A new in-chamber double longitudinal culverts filling and emptying system for high head and large navigation lock

by

LI Jun[1], LIU Ben-qin[2], ZHAO Gen-sheng[3] and XUAN Guo-xiang[4]

ABSTRACT

Xijin hydro-junction is a key project of the Xijiang Golden Waterway in China, a two-step single-lane lock has already been constructed. The proposed 2nd lane lock is designed for the maximum vessel with the tonnage of 3000t. The new lock is located at the right bank of the river and also the 1st lane lock, and it is designed as a single step lock. The effective dimension of the lock chamber is 280.0m×34.0m×5.6m (length × width × water depth over the sill), and its maximum lift height is 20.3m, the designed filling time is 12min. Due to its large dimension and high lift, the comprehensive hydraulic characteristics of the new lock is close to the Three Gorges Locks and the Gezhouba Locks on Yangtze River, so it is quite necessary to determine and improve the layout of the filling and emptying system both by hydraulic analysis and model test study.

The lock chamber is quite wide, so the transverse flow distribution in the chamber during the filling run is the main influencing factor of the ship berthing safety due to the previous experiences. At the beginning, the In-chamber longitudinal culvert system (ILCS) invented by the U.S. Army Corps of Engineers is been adopted for the new lock. A physical model with the scale 1:30 was built for the hydraulic study. The test results of the initial layout indicate that: under the ILCS layout, the transverse flow distribution in the chamber during the filling run especially with single valve opened is quite uneven, there is obvious water surface slope and the transverse hawser forces of the vessel far exceeded the allowable valve.

Based on the test results, we changed the energy dissipating type from flow jet collision to open ditch, which means a "T" type baffle was set between the two bottom culverts, and the height of the holes in the "T" type baffle was adjusted to improve the transverse flow distribution. At the same time, considering the uneven flow distribution problem under single valve opened or asynchronous double valves opening, the layout of the two separate culverts in the ILCS was adjusted that two converged sections were set for the two culverts near the lock heads. The test results under the new layout indicate that the optimizations greatly improved the flow conditions in lock chamber, the transverse hawser forces of the designed vessel reduces nearly by 50%, and the hydraulic characteristics under different conditions all satisfied the requirements of design and standards.

The new in-chamber double longitudinal culverts filling and emptying system has many advantages, such as obvious energy dissipation efficiency, high hydraulic efficiency, simple structure, economic construction and maintenance, and it is a safe and efficient filling and emptying system for high head large navigation lock. Compared to the ILCS, the new system adapts to more lift height, which is recommended under 12m by the U.S. Army Corps of Engineers, and also has more efficiency and safety.

Key words：navigation lock, filling and emptying system, in-chamber culvert, energy dissipation, hydraulics;

1. INTRODUCTION

Xijiang River is one of the high level waterways which are being constructed in recent years, and it is as important as Yangtze River in Chinese inland water transportation. The Chinese government has planned to make Xijiang River become a golden waterway with the annual traffic capacity over 100 million tonnage. A lot of large navigation locks have been or being constructed to achieve the above goal. Among these

[1] Nanjing Hydraulic Research Institute, Key Laboratory of Navigation Structure Construction Technology, Ministry of Transport, lijun@nhri.cn, China
[2] Nanjing Hydraulic Research Institute, bqliu@nhri.cn, China
[3] Nanjing Hydraulic Research Institute, gszhao@nhri.cn, China
[4] Nanjing Hydraulic Research Institute, xuan@nhri.cn, China

locks, the Xijin 2nd lane lock has the second highest hydraulic characteristics, ranked only behind the Datengxia lock (LI Jun et al, 2016) [1].

The designed vessel for Xijing 2nd lane lock is 3000t single vessel and 2×2000t push train. The effective dimension of the lock chamber is 280.0m×34.0m×5.6m (length × width × water depth over the sill), the lock's maximum lift height is 20.3m, the designed filling time is 12min. Due to its large dimension and high lift, the comprehensive hydraulic characteristics of the new lock is close to the Three Gorges Locks and the Gezhouba Locks on Yangtze River, so it is quite necessary to determine and improve the layout of the filling and emptying system both by hydraulic analysis and model test study.

