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ENHANCED SEEPAGE AND ITS EFFECT ON SLOPE STABILITY UNDER TORRENTIAL PRECIPITATE DURING FLOOD DISCHARGE EVENT ON A LARGE HYDROELECTRIC STATION

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ABSTRACT

During flood season, it is a common practice for a hydropower reservoir to discharge its excessive flooding water when necessary. The discharging water generates rain and fog localized over the area surrounding the flood-discharge structure lunge pool. The precipitate could be as intensified as a torrential storm. For example, in Nuozadu Hydroelectric Station on Lancang River in Yunnan, China, the localized rain can be as heavy as up to 200 to 300 mm/hr and last for 5 days. The rainy area could extend about 500 m along the river, about 300 m wide across, and about 200 m high. The heavy rain results in alteration of flow condition of the slope in the energy dissipation area of the discharging floodwater, which, in turn, adversely affects the stability and safety of the engineering slope. Conventional practice treats the subsurface as saturated, neglecting the suction of the rock matrix associated with unsaturated condition. This leads to an overestimation of pore water pressure and thus a severe underestimation of the effective stress. An underestimated effective stress incurs engineering costs much higher than otherwise in protection of the slope, as it calls for more-conservative engineering measures. In this paper, we focused on the response of seepage during discharging events at Nuozadu Hydroelectric Station. Both subsurface flow simulation and laboratory experiment were performed to evaluate the seepage alteration and its impact on slope stability. The seepage model was developed and calibrated with field- and laboratory-measured rock properties and saturation data. The relation of seepage to slope stability is established through correlating saturation with measured rock mechanical data. Results show that the effective stress could be much better represented with the proposed unsaturated flow approach. This study represents one of the first few similar field study cases on this active research area, concerning slope stability issues on intensified infiltration during flood discharge events at large hydroelectric stations. Its methodology and general conclusions are applicable to general slope sites on hydropower structures.

INTRODUCTION

Nuozadu Hydropower Station is the fifth of eight-planned hydroelectric power stations in the middle and lower reach of Lancang River in Yunnan Province in the southwestern of China. The 2.5-km-long river segment at the dam structure site is bent from the South 35º E to the east slightly (Figure 1).

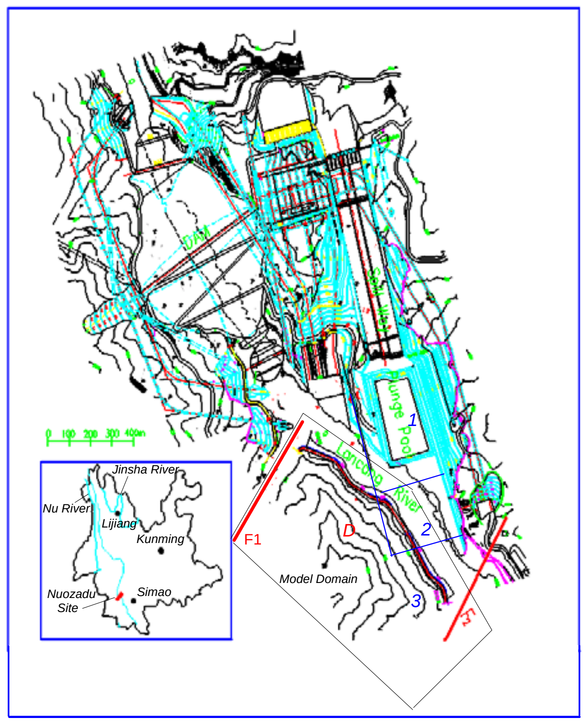

Figure 1. Plan view of the Nuozadu dam site at Lancang River in Yunnan, China. Area D is on the right side of the lunge pool where intensified fog and precipitate are generated from discharging water during discharging events in high flood season. The intensified rain and fog spread from Area 1 to Area 3. (The layout of the site is modified from Kunming Hydroelectric Investigation, Design and Research Institute (KMHIDRI), 2005)).

