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Stability Analysis on the Dam of Mekin Hydropower Plant

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ABSTRACT

This work shows the stability analysis which is carried out on the dam body (section, seepage and slope) of the main and auxiliary dams of Mekin hydropower plant. Based on the results of the design of the structure of the dam body, the calculations of the seepage and slope stability of the dam are done using numerical methods implemented on the Earth and Rockfill dam slide slope stability analysis (STAB) software.

INTRODUCTION

The Mekin hydroelectric dam situated in the south region of Cameroon located after the confluence of the rivers Dja, lobo and Sabe, is constructed to produce 15MW. The main dam and auxiliary dam constitute a reservoir of approximately 11010km^2 with a volume of about $2 \times 10^8 m^3$. [1]

Owners of dams and operating and maintenance personnel must be knowledgeable of the potential problems which can lead to failure of a dam. These people regularly view the structure and, therefore, need to be able to recognize potential problems so that failure can be avoided. If a problem is noted early enough, an expert experienced in dam design, construction and inspection can be contacted to recommend correctives measures, and such measures can be implemented. Acting promptly may avoid possible dam failure and the resulting catastrophic effect on downstream areas [4].

Since only superficial inspections of a dam can usually be made, it is imperative that owners and maintenance personnel be aware of the prominent types of failures and their telltale signs. Earth dams' failures can be grouped into three general categories.

They are: overtopping failures, seepage failures and structural failures [3].

Overtopping failures result from erosive action of water on the embankment. Erosion is due to uncontrolled flow of water over, around and adjacent to the dam. Earth embankments are not design to be overtopped and therefore are particularly susceptible to erosion. Once erosion has begun during overtopping, it is almost impossible to stop [6].

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A well vegetated earth embankment may withstand limited overtopping if its top is level and water flows over the top and down the face as an evenly distributed sheet without becoming concentrated. The owner should closely monitor the reservoir pool level during severe storms [2,5].

All earth dams have seepage resulting from water percolating slowly through the demand its foundation. Seepage must, however, be controlled in both velocity and quantity. If uncontrolled, it can progressively erode soil from embankment or its foundation, resulting in rapid failure of the dam. Erosion of the soil begins at the downstream side of the embankment, either in the dam proper or the foundation, progressively works toward the reservoir, and eventually develops a « pipe » or at direct conduit to the reservoir. This phenomenon is known as « piping ». Piping action can be recognized by an increase seepage flow rate, the discharge of muddily or discolor water, sinkholes on or near the embankment, and a whirlpool in the reservoir. Once a whirlpool (eddy) is observed on the reservoir surface, complete failure of the dam will probably follow. As with overtopping, fully developed piping is virtually impossible to control and will likely cause failure [7,9].

Seepage can cause slope failure by creating high pressures in the soil pores or by saturating slope. A slope which becomes saturated and develops slides may be showing sign of excessive seepage pressure.

Structural failures can occur in either the embankment or the appurtenances such as spillways. Structural failure of a spillway, lake drain or other appurtenance may lead to failure of the embankment. Cracking, settlement and slides are the more common signs of structural failure of embankments [11].

The three types of failure previously described are often interrelated in a complex manner.

The earth dam design gives us the zoning of the dam body, and the sizing of the dam body. The purpose of this work is to carry out calculations and analysis on the dam body structure to ensure the stability and safety of the dam in terms of seepage, slope and sedimentation.

Dam Body Calculation and Analysis

Calculation of Section

The dam bodies and the foundation at all positions of the main and the auxiliary dams must change smoothly, basically without sudden change. For calculation of the dam body, the respective maximum dam height is used as typical calculation section.

See Fig 1-1 for calculated section of main dam, calculated stake No. MainSta0+ 300.000 and calculated stake No. Aux.Sta0+150.000 of auxiliary dam.

