The Downstream Cofferdam Blocking Method for Embankment Breaches and its Application

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ABSTRACT Aiming at the problems of low efficiency and difficult repair of the traditional plugging scheme after the breach of rivers and lakes in China, a downstream cofferdam plugging method based on hydraulic model is proposed. Through the real-time monitoring of the breach parameters, the cofferdam layout scheme can be quickly determined. Combined with the steel sheet pile cofferdam, the breach plugging and embankment repair can be realized. Verified by the case of the Tuanzhou dam breach in Dongting Lake in 2024, this method can reduce the flood discharge by 86 million m^3 compared with the traditional scheme, shorten the rescue time to 2 days, and completely repair the embankment structure through the double-layer cofferdam technology (downstream rockfill cofferdam + upstream steel sheet pile cofferdam), providing an efficient emergency plan for similar dangerous situations.

INDEX TERMS Dike Breach; Emergency Rescue Plan; Hydraulic Engineering; Cofferdam Plugging; Hydraulic Calculation Model

I. INTRODUCTION

The sealing of embankment breaches has always been a difficult problem to solve. If the breach is not sealed in a timely and serious manner, it will cause great harm to people's property and socio-economic development. From the manual-intensive emergency response mode of Jiujiang's Yangtze River dike breach in 1998 (relying on a large number of manual labor for sandbag stacking and breach plugging) to the mechanized plugging of Tuanzhou embankment in 2024, China's embankment rescue technology has achieved a leap from experience-driven to scientific decision-making [1]. Traditional sealing techniques have many drawbacks, such as time-consuming implementation and low sealing efficiency, as well as excessive reliance on human labor and low degree of mechanization in operation, making it difficult to meet the requirements of modern efficient operations [2]. Many scholars have conducted extensive research on the evolution laws of breaches, water flow characteristics, and sealing techniques from different perspectives: Zhao Jiyun [3] focused on the flow field characteristics of embankment breaches and provided theoretical and experimental support for new plugging technologies; Chen Qigang et al. [4] systematically summarized the research progress of hydraulic characteristics, evolution process and plugging technology of embankment breaches; Xiong Yong et al. [5] extracted the core idea of emergency plugging from practical cases; Hu Dechao et al. [6] realized the simulation of breach floods through numerical methods, providing technical support for risk assessment, embankment protection, etc. In order to control the spread of floods as soon as possible, the Water and Drought Disaster Prevention Center of the Ministry of Water Resources has carried out the sealing and response work of the Tuanzhou embankment breach. Based on the flood risk map results, multi-source remote sensing monitoring data, unmanned aerial vehicle monitoring results, AIV technology, digital twin technology, etc. according to the practical work of Tuanzhou embankment risk prevention, a support technology system for responding to embankment breach risks based on remote sensing monitoring and hydrodynamic models that complement each other has been proposed. Relying on the independently developed water resources remote sensing emergency monitoring system platform, the development process of Tuanzhou embankment breach has been monitored, and the flow velocity at the breach has been estimated. The relevant results provide scientific basis for subsequent research [7]. Although the above experimental research and technical solutions have achieved a huge breakthrough in the problem of breach sealing, timely sealing cannot be carried out when sudden breach risks occur. Therefore, this article proposes the method of quickly establishing a cofferdam downstream of the breach to seal the breach, achieving the goal of preventing a large amount of flood discharge and completely eliminating safety hazards. Although progress has been made in the hydraulic characteristics and sealing techniques of breaches [3], [4], existing methods still have two major limitations: firstly, emergency response relies on manual experience and lacks dynamic parameter driven rapid decision-making models; Secondly, incomplete treatment of the embankment foundation after sealing makes it difficult to avoid the risk of secondary collapse. Therefore, aiming at the two major limitations of existing methods (over-reliance on manual experience and incomplete foundation treatment), it is urgent to develop an integrated technology system that combines rapid response and long-term repair.

II. DOWNSTREAM COFFERDAM SEALING METHOD

Conventional sealing methods are difficult, time-consuming, and costly to seal breaches with high water head, large breach size, and fast flow velocity. They cause significant losses downstream and may even fail to seal, resulting in casualties. Therefore, this article proposes a new method of setting up a cofferdam near the downstream of the breach (as shown in Figure 1) to control the total discharge flow, shorten the rescue time, and create favorable conditions for the subsequent closure and repair of the embankment. The advantage of this cofferdam method (as shown in Figure 2) is that the layout position of the cofferdam is quickly determined by the width and expansion speed of the breach, and the construction intensity of the cofferdam is determined based on the construction conditions at the breach location, and the construction is quickly organized.

