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Simulation of Transport Channel in China's Middle Route South-to-North Water Transfer Project*

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Abstract: The unsteady flow in the Middle Route South-to-North Water Transfer Channel was simulated numerically using an implicit solution procedure for the Saint Venant equations. An equivalent roughness was used to simulate the effect of many transfer structures on the water levels in the main channel. Various gate operating and control methods were analyzed to study the response to disturbances produced by varying the flow rates through the Tianjin outlet. The results show that when the inflow at the head changes in the same way as the sum of the flow rates through all the outlets, the transition time and the fluctuation of the water levels using the timed gate operation method are less than when using the simultaneous gate operation method, but the variations of the gate openings and flow rates through each control gate are much larger. The flow disturbances produced by the Tianjin outlet can be rectified within several channel sections and the transition time can be greatly shortened by allowing the water levels immediately upstream of the control gates to vary within proscribed ranges, rather than being held constant.

Key words: Middle Route South-to-North Water Transfer Project; unsteady flow; open channel; control system; simulation

Introduction

With the rapid industrial development and expanding population in northern China, the surface water has quickly been exhausted with large amounts of ground water being pumped creating serious water pollution and deterioration of the environment. The Middle Route South-to-North Water Transfer Project, one of largest projects in China was conceived to deliver water from south China to the north to alleviate the extreme water shortage in the north and to promote the economic and social development of northern China. The project will be completed before 2010.

The head of the Middle Route is located in Taocha, Henan Province, passing through Hebei Province to Beijing, with a branch canal to Tianjin, as shown in Fig. 1. The main channel from Taocha to Beijing is 1276 km long and about 1400 km if including the branch canal. Unlike the State Water Project of California in the United States[1], the water flowing along the Middle Route is mainly driven by gravity. The channel from the head to the Beijuma River of about 1196 km is composed mainly of open channels, after which the water is delivered by pipeline and ultimately pumped to the Tuancheng Lake in Beijing. However, the main and only water supply at the channel head is from the Danjiangkou Reservoir in Hubei Province, located at the boundary of Hubei and Henan Provinces. The water in this reservoir is controlled by a dam that adjusts

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the water flowing in the Han River to guarantee shipping and irrigation. Because a large part of the water will be delivered to the north, other projects are also underway to remedy the effect on the Han River, including divesting some water from the Yangtze River.

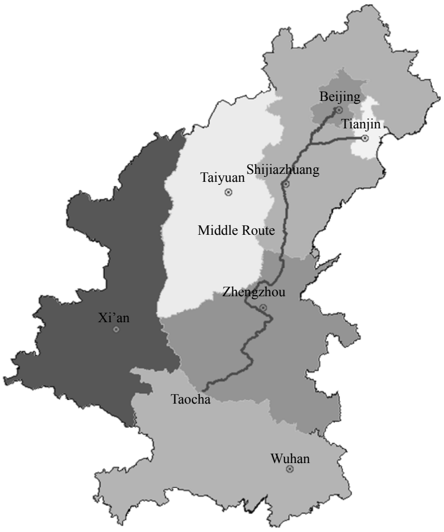


Fig. 1 Sketch of the Middle Route Channel

The designed and enhanced flow rates from Danjiangkou Reservoir are 350 and 420 m^3/s. After the various branches along the line downstream the designed and enhanced flux are 50 and 60 m^3/s at the downstream end in Beijing. To properly deliver the large flow rates to each outlet by the open channel, the top elevation of the Danjiangkou dam must be upgraded to provide sufficient hydraulic head and this project is now also underway. The average bottom slope of the channel is 1/25 000 with a large number of transfers, outlets, crossings, and control structures, about 1747, distributed along the route, including 59 control gates, 71 outlets, and 51 recessions. Besides the open channel, the flow also passes through inverted siphons, culverts, aqueducts, and tunnels. All these complex structures and unknown obstacles in these structures along such a long distance make predictions of the flow rather difficult using unsteady flow simulations of the Middle Route with stable, converged results.

Although there are many unsteady flow simulation models, such as USM, CARIMA, CANAL, DUFLOW, and Modis[2], and three software packages (CanalCAD, Mike 11, and Sobek) which allow users to write their own control routines without direct access to the source code[3], an unsteady simulation program is needed for this project to account for the great size, particular conditions, and the complications of the channel. The one-dimensional Saint Venant equations, which describe the conservation of mass and momentum, are usually solved to analyze unsteady flows in open channels. These are hyperbolic nonlinear partial differential equations that cannot be solved analytically. Thus, the numerical methods are used to solve the governing equations as described in Cunge et al.[4] and Strelkoff and Falvey[5]. The main Middle Route Channel includes 58 pools, with many different types of structures besides the many control gates and the open channel. Analysis of the flow with these structures is rather time consuming.

This paper describes an equivalent roughness method developed to simulate the effect of transportation structures in an open channel on the water level. The method was incorporated into a software package to simulate the unsteady flow in an open channel from Taocha to the Beijuma River. The control gates, outlets, and recessions in the channel are modeled as interior boundary conditions coded into the package for the conservation of mass and energy or momentum equations. The model was then used to analyze the effect of timed and simultaneous gate operations in the downstream control system to respond to both long-term and transient disturbances by the branch outlets.

1 Control Methods and Gate Operation

Control gates are designed to improve the flow responsiveness in the channel and to control water levels and flow rates. Flows through a single gate may be free or submerged depending on the tailwater depth. The discharge coefficients for the two cases differ[6-8], with the equation proposed by Swamee[8] used in this analysis to simulate the head loss through the gate.

