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Energy Dissipation Regimes and Stability of the Overflow Dam (Spillway) for the Mekin Dam in Cameroon

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Abstract: This paper evaluates the efficiency of energy dissipation of the spillway for the Mekin Dam with respect to its capacity by verifying that the flow down the spillway does not result in 'transitional flow' which can induce vibrations dangerous to the structure. It also verifies the stability of the spillway by calculating the resulting safety coefficients at different times.
Keywords: Mekin, spillway, Step flow, nappe flow, skim flow, energy dissipation, stability and stress

I. INTRODUCTION

Spillways are structures constructed to provide safe release of flood waters from a dam to a downstream area, normally the river on which the dam has been constructed. The release of water can go up to and include the inflow design flood level. Spillways can be controlled or uncontrolled. A controlled spillway is provided with gates which can be raised or lowered. The Mekin dam is found at about 220km from the capital Yaoundé in Cameroon and will produce a maximum of 15MW on completion. The water level in the dam during normal functioning is at altitude 612 and that also is the height of the spillway which itself is 115m long. The analysis for the dissipation takes into effect the avoiding the transitional flow which cause bubbles resulting in vibrations that could damage the spillway structure. It should include the different situations of napped and skim flows and considers the conditions of design flood and check flood water levels. Stability analysis should take into account the different load combinations for the calculation of body stress and anti-slide stability.

II. ANALYSIS OF THE OVERFLOW DAM DISSIPATION

Energy dissipation mode of the stepped overflow dam is not only different from the energy dissipation of ski-jump type in the energy dissipation in underflow or surface flow, but also different in the multi stage waterfall energy dissipation in the general chutes. Experimental investigation shows [7], [8] that stepped chute flows for can be divided into two regimes: nappe flow low discharges and skim flow for higher discharges.

Nappe flow is defined as a succession, of free-falling nappes. The water bounces from one step to the next as a series of small free falls. In skimming flow the water flows down the chute as coherent stream, skimming over the steps and cushioned by the circulating vortices trapped between the main stream and the steps. For safety reasons the flow conditions near the transition between nappe and skimming flows must be avoided if possible. Transitory hydrodynamic fluctuations which occur as the flow oscillates between nappe and skimming flow regimes might induce improper or dangerous flow behaviour and unnecessary vibration of the structure.

2.1 Discharge capacity of the overflow dam

The unit discharge of the un-gated overflow dam can be calculated as follows[3,5,6,7]:

$$q = Cm\varepsilon\, \delta_s \sqrt{2g} H_w^{3/2} \qquad (1)$$

Where,
q is the unit discharge (in m^3/s)
C is the slope influence correction coefficient of upstream face (i.e. = 1),
m is discharge coefficient
ε is the coefficient of side contraction (i.e. 0.95),
δ_s is the submerged coefficient(i.e. 1),
g is the gravitational constant,

H_w is the water head over weir(in m).

The water head over weir at design flood condition is 1.45m and the upstream height of weir is 7.2m, the discharge coefficient is therefore 0.504.
The weir head over weir at check flood condition is 1.8m and the upstream weir height is 7.2m, the discharge coefficient is 0.504.

Therefore the unit discharge at design flood level after calculation is 3.7m^3/s
Similarly, the unit discharge at check flood water level is 5.12m^3/s.

2.2 The probable flow pattern for step flow
To check the flow pattern, we would have to calculate the critical depth. The characteristic critical depth is calculated as follows:

$$\hbar_k = \sqrt[3]{\frac{q^2}{g}} \qquad (2)$$

Where
$\hbar_k$ is characteristic critical depth (in m)
q is the unit discharge (in m^3/s)

From calculation the critical depth at design flood level is 1.118m
The critical depth at check flood water level is 1.388m
The step height is 1.0m and length is 0.75m

When $0.2 \leq \frac{\hbar}{l} = 1.33 \leq 6$
Where
h is height of steps and l is step length

The critical value for nappe flow regime is calculated as:

$$\frac{\hbar_k}{\hbar} = 0.096*\left(\frac{\hbar}{l}\right)^{-1.276} \qquad (3)$$

When equation (3) is applied, the critical value obtained for nappe flow is 0.063

The critical value for skimming flow regime is calculated as:

$$\frac{\hbar_k}{\hbar} = 1.057 - 0.465\frac{\hbar}{l} \qquad (4)$$

When equation (4) is applied the critical value for skimming flow is equal to 0.437

The critical value for the design flood water level $\frac{\hbar_k}{\hbar}$ = 0.745 larger than the critical value for skimming flow.
Also the critical value for check flood water level is $\frac{\hbar_k}{\hbar}$ = 0.925 larger than the critical value for skimming flow regime which is 0.437
This therefore tells us that the step flow pattern discrimination for the spillway is skimming flow pattern.