Lancang River has flow rates long term annually averaged at 1,730 m^3/s, with maximum at 13,900 m^3/s and minimum at 388 m^3/s. The river water is 10–16 m deep; the water surface is 80–100 m across the river and approximately 600 m above mean sea level (msl). The tamed water behind the dam at normal capacity is to be built up to about 812 m, spanning 550–560 m across the river valley. The river valley at this site appears as asymmetric V-shaped, with left slope graded 40º below 1000 m and 9º above 1000 m, and right slope graded 45º below 850 m and flatted out as erosion flat at around 850.

The right-bank's slope across from the lunge pool exposes granite rock of late Walixi period~Yinzhi period ($\gamma_4^3 \sim \gamma_5^1$) and Quaternary alluvium and pedalfer layer (Q^{dl}). The granite rocks are made of fine to medium grained feldspar granite, and medium grained granite. The quaternary slope pedalfer layer consists of purple red, yellow brown fine and sandy soil and clay, with varying thickness generally between 2~5 m.

The climate at Nuozadu site is tropic and has distinct dry and rainy seasons, with annual average air temperature at 21.7˚C. Its long-term annual precipitation rate is 1,170 mm, with 84.5% of this rate is contributed from the rainy season. Listed in Table 1 is the maximum precipitation rates measured in the rainy seasons (June to September) from 2002 to 2004

Table 1. Precipitation Rates Measured at the Nuozadu Site[a].

Precipitation	Time interval (min.)	Date June 30, 2002	Date July 15, 2003	Date Sept. 08, 2004
Maximum (mm)	10	16.0	12.7	15.3
Intensity (mm/h)	10	96.0	76.2	91.8
Maximum (mm)	60	45.5	24.7	27.2
Intensity (mm/h)	60	45.5	24.7	27.2

[a]Data source: KMHIDRI (2005)

FOGGED AREA PREDICTION FOR DISCHARGING EVENT

Dense fog forms as discharging water is coming down from the left bank of the river and charging into the lunge pool and spilling into the sky and falling down on the bank of the other side (right side) of the river. The estimate size of the fogged area is listed in Table 2. The longitudinal and transverse dimensions could be as long as 1850 and 1015 m, respectively. The fogged areas are also delineated in Figure 1, with Area 1 susceptible to strong rain storm to moderate rain, Area 2 small to light rain, and Area 3 thin fog. The fogging analysis is based on analog of fogging information from three types of hydropower stations, including Ertan, Laxiwa and Goupitan, which are similar in dam heights and water level drops with Nuozadu Station. In addition, the designed and measured flood rate from Goupitan Station is close to that of Nuozadu station.

The material and data for this paper are cited from CDUT and KMHIDRI (2006) and KMHIDRI (2005) and other sources.

Table 2. The Predicted Fogged Area at Nuozadu Hydropower Station[a].

Dimensional Scales (m)	Dense Fogged Area	Thin and Light Fogged Area
Longitudinal	778	1850
Transverse	390	1015
Maximum Height of Fogged Mass	210	646[b]

[a]Maximum dam height 262.5 m; [b]the top of the fogged area is estimated at 1,252 m above msl.

SITE DISCRIPTION

The slope site, covering from Huoshaozhai Valley F1 fault to the F2 fault to its southeast, is measured about 817 m wide and occurs an undisturbed natural slope. The slope runs N53W, and dips NE with natural slope angle of approximate 50º. Field survey shows that surface-covering layer generally is about 1~2 m thick, and bedrock is of granite origin. The bedrock is seen exposed at the river bank as weakly weathered rock body.

The model domain is shown in Figures 1 and 2. The cross section along profile 1 in Figure 2 is plotted in Figure 3.

