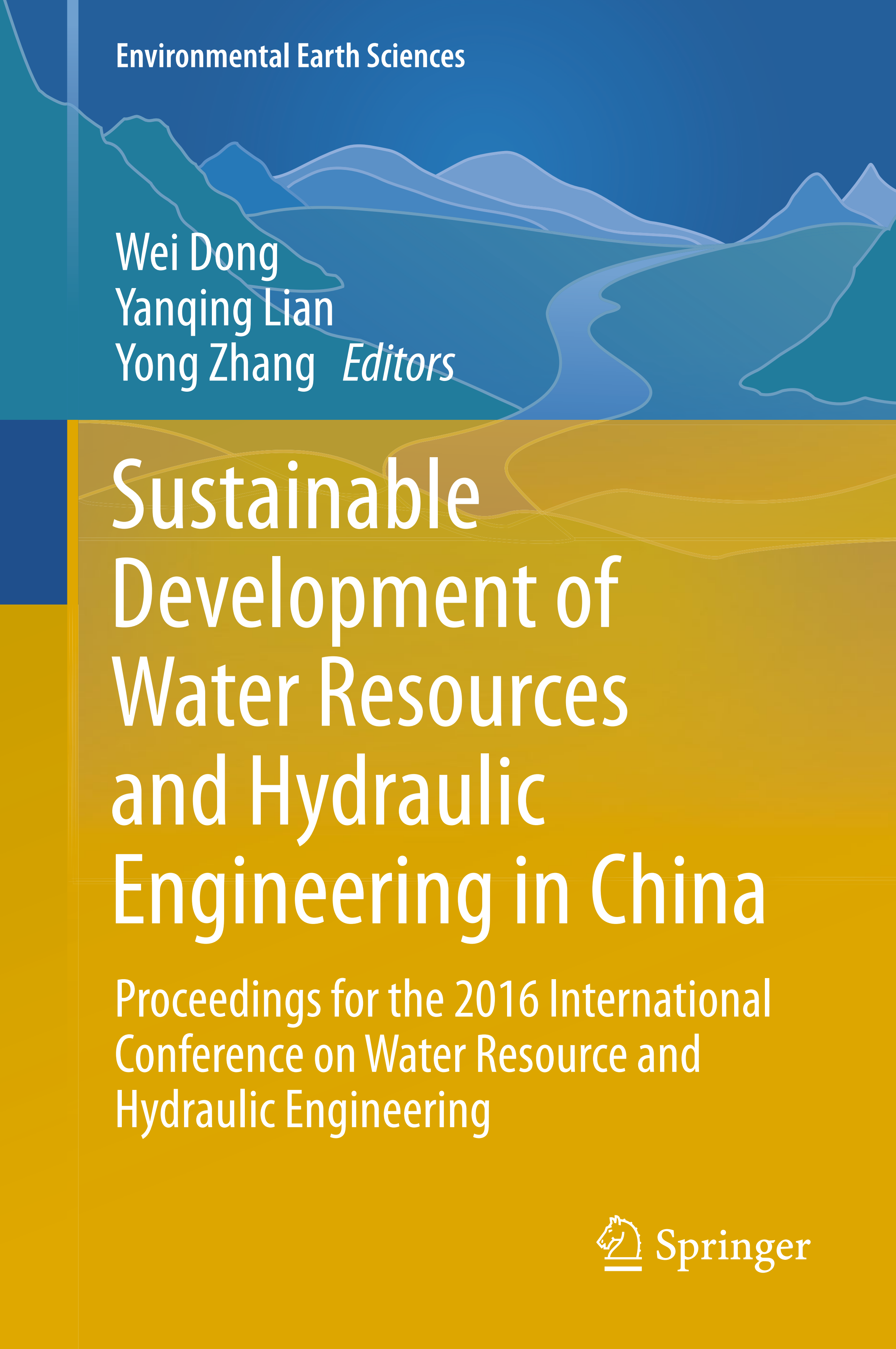

Environmental Earth Sciences

Wei Dong
Yanqing Lian
Yong Zhang *Editors*

Sustainable Development of Water Resources and Hydraulic Engineering in China

Proceedings for the 2016 International Conference on Water Resource and Hydraulic Engineering

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Preface

The "2016 International Conference on Water Resource and Hydraulic Engineering" was held at the Hebei University of Engineering, Handan, China, on October 9–12, 2016. More than 160 professionals attended. This conference was sponsored by the Hebei University of Engineering.