2. SELECTION OF THE FILLING AND EMPTYING SYSTEM

2.1 Selection criteria

According to the Chinese Industry Standard "Design code for filling and emptying system of shiplocks (JTJ306-2001)" [2], the selection coefficient for lock filling and emptying system is as follows:

$$m = \frac{T}{\sqrt{H}} \tag{1}$$

in which, *m* is the selection coefficient, *T*(min) is the designed lock filling time, and *H*(m) is the lock lift height. For Xijin 2nd lane lock, *H* is 20.3m, *T* is 10~12min, so its selection coefficient *m* is 2.22~2.66. According to the design code, when *m* is between 1.8 and 2.5, the lock filling and emptying system can be simple through culverts system including side-port system, in-chamber longitudinal culvert system and in-chamber laterals system; when *m* is between 2.5 and 3.5, the lock filling and emptying system can be through heads system or above through culverts systems.

2.2 System selection and layout

Because the important role and high hydraulic characteristics of Xijin 2nd lane lock, and considering its large chamber dimension, great geological condition, safety, economy and maintenance, the in-chamber longitudinal culvert system becomes an appropriate selection.

Stockstill (1998) first invented a new In-chamber Longitudinal Culvert System (ILCS) for the McAlpine project and carried out a 1:25 model test, numerous culvert designs with various port arrangements were evaluated, some design criteria for this system were given according to the investigation [3]. Hite (1999,2000) carried out the second ILCS model investigation for the Marmet Navigation Project and the second ILCS model study, and also gave some design suggestions and valve operation suggestions [4,5]. Based on the above studies, John E. Hite (2003) carried out further and detailed studies of ILCS, and gave the detailed design guidance for this new system [6], this guidance was written in the U.S. Army Corps of Engineers Engineer Manual "Hydraulic Design of Navigation Locks(EM 1110-2-1604)" (2006) [7]. The investigation of the ICLS showed that this type of filling and emptying system was feasible from a hydraulic performance point of view, and can reduce construction costs associated with large concrete gravity walls, but this system is suggested to be used only in low to medium lift height (3m~12m) large locks.

For studying the applicability of ILCS in high lift large lock, according to the design guidance by U.S. manual and our design experiences of similar system, we designed the ICLS for Xijin 2nd lock, the layout of the system is shown in Figure 1 and Figure.2, and the key characteristics of the system are shown in Table.1.

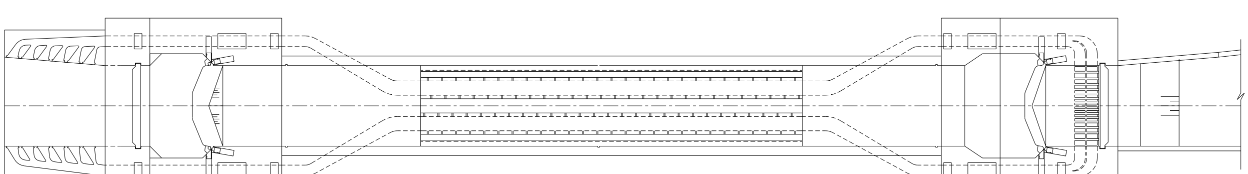


Figure 1: Initial layout of In-chamber Longitudinal Culvert System for Xijin 2nd lane lock

