by vertical offsets in the foundation. *Proc. of Int. Conf. on Soil Mech. and Geot. Eng.*

Potter, M.C., Wiggert, D.C. and Ramadan, B.H. (2010) *Mechanics of Fluids*. Cengage.