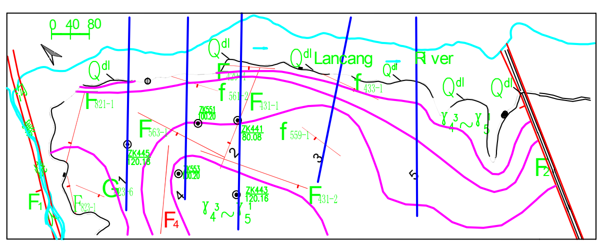

Figure 2. Plan view of geological map at 680-m Horizon. The F and f mark the fault and G the compressed structural plane. ZK marks the borehole location with the denominator for its depth (m) (modified from KMHIDRI (2005)).

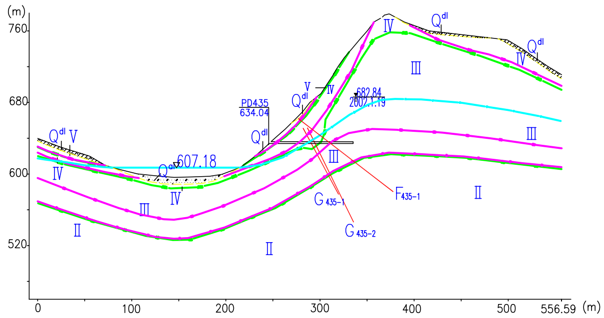

Figure 3. Geological Cross Section along Sectional Profile 1 in Figure 2. The F and f mark the fault and G and g the squeezed zone. The roman numerals indicate the geo-technical quality of the rock body in the scale of I to V with I for the best overall rock quality. PD marks the horizontally dug hole with the denominator for its elevation (m) (modified from KMHIDRI (2005)).

The granite rock bodies can be classified into three layers. Specifically, from the top down, there occur top layer, weakly weathered granite layer, and slightly weathered granite layer. The top layer consists of alluvium and strongly weathered granite layer, with thickness ranging from approximately 8.7 m to 32.1 m (Table 3).

Table 3. Geological Layers and Properties at the Modeling Area of the Nuozadu Site[a].

Geological Layer	Elevation Variation (m)	Average Thickness m	Rock Features
Q	10~80	28	River bed /slope alluvium, residual soil, pedalfer, and strong weathered granite layer
$\gamma_4^3 \sim \gamma_5^1 w$	10~129	39.7	Weakly weathered granite
$\gamma_4^3 \sim \gamma_5^1 f$	1.5~335	137	Slightly weathered, fresh granite

Note: [a]Data Source: CDUT and KMHIDRI (2006) and KMHIDRI (2005).

Faults of different scales exist at the site. Regional faults F1 and F2 are found at the northwest and southwest of the model domain. In addition, structural surfaces averaged 58 m long and those of lesser extent (about an average of 10 m) were found in the field site (Figures 2 and 3). In Figure 3, the roman numerals were used to indicate the geo-technical degree of appropriateness for construction, with class II being considered as the higher quality and bigger number for lower quality. The classification reflects comprehensive quantification of rock quality, considering rock strength, integrity (wholeness), groundwater, stress and other factors. This rock classification was coincided with the layering of hydraulic properties discussed below. The geological layers of the field site were identified by the observed information from field survey, 6 boreholes of 80.08 to 120.18 m in depths, and 8 horizontal dug holes.

Their hydraulic conductivity values were measured from field tests using hydraulic pressure water injection tests conducted in six boreholes. The hydraulic conductivity values were measured at every 5 meters in the boreholes for the strongly to weakly weathered and to slightly weathered rocks. The average values for hydrological layers are listed in Table 4. The measured data from the field tests are listed in Table 5.

Table 4. Hydrogeological Layers and Properties at the Modeling Area of Nuozadu Site[a].