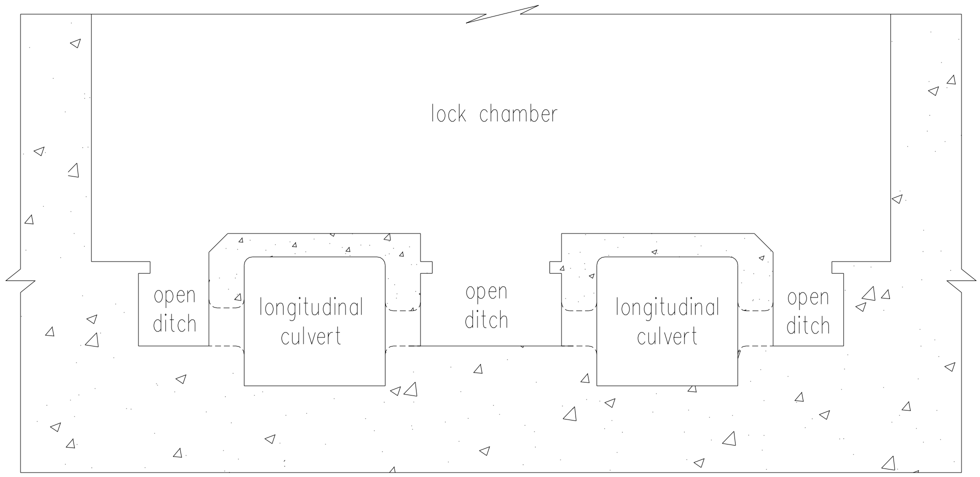


Figure 2: Cross section of lock chamber for Xijin 2nd lane lock

No.	Position	Description	Area (m^2)	Area ratio to valve section
1	Valve section culvert	submerged depth under maximum lift height condition: 7.82m.	2-4.5×6.0=54.0	1.00
2	Intake	6 vertical side ports on guide wall, throat section height of each port is same, throat section width of each port reduces along the flow direction.	2～6×4.5×7.2=388.8	7.20
3	In-chamber longitudial culvert	2 longitudinal culverts, side ports on each side of the culvert. Length of the side port section is 162.0m which is 57.9% of the chamber usable length.	2～6.0×5.5=66.0	1.22
4	Side ports	There are 27 side ports on each side of the bottom culvert. Dimension of the port from upstream to downstream are: 0.50m×1.50m (9 ports, width × height), 0.46m×1.50m m(9 ports), 0.42m×1.50m m(9 ports), port spacing is 6.0m, length of the port is 1.5m, inlet and outlet of the port should be round out, the trimming circle radius is 0.3m.	2～2×9×1.50×（0.5+0.46+0.42）=74.52	1.38
6	Open ditches in lock chamber	Width of open ditches at lock wall sides is 3.0m and open ditche in the center of lock chamber is 6.0m, the depth of the open ditch is 3.6m.	/	/
7	Outlet	Double of the culvert area, inside guide walls should be set up.	2～2×4.5× 7.2=129.6	2.40
8	Energy dissipation chamber	Manifolds in lower sill with 32 top ports and 16 side ports.	Top:4×（2+2+1.5+1.5 +1+1+0.8+0.8）× 4.5=190.8 Side:2×（2+2+1.5+1.5 +1+1+0.8+0.8）× 6=127.2	3.53 2.36

Table 1: key characteristics of In-chamber Longitudinal Culvert System for Xijin 2nd lane lock

3. MOEDL TEST INVESTIGATION OF THE INITIAL ILCS

3.1 Model design

A 1:30 scale model is established for studying the hydraulic characteristics of the filling and emptying system. The accepted equations of hydraulic similitude, based on the Froudian relations, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for the transference of the model data to prototype equivalents, or vice versa, are presented in Table 2.

Parameter	Ratio	Scale relations
Length	$L_r = L$	1:30
Area	$A_r = L_r^2$	1:900
Velocity	$V_r = L_r^{1/2}$	1:5.48
Discharge	$Q_r = L_r^{5/2}$	1:4929.5
Time	$T_r = L_r^{1/2}$	1:5.48
Force	$F_r = L_r^3$	1:27000

Table 2: Model test similitude

The model reproduced part of the upstream approach channel, the entire filling and emptying system including intakes, valves, culverts, outlet, lock chamber, and part of the downstream approach channel.

The lock chamber was constructed of steel sheet, the culverts were constructed of polyethylene(PE) plastic, the valve section culvert and one side of the lock wall were constructed of methyl methacrylate(PMMA) for the convenience of observing hydraulic phenomenon, the upstream and downstream approach channels were constructed of concrete precast slab with cement sand plaster. The model vessels were constructed of glass fiber reinforced plastics. The real model is shown in Figure.3 and Figure.4.

