Case Study

Hydraulic Principles of the 2,268-Year-Old Dujiangyan Project in China

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Abstract: The Dujiangyan Project is a World Cultural Heritage Site with relevance to water conservancy. It has been operated for more than 2,260 years and still plays an important role in irrigation, urban, and industrial water supply, flood control, and tourism. This paper discusses the hydraulic principles of the project, focusing on the reasons for the longevity of the project. In particular, two aspects of the project are reviewed; namely, the practical engineering design of the project and its outstanding historical significance and time-based maintenance. The project ingeniously used the topography of the terrain in the design of weir structures. The tasks of water diversion, irrigation, and flood control were achieved using a two-step approach. The first step was achieved by utilizing the shifting of streamlines and the bend of flow from the town of Guankou to Fish Mouth (a diversion embankment). The discharge of flow and sediment was further optimized by using the second step of combined control of Feishayan (a sediment and flow spillway) and Baopingkou (an irrigating gate). The bend of flow within the Inner River forces the surface water to flow into Baopingkou, whereas the bottom sediments and pebbles discharge from Feishayan. Dynasties throughout history attached great importance to the management and maintenance of the project. Retrofitting and time-based renovation prevented the abandonment of the project due to sediment accumulation and aging of building materials. Because the maintenance and operation costs were far lower than the economic, social, and ecological benefits the project had brought, the Dujiangyan Project was sustainable over the long term. The study of the engineering design and maintenance rules of the Dujiangyan Project has value for the design and construction of modern hydraulic projects. **DOI:** **10.1061/(ASCE)HY.1943-7900.0000675.** *© 2013 American Society of Civil Engineers.*

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Introduction

The development of civilizations was facilitated to a large degree by hydraulic projects. The prominence of hydraulic projects has been closely linked to the rise and decline of civilizations, especially within cultures highly dependent upon irrigation (Jansen 1980). Therefore, the strategy chosen to construct and run a project will have great influence on society and the service life of a project. The history of hydraulic project construction can be traced to the time of human cultural origins, for example, within the cradles of civilization in Babylonia, Egypt, India, Persia, and China (Toby 2011). Many famous ancient hydraulic projects were constructed and played vital roles in human cultural history, but with the lapse of time, they declined for various reasons, such as neglect and lack of repair, sediment accumulation, natural vicissitude, and improper use. Of all the ancient hydraulic projects, the Dujiangyan Project has been operated for more than 2,260 years, and still plays an important role for irrigation, urban, and industrial water supply, flood control, and tourism [Cao et al. 2009; Dujiangyan Administrative Bureau (DAB) 2003; Li and Xu 2006; Peng 2008; Peng and Xiao 2004; Research Team of Study on Reform of Management System for Dujiangyan Hydraulic Project (RSMD) 2004; Tan 2004; Water Resources Office of Sichuan Province (WROSC) and DAB 2004]. The earliest historical record of the Dujiangyan Project dates from 100 BC and is recorded in the book entitled *Shih Chi* (*Canal Book*) by Sima Qian (2002). In January of 2000, UNESCO listed the Dujiangyan Project as a World Cultural Heritage Site (UNESCO 2012).

The Dujiangyan Project is located upstream of the Chengdu Plain (Fig. 1); it was one of the hydraulic projects created to govern the Min River. The Min River is the river branch that carries the largest volume of water in the upper catchment of the Yangtze River. It originates at the south foot of the Min Mountain and joins the Yangtze River in Yibin. The Min River is 735 km long, with a basin surface area of approximately 140,000 km^2. The upstream reach of the river occurs above Dujiangyan City, where goods and services provided by the river include power generation and the transportation of timber by log driving. The middle reach of the river ranges from Dujiangyan City to Leshan City, with the river flowing through the Chengdu Plain. Here, the Min River is used with the Tuo River system and numerous artificial waterway networks to facilitate the Dujiangyan irrigated area. The downstream reach of the Min River occurs below Leshan and is primarily used for shipping. The Min River Basin occurs in a high rainfall region, leading to high water volumes within the river. The annual runoff of the region is more than 90 billion m^3, which is greater than twice that of the Yellow River, and the river contributes one-fifth of the total hydroelectric resource reserves of the Yangtze River. Before the Dujiangyan Project was constructed, flood and drought disasters were frequent within the Chengdu Plain, leading to low