Open-channel networks have many sluice gates to control flow rates and water levels, with various control methods implemented by operating some or all of the control gates in the channel. Various control techniques[4,9,10] have been developed and with various analyses[11-13]. The various control methods can be generally classified as upstream and downstream control. Downstream control is considered to be superior to upstream control in terms of increasing the efficiency of water use and improving the reliability and flexibility of the channel system. In a conventional downstream-control system, a target water level is maintained immediately downstream of each control gate. However, this requires a level upper canal with high dikes along the downstream part of the canal pool, which often makes the system very expensive. To avoid overflow in the Middle Route Channel for the current dike design heights, the target water level is controlled within a limited range at the downstream end of the pool by regulating control gates at both the upstream and downstream ends. This open-channel operation is coded into the unsteady flow simulation.

After the open-channel control method is selected, the next step is to properly regulate the control gates. A water transport system has three modes of gate operation according to the gate timing sequence: serial, simultaneous, and timed gate operations. Serial gate operation is usually used in moderate or slow water delivery systems because it slows the water flow rate and causes large fluctuations of the water level in the canal. Simultaneous and timed gate operations will improve security and responsiveness in the Middle Route Channel. These two gate operation modes will be analyzed in the unsteady flow simulations to study the effect of disturbances due to the Tianjin outlet.

2 Equivalent Roughness Method

Different types of transport structures are used in the Middle Route Channel for delivering water from southern to northern China. There are about 1747 of these structures with rather complex unsteady flow conditions. The development of the unsteady flow simulations will be very difficult if each structure is simulated, resulting in a lack of generality and divergence. In steady flow simulations, the water levels upstream and downstream of the structures can be calculated according to flow rate through the structure and the local energy loss coefficients determined from standard tables, which are usually constant. Thus, the local energy loss caused by each structure directly corresponds to the flow rate for both steady or unsteady flows.

The unsteady-flow simulations can be greatly simplified by replacing these structures with straight and transitional virtual channels without considering the detailed flow inside the structure. The energy loss caused by each structure can be simulated by increasing the local roughness of the virtual channel, with the roughness varying with time in the unsteady flow as the energy loss varies with the flow rate. The roughness of the virtual channel is then a function of the flow rate through the structure in the unsteady flow simulations. Therefore, the effect on the water levels in the channel on each structure is simulated by changing the roughness of the virtual channel, referred to as the equivalent roughness method.

A first step in developing the equivalent roughness method to simplify the unsteady flow package is to obtain the relationships between the roughness of a virtual channel and the flow rate. The equivalent roughness for all the many structures except open channel in the Middle Route were calculated and stored in data files for use in the flow analysis. The flow chart for calculating the equivalent roughness is shown in Fig. 2. The steady flow simulation was developed before the equivalent roughness was calculated.

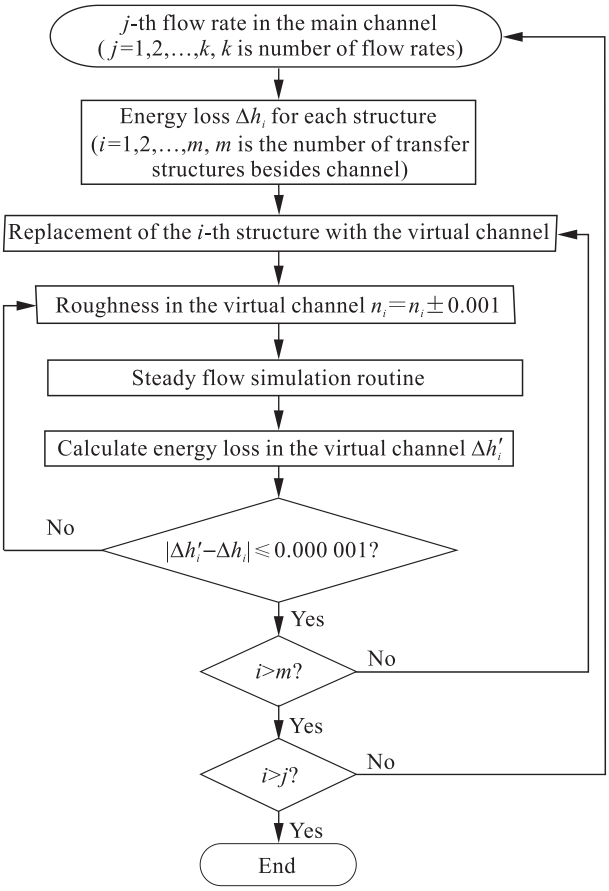


Fig. 2 Flow chart for equivalent roughness calculations

Table 1 lists the equivalent roughness for the Xizhao River inverted siphon, which shows that the roughness of the virtual channel increases with the increase of flow rate through the siphon. However, the trends are not always the same for the other types of structures. For example, the roughness of the virtual channel decreases with increasing flow rate for aqueducts.

Table 1 Equivalent roughness for Xizhao River inverted siphon

Flow rate (m^3/s)	33.8	67.6	101.4	135.2	169	202.8	238	271	304	338
Equivalent roughness	0.025	0.055	0.055	0.057	0.058	0.061	0.061	0.062	0.062	0.063

3 Initial Conditions

The entire open channel is 1196 km from the upstream end at Taocha to the downstream end in Hebei Province, with 59 uninterrupted channels with an average length of 20 km separated by 60 control gates and is bounded by the Danjiangkou Reservoir at the upstream end and the Beijuma River culvert at the downstream end leading to the Huinanzhuang Pumping Station. The upstream and downstream ends of the simulated channel are both controlled by gates with the primary boundary conditions being time series of the flow rate at the upstream end and the water depth at the downstream end. The constant water depth immediately upstream of each control gate is found by using the steady flow simulation for the enhanced flow rate of 420 m^3/s in the channel. In the unsteady flow simulations, the openings of each control gate are then adjusted so that the water depth does not change significantly at the new steady state in the channel.