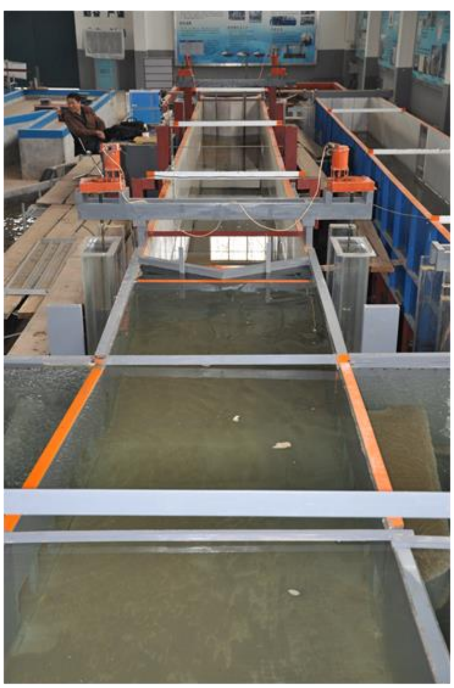


Figure 3: Overall model

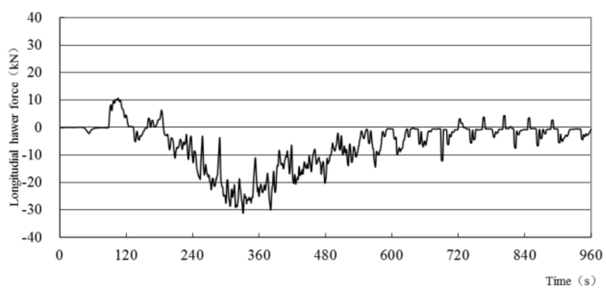
Figure 4: Model of valve section

3.2 Instruments and equipment

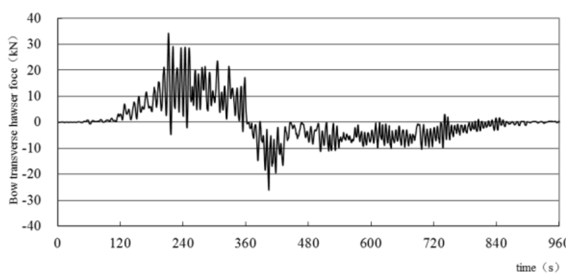
The upstream and downstream water level are controlled by overflow tank, the valve are driven by stepper motor which can achieve stepless speed regulation. The water level in lock chamber and the local transient or fluctuating pressures in culvert are measured by resistance-type pressure sensor, the local average piezometric pressures are measured by piezometric tubes. The vessel's hawser forces are measured by full-circular resistance-type dynamometer invented by Nanjing Hydraulic Research Institute. The discharge is measured by rectangle measuring weir. All the data are collected by WaveBook 516E high-speed data acquisition system.

3.3 Test results and analysis

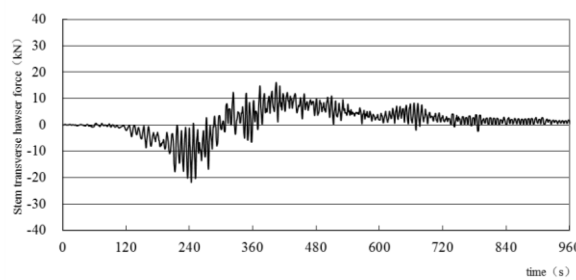
The vessel berthing condition test was firstly carried out. The hawser forces of 2×2000t push train were measured during the filling run, and the results are shown in Figure 5.



a longitudinal hawser force



b bow transverse hawser force



c stem transverse hawser force

Figure 5: Hawser forces of 2×2000t push train under initial layout (double valves operation)

The test results indicate that under the initial ILCS layout, when double filling valves opening in 6min continuously and synchronously, the maximum longitudinal hawser force of the designed 2×2000t push train is 30.9kN, the maximum transverse hawser force is 34.3kN. According to the design code [2], the longitudinal hawser force satisfied the safety need (no more than 40kN), but the transverse hawser force far exceeded the controlling value (no more than 20kN).

Due to the outflow adjustment and energy dissipation by grouped side ports layout and longitudinal open ditches, the longitudinal flow distribution in lock chamber is relatively even, there is no obvious longitudinal water slope, so the maximum longitudinal hawser force of the push train is only 75% of the allowable value. However, because the middle open ditch is wider than side ones, even though the side ports are staggered in the middle open ditch, the outflow in middle open ditch is more than side ones, so there is obvious transverse water slope in lock chamber which induced the large transverse hawser force. Besides, the transverse flow distribution in the chamber during the filling run with single valve opening will be more uneven than double valves opening. Therefore, the initial ILCS must be improved.

4. IMPROVED ILCS AND ITS TEST RESULT

4.1 Improvement of the initial ILCS

Based on the test results of the initial layout, the energy dissipation efficiency was not enough in the middle open ditch which induced more outflow around the center of the lock chamber, so we set a “T” type baffle in the middle open ditch to divide the large open ditch into two smaller ones, which will increase the energy dissipation strength, besides, we set several holes in the baffle to let the flow in the two small open ditches can exchange and mixing, which will further strengthen the energy dissipation efficiency and also can readjust the flow distribution in the two open ditches. The height of the holes in the baffle is the key parameter to improve the transverse flow distribution, and after several tests, we gave the recommended layout of the baffle which is shown in Figure 6.