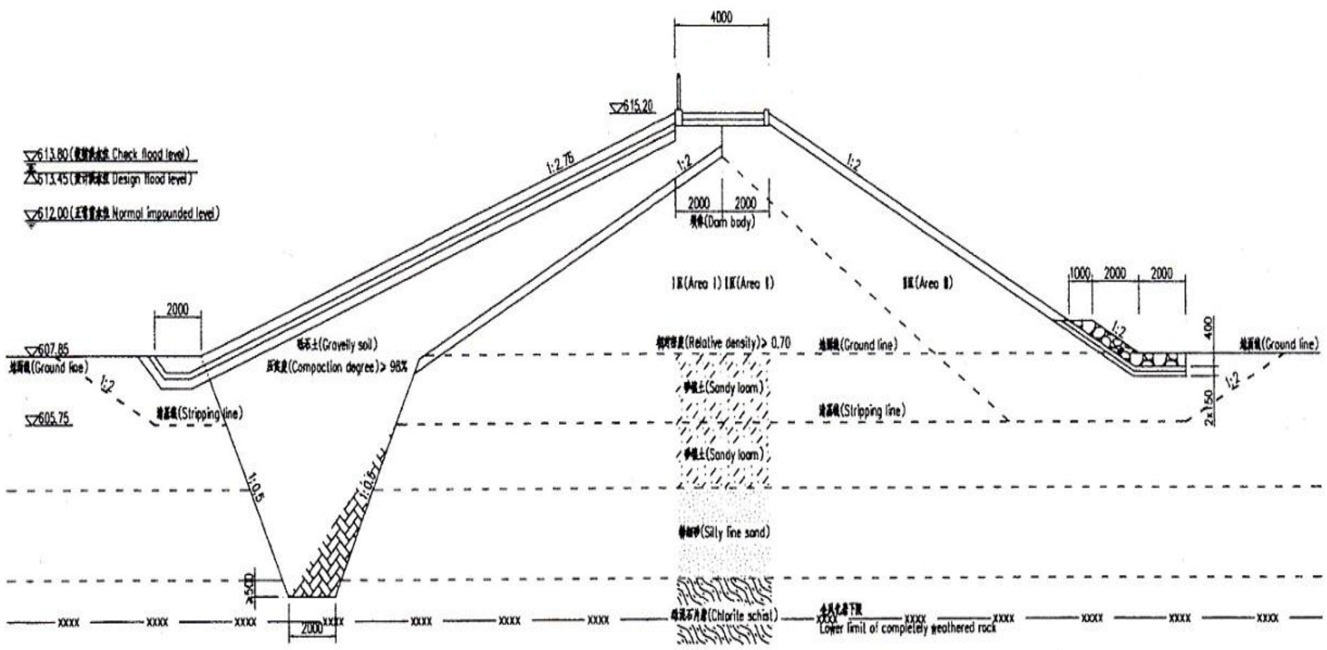

Figure 1-1: Diagram of main and auxiliary dam seepage and dam slope stability calculation

Seepage Calculation

(1) Calculation model

According to the geological conditions of the main and the auxiliary dams, the surface seepage ratio of the cutoff trench substrate rock mass is about 5.00 Lu it may be deemed as impermeable stream [12].

Limited permeable foundation without drainage model in the downstream is used for seepage calculation

See table 1-1 for seepage calculation parameters of the main and the auxiliary dams

Table 1-1: Permeability coefficient for seepage-proofing of dam and dam foundation unit: cm/s

Position	Section	Seepage-Proofing Body Gravelly Soil	Abandoned Residue Of Dam Body Work	Dam Foundation Loam	Dam Foundation Pebbly Loam	Dam Foundation Gravel
Main Dam	Main sta0+300.000	6.00×10^{-7}	5.00×10^{-3}	5.80×10^{-3}	9.25×10^{-3}	1.75×10^{-2}
Auxiliary Dam	Auxiliary sta0+150.000	6.00×10^{-7}	5.00×10^{-3}	5.80×10^{-3}	9.25×10^{-3}	1.75×10^{-2}

(2) Design operation state for dam body seepage

See table 1-2 for design operation state for main dam and auxiliary dam.

Table 1-2: Characteristic water level of reservoir

Working Condition	Flood Standard (Year)	Upstream Water Level (M)	Downstream Water Level (M)	
			Main Dam	Aux. Dam
Check Flood Level	2000	613.80	609.45	No water
Design Flood Level	100	613.45	608.20	
Normal High Level	-	612.00	603.35	

(3) Program used for calculation

All the seepage factors of class 2 dams are calculated by numerical method. Earth and Rockfill Dam Two way stability and instability seepage calculation program in design software for Earth and Rockfill dam of water conservancy and hydro power project is adopted as seepage calculation program.

Two dimensional seepage equation [12]:

$$K_X \frac{\partial^2 H}{\partial x^2} \div K_Y \frac{\partial^2 H}{\partial y^2} = 0 \qquad (Eq\ 1)$$

Where: K_X , K_Y permeability coefficient of x direction and y direction;

H- Seepage pressure head at a certain point in seepage field, m.

(4) Results and conclusion of calculation

See table 1-3 for results of seepage calculation

According to the calculated results of seepage, the total seepage of the main dam at normal storage level is 7.80m/day, the total seepage of the auxiliary dam at normal storage level is 0.60m/day, the total seepage of the two dams is 8.40m/day, the annual seepage amounts to 3065.00m approximately, the average annual inflow rate of the reservoir is 19.74, therefore the seepage of the dams occupies an extremely small proportion at normal storage level of the dams.