2.3 The energy dissipation rate of the right angled stepped overflow dam
The energy dissipation rate of right angled stepped overflow dam can be calculated as follows:

$$\eta = -0.3916 - 0.2247\ln\left[\left(\frac{q}{p^{1.5}}\right)\left(\frac{0.014}{n}\right)^{2.4}\right] \qquad (5)$$

$$n = \frac{\Delta^{1/6}}{2.4} \qquad (6)$$

Where
η is the energy dissipation rate of right-angled stepped overflow dam:
p is the height of overflow dam i.e. 7.2m,
Δ is the outstanding height of steps (i.e. 0.6)

From calculations, the energy dissipation rate of spillway at design flood level is 55.85¨%
Similarly, the energy dissipation rate at check flood water level is 48.55%
As we can see the energy dissipation rate of stepped spillway increases with increase in discharge unit.

2.4 The flow velocity downstream of the overflow dam
The flow velocity of the overflow dam downstream is calculated as follows[2]:

$V=3.92h^{-0.12}q^{E}$ (7)
$E=0.44(h/p)^{0.024}$ (8)

Where V is the flow velocity downstream (in m/s),
h is the step height (i.e.1.0m),
p is the height of overflow dam (i.e. 7.2m),

From calculation the flow velocity of the spillway water downstream at design flood water level is 6.79m/s.
Also the flow velocity of the spillway downstream at check flood water level is 7.78m/s.
Both velocities are less that the recommended maximum velocity downstream which is 15m/s.
The maximum scouring depth estimate of bedrock at design flood condition and check flood conditions is as follows[11],[12].:

$d = (1 + 0.2k\frac{v_t}{v_a})t_c-t$ (9)
$t_c = (p_c + c)\ h_1\eta$ (10)
$F_r=\frac{v_1}{\sqrt{gh_1}}$ (11)
$\xi=\frac{a}{h_1}$ (12)
$\eta = \xi - 0.4 + 1.4F_r$(effective bucket angle is 0^0 (13)
$c= 0.01(\frac{q}{30m^2/s})$ (14)

Where d is the scouring depth (in m),
v_1 is the average velocity of drop sill section (in m/s),
h_1 is the average flow depth of drop sill section (i.e. $0.7h_k$ (in m)
v_a is the allowed maximum velocity of bedrock (15m/s),
k is the characteristic coefficient of riverbed (i.e. 0.3),
t_c is the critical depth of submerged mixing flow (in m),
t is the downstream water depth (in m),
F_r is the Froude number,
ξ is the mixing ratio,
η is the conjugate ratio,
p_c is the pressure correction coefficient of sill surface (i.e. about 0.93 – 1.0),
c is centrifugal force correction coefficient,
a is sill height (at design flood water level is 2.55m and check flood water level is 3.8m without overburden).
From calculation, the scouring depth at design water level is (-2.499 ~ -2.495) and check water level (-2.43 ~ -2.44) all less than 0, meaning that the flow cannot break the spillway foundation.

2.5 Cavitation erosion[1]
Water flow cavitation number is calculated as follows:

$\delta = \frac{h_0+h_a-h_v}{v^2/2g}$ (15)

where,
δ is water flow cavitation number,
h_0 is the time-average pressure head of inflow reference section (in m),
h_a is the height of water column under standard atmosphere (i.e 10.33m),
h_v is the vapour pressure showed by water column height (i.e. 0.24m),

From calculations the water flow cavitation number at design flood water level is 18.85
The water flow cavitation at check flood water level is 10.4
The water flow cavitation numbers of spillway are large numbers so the cavitation erosion phenomenon cannot occur on dam surface.

III. ANALYSIS OF THE DAM STABILITY AND STRESS

3.1 Calculation of dam body stability and stress

This calculation takes into account the maximum dam height as typical section for dam body calculation.

