Research on the Application of Step-pool System in Ancient Irrigation Engineering

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Abstract. The "step-pool system" is a common river topography in mountain rivers. In the application for Heritage Irrigation Structures in 2020, an artificial "step-pool system" built two thousand years ago was shown to the world, which is located in the 36 Weirs of Baishaxi Stream in Wucheng District, Jinhua City, Zhejiang Province. The creator of this ancient irrigation project used the ideas of "Building weirs by ponds" and "Distributed river development" on the Baishaxi stream, which spans 45 kilometers from the end to the end and has a vertical drop of 168 meters, to build this multifunctional ancient super barrage group project. Their experience and insights coincide with modern engineering theories, which have changed the natural characteristics of the river and made positive changes in the ecological environment of the river basin in a direction that is beneficial to human life.

1. Introduction

The riverbed of mountain rivers is usually composed of gentle slopes and steep slopes, coupled with the interconnection of deep pools. This stepped landform in longitudinal section is called the "step-pool system".

In the application for Heritage Irrigation Structures in 2020, an artificial "step-pool system" built two thousand years ago was shown to the world, which is located in the 36 weirs of Baishaxi stream in Wucheng District, Jinhua City, Zhejiang Province. This ancient irrigation project was built in 27 AD. The founder of the weir, Wentai Lu, lived in Cangfu (now Tingju Village, Jinhua City, Zhejiang Province). Lu found that the local soil was fertile but frequent floods and droughts, so he began to dam the river and divert water for irrigation. For more than a hundred years, the 36 Weirs of Baishaxi Stream have been built one after another. The two weirs at the beginning and the end of the project span 45 kilometers, with a vertical drop of 168 meters (Figure 1).
Figure 1. The 36 Weirs of Baishaxi Stream

Compared with other famous irrigation project heritages in the same period, such as Dujiangyan in the northwest of Chengdu Plain, Tongjiyan in Lishui City, Zhejiang Province, and Tianbaopi in Fuqing City, Fujian Province, they are all large-scale irrigation projects that focus on water diversion and irrigation, and also have flood control, which are single water conservancy projects. While the 36 weirs is an ancient super dam group project with multiple functions such as irrigation, flood control, water storage, and hydraulic processing.

In recent decades, all regions of the world have successfully applied the "step-pool system" to engineering practice. The river restoration project of Lake Oswego, Ore., USA uses log weirs on the river to create a stable step-pool landform\(^1\). These log weirs concentrate about 50% of the water head difference and energy consumption on the steep river bed, which is very important for controlling cutting down the riverbed and play an important role in stabilizing the bank slope\(^2\). In the mountainous areas of northern Italy, people use boulders to lay dams to stabilize the riverbed with large slopes, imitating the landform features of step-pool, achieving remarkable results\(^3\). In the Tachia River in Taichung, Taiwan, an artificial stepped structure composed of large rocks with a diameter of 2m effectively controls the undercutting of the river bed\(^4\). The deep gullies in the Xiaojiang River Basin in Yunnan have experienced frequent debris flow disasters and harsh ecological environment. After high-intensity gully management, the river course has gradually developed a “step-pool system”, then the erosion of the gully has been effectively controlled. In the mean while, the riverside vegetation is luxuriant, and the ecological environment and river landscape have been greatly improved.

It can be seen from the above projects that in the past ten years, with the deepening of the research on the system, the artificial "step-pool system" has been used in mountainous undercutting river management in some countries and regions to protect river beds and stabilize bank slopes, maintain...
good river aquatic habitats and ecological functions. The 36 Weirs of Baishaxi Stream has successfully practiced the theory of "step-pool system" two thousand years ago.

2. Engineering system of the 36 Weir of Baishaxi Stream

The “step-pool system” is a common river topography in mountainous rivers (Figure 2). The deep pool is covered with fine sand and coarser sand; the exposed area of the river bedrock develops into steps. In the rivers in lush vegetation areas, some steps are formed by the accumulation of fallen trees. But the term "ladder-deep pool system" appeared until the 1980s. In 1982, Whittaker and Jaeggi named this type of landform the "step-pool system," and this term was widely accepted since then [5].

Two thousand years ago, the ancient Chinese had recognized this principle and used this scientific thought as a guide to artificially transform the river, that’s why the 36 Weirs of Baishaxi Stream is so unique.

2.1. Building weirs by ponds——Find deep pools

In mountain rivers, the step-pool system can maximize the resistance of the river bed, and its energy dissipation function is the key reason for maintaining the stability of the river bed. The energy dissipation effect of the system is reflected in increasing the shape resistance of the river bed, causing the water flow to produce strong vortices during the process of falling from the stairs into the deep pool. The violent mixing and turbulence are accompanied by strong additional shear stress, so that the mechanical energy of the water flow is quickly converted into heat energy. In this way, the stability of the river is maintained, and a good river habitat and ecology can be maintained, which is of great significance to the health and stability of mountain rivers with large slopes.

