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Research Progress on Analysis Methods and Reinforcement Technologies for Culverts Beneath Earth Dams

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Abstract: The culvert of an earth dam is water conveyance and flood discharge structure in hydraulic engineering. Its safety and stability directly affect the safety of the dam operation. Through a literature review, this paper systematically summarizes the functions, cross-sectional shapes, and common defects of culverts. Additionally, the research and application progress of analytical techniques for seepage and structural stability are reviewed. Furthermore, the engineering applicability and durability enhancement effects of recent reinforcement technologies, such as trenchless repair methods and structural reinforcement measures, are summarized. Finally, by analyzing typical engineering applications and recent research on computational and reinforcement technologies, the paper proposes reference recommendations for future development trends in culvert analysis and reinforcement.

1. Introduction of Culverts beneath Earth Dams

1.1 Functions and Structural features

The culvert beneath an earth-rock dam serves several critical functions, including flood discharge, irrigation, and reservoir drawdown. It is a typical water conveyance component in small- and medium-sized earth-rock dams and was widely used in such dams constructed in China from the 1950s to the 1970s [1]. The culvert is typically constructed through the dam from upstream to downstream, as illustrated in Figure 1. Its cross-sectional shape can be designed as circular, rectangular, or city-gate shaped, depending on the topographical and geological conditions of the project. Since the service environment is complex and dependent on internal seepage and external loading, plain concrete and reinforced concrete are commonly used [2] because they were built earlier. Because the design standards were low and construction quality was poor, management and maintenance issues caused structural failures in most old culverts such as cracks, joint misalignment, foundation erosion. These problems lead to more leakage and even piping failure [1].Design parameters of the culvert such as burial depth, engineering properties of the subsoil, and cross-sectional specifications affect internal stress state and stability of the dam. External loads (inhibitory water pressure, soil pressure, uneven settlement) cause deformation, resulting in the structural response of the dam very sensitive [2]. To address these problems, reinforcement technologies based on safety evaluations have been developed for improving the dam-culvert system performance and safety.

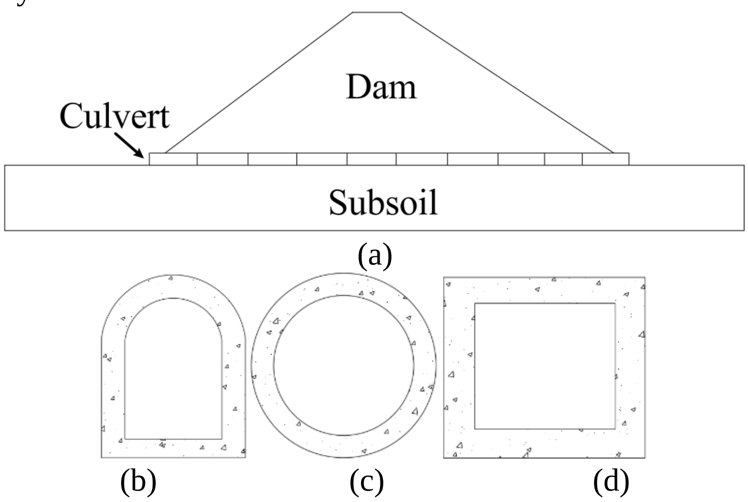

Figure 1: (a) Culvert constructed through the dam from upstream to downstream; (b) City-gate shaped cross-section; (c) Circular cross-section; (d) Rectangular cross-section.

1.2 Common Defects

The earth dam is one of the primary types of dams used in hydraulic engineering projects. Earth dams with through culverts were mainly constructed in China between the 1950s and 1970s. Due to the economic and technical conditions and construction standards of that era, issues such as unreasonable design, poor material durability, and substandard construction quality were common in these culverts. After long-term operation, culverts are prone to quality problems such as dam leakage, concrete cracking, and uneven settlement. These defects affect the structural stability of the dam and the operational functionality of the reservoir [3]. Leakage primarily originates from failure of joint waterstops, carbonation of concrete, or nonuniform deformation between the soil and structure. Longitudinal or circumferential cracks in concrete structures are often caused by thermal stresses, external loads, and insufficient strength of the culvert [4]. Also uneven settlement of the soil under the culvert is due to incomplete foundation treatment, inadequate backfill compaction or changes in external hydrogeological conditions. The formation of these defects is important for safe operation of old earth dams. They are caused by aging materials, environmental erosion, and long-term loading. Hence, they need to be studied and identified precisely to be reinforced and repaired in future.

2. Analysis of Seepage and Structural Stability

2.1 Simulation Methods of Seepage

The earth dam withstands the water head difference between upstream and downstream water levels. Seepage behavior directly impacts dam safety. Currently, seepage analyses generally rely on partial differential equations based on Darcy’s law and the continuity equation. Boundary conditions are derived from saturated-unsaturated flow theory [5]. With advancements in computational mechanics, the finite element method (FEM) has become a common tool for simulating seepage due to its strong adaptability to complex geometric boundaries and nonlinear materials, for example, researches listed in Table 1. The commercial software ABAQUS is one of the most powerful FEM programs because of its multiphysics capabilities and nonlinear solvers. Consequently, it is widely used for solving two-dimensional and three-dimensional seepage problems in earth dam projects. Researches show that cutoff rings at the junction between the culvert and the clay slope can change seepage paths, decrease the pore pressure gradients, and suppress concentrated seepage around the culvert [15]. Variation of flow velocity field, pore pressure distribution and seepage stability indicator can be quantified using numerical models under different loading conditions [5]. Real cases such as earth dam leakage were studied using FEM, and both seepage status and outlet slope stability were evaluated [7]. Combining theoretical analysis with high precision numerical simulation is also a useful way to improve seepage assessment of culverts beneath earth dams.

