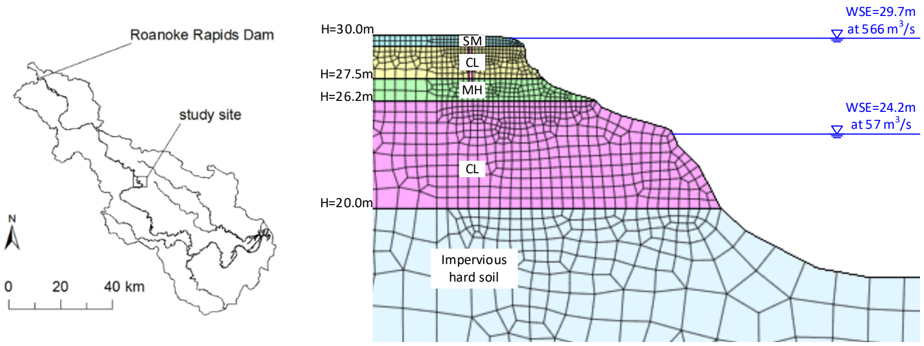
Sustainable Hydropower Dam Operation Considering Downstream Riverbank Stability

Soonkie Nam, Assistant Professor, Department of Civil Engineering and Construction,
Georgia Southern University, Statesboro, GA, snam@georgiasouthern.edu
Marte Gutierrez, Distinguished Professor, Department of Civil and Environmental
Engineering, Colorado School of Mines, Golden, CO, mgutierr@mines.edu
Panayiotis Diplas, Professor , Department of Civil and Environmental Engineering, Lehigh
University, Bethlehem, PA 18015, USA; pad313@lehigh.edu
John Petrie, Hydraulic Engineer, U.S. Army Corps of Engineers, Los Angeles District, Los
Angeles, CA, john.e.petrie@usace.army.mil

ABSTRACT

Hydropower dams are operated not only for generating electricity but also for multiple purposes such as controlling floods and drought, supplying water for drinking and irrigation purposes, offering a safe recreational environment, improving water quality, and minimizing the impact on the ecology of the river downstream. Consequently, different discharge patterns are applied to meet these purposes, which result in changes in flow velocity, fluctuations in water surface elevation (WSE) along the river and subsequent changes in the groundwater table (GWT) in the vicinity of the riverbanks. These are known to be critical factors in bank retreatment including mass failures along a river, which eventually can damage the hydraulic structures and bridge crossings as well as loss of property. Nevertheless, this important aspect has not typically received the necessary consideration when scheduling the operation of a hydropower dam. Therefore, this study evaluates the effects of the operations to the stability of the riverbank taking into account the transient seepage and unsaturated soil conditions due to the fluctuating WSE.

A riverbank located downstream of a hydropower dam in the Roanoke River, NC, was investigated where the typical release rates vary from 57 m^3/s (2,000 cfs) to 566 m^3/s (20,000 cfs) under four different operational modes (Figure 1 (a)) (Dominion Energy 2022). Any discharge rates more than 566 m^3/s were not considered as the riverbank became overflooded. The bathymetry and bank geometry of the selected site were obtained by using the acoustic Doppler current profiler (ADCP), echosounder, and ground-based light detection and ranging (LiDAR). The soil properties were obtained by in-situ and laboratory soil tests as shown in Table 1, and later used to create a numerical model as shown in Figure 1 (b). The additional information on the soil properties and how they were obtained are available in the previous studies (Nam et al. 2021; Nam et al. 2021).



(a) (b)

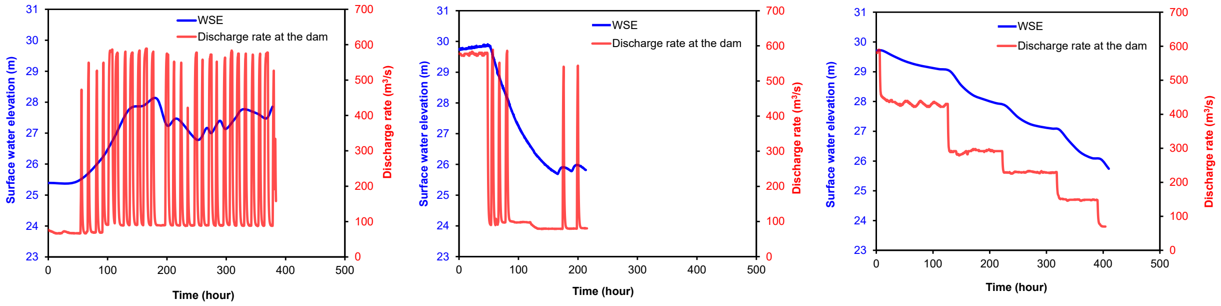
FIGURE 1. (a) the Roanoke River watershed below the Roanoke Rapids Dam and (b) Cross section of the riverbank for modeling transient seepage analysis and slope stability