Manning's coefficient for the channel was set to 0.015 including the effect of all the main bridges on the water levels, as proposed by the Changjiang Water Resources Commission of China (CWRCC). The lateral flow rates are assumed to depend on the operation of the lateral outlets and to not change with variations of the water level in the main channel. The unsteady flow in the entire open channel was simulated by solving Saint Venant equations, using the implicit Preissmann scheme and the double sweep method to solve the algebraic equations. The time step, Δt, and element sizes, Δx, for the simulations were selected based on accuracy and numerical stability considerations[5]. The element sizes, Δx, with original calculations by CWRCC were too big to be used in the unsteady flow simulations so many new nodes were inserted by interpolation. The unsteady flow simulations used a total of 26 003 nodes with a length of less than 50 m. The time interval was taken as 5 min for all the simulations except one. A time weighting coefficient of 0.7 and a distance weighting coefficient of 0.5 were used in the Preissmann scheme.

Assuming that the inflow from the Danjiangkou Reservoir is dependable, 70% of the designed flow rate was assumed to be initially passing through the channel. The flow rate downstream in the main channel decreased gradually as flow was divided to the outlets. The analysis guaranteed that the sum of the flow rates in all the branches and at the downstream end of the open-channel was equal to inflow at the upstream end. The initial opening of each control gate was calculated using the steady flow simulation for 70% of the design flow rate passing through the channel. An initial steady-state condition was approached using unsteady flow simulation with no changes in the gate positions or boundary conditions. A number of tests were then carried out on the channel system described, to compare different gate operating and control methods. During all the tests, the time interval used for adjusting the control gates was equal to the time interval for the simulations.

4 Comparison of Two Gate Operating Methods

The flow rate taken at the Xiheishan outlet leading to Tianjin fills half of the design flow rate in the local main channel so any variations of the flow rate will have a notable effect on the water levels. The outlet is only about 70 m from the upstream inlet to the Xiheishan control gate in a channel controlled by the Gangtou control gate at the upstream end, as shown in Fig. 3. This outlet is used as a typical outlet example in this paper with the unsteady flow in the main channel simulated for various flow rates in the outlet branches from it. The flow rate produced using the simultaneous gate operation (SGO) and timed gate operation (TGO) methods were compared for various disturbances produced by the outlet. The initial flow rate to the outlet was 35 m^3/s (the design maximum rate for the outlet

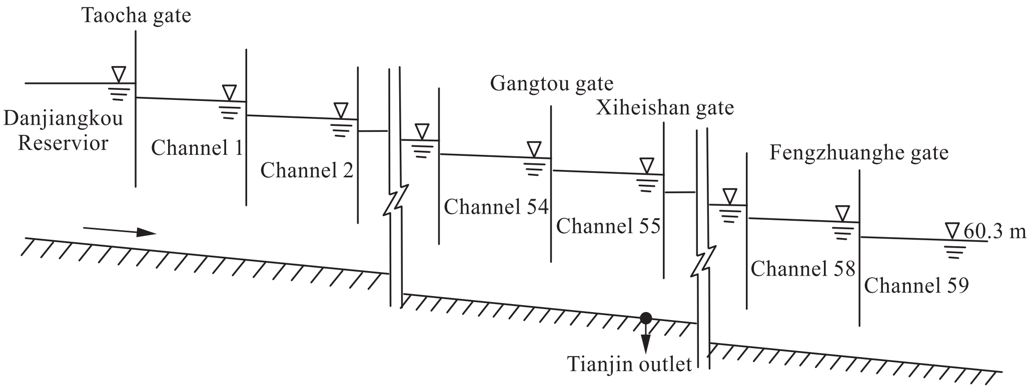


Fig. 3 Sketch of Tianjin outlet in the Middle Route Channel

was 65 m^3/s) with an assumed linear variation of the flow rate from the initial flow rate to the specified flow rate during the given time frame.

4.1 Simulation conditions

The initial inflow from the Danjiangkou Reservoir was assumed to be 245 m^3/s with the water level at the downstream end of the channel (immediately upstream of the last control gate) kept constant at 60.3 m. All the simulation conditions are summarized in Table 2, with the only disturbance being that produced by linearly increasing or decreasing the flow rate out of the Tianjin outlet over a 10-min time span and with or without change the inflow at the upstream end. When changed, the inflow at the channel head was the same as at the outlet. The time intervals for all the simulations were 5 min except for case 4 which used a 1-min time interval.