Table 1: Typical seepage research on earth dams using the finite element method.

Software	Dimension	Reference
ABAQUS	3D	[5]
ABAQUS	2D	[6]
SEEP/W	2D	[7]
SEEP/W	2D	[8]
AutoBank	2D	[9]
COMSOL	2D	[10]
COMSOL	3D	[11]
DIANA	2D	[12]
MIDAS	2D	[13]
ANSYS	2D	[14]

2.2 Analysis Methods of Structural Stability

The structural stability of earth dams is critically important, as it directly affects operational safety. To evaluate the mechanical behavior and stability of culverts, various analytical and numerical methods have been employed in in-depth research. Tian et al. systematically analyzed the stability of the combined downstream slope and retaining wall structure under normal loading conditions using the Morgenstern-Price method and the Geo-Studio program. They clarified the stress distribution characteristics at the contact interface between the retaining wall and the dam. Consequently, sliding and overturning stability safety factors were derived, and the height ratio between the dam and the retaining wall, as well as the downstream slope ratio, were identified as key factors influencing dam stability [16]. Dai et al. simulated the stress and deformation of culverts under high backfill soil conditions using ABAQUS software. Their results showed that the settlement of the culvert center is directly proportional to the height of backfilled soil, and at the same time, the height has different influences on the culvert settlement depending on the buried method used for culverts [17]. Additionally, for circular cross-sectional culverts, Cai et al. established the governing differential equation of an elastic curved beam under complex loading and proposed a closed-form analytical solution for internal forces and displacements. This solution can also be used to validate crack resistance, providing a concise and valuable analytical tool [18]. These studies improve the stability analysis of culverts beneath earth dams, providing technical support for design optimization and safety assessment.

3. Research Progress in Reinforcement Technologies

3.1 Trenchless Repair

In recent years, trenchless technology has shown remarkable technical advantages and promising application prospects in the repair and reconstruction of culverts beneath earth dams. This technology allows to install, replace and repair culverts without excavation and thereby preserve construction safety and stability, and to minimize disturbances to the dam. Among these methods, lining, a trenchless repair method, often uses PE pipes for in-situ insertion and grouting, creates composite structure which increases the impermeability and load-bearing capacity of old culverts [19], and drilling grouting improves density and integrity of the soil by injecting composite grouts into holes and cracks around the culvert and prevent seepage along the culvert [20]. Trenchless horizontal directional drilling technology can achieve directional guiding drilling under difficult geological conditions, avoid dam collapse risk associated with blasting excavation and reduce construction time [21]. Projects have shown that trenchless technology is easy to construct, environmental adaptation and easy maintenance [22,23]. Because of its high performance in improving structural safety and durability, trenchless technology is widely promoted and used for reinforcement and hazard mitigation projects for endangered reservoirs. However, its performance depends on accuracy of geological surveys and control of construction parameters, which requires optimization design and construction strategy.

3.2 Structural Reinforcement

The structural reinforcement of the culverts beneath earth dams is related to overall safety and durability of earth dams. For concrete culverts with cracks or cavitation, one or three layers of high-strength carbon fiber fabric can be applied to the inner walls of concrete culverts to improve strength and waterproof reinforcement [24]. Recently trenchless lining repair technology has evolved rapidly. Flexible lining system and high-strength grouting allow a collaborative load-bearing between new and old structures, not only improve crack resistance and impermeability but also reduce construction disturbance to the dams [25,26]. Studies based on pipeline mechanical behavior analysis show that filling the circular gap can reduce cross-section deformations and therefore cost [27]. Cross-section shape, burial depth, hydrogeological conditions, and construction feasibility should be considered when selecting the structural reinforcement measures. Future work will focus more on new material applications, structural durability and intelligent construction technologies, which will lead to more refined reinforcement solutions for culverts beneath earth dams.

4. Applications and Prospects

4.1 Typical Applications

Safety of culverts directly affects stability of the dam. To solve common problems like aging and leakage of culverts of small reservoirs, trenchless drilling has proved to be efficient and feasible rehabilitation technique because of the low disturbance of the dam and shorter construction time [21]. Hence, this technique allows precise guidance to install new pipes without the structural damage risks posed by traditional excavation. Several small reservoirs successfully have benefited from using it and the culverts were well-functioning repaired. Structural durability and seepage resistance were greatly improved. For culverts with seepage problem, as shown in [7], three dimensional seepage simulations using finite element method can identify seepage escape points and hydraulic gradient distribution, providing solution condition for stability analysis of outlet slope under seepage. Results showed that long-term operation the downstream slope remains stable. This is a valuable technique for reinforcement of culverts under similar situations.

4.2 Future Development

As earth dam service life increases, seepage and aging risks in culverts become more evident. It is important to develop efficient and durable reinforcement technologies that can adapt to complex operations. Simulation methods include coupled analyses of seepage zones, transition zones, and normal zones for determining through-going leakage, as well as DEMs for analyzing soil particle movements under seepage [28,29] for refine analysis and simulation. In addition, recent theories and simulation technologies from related fields (for example underground pipeline engineering [30,31]) can be used to perform sophisticated analysis and simulation. The result is scientific basis for design, construction and reinforcement. Recent advances in trenchless dredging technology have introduced new methods for culvert maintenance. For instance, a vision-guided robot of intelligent dredging robot based on vision-guided obstacle removal reduces structural disturbance [32]. Inspired by the development of new repair materials [33], future work may also explore smart composite lining materials with microcrack self-healing. Intelligent monitoring systems dynamically track seepage evolution and structural deformation to support safety evaluation.

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