TABLE 1. Soil properties

Depth (m)	Soil Type By USCS	γ_t (kN/m3)	ϕ' (°)	c' (kPa)	AEV (kPa)	ϕ^b (°)	VWC (%)	k_{Lab} (m/s)	k_{Auger} (m/s)
0.0-0.6	SM	16.4	33	5.4	10	13.3	46.1	5.09E-07	1.84E-04
0.6-2.5	CL	17.7	28.3	13.3	120	10.2	50.3	7.32E-10	2.64E-05
2.5-3.8	MH	18	32.1	18.4	160	13.5	48.3	4.99E-09	1.35E-05
3.8-10.0	CL	18.5	28.1	18.8	200	9	47.8	1.02E-09	2.58E-05

γ_t: moisture unit weight , ϕ': internal friction angle, c': cohesion, ϕ^b: angle of shearing resistance with respect to matric suction, k: hydraulic conductivity, AEV: Air entry value, and VWC: Volumetric water content.

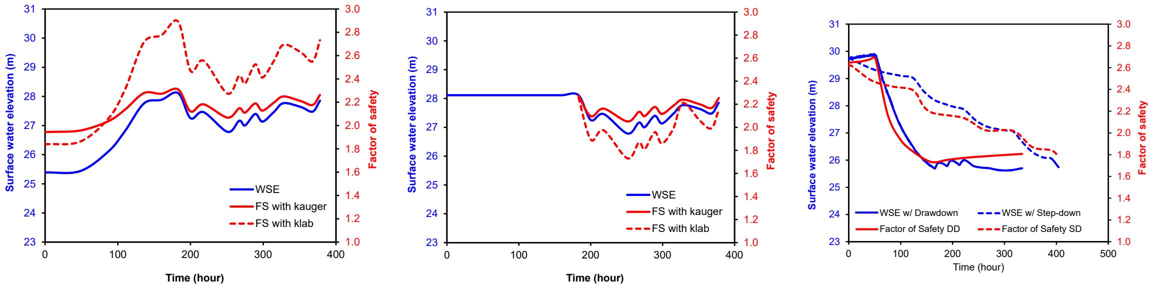
The discharges and subsequent fluctuations of WSE under four different operational modes of the hydropower dam (i.e. steady state, peaking, step down and drawdown) were analyzed based on the field monitored data as shown in Figure 2. Subsequently, the corresponding changes in GWT were investigated and calibrated by transient seepage analysis using a commercial FEM software (MIDAS Information Technology 2010). Then, the riverbank stability under different discharge rates and durations was evaluated and presented in terms of factor of safety (as shown in Figure 3) considering riverbanks' transient flow conditions with its discharge patterns using the same software.



(a) (b) (c)

FIGURE 2. Typical non-steady state dam discharge patterns due to the dam operation (a) peaking, (b) drawdown, and (c) step-down

The fluctuation of the WSE at the study site was not as drastic as that at the dam as shown in Figure 2. It was also noticed that the further a riverbank is located, the smaller the fluctuation is, and thus, the stability of the riverbank does not change drastically either. Overall, the factors of safety decreased as the WSE decreased, and also as the hydraulic conductivity decreased. Peaking did not create the unstable environment because of its short cycle, while the drawdown and step-down lowered the factor of safety the most. It is expected that the probability of the failure would increase when such adverse factors are combined.



(a) (b) (c)

FIGURE 3. Stability of the riverbank at different dam operations and consequent flow conditions. (a) peaking from low initial WSE, (b) peaking from high initial WSE,, and (c) drawdown and step-down

As a result, it is found that the hydropower dam operational modes are not the most critical factors to the slope failure of the analyzed riverbanks, but instability is expected when multiple factors were considered simultaneously. It is concluded that the hydropower dam at the study site does not seem to create adverse conditions for the analyzed riverbanks. However, the analysis proposed here for determining the WSE fluctuations caused by the dam operation and their potential impact on riverbank stability, is recommended for ensuring sustainable dam operation, which will optimize power generation and minimize any adverse effects on bank stability.

References

Dominion Energy (2022). "Operational Modes - Roanoke Rapids and Gaston Power Stations in North Carolina -." <https://www.dominionenergy.com/lakes-and-recreation/lake-gaston-and-roanoke-rapids-lake-nc/operational-modes>. (12/15, 2022).

MIDAS Information Technology. 2010. Midas GTS, version 4.1.0, Seoul, Korea.

Nam, S., Gutierrez, M., Diplas, P., and Petrie, J. (2021). "Effects of Hydropower Dam Operation on Riverbank Stability." *Infrastructures*, 6(9), 127.

Nam, S., Gutierrez, M., Diplas, P., and Petrie, J. (2021). "Laboratory and In Situ Determination of Hydraulic Conductivity and Their Validity in Transient Seepage Analysis." *Water*, 13(8), 1131.