Table 1-3: Results of seepage calculation

Position	Application Conditions	Upstream Water Level (M)	Downstream Water Level (M)	Seepage Per Unit Width $(m^3/day.m)$	Slant Wall Escapement Point (M)	Dam Slope Escapement Point (M)	Total Seepage Flow (m^3/day)
Main Dam	Normal storage level	612.00	603.35	0.016	0.00	0.00	7.80
	Design flood level	61345	608.20	0.025	0.00	0.00	
	Check flood level	613.80	609.45	0.032	0.55	0.55	
Auxiliary Dam	Normal storage level	612.00	No water	0.002	0.00	0.00	0.60
	Design flood level	61345		0.009	0.00	0.00	
	Check flood level	613.80		0.011	0.00	0.00	

Seepage Stability Calculation

The seepage destruction types and allowable hydraulic gradient have been described and calculated in the section of various fillings of dam foundation and dam body. The type of deformation of seepage-proofing body is discriminated with the method given in Technical specification for geological investigation of water conservancy and Hydropower Projects (GB50287-99[13].

Fine particles are discriminated for following soil and piping:

$$d_f = \sqrt{d_{70}d_{10}} \qquad (Eq\ 2)$$

Where: $d_{70,}d_{10}$ –Diameter of particles less than this diameter whose content covers percentage of the total soil weight, mm. We have these parameters values [12,13]:

$d_f = 0.245,\ P_c = 45$

$$n = \frac{G_s(1+\omega)}{\gamma} - 1 \quad (Eq\ 3)$$

$G_s = 2.76\ \ ;\ \omega = 19\%$

$n = 0.825$

Design void ratio:

$$P_c = 45 > \frac{1}{4(1-n)} \times 100 = 14 \quad (Eq\ 4)$$

Where: n=void ratio.

The type of destruction occurred in gravelly soil seepage-proofing body is piping.

Critical hydraulic gradient of piping in seepage-proofing body:

$$J_{cr} = 2.2(G_s - 1)(1-n) \qquad (Eq\ 5)$$

$J_{cr} = 0.675$

Permissible gradient:

$$J = \frac{J_{cr}}{K} \quad (Eq\ 6)$$

$J = 0.34$

Where J_{cr} – critical hydraulic gradient of soil

K- Safety factor, 2.0 is selected according to the importance of the work.

According to the geological conditions of the dam foundation, mainly loam and gravelly loam are used for filling of the dam body. The destruction type and permissible hydraulic gradient of each soil layer of the seepage -proofing body, dam body and dam foundation are listed in Table 1-4 through seepage calculation, the calculated results of seepage stability are listed in table 1-4

Table 1-4: Calculated results of seepage stability

Position		Type Of Soil Particle	Type Of Destruction	Permissible Gradient	Calculated Gradient		
					Normal Storage Level	Design Flood Level	Check Flood Level
Main dam	Seepage-Proofing Body	Gravelly Soil	Piping	0.34	0.20	0.20	0.20
	Dam Body	Mixed Residue	Flowing Soil	0.20	0.00	0.00	0.00
	Dam Foundation	Loam, Gravelly Loam	Flowing Soil	0.30	0.00	0.00	0.00
Auxiliary dam	Seepage-Proofing Body	Gravelly Soil	Piping	0.34	0.10	0.10	0.10
	Dam Body	Mixed Residue	Flowing Soil	0.20	0.00	0.00	0.00
	Dam Foundation	Loam, Gravelly Loam	Flowing Soil	0.30	0.00	0.00	0.00

According to calculated results of seepage:

- Maximum gradient of each position in the dam body is less than corresponding permissible gradient;
- Gradient at escapement point is downstream of dam foundation is less than permissible seepage gradient of dam foundation

The seepage of the dam is stable and safe.

Calculation of Dam Slope Stability

(1) Design operation state:

Normal storage level stable seepage period (612.00m) (normal)
Design flood level stable seepage period (613.45m) (normal)
Check flood level stable seepage period (613.80m) (abnormal)

(2) Program used for calculation

Dam body side slope stable sip circle calculation is done by means of Earth and Rockfill dam slide slope stability analysis (STAB) in Design software for Earth and Rockfill Dam of water conservancy and Hydropower Project. Simplified bishop method accounting for acting force between stripe block is used for calculation.

$$K = \frac{\sum\{[W\sec\alpha - \mu b\sec\alpha]\tan\varphi' + c'b\sec\alpha\}[1/(1+\tan\alpha\tan\varphi/K)]}{\sum W\sin\alpha} \quad (Eq\ 7)$$

Where: W- weight of soil stripe
μ- Void pressure acting on the bottom face of soil stripe;
α- Included angle between stripe block gravity line and the radius passing through the bottom face central point of the stripe block;
b- Width of soil stripe;
c', φ'- Effective stress shearing strength index of soil stripe bottom face.