Hydrological Layers	Hydraulic Conductivity (m/day)		
	Kx	Ky	Kz
Quaternary, strongly weathered (Q)	0.066	0.066	0.03
Weakly weathered bedrock layer ($\gamma_4^3 \sim \gamma_5^1 w$)	0.041	0.041	0.02
Slightly weathered, fresh rock layer ($\gamma_4^3 \sim \gamma_5^1 f$)	0.025	0.025	0.01

Note: [a]Data Source: CDUT and KMHIDRI (2006).

Table 5. Measured Hydraulic Conductivity (K) at Nuozadu Slope Site[a].

Borehole	K (m/day)		
	Q^{dl}	$\gamma_4^3 \sim \gamma_5^1$ w	$\gamma_4^3 \sim \gamma_5^1$ f
ZK441	0.0853 (1)[b]	0.0214 (9)	
ZK443	0.06918 (1)	0.06376 (11)	0.06097 (9)
ZK445	0.02464[c]	0.05935 (23)	
ZK449[b]	0.5118 (3)	0.1796 (14)	
ZK551	0.03506 (1)	0.03029 (10)	
ZK553	0.06634[c]	0.04096 (6)	0.02511 (10)

Note: [a]Number of pressure tests, [b]fault presented and [c]measured from pumping test.

NUMERICAL MODEL

The model domain is located in the slope on the right bank of the lunge pool. The X-axis starts from the upstream Huoshaozhai Valley to the downstream model boundary at the F2 fault, spanning 980 m. The Y-axis is approximately vertical to Lancang River, covering the groundwater divide in the southwest to the river centerline (Figures 1 and 2) for approximately 840 m. The vertical Z-axis starts from Elevation 485 m above msl to the maximum elevation 890 m of the hill.

The domain is divided into 50 rows and 30 columns and 12 layers. The groundwater flows from the southwest high land to Lancang River. Along the regional flow the model is bounded by no flow boundaries along the Huoshaozhai F1 fault on the northwest side and F2 fault on the southeast side. The upstream is defined by the groundwater divide under the mountain. The flow is ended in the river centerline. The infiltration rates takes 15% of the observed regional multiple annual precipitation rates.

The numerical simulation was originally performed with MODFLOW and later was extended to multiphase flow to incorporate the under saturated conditions using multiphase flow simulator TOUGH2 (Pruess, 1991).

RESULS AND DISCUSSIONS

The model is run to at steady state using the recharge rate in the dry season. Then it is run with the infiltration rate for dry season. The seasonal variations of the groundwater levels are shown in Figure 4.

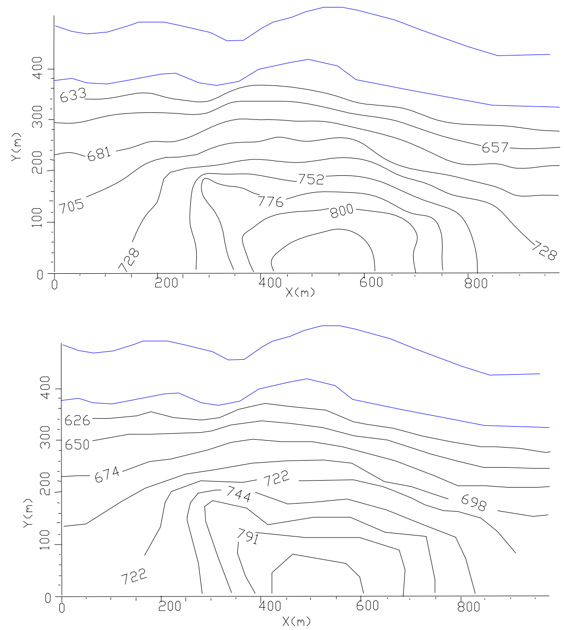

Figure 4. Plan view of groundwater table contours: upper map for dry season and the lower map for the rainy season.

Cross sections of the water table are shown in Figure 5 for the dry, rain season and under lasting torrential storms. These three scenarios separate themselves, with the torrential storms creating enhanced water table about 20 m additional to the rainy season's groundwater table.

