Researches in Application of Stockade Box Structure in Ancient Dams

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Abstract. With advantages of stability and long service life, stockade box structure had made significant contributions to water conservancy in ancient times, by reducing the damage caused by flood. This paper focuses on the structure’s working principle, effects, mechanical property, etc., and provides improvement suggestions by applying modern scientific and technological approaches, in order to provide reference from the knowledge and design of the ancients in modern water conservancy projects.

1. Introduction

Under the circumstance that the ancients only had poor infrastructure and quite undeveloped science and technology, dam played an important role in our development of agriculture [1]. According to the record of world’s dam project history, the world’s first dam was built over 5000 years ago, while the earliest dam project in existence in China, Liangzhu Dam located in Hangzhou, was built over 4700 years ago.

By construction material, ancient dams can be classified as earth dam, wood dam, hay dam, ash dam, wood cage filled with stones, etc. However, affected by multiple factors, the structure of most ancient dams was not stable, resulting in a comparatively short service life. For example, earth dam illustrated in Figure 1 and wood illustrated in Figure 2, have poor structural stability with limitation of construction technology and materials in ancient times. Therefore, after summarizing the advantages and disadvantages of each material and structure of dams, the ancient Chinese developed stockade box dam. Stockade box dam is formed with each unit enclosed by corrosion resistant pine boards, and filled with coarse aggregate and fine aggregate to enhance the stability, which makes the dam a whole stable structure with high reliability. Preserved dams with this structure still perform well so far, emphasizing the ancient wisdom in water conservancy.

Through study on ancient stockade box dam, this paper elaborates its fundamental concept and form, explains its working principle, and analyses its structural rationality by mechanical analysis. In the end
of this paper, based on today’s technology and building material, we list several improvements for this dam structure, which may provide inspirations to specific projects.

2. Basic conception and form of stockade box dam

In ancient times, without rebar and concrete as common building material, the ancients had developed lots of technologies to resolve the issue of flood and waterlog, including the stockade box dam [2]. Classified by construction material, stockade box is a wood structure. Similar with most Chinese historic buildings, pine is the first choice because of its corrosion resistance, stiffness and high density. It was widely used to build barrages and dams since pine structure sinks in water instead of floating upon water. The structure is similar to steel sheet pile, and mortise-tenon joints and binding straps ensure the structural stability. And the structural stability is further enhanced by filling well graded clay and gravel into the enclosed stockade box. Embedded into bed, stockade performs a function of anchorage of the dam, just like caisson foundation. Due to the large scope of work, a dam is usually divided into many separate units bonded to each other. Each unit is enclosed with combinations of stockade, and filled with clay inside. Because of the wide range a dam surrounds, no brace can hold the dam side. Thus, each unit is capable of resisting overturning, sliding and tension at the joints. Common styles include cylinder, partition wall type, etc.

3. Working principle of stockade box dam

Stockade box structure takes its fundamental effect through basic water retaining and strengthening of earth dam. One unit of stocked box can be divided into two parts: the first part is its exterior framework, a box built by numbers of pine boards shaped into rectangular with 3 to 4 meters long and 0.4 meter wide, fixed to each other by mortise-tenon joints and straps, the bottom end of which is pointed in order to help anchor the box into the bed; the second part is the aggregate filled inside, which usually contains gravel, coarse sand, fine sand, straw, lime, etc. Volumes of gravel piled in the bottom, plays a big part in lowering the centre of gravity to improve the stability. And then, fine aggregate is poured into the box after fully mixed. When the stockade box structure is settled into water, because of wood boards pressing to each other after water swelling, wood framework will become even firmer, and provide extra structural reliability. Even long-term service shows no structural failure, which proves stockade box structure a very stable dam structure that is even practical in some deep-water projects.

![Figure 3. Illustration of stockade box dam](image)

4. Effects of stockade box dam

In the middle and lower reaches of the Long River, the major site classification of soil is sand, the properties of which include high permeability and poor structure. Meanwhile, the value of Plasticity Index of the bed silt is relatively low. Common wood piles or dams are effective at completion. However, silt is washed away easily during the service life, resulting in structural failure at the bottom of dams. Stockade box structure provides an effective solution to this issue. Because this dam structure is a group of separate heavy box units, it can be solidly anchored into bed silt by corrosion resistant pine boards. Besides, once driven into the bed, air pressure will help fix its bottom to the bed thanks to the large
bottom area. In addition, even if one unit failed, other units still work, which reduce the loss and improve the maintainability. Thanks to all these properties, stockade box dam has the advantages of high corrosion resistance, high overturning resistance, etc. Nowadays, this structure can still be found in some well-preserved water conservancy projects.