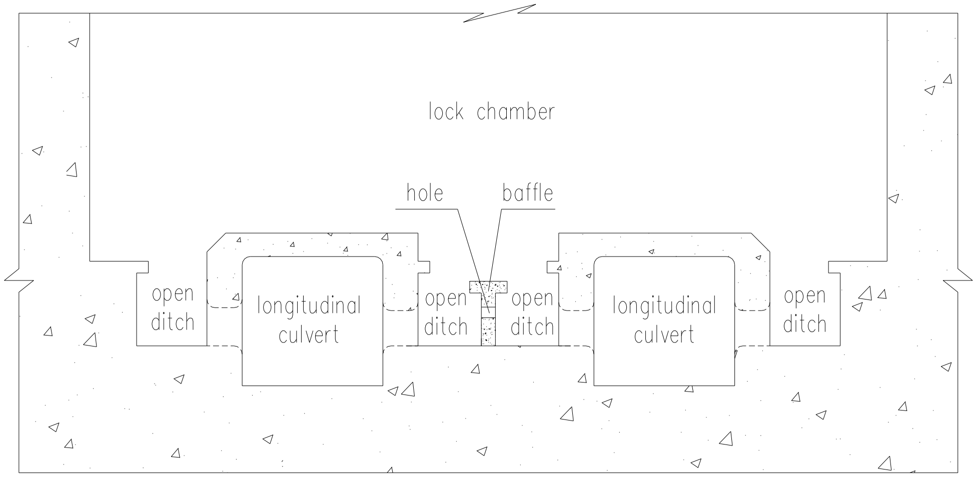


Figure 6: Cross section of lock chamber after improvement

At the same time, considering the uneven flow distribution problem under single valve opened or asynchronous double valves opening, the layout of the two separate culverts in the ILCS was adjusted that two converged sections were set for the two culverts near the lock heads. The recommended layout of the improved ILCS is shown in Figure 7.

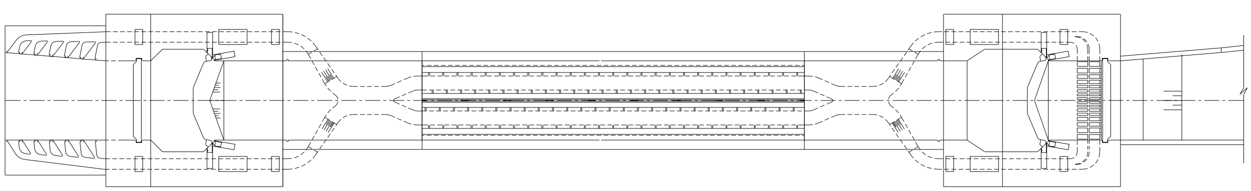


Figure 7: Layout of improved In-chamber Longitudinal Culvert System for Xijin 2nd lane lock

4.2 Test results and analysis

4.2.1 Vessel’s berthing condition

The test results of vessel’s hawser forces under the new layout are shown in Table 3. It indicates that the optimizations greatly improved the flow conditions in lock chamber, the flow distribution in lock chamber became more even, the transverse hawser forces of the designed push train reduces nearly by 50%, the maximum longitudinal hawser forces of push train and barge have further reduced and are only 64% and 67% of allowable value respectively, all of the forces satisfied the code. The improvements of the system have obvious effects.

Vessel type	Valve operation pattern	Vavle opening time (min)	Berthing position	Longitudinal hawser force (kN)	Bow transverse hawser force (kN)	Stem transverse hawser force (kN)
2×2000t push train	Double valve continuous opening	5	Upper chamber	23.0	16.8	17.7
			Middle chamber	25.5	18.6	18.6
			Lower chamber	23.9	13.0	11.8
	Single valve continuous opening	5	Upper chamber	17.7	16.0	17.8
			Middle chamber	15.7	18.0	14.4
			Lower chamber	16.5	14.1	9.5
3000t barge	Double valve continuous opening	5	Upper chamber	24.7	14.5	21.7
			Middle chamber	31.0	11.3	16.6
			Lower chamber	9.6	14.9	17.7
	Single valve continuous opening	5	Upper chamber	13.2	11.2	17.7
			Middle chamber	31.0	14.2	19.3
			Lower chamber	14.3	16.7	14.3

Note: According to the Chinese Standard, the allowable longitudinal hawser force for 2000t and 3000t vessel are 40kN and 46kN respectively, the allowable transverse hawser force for 2000t and 3000t vessel are 20kN and 23kN respectively.

Table 3: Hawser forces of designed vessels under improved layout

4.2.2 Hydraulic characteristics of filling and emptying runs

The main hydraulic characteristics under maximum lift condition (lift height: 20.3m) are shown in Table 4 and Fig8.