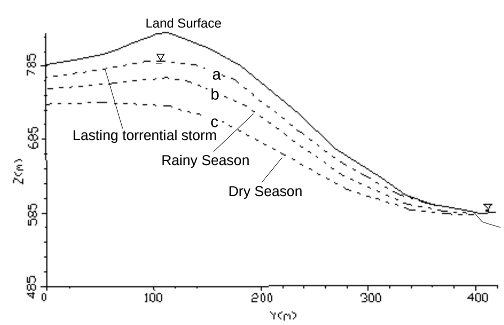

Figure 5. Groundwater Tables in Profile 1 at dry, wet season and lasting torrential storms.

The saturation is related to the strength of the rock. Generally speaking, the rock is weakened with increased saturation (Figure 6). Thus we may draw a conclusion that the torrential storms generated in the flood discharging event would significantly weaken the strength of the rock and subsequently weaken the stability.

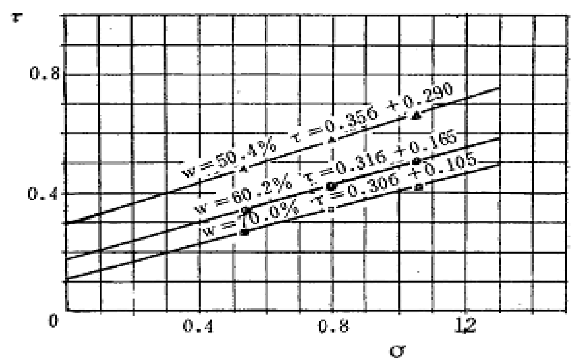

Figure 6. Relationship of shear stress τ (kg/cm^2) and normal stress σ (kg/cm^3) under varied saturation w *(modified from Xiang (1986)).*

PRELIMINARY CONCLUSION

This paper tried to characterize the effect on slope stability from intensified precipitate that will be generated during the multiple-day discharging event in flood season at Nuozadu Hydroelectric Power Station, Yunnan, China. Preliminary results show the rain season and dry season have distinct variation of the groundwater tables.

The lasting torrential discharging event was predicted to generate additional significant recharge to the groundwater additional to the rainy season's groundwater level. The groundwater variation occurs in the highly weathered soil zone that would change the under saturation in the soil to saturated condition. The soil in the unsaturated zone has a limited increase in saturation. The strongly weakening of rock strength occurs in the water fluctuation zone according to the rock strength's inverse relation with rock saturation. Future work will include a hydrological mechanical coupling for the analysis of the slope stability.

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REFERENCES

CDUT (Chengdu University of Technology) and China Hydroelectric Consulting Group Kunming Hydroelectrical Investigation, Design and Research Institute (KMHIDRI), Nuozadu Hydroelectrical Power Station Site's High Slope Engineering Features and Its Stability Study, 2006.

KMHIDRI (Kunming Hydroelectric Investigation, Design and Research Institute), CHECC, Yunnan, China), Nuozadu Hydroelectrical Power Station Exploration Report, Kunming, Yunnan, 2005.

McDonald, M.G., and A.W. Harbaugh. A Modular Three-dimensional Finite Difference Groundwater Flow Model. U.S. Geological Survey Techniques of Water Resources Investigations, Book 6.

Pruess, K. TOUGH2–A General-purpose Numerical Simulator for Multiphase Fluid and Heat Flow. LBL-29400. Lawrence Berkeley National Laboratory, 1991.

Wu, Yu-Shu, Guoping Lu, Keni Zhang, and G. S. Bodvarsson. A Mountain-Scale Model for Characterizing Unsaturated Flow and Transport in Fractured Tuffs of Yucca Mountain, *Vadose Zone Journal*, 3:796-805, 2004.

Xiang, Jiannan. The Effect of Water on the Mechanic Properties of Soft and Weak Layer, in "Hydrogeology and Engineering Geology Series 1", Geology Press, 1986.