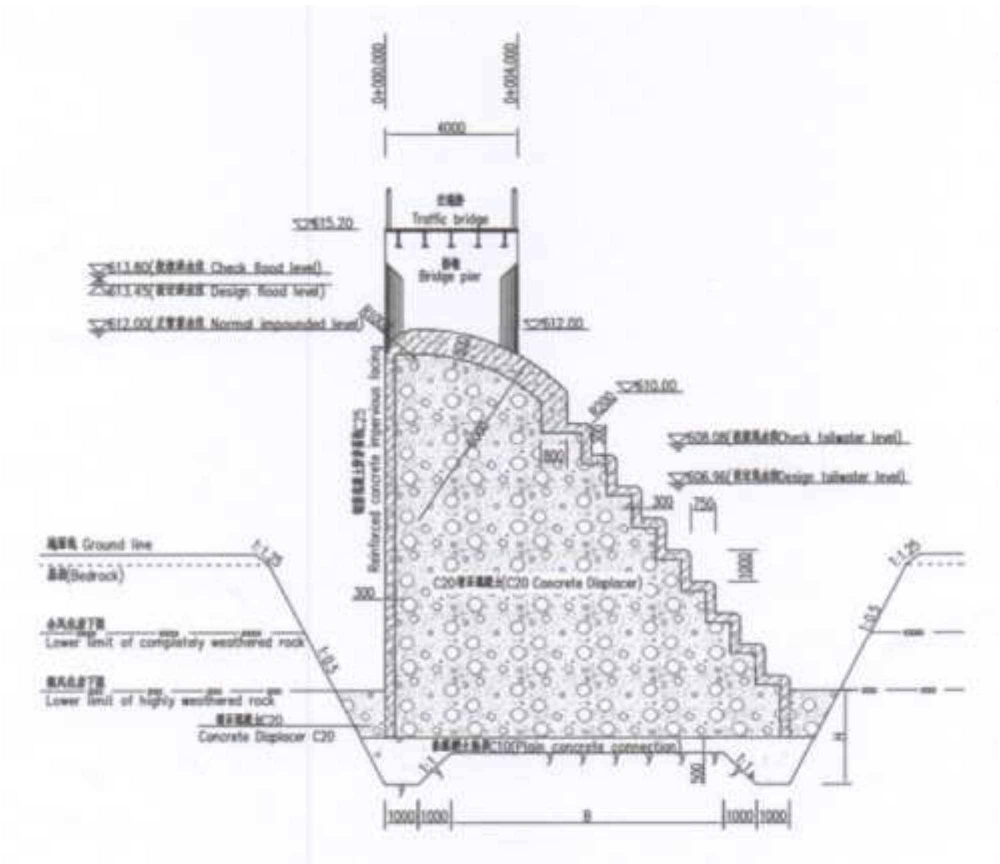

Fig. 1: Typical calculation section of overflow dam body

3.2 Different loads and combinations

Load combinations for the calculation of dam body anti-slide stability and dam body stress are divided into basic and special combinations. The load combination for masonry dam is as follows[9]:

Table 1: Different Load combinations

Load Combination	Major consideration	Load							
		Dead weight	Static water pressure	Uplifting pressure	Silt pressure	Wave pressure	Dynamic water pressure	Soil pressure	Other loads
Basic combination	Normal storage level	√	√	√	√			√	√
	Design flood water level	√	√	√	√		√	√	√
Special combination	Check flood water level	√	√	√	√		√	√	√

3.3 Stability and stress calculation

Anti-slide stability is in the following formula:

$$K = \frac{f'\sum W + C'A}{\sum P} \qquad (16)$$

Where K is anti-slide safety coefficient,

f' is shearing friction coefficient of contact face of dam concrete and dam foundation,

C' is shearing cohesive force of contact face of dam concrete and dam foundation,

$\sum W$ is normal component force of all loads acting on dam body to the slide plane (in KN),

$\sum P$ is the tangential force of all loads acting on dam body on the slide plane (in KN)

A is the sectional area of dam base level, in m^2, Formula for calculation of dam base level stress is:

$$\sigma_{min}^{max} = \frac{\sum W}{A} \pm \frac{\sum M.x}{J} \qquad (17)$$

Where,

$\sum W$ is normal component force of all loads acting on dam body on the slide plane (in KN),
$\sum M$ is tangential component force of all the loads acting on dam body on the slide plane (KN),
J is inertia moment of sectional area of dam base level to centroidal axis (in m^4),
x is distance from calculation point of dam base level section to centroidal axis (in m).
From experiment, shearing friction coefficient and shearing cohesive force between various materials are listed in following table:

Table 2: Parameters for the calculation of stability

	Base rock – base rock	Cushion concrete - base rock	Masonry body-cushion concrete
Shearing friction coefficient	0.5	0.8	0.6
Shearing cohesive force (KN/m^2)	150.00	600.00	350.00

See the following table for results of dam section anti-slide stability and dam foundation face stress calculations.