5. Mechanical analysis of stockade box dam

From the bottom stiff saturated soil to the top flow surface, being immersed in water all the time, a dam is bearing loads from both earth pressure and water pressure. The soil underneath water is all saturated soil with maximum moisture content value. The stockade box dam studied this time has a depth of 4 meters under water. It sits on impermeable rock, with an embedment depth of 1.5m in silty clay, and 2.5m above clay. Loads can be divided into two parts: water pressure above the clay and active earth pressure from the clay.

Several assumptions are made in this analysis: firstly, soil retained by the dam is idealized as homogeneous isotropic material; Secondary, assume that the dam is under constant loads (ignore the difference of water flow, displacement and settlement of soil); Thirdly, the dam is idealized as a whole rigid object [3].

The retained soil is saturated silty clay. Given $\gamma_{sat} = 17\text{kN/m}^3$, $\phi = 26^\circ$, $c = 0\text{kPa}$. Use the density of water $\gamma_w = 10\text{kN/m}^3$.

Using Rankine Approach:

Calculate the water pressure

$$P_w = \gamma_w \times H = 40\text{kPa}, \text{ where } H = 4\text{m}$$

Calculate active earth pressure

$$K_a = \tan^2 \left(45^\circ - \frac{\phi}{2}\right) = 0.39$$

$$\gamma' = \gamma_{sat} - \gamma_w = 7\text{kN/m}^3$$

$$P_a = (\gamma' \times h_2) \times K_a - 2c \times \sqrt{K_a} = 4.10\text{kPa}$$

Where $h_2 = 1.5\text{m}$.

Total overturning moment per meter $m_0$ can be calculated as follows,

$$m_0 = P_w \times \frac{H}{2} \times \frac{H}{2} + P_a \times \frac{h_2}{2} \times \frac{h_2}{3} = 108.20\text{kN} \cdot \text{m/m}$$

Idealize a stockade box unit as a $3\text{m} \times 3\text{m} \times 4\text{m}$ cuboid with its center of gravity also its centroid, whose density $\gamma_2 = 20\text{kN/m}^3$. Thus one unit weights $G$ is

$$G = H \gamma_2 \times L = 720\text{kN}, \text{ where } L = 3\text{m}$$

Total overturning moment on one unit $M_0$ is

$$M_0 = m_0 \times L = 324.60\text{kN} \cdot \text{m}$$

The resisting moment from its weight $M_R$ is

$$M_R = \frac{GL}{2} = 1080\text{kN} \cdot \text{m}$$

It can be seen that $M_0 < M_R$. Thus, a dam with stockade box structure can resist overturning moments and perform well in ideal condition[4].
6. Improvement suggestions for stockade box dam

6.1. Materials
Stockade box structure is very similar to modern box abutment. In terms of structural system, it is truly advanced and stable. But in terms of material, timber is more fragile and less durable than steel. Thanks to the development of modern materials science, pine can be replaced by many alloys with anti-corrosive coating to protect the box from corrosion.

6.2. Structural design
Adding flood drainage system into stockade box structure can help reduce the water pressure and improve stability. And stockade box can also be designed as a structure with given water permeability. For example, by opening filtering access on the box, and adding charcoal or other water purification material into the filling aggregate, it can fulfill the function of water purification.

6.3. Function
The stockade boxes in ancient dams were arranged in a line or a curve. While concrete dam is more practical at present, stockade box dam is more applicable in shallow streams with slow water flow [5]. But stockade box can be used as a separate functioning component for water conservancy. Prefabricated by manufacturers, it can be placed in each segment of a stream. First, with the testing instrument assembled together, it is capable of keeping updating information of water flow and water quality of corresponding stream segment, by collecting data and providing feedback just in time. Second, when placed into streams demanding purification with water purifier, it can function not just as a permanent observation spot, but also as a water purifying plant. According to the situation, stockade boxes can be arranged at several locations to monitor the purification effect in each segment, provide up-to-date information and help make preparation for purification at next stage.

7. Conclusions
The ancients developed stockade box structure to manage water resource, which significantly reduce the probability of flood and waterlog. With good structural stability and long service life, stockade box dam has better ductility and better resistance against moment and overturning than common dams. And even at present with more developed science and technology, stockade box can make more contributions to water conservancy with some improvement.

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