The builders of the 36 Weirs, in view of the characteristics of the Baishaxi Stream's large drop, rapid water flow, and many deep pools, proposed "building weirs by ponds" at the beginning of the construction. That is, look for natural deep pools along 45 kilometers of the river, and build weirs in front of the pools. The ancients keenly discovered that the pond behind the weir can effectively prolong the use time of the weir and avoid the weir being frequently washed away by sudden floods. There is a natural deep pool in front of most of the 36 weirs, such as Qingcao Weir (Figure 3). In the mean time, there is a deep pool on the weir and the site is located at the turning point of the river. The topographical features are fully utilized to reduce water energy and protect barrage.
Not only did the builders search for lakes and build weirs in site selection, they also consciously deepened the natural pools. The builders summed up the scientific experience of "deep pools with low weirs" in the process of annual repairs. Obviously the ancients have found that deep pools have a stronger energy dissipation effect, which not only slows the impact of hydraulic power on the weir, but also improves water storage and water diversion capacity. On the other hand, the low weirs can protect the embankment while the water rises by itself, and allow the water to accumulate and irrigate the fields. It can extend the life cycle of the weir, improve the stability of the river bed, and meet the irrigation requirements. In fact, it also protects the biodiversity of rivers.

2.2. Distributed river development——Form a ladder
The 36 Weir of Baishaxi Stream was built on the Baishaxi Stream within 45 kilometers. The height difference between the first and last weirs is 168 meters (Figure 1). The builder adopted the irrigation method of "high water and high irrigation, low water and low irrigation", and distributed river development methods to slow down the impact of water flow. The diversion and erosion reduction effects of 36 weirs and the distributed river development method enable the downstream farmland to be fully irrigated, which can not only ensure people's irrigation needs, but also achieve the multi-functional functions of flood prevention, drainage, and water storage. The distributed group weirs are located on the Baishaxi Stream, which stretches for 45 kilometers in the mountains of central Zhejiang, and 36 "stairs" have been artificially built.

The construction of distributed weir groups on a single water system will inevitably affect the ecological environment of the river basin, but this effect is different from the impact of a large-scale single weir on the ecological environment. For distributed group weirs, compared to a large-volume single weir, it greatly reduces the construction difficulty and construction cost, and also greatly reduces the risk of flooding the overall damage to the weir. The construction of distributed group weirs has long-term and synergistic effects, and study its cumulative impact on the ecological environment of the river. Including changes in natural water flow, sediment transport methods and water temperature, changes in aquatic biodiversity and other natural ecosystem products and services, compared to large single weirs, it is more environmentally friendly.

2.3. Obtain raw material locally——Construction according to local conditions
The founder of 36 Weir, Lu Wentai, built many dams weirs. Tingjiu was the place where the founder Lu Wentai settled. The first Baisha weir was built right in his residence, which provided more than 30 other weirs the practical experience of "inline weirs" and the “Stone cage and stone method" (Figure 4). They are all constructed according to local conditions. Firstly, the bamboo was cut into nine, eight, and ten strands, and then the pebbles were put into the bamboo strip cage. After filling, use the strip hoop to solidify, and then connect the strips filled with the pebbles. Put them in the stream from this end to the
opposite bank, until it becomes a dam with a cage wall, then use firewood to close the gap between the stick cage and the stick cage. After that, it needs to be smeared repeatedly with extremely viscous yellow clay to ram the weir, and then changed to more viscous lime. After the foundation works of the weir are completed, a sluice gate will be built. His descendants inherited his skills until the 36 Weir of Baishaxi Stream was built. The masonry is built with pine piling, sand and gravel in a cage, and the low weir shape, combined with the construction method of the cascade weir group, minimizes the difficulty of construction and engineering risks.

Figure 4. Traditional construction

3. Conclusion
Two thousand years ago, the insights and experience of the builders of the 36 Weir of Baishaxi Stream coincided with today’s engineering theory "step-pool system". They are creatively used in the use and control of the river, changing the natural characteristics of the river, and converting the variable natural flow into the amount of water discharged by humans, making positive changes to the ecological environment of the river basin in a direction beneficial to human life.

In 2020, the 36 Weir of Baishaxi Stream was successfully selected into the Heritage Irrigation Structures, not only showing the excellent water management wisdom of traditional irrigation projects, but also providing historical experience and inspiration for sustainable irrigation development. In the mean while, it allows more people to understand the unique operating principle of the 36 Weir for two thousand years, and to understand China's "step-pool system" two thousand years ago.

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