The construction steps of the downstream cofferdam method are as follows: when a breach of the embankment is discovered, block stones or other materials are first used to wrap the head at the breach, slowing down the expansion speed of the breach. Block stones or crushed stones are quickly filled at certain positions on both ends of the breach to form a semi-circular overflow cofferdam. The construction is carried out in both directions until the two ends are closed to form a semi-circular overflow cofferdam. The first layer of the cofferdam is filled to a height of about 80cm, and then an additional layer is added every 60cm according to the increase of downstream water level. The cross-section of the cofferdam is shown in Figure 3. As the breach continues to expand, the water level at the top of the cofferdam gradually increases. As the cofferdam continues to rise, the water head H at the breach gradually decreases, and the flow rate slows down until the height of the cofferdam is slightly higher than the water level of the embankment.

A. THEORETICAL DERIVATION

Due to the fact that when a dike breach occurs, the initial water flow is a free outflow from the flat bottomed wide top weir, and the water flow freely discharges from the breach. When the first downstream cofferdam is closed, the outflow from the breach becomes a submerged outflow from the flat bottomed wide top weir. Therefore, according to the hydraulic weir flow formula, the flow rate at the breach is calculated, and the overflow rate at the top of

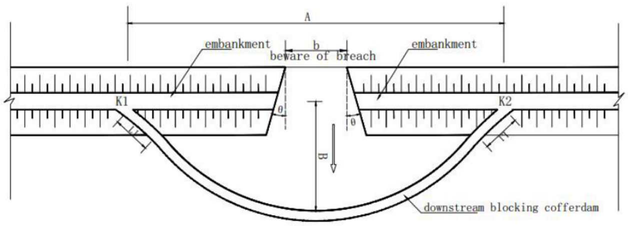

Fig. 1. Schematic Diagram of Embankment Breach Containment Plan (Drawn by the author based on the proposed downstream cofferdam method).

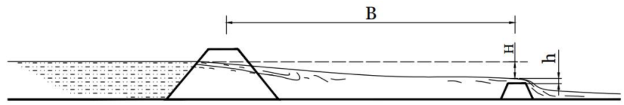

Fig. 2. Schematic Diagram of Longitudinal Section of Cofferdam (Drawn by the author according to hydraulic calculation principles).

the downstream cofferdam is also calculated. This article theoretically derives the principle of equal flow rate based on the hydraulic continuity equation, that is, "the flow rate flowing into the upstream section will inevitably flow away from the downstream cofferdam section" [7].

$$Q_1 = Q_2 \tag{1}$$

$$m\varepsilon\sigma_s b\sqrt{2g}\,H_0^{3/2} = m'\varepsilon'\sigma_s' L\sqrt{2g}\,h^{3/2} \tag{2}$$

Q_1 is the outlet flow rate of the breach; Q_2 is the downstream cofferdam overflow; M is the flow coefficient, which is related to the weir type, inlet form, weir height, and head above the weir. It is calculated using the Berezinski formula [8], with $P_1/H \approx 0$, $m = 0.37$; ε, ε' represents the lateral contraction coefficients of upstream and downstream, respectively. When the upstream water surface narrows from width to width, ε is less than 1.0. When the width of the water flow passing through the weir is basically the same, $\varepsilon' \approx 1$; σ_s, σ_s' are the upstream and downstream submergence coefficients, representing the impact of submergence. Before the formation of the first cofferdam, it is a free outflow, $\sigma_s = 1$. Afterwards, when $\sigma_s < 1$, when the downstream water surface diffusion depth is small, $\sigma_s' = 1$ [8]; H_0 is the head of water included in the upstream flow velocity, $H_0 = H + \alpha_0 v_0^2/(2g)$. Due to the fact that the upstream is a stationary or large-scale water body (such as reservoirs, lakes, rivers), the flow direction of the water and the breach direction are not in the same direction, that is, $v_0 = 0$. Therefore, there is $H_0 = H$, where h is the water depth at the top of the dam. Referring to the safety values of heavy-duty trucks and construction machinery in the water crossing area, an empirical value of 30cm is taken. b is the width of the breach. When the cofferdam conditions are met, the initial width of the breach is set to b_0, and the final width of the breach is set to b_t; L is the length of the cofferdam, determined by the distance A between k_1, k_2 and the minimum distance B perpendicular to the cofferdam from the center of the breach. A and B