Operation pattern		t_v (min)	H (m)	T (min)	Q_{max} (m³/s)	$U_{\max}$ (m/min)	U_a (m/min)	d (m)
Filling	Double valves Continuous opening	5	20.3	11.92	653	3.33	1.70	+0.62
		6	20.3	12.63	625	3.18	1.61	+0.62
		7	20.3	13.20	592	3.02	1.54	+0.62
	Single valve Continuous opening	5	20.3	16.75	479	2.44	1.21	+0.46
		6	20.3	17.47	460	2.34	1.16	+0.46
		7	20.3	18.00	441	2.25	1.13	+0.46
Emptying	Double valves Continuous opening	5	20.3	12.96	601	3.06	1.57	-0.43
		6	20.3	13.50	566	2.88	1.50	-0.43
		7	20.3	14.04	530	2.70	1.45	-0.43
	Single valve Continuous opening	5	20.3	18.21	437	2.23	1.11	-0.38
		6	20.3	18.80	426	2.17	1.08	-0.38
		7	20.3	19.39	418	2.13	1.05	-0.38

Note： t_v is the valve opening time, H is the lock lift height, T is the filling or emptying time, $Q_{\max}$ is the maximum filling or emptying discharge, $U_{\max}$ is the maximum rate-of-rise or rate-of-fall of the water level in lock chamber, U_a is the average rate-of-rise or rate-of-fall of the water level in lock chamber, d is the overfill or overempty.

Table 4: Hydraulic characteristics of filling and emptying runs under improved layout

The test results indicate that:

1) If the filling and emptying valves both open in 5min continuously and synchronously, the average operation time is 12.44min, considering the scale effect of lock hydraulic model test, the prototype discharge coefficient will increase compared with model, the prototype operation time will decrease, so the prototype operation time will less than 12min.
2) When double filling and emptying valves all open in 5min continuously and synchronously, the maximum filling discharge are 653m³/s and 601m³/s respectively. The velocities in different sections of the improved system all can satisfy the code (flow velocity in culvert should not exceed 15m/s, average velocity of intake should not exceed 2.5m/s) and operation safety.
3) The overfill and overempty under different conditions are both over 0.30m which are higher than the allowable value (0.25m) according to the code. In prototype, we can use the countermeasure to reduce the overfill and overempty that opening the miter gate when the water levels become equal on both sides of the gate, and this countermeasure has been successfully used in the Three Gorges Locks.

4.2.3 Resistance coefficient and discharge coefficient

According to the steady flow test results we can calculate the resistance coefficients and discharge coefficients under different conditions. The filling and emptying discharge coefficients under double valves open are 0.841 and 0.729 respectively, and the filling and emptying discharge coefficients under single valve open are 1.027 and 0.979 respectively.

5. Conclusion

The new in-chamber double longitudinal culverts filling and emptying system has many advantages, such as obvious energy dissipation efficiency t, high hydraulic efficiency, simple structure, economic construction and maintenance. Compared to the ILCS, the new system adapts to more lift height, which is recommended under 12m by the U.S. Army Corps of Engineers. So it is a safe, efficient and economic filling and emptying system for high head large navigation lock.

6. REFERENCES

[1] LI Jun, XUAN Guo-xiang, et al. (2016). Application of two-section four-manifold total-balanced filling and emptying system in 40m-grade single-step giant ship lock. Port & Waterway Engineering. 2016(12). (in Chinese)

[2] Chinese Industry Standard, Design code for filling and emptying system of shiplocks (JTJ306), 2001. (in Chinese)

[3] Stockstill, R. L. (1998). “Innovative lock design; Report 1, Case study, New McAlpine Lock filling and emptying system, Ohio River, Kentucky,” Technical Report INP-CHL-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

[4] Hite, J. E., Jr. (1999). “Model study of Marmet Lock filling and emptying system, Kanawha River, West Virginia,” Technical Report CHL-99-8, U.S. Army Engineer Waterways Engineer Station, Vicksburg, MS.

[5] Hite, J. E., Jr. (2000). “New McAlpine Lock filling and emptying system, Ohio River, Kentucky,” Technical Report ERDC/CHL TR-00-24, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

[6] John E. Hite, Jr. (2003). “In-Chamber Longitudinal Culvert Design for Lock Filling and Emptying System”, Technical Report ERDC/CHL TR-03-8, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

[7] Hydraulic Design of Navigation Locks (EM 1110-2-1604), US Army Corps of Engineers,2006.