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Sluice Safety Reliability Analysis - Application for Baovan Sluice in Vietnam

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Abstract*: The article summarizes the irrigation works designing methods in Vietnam and other countries. While in Vietnamirrigation systemdesign method is deterministic and based on safety factors analysis, in other countries it's popular with random design and reliability analysis. This is a modern design model and widely used in many fields in the world. Therefore, in this study, the authors presented how to develop sluice reliability calculation method under system analysis approach: definition of sluice s, problem tree, reliability functions for system simulation, calculation of reliability for works and works system, calculate reliability Bao Van sluice in Thanh Hoa province according to the introduced calculation model and proposie solutions to improve the reliability of the sluice if repaired or upgraded..

Keywords*: sluice, sonfidence function, reliability, destruction mechanism, random variable.

I. INTRODUCTION

In Vietnam irigation works design are mainly deterministic which is based on analysis safety factors. The safety level of the systems is assessed through hydraulics, stability and durability problems, in which technical specifications of the works are simulated in discharge and load bearing capacity of the works, regardless the effect of random variables and works components. Currently, many advanced countries in the world such as: Russia, China, Japan and some European countries have used random design methods and reliability standards in works safety assess. In random design methods, problems are more practical because this method fully considers the extent to which the randomness of the properties of construction materials and soils, as well as the load on the works. This method in addition to safety probability calculation for the entire system also provides a premise for risk analysis process in the future [1].

In Vietnam, there have been many studies on the reliability of irrigation works according to random theories: dykes, earth dams, culverts, spillways, ..., however, the application of this theory in calculation of reliability of sluice has rarely mentioned. For those reasons, the study has developed a method for calculating the reliability of sluice under system analysis approach. Reliability calculation is applied for Bao Van sluice in Thanh Hoa which results are analyzed to determine the level of impacts of various problems on the general reliability of the entire system against Russian reliability standards. Based on that, the authors introduced safety measures according to the reliability standards for the Bao Van sluice in case the sluice is in the need for upgrade, repair or new construction.

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II. THEORY

A. *Definition of an sluice*

Sluice is a type of hydraulic works that is used for flow regulation and water control, it's open, i.e., not covered with soils

This type of sluice is very popular for irrigation, drainage, flood protection, tile prevention, sands discharge works, and so on. It's often wide which width ranges from some meters to tens meters, thus, divided into openings. A typical sluice has 3 main parts [2]:

- Upstream serial part: maintaining forward, stable inflow with less water loss.
- Sluice body part: is the most important part of a sluice which regulates flow, controls water level, connects sluice with banks or other works.
- Downstream serial part: is the transition reach that maintains easy and evenly diffused outflow.

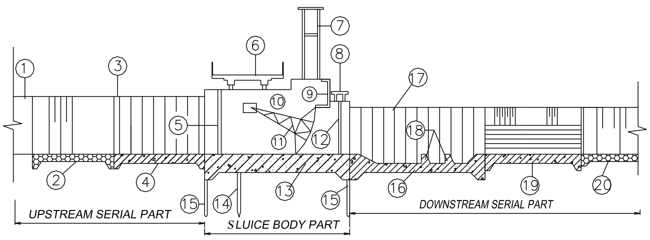

Fig. 1. Longitudinal section of a sluice

1. Upstream diversion; 2. Upstream stone masonry yard; 3. Upstream wing wall; 4. Upstream reinforced concrete yard; 5, 12. Stop-log; 6, 7. Bridge; 8. Stop-log placing bridge; 9. Retaining wall; 10. Abutment; 11. Valve gate ; 13. Bed sheet; 14 Reinforced concrete pier; 15. Anti-seepage piles; 16. Stilling basin bed; 17. Downstream wing wall; 18. Abutment;19. Downstream reinforced concrete yard; 20. Downstream stone masonry yard.

B. *Sluice simulation*

1) *Sluice's problem tree*

Problems of an sluice may arise by one or several associated causes. When mechanism of operation of a sluice is determined, problem tree is developed for sluice body which is considered as a system and each failure can be simulated with a destructive mechanism that may cause problem for the system.

Based on analysis of working characteristics of a sluice and the current sluice design standards, problem tree can be developed as in Figure 2 [3], [4].

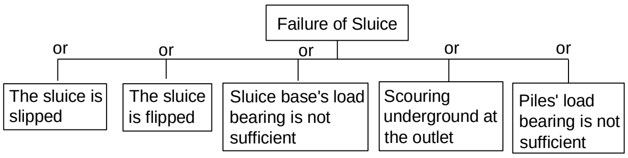

Fig. 2. Problem tree of a sluice

2) . Destructive mechanism and reliability function

Destructive mechanism is the cause of problem. Each destructive mechanism as illustrated in figure 2 constitutes a reliability function Z, which represents the relationship between load bearing and loads on the works [4].

$$Z = R(x_i) - N(y_j) \qquad (1)$$

In which:

$N(y_i) = N(y_1, y_2, ..., y_n)$ is load function;

$R(x_i) = R(x_1, x_2, ..., x_n)$ load bearing function.

x_i : main random variables, including: impact of water environment, soils and stone environment, works environment that constitute resistance against works' destruction.

y_i : main random variables, including: impacts of water environment, effect of ground environment through propterties of soils and stones as well as loads of works through properties of construction materials.