Table 3: Results of overall dam anti-slide stability and dam foundation face stress calculations

Design combination	Type of activity	Lasting state		Occasional state
Activity combination		Basic combination		Special combination
Consideration		Normal storage level	Design flood level	Anti-slide stability coefficient
Anti-slide stability coefficient	Base rock – base rock	3.03	3.55	3.87
	Cushion concrete – base rock	9.48	11.33	12.38
	Masonry body – cushion concrete	5.82	6.93	7.56
	Standard	3.00	3.00	2.50
Dam heel vertical positive stress	Calculated value (MPa)	0.09	0.09	0.07
	Permissible value (MPa)	>0		
Dam toe vertical positive stress	Calculated value (MPa)	0.25	0.24	0.23
	Permissible value 'MPa)	Min (1.60/3.50, 1.00)		Min (1.8/3.00,1.00)

It can be seen from the above calculations that the dam section anti-slide stability safety coefficients meet the specifications; there is no tensile stress at the dam heel, the compressive stress at the dam toe is less than the permissible stress value which meets the design specifications.

3.3 The sliding stability of the overflow dam

According to geological provisions, if a structural plane of gentle inclination exists in the bedrock of the dam then calculation of sliding stability of dam is necessary. By definition of gentle dip angles (less than 25^0) the dip angle of main failure are on the plane 7.5^0, 15^0 and 25^0 and the second failure planes are 15^0, 30^0 and 45^0: The inclination faults and angle of cracks are not given on the geological documents but when the angle between two sliding faces increases to a critical angle, the sliding stability can be calculated by the horizontal fault. According to the topography of spillway downstream, the deep sliding can be considered in general as double sliding face.