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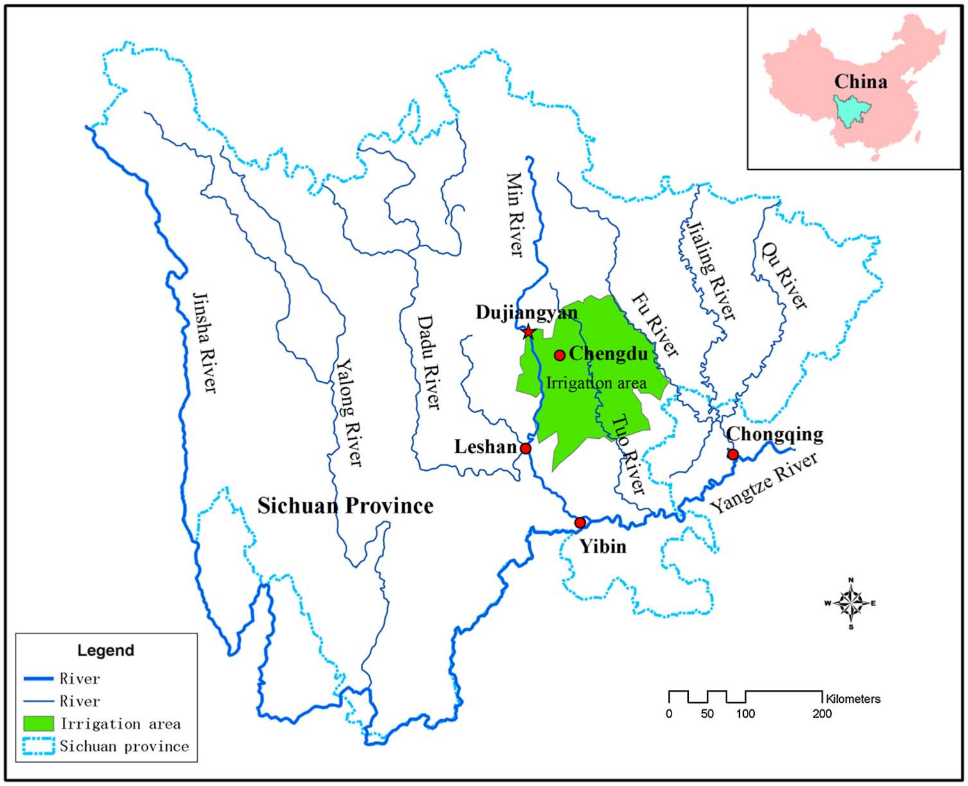

Fig. 1. Geographical location map of the Dujiangyan Project

food production. During the past several dozen centuries, the Dujiangyan Project has facilitated water supply for production and domestic needs within the Chengdu Plain, and has played a pivotal role in transforming the Chengdu Plain into a fertile plain.

During the Warring States period of ancient China, the Qin Kingdom conquered the Shu Kingdom (now Sichuan Province) in 316 BC. This resulted in many people of Qin immigrating into Shu, and the advanced farming technology of the Central Plain (the Yellow River Basin) was introduced to the Shu Kingdom, as was the widespread use of iron. Subsequently, agriculture within the Chengdu Plain developed rapidly, which stimulated the need for a large water conservancy project for irrigation, drainage, the shipping trade, and building cities. In 256 BC, Li Bing, the governor of the Shu Shire under the Qin State, built a diversion embankment according to the special terrain and the fluid state of the Min River. The diversion embankment is called Fish Mouth and is located at the upper end of the Chengdu Plain, where the river emerges from the mountainous region (Cao et al. 2009). The embankment divides the Min River into two parts: the Outer River and the Inner River. The Outer River comprises the primary flow of the Min River, whereas the Inner River is used to divert water to the project. Baopingkou was dug out from the Yulei Mountain to draw water from Inner River to the Chengdu Plain. A sediment and flow spillway named Feishayan was built upstream of Baopingkou on the side next to the Outer River to discharge flood and sediment from the Inner River. The project played a crucial role in flood control, irrigation, and water supply for the Chengdu Plain, and subsequently, the Chengdu Plain has become a vastly fertile land, commonly referred to as "The Land of Abundance" (Tan 2004).

The Dujiangyan Project currently includes two major parts: the Headwork and the irrigated area. The layout of the project is shown in Fig. 2. The Headwork is composed of three primary projects: Fish Mouth, Feishayan, and Baopingkou, and auxiliary projects such as the Renzi Dike, the Outer River Check Gate, and the Industry Water-Drawing Gate. The irrigated area diverts water from the Headwork and finally forms the fan-shaped gravity irrigation system with a series of channels and water gates; with a total irrigation area of 0.68 million ha, it is the biggest irrigation district in China (DAB 2003; WROSC and DAB 2004).

The objective here is to present the engineering design and operational principles of the Dujiangyan Project. Discussed are the technical merits and reasons for the structural longevity of the project in the context of the project's layout, and the water and sediment control principle it used. The reasons for the longevity of the project are also discussed based on the historical development and maintenance of the project.

Layout and Function of the Dujiangyan Project

Layout of the Dujiangyan Project

The Min River flows to Zipingpu and runs out from the Guankou mountain pass, where the mountainous terrain is immediately replaced by flatter plain, the river widens, and the flow velocity declines. These factors provide a unique geographical and hydrological condition for facilitating the Dujiangyan Project. The mainstream of the Min River is slightly curved from Guankou to Fish Mouth, as shown in Fig. 2. The curved river reach, Hanjiaba shoal patches, and a series of projects such as Baizhang Dike, Fish Mouth, Jingang Dike, Feishayan, Renzi Dike, and Baopingkou serve to form the non-dam water intake headwork system of Dujiangyan (Chen 1982). The weir structure has a total length of 3,020 m from Guankou to Baopingkou. The first 1,950 m above Fish Mouth have a river channel width of 300–500 m, whereas 1,070 m below Fish Mouth consists of the 70–150-m-wide Inner River and the 110–130-m-wide Outer River. The Headwork of the Dujiangyan Project is situated at the top of the Chengdu Plain, at an