See tables 1-5 and 1-6 for calculation parameters of dam body side slope stability

Table 1-5: Physico-mechanical indices of compacted soil

Statistical Index	Max Dry Density	Optimum Water Content	Compressibility Factor	Compressibility Modulus	Cohesion	Int. Friction Angle	Permeability Coefficient	
							Vertical	Horizontal
	P_{dmax}	W_{op}	A_v	E_s	C	Φ	K_v	K_h
	G/Cm³		Mpa⁻¹	Mpa	Kpa	Degree	Cm/S	
Design Value	1.80	19.00	0.08	19.45	25.00	25.00	6.00×10^{-7}	

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Table 1-6: Design indices of mixtures for dam body

Statistical	Max Dry Density	Compressive Modulus	Cohesion	Internal Friction Angle	Permeability Coefficient
	g/cm³	MPa	kPa	Degree	cm/s
Design Value	>1.70	>15.00	0.00	>30.00	$>5.00\times10^{-3}$

(3) Calculation results and conclusion

See table 1-7 for calculation results of dam body side slope stability.

Table 1-7: Calculation results of dam body side slope stability of main and auxiliary dams

Work Position		Operation State		Water Level (M)	Safety Facto	Specification Requirement
Main Dam	Upstream side slope	Normal application	Normal storage level stable seepage period	612.00	2.83	1.35
			Design flood level table seepage period	613.45	3.37	1.35
		Abnormal application	Check flood level table seepage period	613.80	3.96	1.25
	Downstream side slope	Normal application	Normal storage level stable seepage period	612.00	2.30	1.35
			Design flood level table seepage period	613.45	2.30	1.35
		Abnormal application	Check flood level table seepage period	613.80	1.99	1.25
Auxiliary Dam	Upstream side slope	Normal application	Normal storage level stable seepage period	612.00	2.54	1.35
			Design flood level table seepage period	613.45	3.43	1.35
		Abnormal application	Check flood level table seepage period	613.80	3.86	1.25
	Downstream side slope	Normal application	Normal storage level stable seepage period	612.00	2.30	1.35
			Design flood level table seepage period	613.45	2.30	1.35
		Abnormal application	Check flood level table seepage period	613.80	1.99	1.25

According to the calculation results of side slope stability, the stability of both upstream and downstream side slopes is safe in all the operation states.

Sedimentation Calculation

(1) Program used for calculation :

In accordance with cohesion soil sedimentation calculation formula is [10], [12]:

$$S_{\infty}=\sum_{i=1}^{n}\frac{P_i}{E_i}h_i \qquad (Eq\ 8)$$

Where:

S_{∞} – Final sedimentation of dam body or dam foundation:

P_i – Vertical stress generated by dam body load in calculation soil layer i:

E_i – Deformation modulus of calculation soil layer i:

h_i – Thickness of calculation soil layer i:

Weight of earth pillar above unit area is used as total vertical stress caused by deadweight at an arbitrary point in main dam and auxiliary dam body.

The ratio of dam foundation compressible stream thickness to dam foundation width is less than 0.25 for both the main dam and the auxiliary dam. As recommended by the specification, the following formula is used for calculation of the additional stress [12, 14]:

$$P_{max} = \frac{2R}{B + 2y} \qquad (Eq\ 9)$$

Where

P_{max} – Maximum vertical stress on the calculated stratum;
R- Deadweight resultant force of dam
B- Width of dam bottom
y- Depth of dam foundation at calculating point.

(2) Calculation results and analysis

Through calculation, the sedimentation calculation results of dam body and dam foundation at two typical sections of the main dam and the auxiliary dam are shown in table 1-8.

Table 1-8: Sedimentation calculation results of dam and dam foundation unit: mm

Position	Section	Sedimentation Of Dam Body	Sedimentation Of Dam Foundation	Percentage To Dam Height	Sedimentation In Construction Period	Reserved Super Elevation
Main Dam	Main Sta0+300.000	35	40	0.50%	60	15
Auxiliary Dam	Auxiliary Sta0+150.000	15	20	0.35%	28	7

Remarks: sedimentation in construction period is 80% of total sedimentation.

Through calculation, the dam body sedimentations of both the main dam and auxiliary dam are less than 1% of dam height, which meets the specification requirement.

CONCLUSION

The objective of this work was to carry out calculations and analysis of the dam body to insure safety and stability.

The models and calculations used in this study were based on international standards. Concrete results were obtained which are being implemented on the construction site of the dam. Detailed calculations of the seepage and slope stability of the dam were done using the Earth and Rockfill dam slide slope stability analysis (STAB) software.

At the end, we can say that:

- The seepage of the dams occupies an extremely small proportion at normal storage level of the dams. The seepage of the dam is stable and safe.
- The stability of both upstream and downstream side slopes is safe in all the operation states.
- The dam body sedimentations of both the main dam and auxiliary dam meet the specification requirement.

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