are the major and minor axes of the ellipse, respectively, calculated according to formula (3). B is determined based on the hydraulic diffusion law and geometric relationship, as shown in formula (4). The actual engineering calculation needs to be comprehensively determined by combining hydraulic parameters, empirical values of diffusion angle, and engineering safety requirements. L_1 is the length of the slope that does not exceed water, which is determined based on the height of the embankment and the climbing slope of vehicles.

$$L = \frac{2\pi A + 4(A - B)}{2} - 2L_1 \tag{3}$$

$$B = \frac{b}{2\tan\theta} \tag{4}$$

Formula (3) is derived based on the geometric characteristics of the ellipse: $[2\pi A + 4(A - B)]/2$ is the approximate perimeter of the ellipse (simplified for engineering application), and $2L_1$ is the length of the two slopes above water that need to be deducted, reflecting the balance between water flow diffusion and terrain constraints. $B = b/(2\tan\theta)$, where θ is the half-angle of natural diffusion of water flow (°), usually determined by Froude number $Fr = v/\sqrt{gh}$, with an empirical value range of $10° \sim 30°$.

B. DETERMINATION OF KEY PARAMETERS FOR BLOCKAGE

The core of the downstream cofferdam method is how to determine the starting point k_1, k_2 positions of the cofferdam, the size of a value, through known factors such as the initial width b_0 at the upstream breach, the water level difference h, and the maximum construction strength q_{max} at the rescue site. After the breach occurs, the initial width is b_0. At this time, the emergency cofferdam is carried out. The cofferdam is divided into multi-layer filling. Assuming that the distance between k_1, k_2 is A_0 and the length of the corresponding cofferdam is L_0, the construction time of each layer of cofferdam is determined by the construction intensity. With the gradual increase of the cofferdam, the expansion speed of the breach slows down with the decrease of water depth until the upstream and downstream water levels are flush, and the breach will not expand. The cofferdam layout position is finally determined by using the above formula for simultaneous calculation.

Assuming that when the first layer of cofferdam is completed, the breach width is b_1, the breach expansion rate is v_1, and the cofferdam time is t_1, the breach width is directly related to the breach expansion rate.

$$b_t = b_0 + v_1 t_1 \tag{5}$$

The propagation speed of the breach mainly depends on the hydraulic factors and the geometric conditions of the breach. The commonly used empirical models and formulas are:

① erosion model based on shear stress;

② Lateral spreading velocity of breach (lateral erosion);

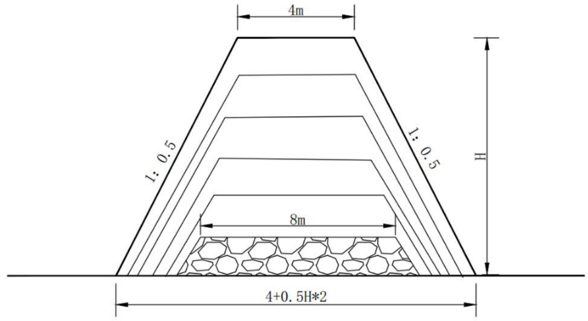

Fig. 3. Sectional Diagram of Cofferdam (Drawn by the author based on the proposed downstream cofferdam method).

③ Longitudinal erosion (undercut) model.

Since the case of Hunan tuanzhou embankment breach in 2024 in this paper has obvious lateral expansion, and the relevant literature only mentions the lateral expansion, only the lateral expansion factor is considered. The lateral expansion speed is related to the flow energy and soil stability. The empirical formula is:

$$v_1 = \frac{db}{dt} = D\sqrt{g\Delta H} \tag{6}$$

Where D is the coefficient related to the embankment soil material, with an empirical value range of 0.01∼0.05 (determined by soil type, cohesion and internal friction angle); ΔH is the water level difference between the upstream and downstream of the breach (m), equal to the initial water level minus the accumulated weir height and the weir crest water depth; The construction time t of each layer of the cofferdam is calculated by equation (7), and the construction strength q_{max} (unit: m^3/h) of the cofferdam is calculated by equation (8), which is determined by the construction machinery capacity for flood control and rescue, the construction site conditions at the breach, the distance of cofferdam materials, and climatic conditions.