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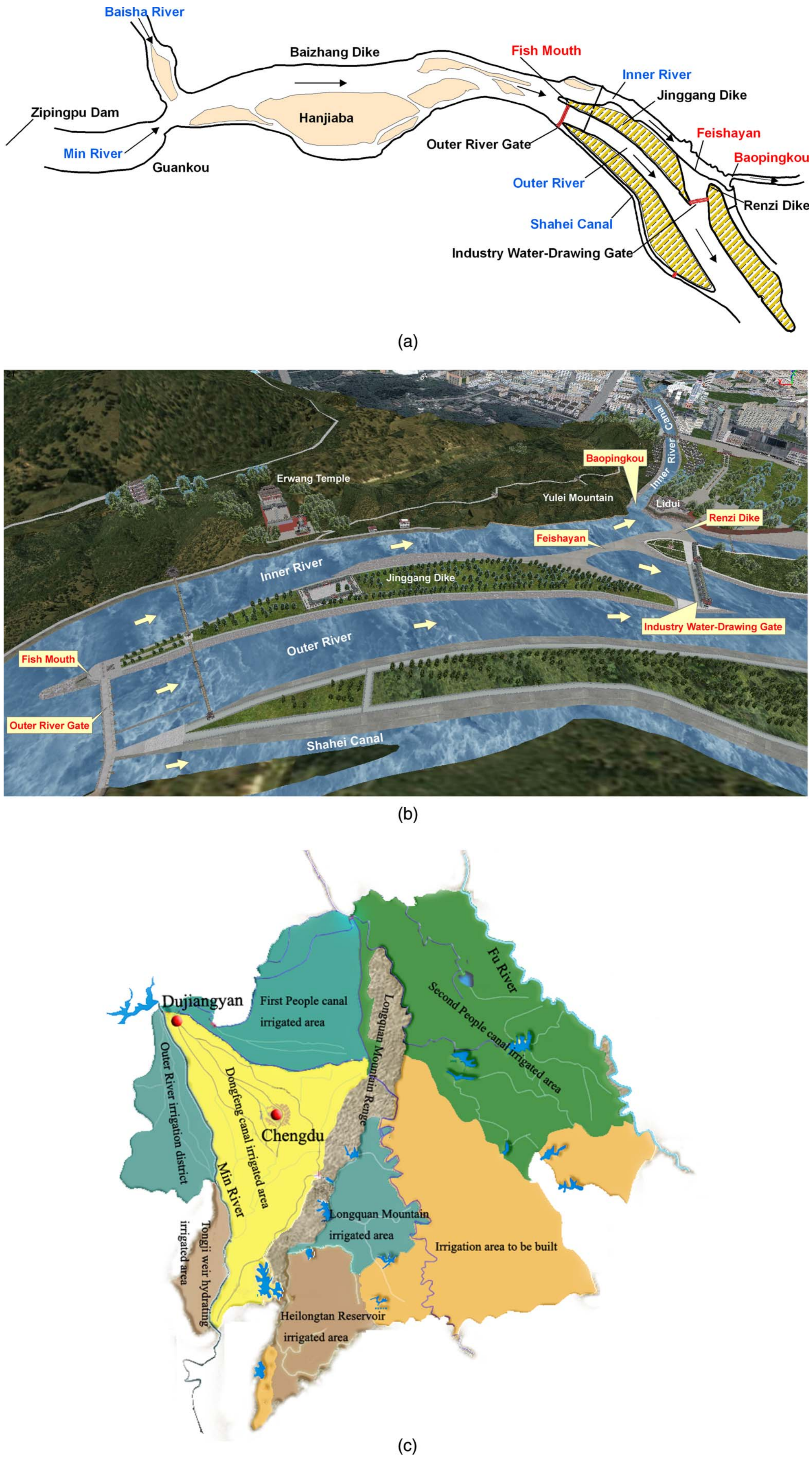

Fig. 2. Layout of the Dujiangyan Project: (a) plane layout of the Headwork; (b) three-dimensional virtual environment of the Headwork; (c) layout of the irrigated area

elevation of 739 m, providing a commanding position for controlling the Min River as it emerges from mountain valleys. This allows the protection of the Chengdu Plain from flood, and the realization of gravity irrigation of the region.

The Dujiangyan Project is the water intake project for the Chengdu Plain, and the primary channel leading to the Chengdu Plain connects directly through Baopingkou. The project divides the Min River into three parts, namely, the Inner River on the left bank and the Outer River and the Shahei canal on the right bank. While flowing into Baopingkou, the Inner River is split into two from the Yangtianwo Check Gate, and is further split into four after flowing though the Pubo and Zoujiang Gates. These branches follow the topographical tilt that is higher in the northwest and lower in the southeast, to form a gravity system of irrigation channels that irrigates over 0.68 million ha of farmland in the Chengdu Plain and the hilly region. The Outer River mainstream is the flood discharge channel of the Min River. The lands on the right bank of the Min River are irrigated by the Shahei Canal.

Functions of the Three Primary Projects

Fish Mouth

Fish Mouth is the first of three major projects, which is called "Fish Mouth" because it is shaped like the head of a fish. Fish Mouth is approximately 80 m in length, and has an elevation of 730 m at its head, rising gradually downstream. The diversion embankment that was formed by Fish Mouth and the Jingang Dike is Dujiangyan's control project for water and sediment diversion. The Inner and Outer Jingang Dike are the left and right bank protection levees, respectively, for the central shoal below Fish Mouth. The Outer River on the right is the stem stream used primarily for flood and sediment discharge. The Inner River on the left is an artificial water-intake channel designed primarily for irrigation purposes. The Fish Mouth and the curved river reach beginning from Guankou facilitate the automatic diversion of flow and sediment (Yang et al. 2011).

Feishayan

Feishayan is a low spillway dam located in the lower segment of Jingang Dike. Its upper end is located 710 m from Fish Mouth, and its lower end is located 120 m from Baopingkou. The crest of the weir that is situated along the Inner River is 240 m wide. The average elevation of the crest is 728.25 m. Its upstream dam slope is 1:5 and its downstream dam slope is 1:50.