Table 2 Simulation conditions

Case	Tianjin outlet		Inflow at the head (m^3/s)	Gate operation
	Branching out (m^3/s)	Time used (min)		
1	35→50	10	Unchanged	TGO
2	35→50	10	245→260	TGO
3	35→20	10	Unchanged	TGO
4	35→20	10	245→230	TGO
5	35→50	10	245→260	SGO
6	35→20	10	245→230	SGO

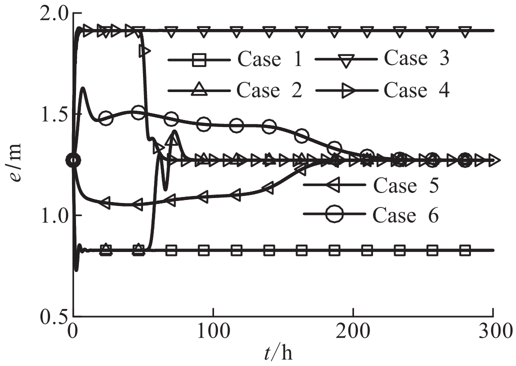
4.2 Analysis of openings, water levels, and flow rates

The response of the Gangtou and Xiheishan control gates, the variation of the water level immediately upstream of these gates, and the flow rates through them are plotted in Figs. 4 and 5 for the given disturbances. The water level immediately upstream of each gate returns to its initial level once the new steady state is reached. When the inflow from the head of the channel is kept constant, the openings and discharges of all the control gates downstream from the Tianjin outlet change while those upstream return to their initial values. When the inflow from the head changes according to the flow rate at the Tianjin outlet, the upstream gates all change while the downstream gates remain unchanged, which is just reversed and the transitional time is much longer.

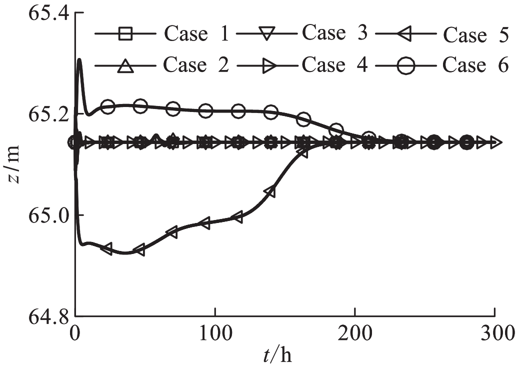
The variations of the water levels immediately upstream of the two control gates for cases 1-4 which use the TGO method are rather small and do not exceed 0.06 m. In case 4 the time interval was 1 min, so water level variations were less than cases 1-3 because the control gates openings were adjusted more frequently to move quickly returning the water levels immediately upstream of gates to their initial values. With the SGO method in cases 5 and 6, the largest variations immediately upstream of the Xiheishan gate were 0.22 m and 0.16 m for cases 5 and 6 and upstream of the Gangtou gate were 0.11 m and 0.14 m, which are more than when the TGO method was used. For the same conditions, the transition times with the SGO method are much longer than with the TGO method.

4.3 Water levels at the Tianjin outlet and outflow at the end of the channel

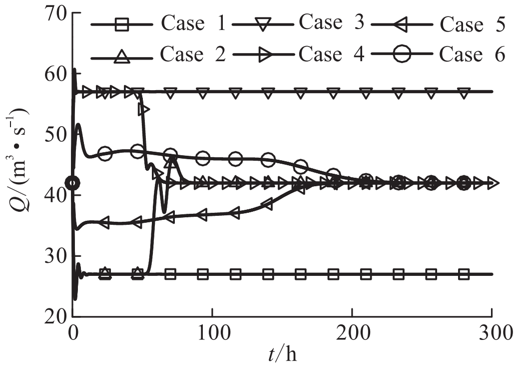
The variations of the water level at the Tianjin outlet shown in Fig. 6 are almost the same as in Fig. 4b because the outlet is very close to the Xiheishan gate. The largest variations in cases 1-4 do not exceed 0.07 m with changes of –0.23 m in case 5 and 0.176 m in case 6.



(a) Gate opening

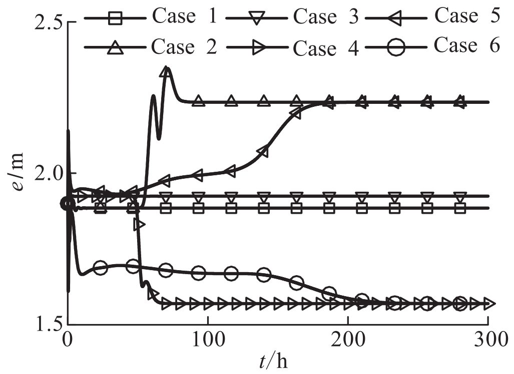


(b) Water level changes

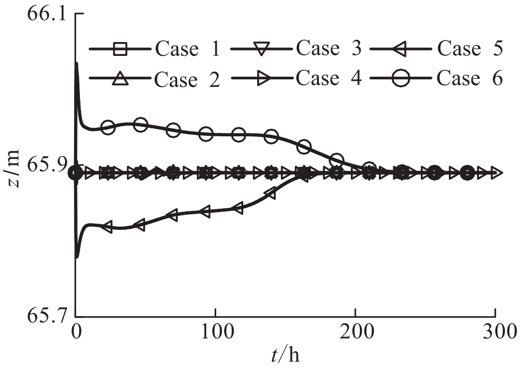


(c) Discharge rates

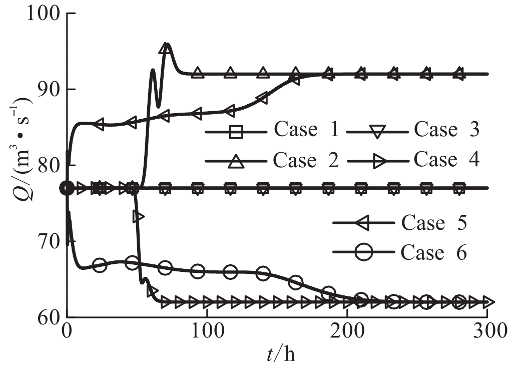
Fig. 4 Response of the Xiheishan control gate to flow rate variations at the Tianjin outlet