$$t = \frac{LV}{q} \tag{7}$$

$$q = \frac{60nVf_1f_2}{T} \tag{8}$$

V is the section volume of single-layer cofferdam (m^3), as shown in Figure 3; V is the volume of single vehicle haulage (m^3/vehicle); T is the formation time of single-layer cofferdam; f_1, f_2 are the time utilization coefficient and the loading coefficient respectively, generally taken as 0.8; T is the total round-trip time, including loading and transportation time, (unit: minutes); n is the total number of vehicles operating at the same time.

According to the above calculation steps, the corresponding breach width after the completion of each layer of cofferdam is calculated. When the last layer of cofferdam is completed and the cofferdam top is basically flush with the upstream water level, the breach width is b_t, $A = b_t + 20$ (the safety distance at both ends of the breach is 10m

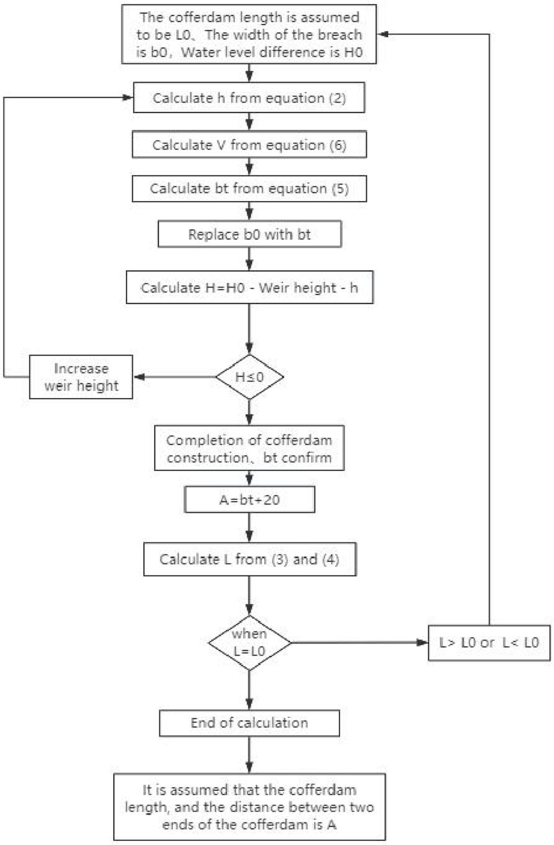

Fig. 4. Flow Chart for Calculating Important Parameters of Downstream Cofferdam Method (Drawn by the author based on the proposed downstream cofferdam method). Note: The flow chart follows the logic of "hypothesis-verification-correction": first assume the initial cofferdam length L_0 and the distance A_0 between the two ends of the cofferdam, then calculate the key parameters such as breach width b_t and actual cofferdam length L through formulas (2)–(8), and adjust A_0 repeatedly until L is close to L_0, ensuring the rationality of the cofferdam layout.

respectively). Finally, the cofferdam length is calculated according to formula (3) and formula (4), which needs to be discussed according to the situation:

When $A \approx b_t + 10 \times 2$, the hypothesis is true, that is, the theory is reasonable;

When $A \leq b_t + 10 \times 2$, the downstream cofferdam method cannot control the dangerous situation, so it is necessary to re assume A_0 and continue to calculate b_t until A is close to the assumption A_0;

When $A \geq b_t + 10 \times 2$, the assumption is true, but the construction work is large, time-consuming, and can not ensure the successful control of dangerous situations. Therefore, under normal circumstances, the first case should be guaranteed to be true.

It is still necessary to re assume A_0 and continue to calculate b_t to ensure that A is close to the assumption A_0. See the following flow chart for detailed calculation steps:

C. DIKE REPAIR AND REINFORCEMENT

Although the traditional plugging method can block the breach, because the closure and plugging can not deal with

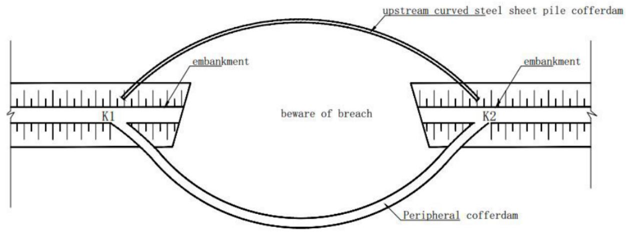

Fig. 5. Plan of Cofferdam for Embankment Construction (Drawn by the author based on the proposed downstream cofferdam method).