Feishayan serves the functions of water diversion and sediment and flood discharge for the Inner River. Up until the flow volume of the Inner River reaches 350 m^3/s, the water is below or at the same level as the dam crest, and all flow in the Inner River enters Baopingkou, guaranteeing water supply for the irrigated region. When the water level of the Inner River is high and water demand for irrigation is large, bamboo cages filled with pebbles can be added onto the dam crest, temporarily raising the water level for drawing water. These cages are automatically destroyed by impending floods. Hence, Feishayan is an integrated part of the right embankment of the Inner River. After the Industry Water-Drawing Gate was constructed, the bamboo cages were replaced, resulting in even more flexible options for retaining water.

Baopingkou

Baopingkou is located on the concave left bank of the Inner River, 120 m away from the lower end of Feishayan. It was artificially dug out of the mountain ridge of Yulei Mountain, which stretches toward the Min River, and served as the water diversion throat of the Inner River irrigated area. After construction of Baopingkou, a rock pile called Lidui was left standing across the river on the right bank against Yulei Mountain. Baopingkou has an average width of 20.4 m, height of 18.8 m, length of 36 m, and bottom elevation of 716.3 m. During the periods of low water volume, water in the Inner River is conducted into the Chengdu irrigated area from Baopingkou. In contrast, during the flood period, the narrow cross section of Baopingkou restrains the amount of water entering the irrigated area and raises the water level together with Lidui, thereby enhancing the flood discharge of Feishayan. Therefore, Baopingkou is not only the throat of water intake for irrigated areas, but also protects the Chengdu Plain from the threat of flood.

Characteristics of Water and Sediment Transport

For over 2,000 years, the Dujiangyan Project has functioned in a sustained manner. In addition to its ideally suited geographical position and its human management and maintenance, the movement of water and sediment helps to naturally maintain its function.

Dynamic Water Diversion Process

The Inner and Outer Rivers can achieve different water diversion ratios for different seasons. During the dry season, the mainstream flows along the Inner River, which diverts approximately 60% of the total water to irrigated areas. During the flood season, the bend of the Min River drives the mainstream out to the Outer River, where approximately 60% of the total water is diverted to the Outer River. However, the ratio of diversion created by Fish Mouth is not strictly 4:6 or 6:4 (Sun et al. 2006). There is also no clear distinction between the so-called dry and flood seasons. The general rule for the Inner River is that its proportion of flow is greater than 50% during low flow, but less than 50% during high flow.

The natural conditions of the reach above Fish Mouth make the self-regulation of flow diversion possible between the Inner and Outer Rivers. Guankou, the control node of the Min River outlet, can be regarded as the entrance of the Dujiangyan Project, which plays an important role in directing the flow orientation. During the low flow period, the flow is deflected by the spur on the right bank of Guankou running towards the left bank. Because there is no overflowing of the central shoal, Hanjiaba, during low flow, the mainstream will run along the curved left bank until it reaches Fish Mouth, resulting in more than 50% of the total water diverting to the Inner River. During the flood season, the influence of the spur is reduced, and the central shoal of Hanjiaba allows overflow. Hence, the main stream runs straight to Fish Mouth, and more than 50% of the total flow volume is diverted to the Outer River. The mainstream line during the flood and dry seasons is shown in Fig. 3, and the water diversion ratio of the Inner River to the Min River (DAB 2003) is shown in Fig. 4.

During the long history of the Dujiangyan Project, small to middle-sized discharges have been controlled by many artificial factors. For example, during the spring irrigation period, wooden cofferdams (bamboo cages with wood tripods) are built before Fish Mouth to force the water into the Inner River, so the water diversion ratio of the Inner River to the Outer River was considerably higher than it would have been without intervention. When the demand for water is high, all of the water within the Min River may be conducted into the Inner River, and the Outer River will dry up. After the spring irrigation, the wooden cofferdam has to be removed to allow flood discharge and then rebuilt to increase the amount of water to the Inner River during the summer drought period. To reduce labor, a check gate was built across the Outer River in 1974 (Chen 1983). This greatly improved the control of the water intake for the irrigated regions and sediment discharge,

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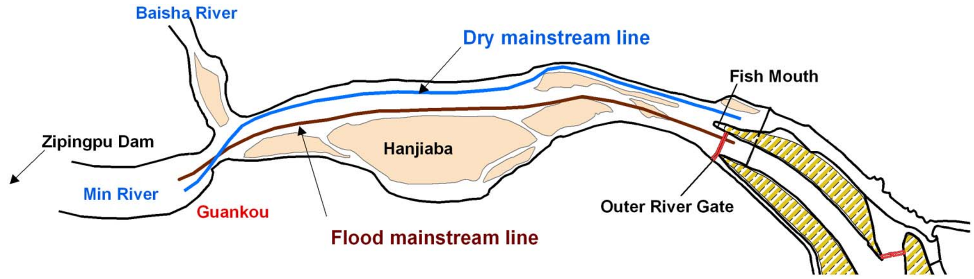

Fig. 3. Main stream line sketches of flood and low water in the upstream reach of the Fish Mouth