(a) Gate opening



(b) Water level changes



(c) Discharge rates

Fig. 5 Response of the Gangtou control gate to flow rate variations at the Tianjin outlet

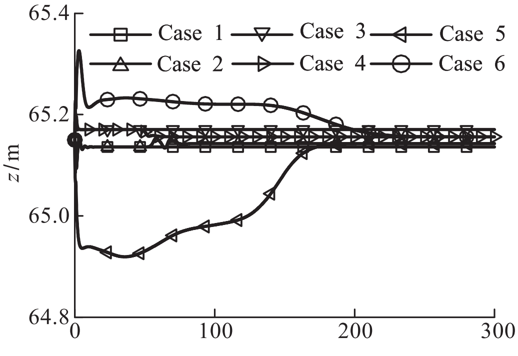


Fig. 6 Water level changes at the Tianjin outlet

Figure 7 shows that the flow variation and the fluctuations produced by the Tianjin outlet reach the end in about 4 hours. The flow rate at the end of the open-channel entering the Huinanzhuang channel varies whether or not there is inflow at the head. The largest flow changes at the end are −18 and 15 m^3/s when the TGO method is used to operate all the control gates and 6.5 and −5.3 m^3/s when the SGO method is used. Figure 7 also shows that the SGO method requires more time to reach a new steady state than the TGO method.

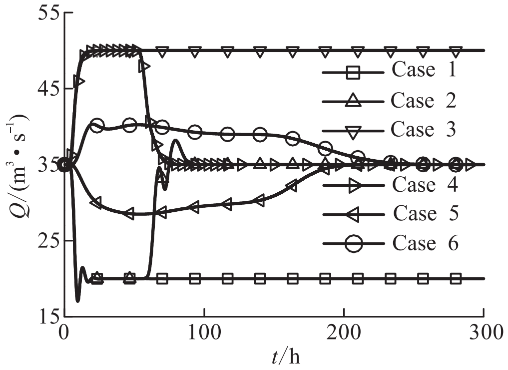


Fig. 7 Outflow changes at the channel end

4.4 Comparison of two gate operating methods

The transition times, water level variations immediately upstream of the control gates, and the gate opening and discharge variations are all shown in Table 3. The transition times are much shorter when the inflow at the head of the channel is kept constant. For the same boundary conditions, the transition times and water level variations in the main channel are smaller with the TGO method than with the SGO method, but variations of the gate discharges and openings are greater.

The slower response of the control gates with the TGO method make it more useful when only some of the gates in a channel are to be adjusted. Reallocation of the flow rates between some of the outlets, rather than changing the inflow at the head can be a preferred measure to shorten the transition time and distance along the channel affected by the changes when the TGO method is used to operate the control gates in response to disturbances. The outflow at the end of the open channel into the Huinanzhuang pool are affected by both gate operating methods, so regulation and storage capacity are needed to prevent excessive fluctuations of the water level and guarantee normal working of the pumps.

Table 3 Comparison of gate operating methods

Case	Transition time (h)	Largest variations immediately upstream of the gate (m)		Largest variations of the gate openings (m)		Largest outflow variations at the channel end (m^3/s)
		Xiheishan	Gangtou	Xiheishan	Gangtou	
1 (TGO)	21.6	−0.05	−0.01	−0.54	−0.09	−18.0
2 (TGO)	92.0	−0.06	−0.01	−0.54	0.44	−18.0
3 (TGO)	19.5	0.05	0.01	0.64	0.10	15.0
4 (TGO)	75.8	0.00	0.00	0.64	−0.33	15.0
5 (SGO)	210.0	−0.22	−0.11	−0.22	0.33	−5.3
6 (SGO)	260.0	0.16	0.14	0.35	−0.33	6.5

5 Control Methods

Each gate is adjusted continuously in the unsteady flow simulations to restore the water level immediately upstream of each gate to its initial value at the new steady state. The results show that the two control methods both have advantages and disadvantages with the outflow at the channel exit affected by both methods because a rather long time is needed for the extra inflow at the head increased or decreased to reach the Tianjin outlet. At the same time the target of each gate operating method is to keep the water level upstream of each gate constant, rather than meeting the variation of flow rate at the Tianjin outlet by changing the flow rate at other outlets. As a result the outflow at the channel end is always affected. In some cases, since each channel segment along the Middle Route Channel has some regulating and storage capacity, small fluctuations in the main channel produced by the Tianjin outlet can be balanced before they reach the exit by moderate increases or decreases of water level upstream of each control gate. This control method of allowing water level immediately upstream of each gate to change within a limited range in response to a disturbance at the Tianjin outlet was also simulated. If the water levels vary within controlled ranges, the target of each gate control is to satisfy the flow rate requirement divided by all the outlets in the downstream direction. If not possible, the gate positions are varied so that the water levels return to their desired ranges.

5.1 Simulation conditions

The initial inflow at the channel head is 245 m^3/s and the water level at the downstream end of the channel is kept constant. All the simulation conditions summarized in Table 4 involve increasing or decreasing the flow rates to account for the flow rate change at the Tianjin outlet which occurs in a 10-min time span, with five different water level control ranges immediately upstream of each control gate, with water surface level changing freely in cases 1 and 2. The fluctuation ranges in all the previous cases were all zero because the control method restored the water level immediately upstream of each gate to its initial value. The TGO control method was used in all cases because the new steady state is reached in much less time than with the SGO method. The inflow at the head was varied according to the net flow rate change at all the outlets to maintain the water volume balance in the channel. The time interval for all the cases was 5 min.