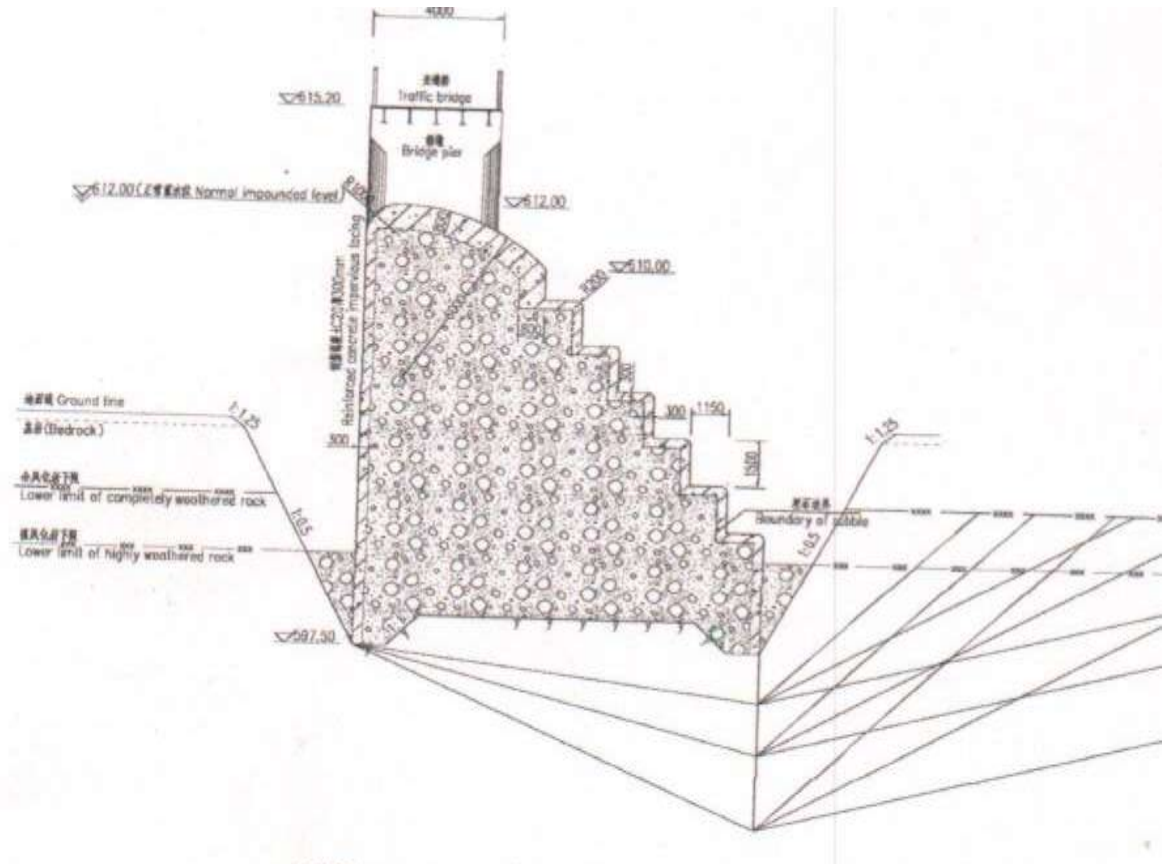

Fig. 2: Typical section for deep sliding stability of overflow dam

2.3.1 Load combinations

The sliding stability check only considers the normal level conditions due to the fact that downstream water level at design flood water level and check flood water level are favourable but to second slide mass.

2.3.2 Stability calculation

The deep sliding formula of dam foundation:

The first slide mass stability formula:

$$K_1^{'} = \frac{f_1^{'}[(W+G_1)cos\alpha - Hsin\alpha - Qsin(\varphi-\alpha) - U_1 + U_3 sin\alpha] + C_1^{'}A_1}{(W+G_1)sin\alpha + Hcos\alpha - U_3 cos\alpha - Qcos(\varphi-\alpha)} \quad (18)$$

The second slide mass stability formula:

$$K_2^{'} = \frac{f_2^{'}[G_2 cos\beta + Qsin(\varphi+\beta) - U_2 + U_3 sin\beta] + C_2^{'}A_2}{Qcos(\varphi+\beta) - G_2 sin\beta + U_3 cos\beta} \quad (19)$$

$K^{'}$and Q can be calculated by $K_1^{'} = K_2^{'} = K^{'}$

Where,

$K_1^{'}, K_2^{'}, K^{'}$ are the anti-slide stability safety coefficient (calculated by shear strength),
W is the vertical component force of all loads (without uplift pressure) acting on the dam body (in KN),
H is horizontal component force of all loads (without uplift pressure) acting on the dam body (In KN),
G_1, G_2 are vertical forces of first and second slide mass respectively (in (KN),
$f_1^{'}$, $f_2^{'}$ is shear strength friction coefficient of first and second sliding mass respectively,
$C_1^{'}$, $C_2^{'}$ are shear strength cohesion of first and second sliding planes respectively (in KPa),
A_1, A_2 are the areas of the first and second sliding face respectively (in m^2),
α, β are the angles between first and second horizontal planes respectively,
U1, U2, U3 are uplifts pressures of first, second and difference between two slide mass (in KN),
Q is the force between two slide mass and φ angle between horizontal planes respectively.

From the geological document, the shear strength friction coefficients of the first and second sliding face are 0.5, the shear cohesion strength of the first and second sliding face is 150Kpa.

The deep sliding stability calculated results of dam foundation are in the table below:

Table 4: The table of deep sliding stability calculated results.

α	7.5			15			25		
β	15	30	45	15	30	45	15	30	45
Q(KN)	278.50	252.5.	248.50	524.00	450.5.	444.50	954.00	828.00	817.50
K	3.30	3.20	3.20	3.15	3.05	3.05	3.10	3.00	3.00

As can be seen from the results, the safety factor (K) of the deep sliding stability meets the design requirement.

IV. CONCLUSION

From the above analysis, as the Mekin the spillway discharges its water the flow down the spillway is skimming flow. The water loses about 55% of its energy before reaching the downstream pool when the upstream water level upstream is at design flood level. When the water level upstream is at check flood water level the energy dissipation rate is about 48%. The dissipation rate decreases as unit width discharge increases.

Also, the water velocity of the spillway as it reaches downstream at design water level is $6.79m^3/s$ and is $7.78m^3/s$ when the water level upstream is at check flood level. Both velocities meet the maximum velocity condition which is $15m^3/s$. The scouring depths at deign and check flood water level are less than zero, meaning the flows cannot break the spillway foundation. The cavitation numbers for both design flood and check flood water levels are 18.85 and 10.4 respectively. These spillway cavitation numbers are very big meaning the cavitation erosion phenomenon cannot occur on dam surface.

Finally, the results obtained on table 3 show that the anti-slide stability safety coefficients meets the safety specifications as there is no tensile stress at dam heel and the compressive stress at dam toe is less than the permissible vale. Also the results on table 4 show the safety factor of deep sliding stability meet the design requirements.

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