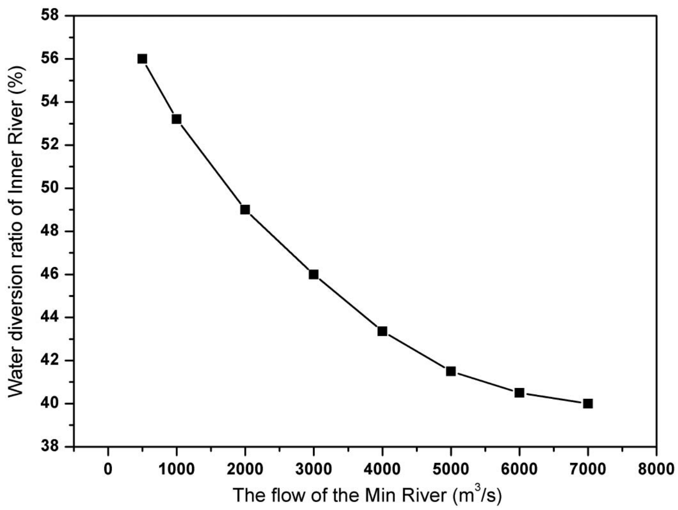

Fig. 4. Water diversion ratio of the Inner River to the Min River (data from DAB 2003)

and an extra 700 million m^3 of water could be drawn into the Inner River to meet the seasonal demands each year.

These results suggest that under natural circumstances, it is not Fish Mouth that automatically regulates the water diversion ratio, but the reach above Fish Mouth that controls the mainstream line during flood and dry seasons, so the ideal water diversion effect is achieved. The construction of the wooden cofferdam determined the diversion ratio during the spring irrigation, so that the ratio of water diverted to the Inner River was greatly increased. After the check gate was built, the diversion ratio was artificially controlled during small and medium flows.

Bend Flow

Flow in a curved channel is affected by centrifugal force due to curvilinear movement. Taking a water column with unit area height, H, as an example, the distribution of centrifugal force (F) along the depth of the channel is similar to the vertical distribution of longitudinal velocity [Fig. 5(a)]. A constant pressure force (ΔP) is formed along the depth profile because of the different water levels between the inner and outer sides of the water body. The combination of the centrifugal force and the pressure force [Fig. 5(b)] causes the flow in curving channels to rotate laterally, with the upper part of the water body moving to the concave bank and the lower part to the convex bank [Fig. 5(c)]. The vertical distribution of suspended sediment increases exponentially at lower elevations in the flow depth [Fig. 5(d)]. Under this condition, a lateral sediment transport is formed by the interaction between the structure of bend flow and the vertical distribution of suspended material. In other words, because of this interaction, surface water containing a low concentration of suspended sediment, S_L, moves to the concave bank, whereas bottom water with a high sediment concentration flows to the convex bank [Fig. 5(e)] (Faruk et al. 2007).

Within the Dujiangyan river reach, the annual average suspended load transport is approximately 8.68 million tons. The median diameter of the suspended sediment $(D_{50}) = 0.104$ mm. Bed load transport capacity is 1.5–2 million tons with $D_{50} = 61.0$ mm, and bed material load $D_{50} = 128.1$ mm (Zheng et al. 2006). Suspended load essentially forms the wash load, and sediment deposition is primarily formed by the moving pebble bed load in the flood season (Wang et al. 2006). During low flow, the pebble load is difficult to move; therefore, the bed load is small, so there is not much sediment in 60% of the total water going into the Inner River. During the flood season, the mainstream discharges into the Outer River and naturally takes away most of the moving pebble bed load. In addition, because the entrance of Inner River lies on the concave bank of the slightly curved river section,

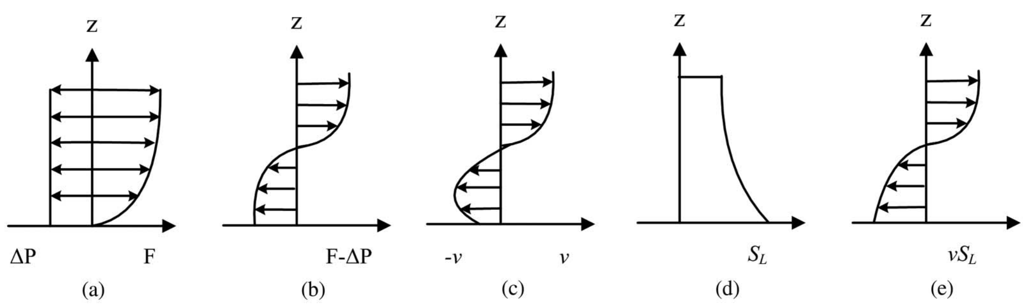

Fig. 5. Formation of bend flow and transverse sediment transportation (F: centrifugal force; ΔP: water pressure force; v: velocity in vertical; S_L: sediment concentration of suspended load), (a) the vertical distribution of centrifugal force (F) and water pressure force (ΔP); (b) the resultant of centrifugal force and water pressure force ($F - \Delta P$); (c) the distribution of velocity in vertical v; (d) the vertical distribution of suspended load concentration S_L; (e) the flow direction of high sediment concentration and low sediment concentration (vS_L)

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the gravel bed load is transported along the convex bank and discharged into the Outer River under the action of lateral sediment transport by bend flow (Fang et al. 1988). According to measured data, the amount of gravel transported into the Inner River is approximately 26% of the total load in the Min River.