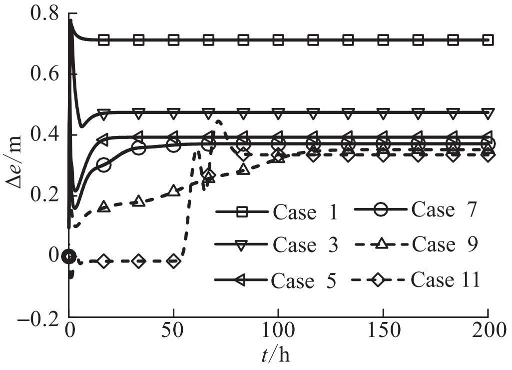
Table 4 Simulation conditions

Case	Variation of the flow rate at the Tianjin outlet (m^3/s)	Allowed water level variation immediately upstream of each gate (m)
1	35→50	Uncontrolled
2	35→20	Uncontrolled
3	35→50	± 0.30
4	35→20	±0.30
5	35→50	± 0.15
6	35→20	± 0.15
7	35→50	± 0.10
8	35→20	± 0.10
9	35→50	± 0.05
10	35→20	± 0.05
11	35→50	0
12	35→20	0

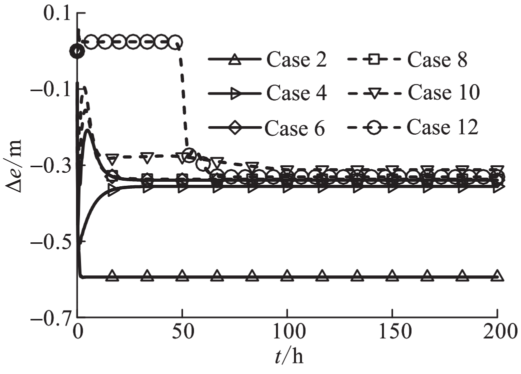
5.2 Openings, water levels, and time for each gate to reach steady state

The time when the flow rate through the Tianjin outlet begins to change was taken as the initial time. The responses of the Gangtou and Xiheishan control gates and the water level variations immediately upstream of these gates are plotted in Figs. 8-11. Δe and Δz represent the variations from the initial gate openings and water levels. The sudden variation of the flow rate through the Tianjin outlet causes a rapid increase or decrease of water level immediately upstream of the control gates and rapid change of the gate openings because each gate control scheme initially seeks to satisfy the flow rate requirements at each outlet immediately downstream of the gate. If the water levels are completely uncontrolled, the water levels and gate openings vary more from the initial values, resulting in less transition time than when the water levels are controlled. The flow rates through each control gate upstream of the Tianjin outlet increased or decreased in accordance to the flow rate changed at the Tianjin outlet, while others returned to their initial values in the new steady state.

The variations of the gate openings and water levels and the time needed for the Gangtou and Xiheishan gates to reach their final positions for the new steady state are listed in Table 5. The transition times are considerably shorter when the water level immediately upstream of the control gates is allowed to vary within