Under the research, some reliability functions have been developed upon the potential destrictive mechanisms for sluice : slipping, overturning, foundation's load bearing is not sufficient and scour at the outlet

a) Flat slides

Reliability function Z_1 is developed with calculation formula of probability of flat slide through contacting face between toe wall of sluice bed and ground soils [1], [4].

$$Z_1 = (\mathrm{P.tgj_I} + \mathrm{m_1.E_{b2}} + \mathrm{A.C_I}) - (\mathrm{T_1} + \mathrm{E_{C1}} - \mathrm{T_2}) \qquad (2)$$

In which: gross vertical forces P, passive pressure of soils on the downstream E_{b2}, working condition coefficient m_1, sliding surface area A, total upstream and downstream horizontal forces of the works T_1, T_2, active pressure of soil from upstream E_{C1}: are random variables identified upon surveys and monitoring records at the time of calculation.

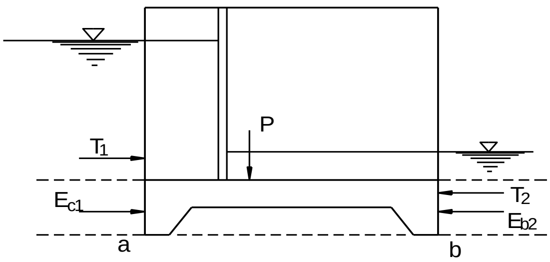

Fig. 3. Flat slide calculation

b) The sluice is flipped around an axis at downstream toe wall

The sluice may be flipped around an axis at the downstream toe wall when the total anti-torque moment $\sum M_{cl}$ is smaller than flipping moment $\sum M_{gl}$ [4], [6]. Reliability function Z_2:

$$Z_2 = \sum M_{cl} - \sum M_{gl} \qquad (3)$$

In which: $\sum M_{cl}$ load bearing function, $\sum M_{gl}$ load function. Random variables for calculating moment values such as water levels upstream and downstream sluice; density of concrete, the size of the sluice, the physical and mechanical properties of the foundation, are determined from the monitoring documents for many years, surveys and assessments of the current status of the works. at the time of calculation.

c) Sluice foundation's load bearing is not sufficient

The largest stress on the sluice often occurs at the upstream or downstream foot of the sluice. When the average stress at the foot ofsluice foundation exceeds the load bearing capacity of the sluice foundation, the sluice base is damaged ***[4]***.

$$Z_3 = R^{TC} - \sigma_{TB} \qquad (4)$$

In which:

R^{TC}: load bearing of ground soils;

σ_{TB}: average stress of sluice foundation.

R^{TC} and σ_{TB} function of many random variables such as : upstream and downstream water levels of the sluice; density of concrete, the size of the sluice, the physical and mechanical properties of the foundation, are determined from the monitoring documents for many years, surveys and assessments of the current status of the works. at the time of calculation.

d) Ground erosion at outlet

At the outlet of an sluice on fine sandy ground, ground erosion occurs when the permeability gradient at the outlet exceeds the permeability limit of the ground. Reliability function Z_4 is established on the correlation between slope of seepage flow at outlet (J_{ra}): function of load and limit seepage slope at outlet (J_{gh}) : load bearing function [3].

$$Z_4 = \left[(\gamma_d - \gamma_n).(1-n) + 0{,}5.n - \frac{H}{T_{tt}}.\frac{1}{\alpha.\sum \xi_i}\right] \qquad (5)$$

Random variables: γ_d, γ_n, n is the specific gravity of soil, water and soil porosity; $H, T_{tt}, \sum \xi_i$: is the permeable water head, the calculated thickness of the permeability layer, the total resistance coefficient of the parts in the basement permeability calculation diagram; α: coefficient.

e) Pile's load bearing is not sufficient

Individual piles' load bearing is not resistant against the largest load (P_{max}), excessive the pile's standard load bearing (P_o) and minimum load on the pile P_{min}) is below 0 [3]. Reliability function of problem is calculated according to (6a) and (6b)

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$$Z_{5.1} = P_o - P_{max} \quad (6a)$$
$$Z_{5.2} = P_{min} \quad (6b)$$

$Z_{5.1}$ and $Z_{5.2}$ are function of many random variables: dimension of pile (d), interval between piles (C), upstream and downstream water levels, density of concrete of sluice; size of sluice, physical and mechanical properties of ground.