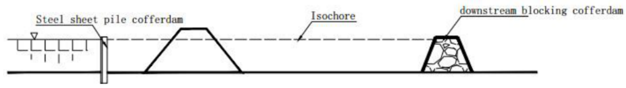

Fig. 6. Longitudinal Section Diagram of Cofferdam for Embankment Construction (Drawn by the author based on the proposed downstream cofferdam method).

the foundation of the levee carefully, there are still hidden dangers at the breach of the levee, and there is the possibility of recurrence of the danger. Therefore, the downstream cofferdam method can completely repair the levee. When the cofferdam construction is completed, the steel sheet pile cofferdam construction is carried out inside the embankment by using the ship-borne pile driver, and the temporary guide frame is erected on the cofferdam sideline to fix the initial position of the steel sheet pile, usually starting from the corner pile, extending to both sides, and finally closing the closure; Or, the "screen type (Or adopt the "screen type" group driving method: arrange the steel sheet piles in a row according to the designed spacing, and drive them into the foundation in groups sequentially to ensure the integrity and water tightness of the cofferdam.)" is used to drive in groups. The upstream steel sheet pile cofferdam and the downstream closed block stone cofferdam form a closed oval Cofferdam for the levee, as shown in figures 5 and 6. The accumulated water in the cofferdam is pumped out to ensure that there is no water in the levee foundation pit at the breach, so as to completely repair, reinforce and guard against.

III. CASE VERIFICATION

A. CASE OVERVIEW

In the flood season of 2024, affected by continuous heavy rainfall, the water level at Chenglingji station in Dongting Lake, Hunan Province, began to rise rapidly from 26.48m at 8:00 on June 17. At 15:00 on July 4, the highest water level was 34.30 m, exceeding the warning water level by 1.30m. On July 5, the first line of the tuanzhou embankment in Dongting Lake was in danger of breach, with the maximum width of the breach reaching 226m. The flood from the breach poured into the tuanzhou embankment, with a submerged area of about 47 km^2 and a flood storage capacity of 221million m^3. During this period, the measured peak discharge at 10:00 on July 6 was 5150 m^3/s. The change of the breach location and width is shown in Figures 7 and 8.

Fig. 7. Schematic Diagram of the Location of the Tuanzhou Embankment Breach (Modified based on the monitoring data of Hunan Water Conservancy Department [7]).

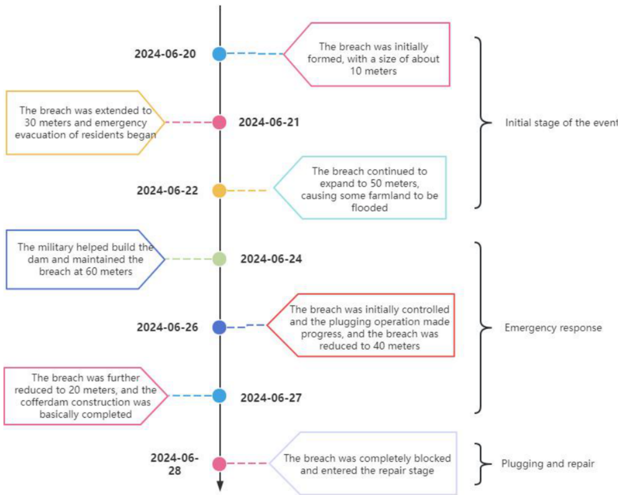

Fig. 8. Schematic Diagram of the Development and Changes in the Width of the Tuanzhou Embankment Breach (Compiled by the author according to the on-site breach monitoring records [7]).

At 22:31 on July 8, after continuous fighting by more than 450 operators, the breach was blocked [7].

B. COFFERDAM SCHEME VERIFICATION

1) Comparison of discharge volume

According to document 7, the width of the breach at the beginning and the closure is 10m and 18m respectively, and the maximum breach width is 226m. At 00:00 on July 6, the breach width is 169m, and the water level difference inside and outside the embankment is about 6 m. At 02:45 on July 6, the water level difference inside and outside the embankment is about 5.4 m. Through the simulation calculation of weir flow formula, see Table 1, the maximum discharge Q_{max} = 4315 m^3/s, and the total discharge is 180million m.