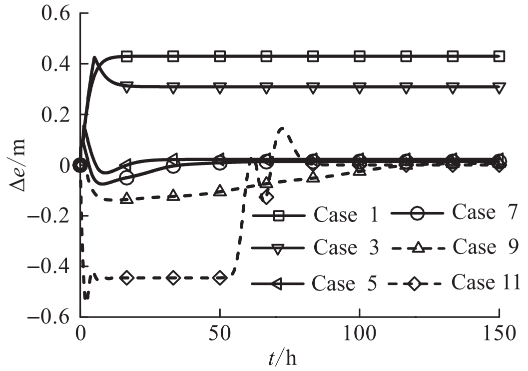


(a) Increasing flow rates

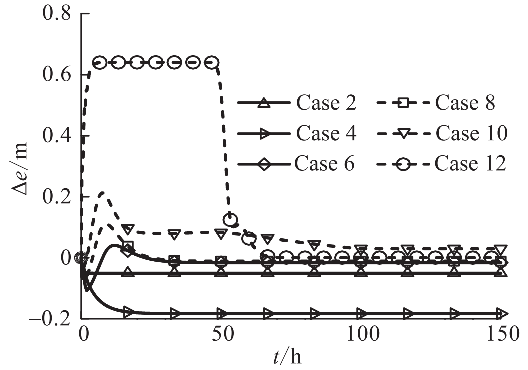


(b) Decreasing flow rates

Fig. 8 Gate openging changes of the Gangtou control gate

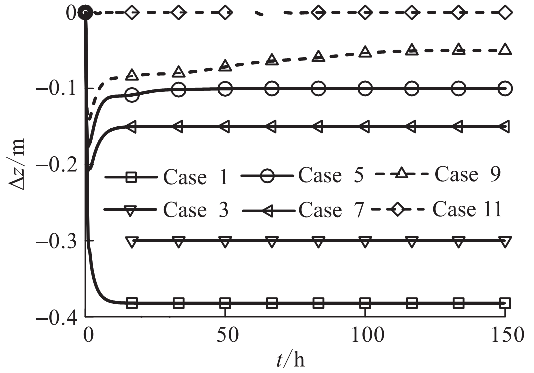


(a) Increasing flow rates

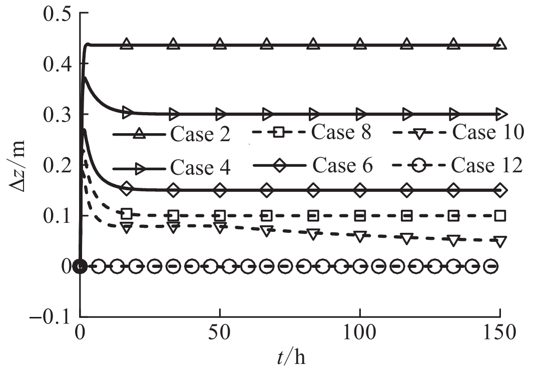


(b) Decreasing flow rates

Fig. 9 Gate opening changes of the Xiheishan control gate

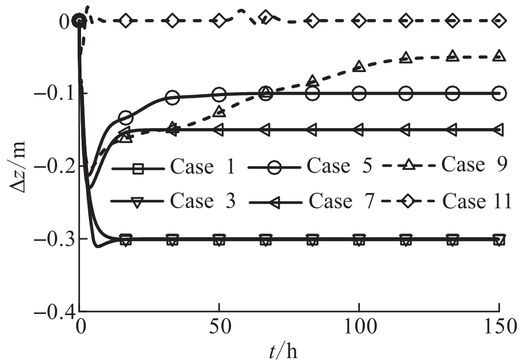


(a) Increasing flow rates

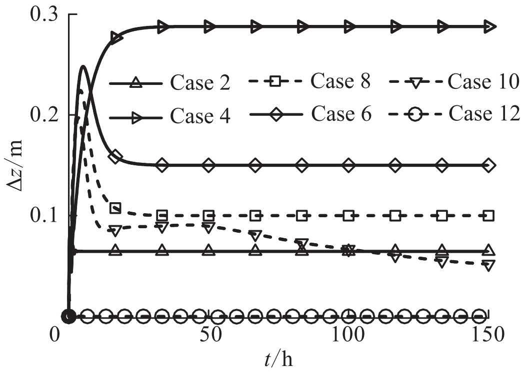


(b) Decreasing flow rates

Fig. 10 Water level changes immediately upstream of the Gangtou control gate



(a) Increasing flow rates



(b) Decreasing flow rates

Fig. 11 Water level changes immediately upstream of the Xiheishan control gate

a designed range because the storage in each channel segment reduces the disturbances produced by the flow rate change at the outlet. However, the integrity of the channel and the flow rates in other outlets will be affected if the water levels immediately upstream of the gates are allowed to vary over very large ranges. However, if the water level variations are too narrow, the transition time will actually be longer. For the 0.15 m/h limit for water level change recommended by the CWRCC, the water levels immediately upstream of the control gates can be allowed to vary within a range of ±0.15 m.

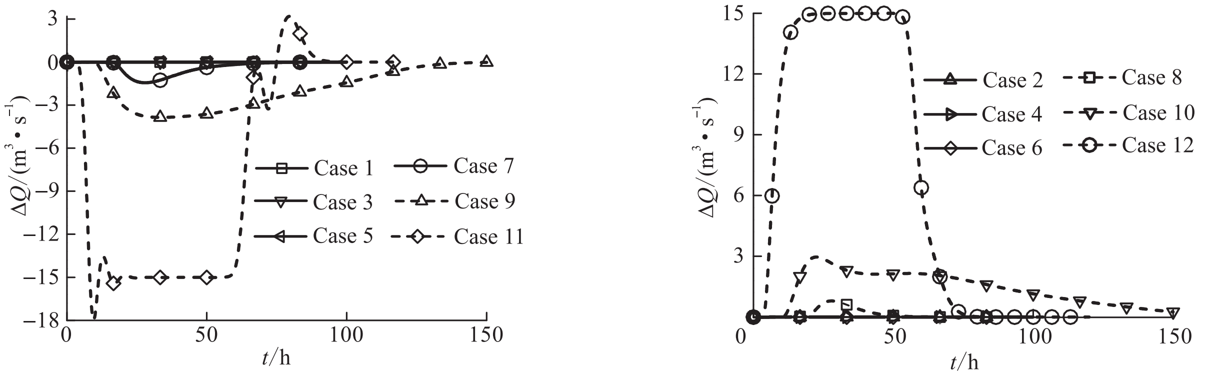
5.3 Flow rate changes at the channel exit

The flow at the open channel exit enters the Huinanzhuang pool and is then pumped to the Tuancheng Lake in Beijing. Thus, the water level in the pool cannot fluctuate too much to guarantee stable operation of the pumps. However, the pool storage is rather limited, so the flow rates at the open channel exit need to remain stable or return to the target value as soon as possible.

Table 5 Gate openings, water levels, and times to reach steady state

Case	Gate opening changes (m)		Water level changes immediately upstream of the gates (m)		Time (h)	
	Gangtou	Xiheishan	Gangtou	Xiheishan	Gangtou	Xiheishan
1	0.71	0.43	−0.38	−0.31	9.9	15.4
2	−0.59	−0.05	0.44	0.06	2.8	2.1
3	0.47	0.31	−0.30	−0.30	19.8	20.4
4	−0.36	−0.18	0.30	0.28	27.7	24.8
5	0.39	0.02	−0.15	−0.15	22.6	30.5
6	−0.34	−0.02	0.15	0.15	26.5	38.5
7	0.37	0.01	−0.10	−0.10	58.6	62.6
8	−0.34	−0.01	0.10	0.10	26.4	37.3
9	0.35	0.01	−0.05	−0.06	128.3	133.3
10	−0.31	0.04	0.06	0.07	89.7	90.4
11	0.33	0.00	0.00	0.00	81.0	81.5
12	−0.33	0.00	0.00	0.00	68.0	68.5

The flow rate changes at the open channel exit entering the Huinanzhuang pool are shown in Fig. 12. The flow rates in cases 1-6 remain constant, while cases 7-12 cannot return to the initial value for a very long time for both increases (Fig. 12a), or decreases (Fig. 12b) of the flow rates through the Tianjin outlet. Thus the water level at the Huinanzhuang pool will not be affected in cases 1-6 and will be affected in the other cases. Figure 12 also shows that smaller allowed ranges for the water level changes immediately upstream of the control gates lead to larger changes of the flow rates and longer transition times at the exit, so the water level in the Huinanzhuang pool is affected more. The flow rate variations at the open channel exit for all cases are characterized in Table 6. Considering how gate opening changes affect the flow rates at the open channel exit, the water level in the pool, and transition times, the water levels upstream of the control gates can be allowed to vary by ±0.15 m.