C. *Reliability of sluice*

1) *Reliability of individual problems*

Safety probability (reliability) [5]:

$$P_{at} = P(Z > 0) \quad (7)$$

The calculation of works reliability level II, it's able to calculate P_{at} according to standard distribution function $\phi(\beta)$ [5]

$$\boldsymbol{P = P(Z > 0) = \phi(\beta)} \quad (8)$$

β: reliability indicator, calculated according to (9)

$$\beta = \frac{\overline{Z}}{\sigma_Z} = \frac{\overline{R} - \overline{N}}{\sqrt{\sigma_R^2 + \sigma_N^2}} \quad (9)$$

In which: $\overline{N}, \overline{R}, \overline{Z}$ và $\sigma_N, \sigma_R, \sigma_Z$ are mathematical expectation and standard deviation of load distribution function N, load bearing R and reliability function Z.

2) *Reliability of individual elements of the works*

It is assumed that the system has n works and m mechanisms of problems occurred in individual works, considering the mechanism of problem occurring independently. The problems are associated each with other according to the "or" port, the safety probability of the works i [6], [7]:

$$P_{at}^{CTi} = 1 - \sum_{j=1}^{m} \left(1 - P_{ij}\right) \quad (10)$$

The problems associate each with other according to the "and" port, the safety probability of the work i:

$$P_{at}^{CTi} = 1 - \prod_{j=1}^{m} \left(1 - P_{ij}\right) \quad (11)$$

In which**:** P_{ij} – Safety probability of individual problems is calculated according to (7)

3) *Reliability of sluice system*

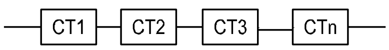

Fig. 4. Serial working diagram

A works is also considered a system of many interconnected elements, a sluice is also considered a system. The safety probability of the system according to the serial diagram (Fig. 4) is calculated according to (12) [7].

$$P_{at}^{HT} = \prod_{i=1}^{n} P_{at}^{CTi} \quad (12)$$

The system is safe if:

$$P_{at}^{HT} \geq [P_{at}] \quad (13)$$

In which: $[P_{at}]$: allowable reliability [8]

III. RESULTS AND DISCUSION

A. *Introductions to Bao Van sluice in Thanh Hoa*

Bao Van sluice is a works of grade II, built on Len river in Ha Trung district, Thanh Hoa province. The sluice's tasks are flood protection, drainage of flood water and taking water in Len river to supply water in dry season. The sluice design flow Qtk = 148.1 m3/s, it has 3 openings of 8m each, piers and abutment are 1.4m thick, valve gates are radial, sluice body is 17.6m in length. On the top of the culvert, there is a bridge, working bridge, bridge for stop-log and other specialized equipment. At the bottom of the sluice, there are 84 concrete piles which diameter is d = 0.3m. Based on observations, surveys and research and analysis of data about the Bao Van sluice, the potential damages are determined [9]. Calculations of sluice durability include:

- Check of stability of sluice body: sluice body slipped, overturned.
- Check the stability of the sluice: load capacity of the foundation, permeability transformations at the exit.
- Check the load capacity of the piles at the bottom of the sluice.

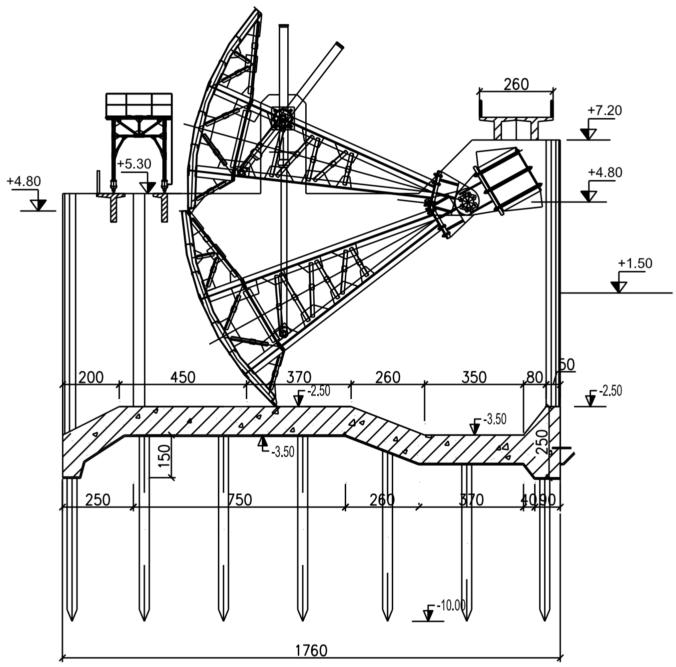

Fig. 5. Longitudinal section of Bao Van sluice in thanh Hoa

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B. Calculation data

Tab 1. Statistic characteristics of random variables ofreliability of sluice [9]