Flood and Sediment Discharge Function of Feishayan

The water in the Inner River flows from Baopingkou into the irrigated area to ensure the provision of water demand for irrigation during low flow. Water in the Inner River is mostly discharged from Feishayan during the flood period. In addition, flow discharged from Feishayan during the flood period moves sediments out of the Inner River. This duel function of Feishayan protects the irrigated area from flooding, and sediment deposition in Baopingkou is prevented. Because it is cleverly designed to guarantee water and sediment discharge from the Inner River, Feishayan, together with Baopingkou, performs the function of secondary water and sediment diversion.

With respect to water diversion, Feishayan serves the dual function of holding back water from entering Baopingkou and discharging floods from the Inner River. Its dam crest elevation must be designed to eliminate flood discharge, because a lower elevation will not suffice to stop water, whereas a higher elevation affects flood discharge. When greater water intake is needed, temporary bamboo cages are placed on top of the dam to add extra height and are automatically destroyed when flooding occurs. The cages are designed to be temporary structures, and if the cages have not been promptly destroyed during the flood season, then flooding may occur. When flow changes frequently between low and high, it is difficult to guarantee water intake and flood control. At the end of 1992, a check gate was constructed at the tail of Feishayan to control the variability of the flow, thereby increasing the guaranteed water intake to Baopingkou from 330 to 530 m^3/s.

Because the width of the Baopingkou entry channel is merely one-tenth of the width of Feishayan, flood waters entering the Inner River primarily flow out into the Outer River via Feishayan. The discharge capacity of Feishayan increases with the increasing water flow in the Inner River, and is proportional to the cross-sectional area of Feishayan. The largest diversion capacity of Feishayan amounts to over 75% of the flood discharge of the Inner River. Measured Feishayan discharge capacity (DAB 2003) is shown in Fig. 6.

The Inner River reach below Fish Mouth is curved and has a steep average surface slope of 2.31%, resulting in the generation of a strong bend flow (the curvature radius of the bend is approximately 1,000 m). The plan view flow pattern is shown in Fig. 7(a). The surface flow has great velocity and inertia. The main stream points to the concave bank and dives down at the bank, pushing the low velocity water at the bottom towards the convex bank, thus forming spiral flow. Under the action of bend flow, over 90% of the pebbles carried into the Inner River by the main stream are discharged into the Outer River via Feishayan. The section flow pattern is shown in Fig. 7(b). The measured diameter of pebbles discharged from Feishayan exceeds 600 mm. To demonstrate the power of the flow, a stone block weighing over two tons flew over the top of Feishayan on July 28, 1966, when the mortar pebble levee at the foot of the Erwang Temple was destroyed by a flood [Chinese Local Chronicles Compilation Committee in Sichuan Province (CLCCCSP) 1993]. On the Feishayan crest, the bottom flow traverses the river, so pebbles and high-concentration suspended sediment near the bottom can be effectively discharged. The surface water flows downstream almost parallel to the dam crest. Thus, the unique pattern of flood discharge per unit area of cross-sectional area is formed as high at the bottom but low near the surface.

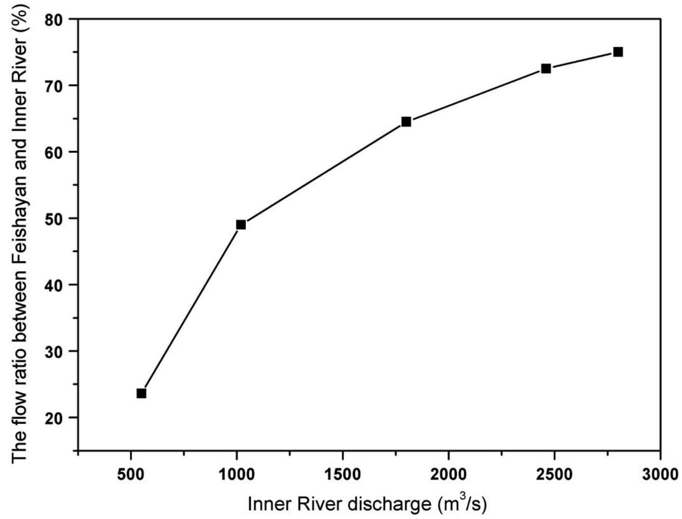

Fig. 6. Water diversion ratio of Feishayan to the Inner River (data from DAB 2003)

The Feishayan sediment discharge capacity increases with flood discharge capacity. It has been observed that when the Min River flows through Fish Mouth, most of the sands flow with the main stream into the Outer River, but the remaining 47.5% of the suspended sediment and 26% of bed load are diverted into the Inner River. Feishayan begins to divert flow when the discharge in the Inner River exceeds 330 m^3/s, but does not discharge sediment until the flow volume exceeds 500 m^3/s and the water diversion ratio of Feishayan to the Inner River exceeds 20% (Du 2008). When the Min River discharge exceeds 2,000 m^3/s and the Inner River discharge exceeds 1,000 m^3/s, the water diversion ratio of Feishayan to the Inner River will be more than 40% and sand diversion ratio of Feishayan to the Inner River will increase up to 70%. The greater the magnitude of the flow, the higher the diversion ratio, and the more efficient sediment discharge by Feishayan.

Water Intake Function of Baopingkou

Baopingkou is not only the throat of water intake for the irrigated area, but also a flood prevention barrier for the Chengdu Plain. When the flow is low, water in the Inner River is conducted from Baopingkou to the irrigated district of Chengdu. During a major flood event, the main stream in the Inner River runs straight into the concave cliff of Lidui and is reflected, forming a transverse jet almost vertical to the incoming direction of the water in Baopingkou (Fig. 8). This process greatly compresses the cross-sectional area of Baopingkou and controls the intake capacity of Baopingkou, forcing most of the water in the Inner River to flow out from Feishayan. In addition, the Renzi Dike also diverts some of the flood water. Therefore, greater flood events in the Min River result in a smaller water diversion ratio at Baopingkou. For instance, the water that flowed into Baopingkou during a flood event in 1964 was only 738 m^3/s, which was less than 10% of the total Min River volume of 7,700 m^3/s.