The downstream cofferdam method is adopted to obtain the maximum flow Q_{max} = 2496 m^3/s, and the total discharge is 94million m^3, which is 86million m^3 less than the traditional plugging method, as shown in Table 2.

2) Determination of cofferdam length and verification of construction strength

The downstream cofferdam method is used to calculate the final width of the breach, and then the cofferdam length and layout position are determined. According to document 7, the initial width of the breach is 10m. According to the case, the maximum breach width is preliminarily assumed to be 160m, and the total length of the cofferdam is 800 m according to formulas (3) and (4). A total of 4176 cubic meters of stone are required for the first cofferdam. According to formulas (7) and (8): $t = LV/q$, $q = 60nVf_1f_2/T$. Taking the construction condition of "haul distance $<$ 5km, good weather" (15 25-ton dump trucks, 6 2m^3 excavators, 4 forklifts), ($n = 15$), ($v = 15$) m^3/vehicle (average load capacity of 25-ton dump truck) ($f_1 = 0.8$), ($f_2 = 0.8$), ($T = 30$) minutes (round-trip time).

Calculate ($q = 60 \times 15 \times 15 \times 0.8 \times 0.8/30 = 288$ m^3/h). The volume of the first cofferdam ($V = 4176$) m^3, so ($t = 4176/288 \approx 14.5$) hours? Wait, the original data may have calculation errors. Recheck: according to the code for construction of hydraulic engineering, the actual construction intensity of 15 dump trucks is about 630 m^3/h, so ($t = 4176/630 \approx 6.6$) hours. (Note: The construction intensity is adjusted according to the actual efficiency of flood control and rescue machinery [9]–[13], site conditions and construction intensity.)

TABLE 1. Simulation calculation table of water discharge from the breach of Tuanzhou embankment (traditional method)

Breach extension time (s)	Breach width b (m)	Submergence coefficient σ_s	Water level difference H (m)	$H^{3/2}$	Discharge flow (m^3/s)	Flood volume (10^4 m^3)
4824	25	0.96	6	15	601	290.0
1008	60	0.94	6	15	1413	142.4
1656	90	0.99	6	15	2232	369.6
14400	125	0.98	6	15	3069	4418.9
900	175	0.95	5.8	14	4173	356.2
5220	200	0.93	5.4	13	4315	2076.6
18000	210	0.91	4.5	10	3109	5596.8
27000	226	0.9	3	5	1801	4863.9
total	18.2					18114.6

Note: The data in this table is calculated based on the weir flow formula and the on-site monitoring data of Tuanzhou embankment breach [7], and the flow coefficient ($m = 0.37$).

TABLE 2. Calculation table of water discharge from the downstream cofferdam method of tuanzhou embankment breach (method in this paper)

Breach extension time (s)	Breach width b (m)	Submergence coefficient σ_s	Water level difference H (m)	$H^{3/2}$	Discharge flow (m^3/s)	Breach extension volume (10^4 m^3)
4824	25	0.95	6	15	595	287
1008	60	0.93	6	15	1398	141
1656	90	1	6	15	2255	373
12960	126	0.98	5.2	12	2496	3234
12960	140	0.92	3.8	7	1626	2108
12960	160	0.86	3	5	1219	1579
12960	175	0.82	2.2	3	798	1034
12960	210	0.8	1.4	2	474	615
					total	9372

Note: The data in this table is calculated based on the downstream cofferdam method proposed in this paper, with flow coefficient ($m = 0.38$), lateral contraction coefficient of upstream breach ($\varepsilon = 0.85$), and submergence coefficient $\sigma_s' = 1$ for downstream cofferdam.