No	Random variable	Symbol	Mathematical expectation: μ	Standard deviation:σ	Probability distribution law
1	Density of concrete	γ_{bt} (KN/m^3)	25	1.19	standard
2	Length of sluice bed	L (m)	17	0.1	Standard
3	Elevation of threshold of sluice	Z_n (m)	-2.50	-	Deterministic
4	Elevation of crest of pier	Z_d (m)	+5.30	0.05	Standard
5	Width of 1 opening	b	8	0.08	Standard
6	Thickness of middle pier	Dg (m)	1.4	0.05	Standard
7	Thickness of bed	δ (m)	1.2	-	Deterministic
8	River side water level	H_1 (m)	+4.30	0.014	Standard
9	Land side water level	H_2 (m)	+1	0.01	Standard
10	Dry density of ground soils	γ_k (KN/m^3)	16.3	3.26	Standard
11	Internal friction angle of ground soils	φ (degree)	3.1	0.62	Standard
12	Unit cohesion	C (KN/m^2)	5.5	1.1	Standard
13	Porosity of ground soils	n	0.35	0.035	Standard
14	Thickness of seepage layer	T_o (m)	11	1	Standard
15	Density of water	$\gamma_n\left(KN/m^3\right)$	10		Deterministic
16	Thickness of seepage layer	T_o (m)	11	1	Standard
17	Total coefficient of resistance of parts at the sluice bed	$\sum \xi_i$	4.685	-	Deterministic
18	Coefficient α according to Antipov	α	0.621	-	Deterministic
19	Dry density of ground soils	γ_k (KN/m^3)	16.3	3.26	Standard

Tab 2. Statistical characteristics of random variables when calculating pile load bearing capacity [9]

No	Random variable	Symbol	Mathematical expectation: μ	Standard deviation: σ	Probability distribution law
1	Quantity of piles	n	84	-	Deterministic
2	Dimension of pile	d (m)	0.3	0.01	Standard
3	Distance between piles	C (m)	1.3	0.05	Standard
4	The compressive strength of concrete of pile	R_b (kg/cm^2)	135	6.75	Standard
5	The compressive strength of steel	R_a (kg/cm^2)	2700	50	Standard

C. Analysis of Calculations

Standard reliability is taken according to Russian reliability standards, [P_{HT}] system = 0.95 [8]. The system ensures safety according to the standards of reliability when: $P_{at}^{HT} \geq \left[P_{at}^{HT}\right]$

Tab 3. Calculated reliabilitys of Bao Van sluice

No	Problem mechanism	Reliability: P_{at}
1	Flat slide	0.9633
2	Overturning	0.9993
3	Sluice base's load bearing is not sufficient	0.9911
4	Ground erosion at outlet	0.9936
5	Pile's load bearing is not sufficient	0.9648
6	Reliability of sluice	0.9121

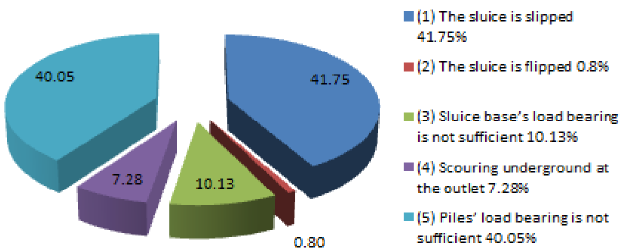

Fig. 6. Impacts of problems on Bao Van sluice

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- With the current data collected from the Bao Van sluice, reliabilitys calculations of various problems and

reliability of the system, showed that: $P_{at}^{HT} = 0.9121 \le \left[P_{at}^{HT} \right] = 0.95$ so the sluice is not safe according to the reliability standards. The sluice is likely to be of problem by two main causes: flat sliding and the piles under the sluice bed are not able to bear the load, which impacts on the reliability of the system are 41.75% and 40.05 %, respectivel. Other impacts are insignificant on the reliability of the system.

- Currently, Bao Van sluice operates stably according to Vietnamese design standards but does not meet the standards of random design and reliability analysis. Analysis of the reliability of the system showed that: 2 main causes of problems of Bao Van sluice are: sluices are likely to slip and piles that are not able to bear the load. Therefore, it is necessary to allocate the appropriate probability and weight for those porblem mechanisms when designing a new one or upgrade or repair of the headworks are required

IV. CONCLUSION

The study has summarized the research and design methods of irrigation works in Vietnam, and introduced a method to calculate the reliability of sluice in system analysis approach. It also performed reliability calculations for Bao Van sluice in Thanh Hoa, comparison against reliability standards and provided orientated remarks on the causes of problems for the sluice based on that solutions are recommended to maintain safety according to reliability standards if repair, upgrade or design a new sluice are required. The contents of the article is a practical reference for the design and safety management of irrigation works in Vietnam

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