Maintenance of the Dujiangyan Project

Historic Significance of the Dujiangyan Project

The key to the successful running and longevity of the Dujiangyan Project is its remarkable historic significance and scientific maintenance system. Since Li Bing first constructed the Dujiangyan

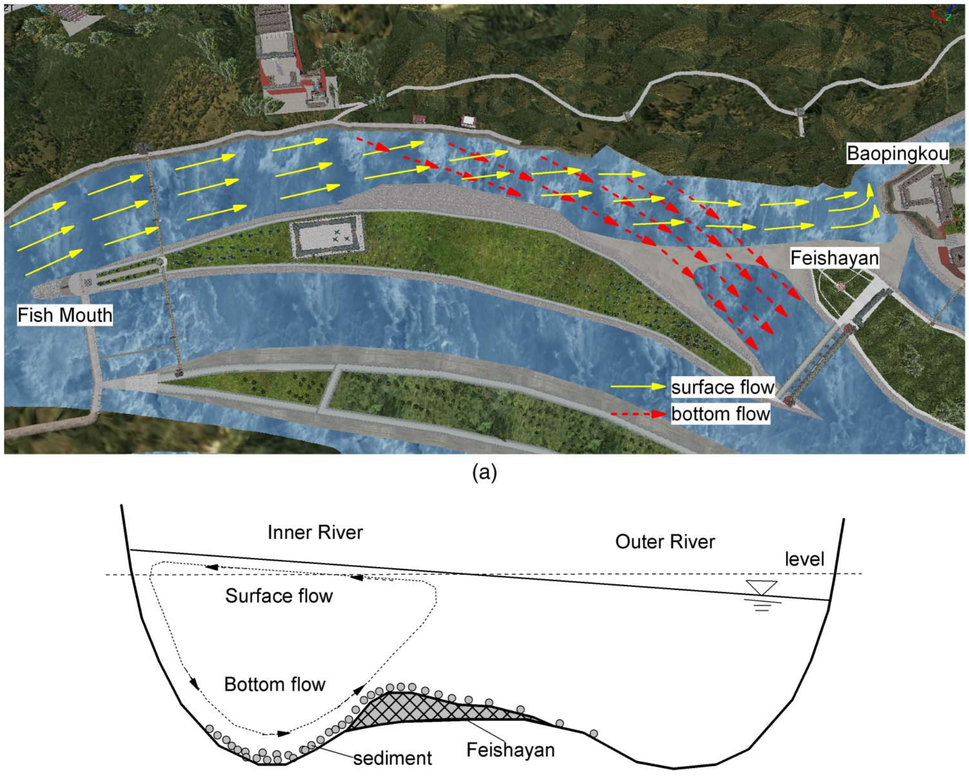

Fig. 7. (a) Flow pattern of Inner River reach; (b) sediment ejection sketch of Feishayan under the condition of circulation flow

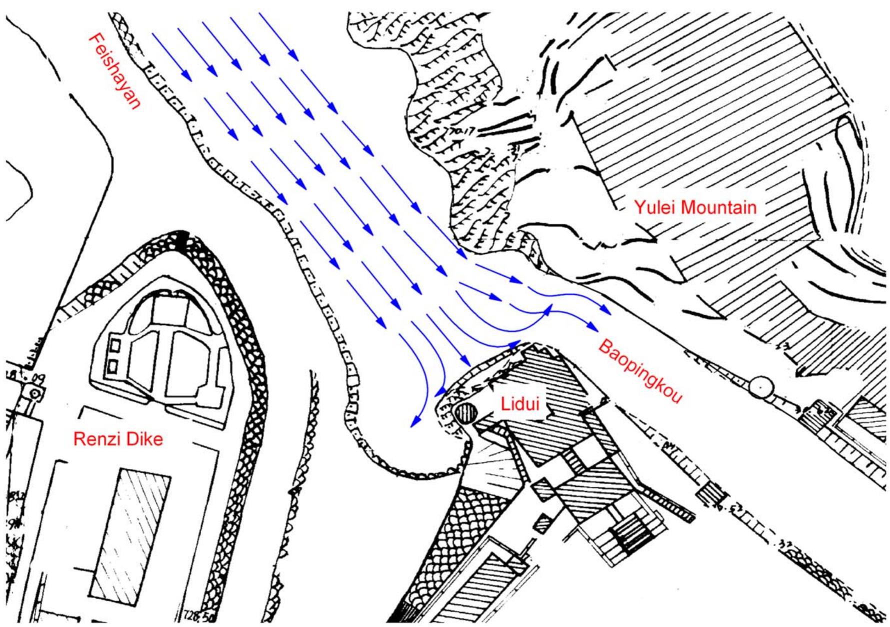

Fig. 8. Plugging operation sketch of the crossflow of Baopingkou under the condition of a large flood

Project, it has become a significant project monitored by the central government. The focus of managing the Min River is not in controlling floods, but the continual expanding and perfecting of the Dujiangyan Project and operating the regional water transportation network and irrigation network, which made Chengdu the management center for the region. The developed water transportation and agriculture provided an abundant and consistent harvest, irrespective of drought or flood conditions. This established the Chengdu Plain as the southwest political economic center for more than 2,000 years, while increases in the societal requirement of water provided the incentive for the constant improvement and continuation of the Dujiangyan Project. This contrasts with the many outstanding waterworks of antiquity that eventually declined into disuse because of neglect.