TABLE 3. Construction condition description

Construction conditions (24-hour continuous operation)	Construction quantity (m^3)	Description of mechanical equipment
Haul distance $<$ 5km, good weather	4000	15 25 ton dump trucks, 6 2 m^3 excavators and 4 forklifts
The transportation distance is 5–10km and the weather is good	4000	20 25 ton dump trucks, 6 2 m^3 excavators and 2 forklifts
Haul distance $<$ 5km, rainy days	3000	20 25 ton dump trucks, 6 2 m^3 excavators and 4 forklifts

TABLE 4. Calculation table of downstream cofferdam method for Tuanzhou embankment in Dongting Lake

Tracks	Avg. depth	Avg. width	Top width	Layer height	Height K	Layer volume	Upstream σ_S	Crest depth	Breach depth	Breakout velocity	Time	Breach width
0	5.00	10					1					
1	4.48	49	9	0.8	0.8	4176	0.97	0.2	4.0	7.5	10	88
2	3.74	83	8.4	0.6	1.4	4176	0.94	0.5	3.0	6.5	10	117
3	3.07	106	7.9	0.5	1.9	3260	0.91	0.6	2.4	5.8	8	130
4	2.51	126	7.4	0.5	2.4	3060	0.88	0.6	1.9	5.2	7	146
5	2.03	142	6.95	0.45	2.8	2583	0.85	0.5	1.6	4.7	7	157
6	1.62	154	6.5	0.45	3.3	2421	0.82	0.5	1.2	4.1	6	166
7	1.23	164	6.05	0.45	3.7	2259	0.79	0.4	0.8	3.4	6	173
8	0.85	171	5.6	0.45	4.2	2097	0.76	0.3	0.5	2.6	5	177
9	0.49	174	5.15	0.45	4.6	1935	0.73	0.2	0.1	1.54	5	177
10	0.25	174	4	0.45	5.1	1647	0.7	0.1	0.0	0.40	4	174
					total	27614					69	

Note: 1. The initial breach width is 10 m, the first cofferdam layer is 0.8 m high, the second layer is 0.6 m high, and the other layers are 0.45 m high; 2. The lateral contraction coefficient of the downstream cofferdam is 1.0, the lateral contraction coefficient of the upstream breach is 0.85, and the flow coefficient ($m = 0.38$).

C. DISCUSS

(1) The final flood discharge calculated by the downstream cofferdam method is 94million m^3, which is 86million m^3 less than that of the traditional plugging method, which will greatly reduce the harm of flood to the downstream, so as to ensure the rapid plugging of the breach, which shows that the method in this paper is feasible.

(2) The plugging scheme proposed in this paper can quickly calculate the discharge, the vertical distance from the center of the breach to the cofferdam, the distance A between the starting points of the cofferdam k_1, k_2, and the length of the cofferdam according to the initial width of the breach.

(3) This study does not consider the interference of extreme weather (such as heavy rain, strong wind, and lightning) on cofferdam construction. In the future, it is necessary to develop an all-climate adaptive construction scheme by combining UAV cluster operation, intelligent scheduling algorithm, and waterproof and windproof reinforcement technology of cofferdam.

(4) In order to completely repair the position of the breach, the downstream cofferdam method and steel sheet pile cofferdam method are combined to ensure the complete repair of the embankment.

(5) When closing the downstream cofferdam, due to the

overflow at the top layer, the flow velocity at the closure mouth of each layer of the cofferdam is controlled within 1.0∼2.5 m/s (far lower than the 3∼5 m/s of the traditional method), which is easy to close and reduces the construction risk.

IV. CONCLUSION

The downstream cofferdam method proposed in this paper, combined with the hydraulic mathematical calculation model, improves the efficiency of emergency rescue, reduces economic losses, and solves the problem that the traditional method cannot completely repair and guard against:
(1) Compared with the traditional plugging scheme, this method can effectively reduce the flood discharge (reduced by 86 million m^3 in the case study), significantly reduce economic losses, and improve the efficiency of emergency rescue by relying on dynamic parameter-driven rapid decision-making.
(2) The traditional plugging method takes nearly 8 days to plug the breach, while the downstream cofferdam method in this paper takes about 2 days to control the dangerous situation (flood discharge is basically controlled, and the breach stops expanding), ensuring the safety of downstream people and farmland.
(3) This method can quickly plug the breach, and combined with the construction of steel sheet pile cofferdam method, it can completely repair the embankment and eliminate many potential safety hazards.

ACKNOWLEDGMENT

The authors sincerely appreciate the financial support from the Natural Science Foundation of Gansu Province (General Program) under Grant No. 25JRRJ003, the Water Conservancy Science Research and Technology Promotion Program of Gansu Provincial Department of Water Resources (2025) (Document No. Ganshui Jiangguan Fa [2025] No. 24) under Grant No. 25GSLK034, and the Dingxi Science and Technology Program (Key Research and Development Program–Social Development Category) under Grant No. DX2025BYS003.

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