(a) Increasing flow rates

(b) Decreasing flow rates

Fig. 12 Flow rate changes at the channel exit

Table 6 Characteristics of the flow rates at the open channel exit

Case	Maximum flow rate change (m^3/s)	Beginning time for changing (h)	Time to return to its initial value (h)	Duration variation (h)
1-6	0	—	—	—
7	−1.4	17.5	65.5	48.0
8	0.7	20.5	47.6	27.1
9	−3.9	10.7	137.1	126.4
10	3.0	3.8	166.5	162.7
11	−18.0	4.0	91.9	87.9
12	15.0	3.8	75.9	72.1

6 Conclusions

An equivalent roughness is presented to simplify the effect of each hydraulic structure on water level in the Middle Route of the South-to-North Water Transfer Channel except for the open channel in unsteady flow simulations. The method controls the energy losses through each structure relative to the flow rates in the unsteady flow simulations because the hydraulic head loss allotted to each structure for transferring large volumes of water in the open channel is very limited. This method can efficiently predict the flow rates when the flow mechanism does not need to be externally accurate.

Two gate operating and control methods were used in the one-dimensional virtual channel model to evaluate the responses to disturbances produced by varying of the flow rates through the Tianjin outlet. The transition times are shorter with the timed gate operation control method for reallocating the flows through the outlets while keeping the inflow at the channel head unchanged when each gate is adjusted to return the water level immediately upstream of the gate to its initial value. If the inflow at the head changes the same amount as the flow rates through all the outlets, the transition time and the fluctuations of the water levels are less with the timed gate operation than with the simultaneous gate operation, but the variations of the gate openings and flow rates through each control gate are larger. The flow rates at the open channel exit entering the Huinanzhuang pool are affected when the water levels immediately upstream of the control gates remain unchanged for both the SGO or TGO control methods.

The results show that the flow variations by the Tianjin outlet can be accommodated within several channel segments and the transition times can be shortened by allowing water levels immediately upstream of the control gates to change within reasonable ranges. Excessively large fluctuations of the water levels will lead to instabilities and damage the channel integrity while very small changes allowed will result in very long transition times and will affect the water level in the Huinanzhuang pool from which water is pumped to the Tuancheng Lake in Beijing. Considering the safety, transition times, and the effect on the flow rates at the open channel exit, the water levels immediately upstream of the control gates can be allowed to vary within a range of ±0.15 m. This range can be adjusted for the various channel segments according to the actual conditions in the channel.

References

[1] Lefkoff L J, Kendall D R. Optimization modeling of a new facility for the California State water project. *Water Resources Bulletin*, 1996, **32**(3): 451-463.

[2] American Society of Civil Engineers (ASCE). Unsteady-flow modeling of irrigation canals. *J. Irrig. Drain. Eng.*, 1993, **119**(4): 615-630.

[3] Clemmens A J, Bautista E, Wahlin B T, et al. Simulation of automatic canal control systems. *J. Irrig. Drain. Eng.*, 2005, **131**(4): 324-335.

[4] Cunge J A, Holly F M, Verwey A. Practical Aspects of Computational Hydraulics. London: Pitman Advanced Publishing Program, 1980: 20-501.

[5] Strelkoff T S, Falvey H T. Numerical methods used to model unsteady canal flow. *J. Irrig. Drain. Eng.*, 1993, **119**(4): 637-655.

[6] Henry H R. Discussion of diffusion of submerged jets by M. L. Albertson, Y. B. Dai, R. A. Jensen, and H. Rouse. *Transaction of ASCE*, 1950, **115**: 687-694.

[7] Rajaratnam N, Subramanya K. Flow equation for the sluice gate. *J. Irrig. Drain. Eng.*, 1967, **93**(3): 167-186.

[8] Swamee P K. Sluice-gate discharge equation. *J. Irrig. Drain. Eng.*, 1992, **118**(1): 56-60.

[9] Liu F B, Feyen J, Berlamont J. Downstream control of multireach canal systems. *J. Irrig. Drain. Eng.*, 1995, **121**(2): 179-190.

[10] Reddy J M, Dia A, Oussou A. Design of control algorithm for operation of irrigation canals. *J. Irrig. Drain. Eng.*, 1992, **118**(6): 852-867.

[11] Burt C M. Overview of canal control concepts. In: Proc. Plng. Operation, Rehabilitation and Automation of Irrig. Water Delivery Systems, ASCE Symp. New York, 1987: 81-109.

[12] Buyalski C P, Ehler D G, Falvey H T, et al. Canal systems automation manual, Vol. I. U.S. Bureau of Reclamation, Denver, Colo., USA, 1991.

[13] Clemmens A J, Replogle J A. Control of irrigation canal networks. *J. Irrig. Drain. Eng.*, 1989, **115**(1): 96-110.