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Annual Maintenance

From the initial stage of the Dujiangyan Project, the irrigation area was continuously enlarged and increasing emphasis was placed on the establishment and development of the management system throughout the succession of dynasties. Beginning in the Song Dynasty (960–1276 AD), the annual maintenance system was gradually formed to cut off the river in winter and wash out accumulated sediments in spring, because agriculture is suspended during winter. Those tasked with managing and maintaining the project developed a set of management and maintenance rules to keep the project updated and stable. Because the maintenance and operation costs were far lower than the economic, social, and ecological benefits the project had brought, the Dujiangyan Project was sustainable over the long term.

Within the long historical process and with the changes to the Min River, the Dujiangyan Project developed the present layout through reconstruction, maintenance, and improvement within each dynasty. The location of the Fish Mouth has gone through many changes, and the construction and design of Feishayan has also been adjusted several times throughout the ages. For example, the Fish Mouth was initially located at ancient Baishayou, which was 1,650 m upstream of the present location. During the Yuan Dynasty (1279–1368 AD), the Fish Mouth was located approximately 2,000 m upstream of the location of the current Fish Mouth. In the period of the Qing Dynasty (1644–1911 AD), the Fish Mouth was moved to the river center opposite to Tiger Rock and 700 m below the present location of Fish Mouth. In 1936, Fish Mouth was constructed at its present location using mortar and stone. It was re-reinforced in 1974, and in 2002 it was rebuilt using concrete. Different construction materials have been used to build the Fish Mouth over the ages; the primary materials in order of succession have been pebble bamboo cages, stone masonry, iron turtle structures, iron tractor structures (iron turtle structure and iron tractor structure were all upstream levees of the Fish Mouth, which were used to divide water: the iron turtle structure was constructed with 8,000 kg of iron and was a turtle in shape; the iron tractor structure was constructed with 33,500 kg of iron and was in the shape of two oxen), mortar, and stone, and concrete. Although the rock of Baopingkou is still solid after 2,000 years, the bamboo cages and masonry used to construct the Dujiangyan Project are required to be repaired and replaced frequently. In this regard, the durability of the building materials cannot completely determine the service life of the project. Material damage can be repaired in time and the repair process can also adopt new technologies and new materials to perfect the project, so that the health of the project can be maintained and the life of the project can be extended.

The abandonment of many ancient irrigation works was primarily because of sediment accumulation, resulting in the loss of function for irrigation and drainage. The Min River contains a relatively large amount of sediment as upstream flow moves through the mountainous area at a high velocity. As the flow moves into the Dujangyan area, the mountainous terrain is immediately replaced by flatter plain, the river widens, and the flow velocity declines. Therefore, the sediment is most easily deposited here. The majority of sediment transport (90%) within the Min River occurs during the flood season from May–October. When flood waters cross Feishayan, the velocity of the flow is decreased and sand and gravel are deposited along Feishayan. Annual maintenance predominantly involves the removal of the deposited sand in the Dujiangyan weir district to dredge the river, with Feishayan the focus of the annual maintenance. The Dujiangyan Project intercepts most of the sediment and pebbles transported by the Min River from upstream. Annual maintenance of the project reduces the sand deposition in the Inner and Outer Rivers, thereby solving the problem of sediment accumulation that has caused the ultimate abandonment of other irrigation projects. This method of reducing sediment accumulation by making full use of engineering design and regular maintenance has a high reference value for modern water diversion projects.

Summary and Conclusions

The Dujiangyan Project is a hydraulic project with a history of 2,268 years. It continues to deliver great benefits to this day to the irrigation area of the project of 0.68 million ha. The Dujiangyan Project has become a global case study of a hydraulic project that displays harmony between human civilization and nature.

The Dujiangyan Project has endured for two primary reasons. The first is the sound engineering design. The Headwork of the Dujiangyan Project ingeniously uses topography and engineered regulation, thereby achieving water diversion and flood discharge via two steps. The first step is primarily affected by the shifting of streamlines and the bend of flow from Guankou to Fish Mouth. The second step is facilitated by the combined function of the Inner River's bend flow, Feishayan, and Baopingkou, using the natural curvature-induced flow patterns of the Inner River to discharge the pebbles and silt. The second reason for the longevity of the Dujiangyan Project is the important role played in the development of the Chengdu Plain, which resulted in every level of government paying attention to the management and maintenance of the project. Time-based renovation prevented the abandonment of the project due to sediment accumulation and aging of building materials. The improvement of the project with new technology throughout the succession of ages facilitated and ensured regular service of the project for dozens of centuries.

Although modern technology and tools have improved vastly from those available in ancient periods, the methods used in the Dujiangyan Project are still valuable for reference in modern diversion works. For example: the strategy of making full use of bend flow to achieve water and sediment diversion; the use of a system approach to develop maintenance and operational plans, to coordinate the function of irrigation and flood control and to ensure the regional protection of the ecological environment; the performance of time-based renovation under the rules of engineering economy. The project design subscribes to the philosophy of maintaining harmony between humans and nature, and therefore, the technology used in the Dujiangyan Project has been retained, further strengthened, and improved throughout the change of dynasties.

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