The central theme of the conference focused on sustainable development of water resources and the environment. Papers for conference presentation were selected from a wide variety of research areas, including watershed hydrology, river hydraulics, groundwater hydrology, water resource management and sustainability development, water supply planning under climate change, water quality analysis and water pollution, Sponge City Development and urban watershed management, environment and sustainability, global connection of air and water, irrigation and drainage issues for agricultural engineering. Out of 72 submitted papers, 34 were selected for this proceedings.

Global climate change and variability have had great impacts on the hydrologic cycle and subsequently on our living environment. Human activities have placed significant roles in an altered hydrologic environment. China has already experienced some environmental impacts from its rapid economic development in recent years. Issues such as air quality, surface water and groundwater environment, flooding especially in big cities, sustainable water resources, etc., have become major concerns by the Chinese government and general public. The central government of China is promoting the Sponge City or Low Impact Development concept to address these issues to sustain the continuing economic growth in China and at the same time to create a healthier and eco-friendly environment. Papers selected from this conference for the proceedings covered research related to these on advanced technology for air quality and water quality monitoring, and research on sustainable water resource development under global climate change and variability.

Papers in this proceedings shall be of interest to a worldwide audience in addressing emerging problems a developing country might face and by research and practice to successfully deal with these issues for a greener and eco-friendly living environment.

Handan, China	Wei Dong
Champaign, USA	Yanqing Lian
Handan, China	Yong Zhang
Tuscaloosa, USA	Jim LaMoreaux

The original version of the book was revised: A new chapter has been included. The erratum to the book is available at https://doi.org/10.1007/978-3-319-61630-8_36

Contents

Establishment of Groundwater Level Warning for Covered Karst Areas in Northern China

Xiaowei Wang, Lizhi Wang, Jingli Shao and Zhiwei Zhao

Abstract In view of the resources shortage and geological environment problems caused by over-exploitation of groundwater in northern China, the delineation of the groundwater level warning (GLW) is urgently needed. Based on the comprehensive consideration of the management objectives of water resources supply guarantee and karst collapse hazards warning, this paper proposed a method for the delineation of karst GLW in covered karst areas. Specific steps include: (1) establish the criterion of GLW based on statistical analysis of groundwater level using the groundwater depth criterion model of Pennsylvania as a reference; (2) establish the criterion of GLW for karst collapse in line with the experience and mechanism research; (3) establish the comprehensive judgment criterion model to determine the GLW of a single observation well; and (4) determine the GLW divisions based on observation wells cluster and issue and renew the warning afterward. The method was verified in the Chengqu-Jiuxian Karst System (CJKS) of Taian City in Shandong Province. It is demonstrated that the GLW conducted by the method in the study area was reasonable and reliable, and was appropriate for decision making for water authorities and governments.

Keywords Groundwater level warning · Covered karst areas · Statistical analysis
Karst collapse

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1 Introduction

As the most important water resources of covered karst areas in northern China, groundwater is severely overexploited due to rapidly increasing demand in recent years. The groundwater level is continuing to decrease. A series of karst collapse hazards were initiated by the intense groundwater level fluctuation when the over-exploitation occurred in strong flow areas of karst groundwater. It is necessary to research groundwater warning to prevent a water supply crisis and geo-environmental problems.

Groundwater Warning (GW) is identified as the evaluating model of groundwater status based on the integrated analyses of factors of groundwater benefits, qualities and geo-environmental hazards initiated utilizing groundwater monitoring data [1]. The groundwater level is composed of Groundwater Warning Level (GLW) and Groundwater Quality Warning (GQW). Common methods in current GLW research consist of numerical simulation [2, 3], multiple regression [4], combining relevant indicators [5] and statistical approaches. The statistical approach can warn and predict groundwater level states rapidly and dynamically compared with other methods due to its available analyses of groundwater monitoring data which is relatively easy to gather. A typical research was conducted to monitor dynamic warning based on the mathematical statistics method in Pennsylvania, USA by the United States Geological Survey (USGS) in 2002, which was adapted for the GLW in the Beijing plain areas [1].

There is not enough research on GLW of covered karst areas in northern China, especially on comprehensive consideration of groundwater supply and geo-environmental problems in an integral karst system. This study promoted a method for GLW in covered karst areas using the groundwater depth criterion model of Pennsylvania as a reference and combining the GLW of karst collapse. The method was verified in Chengqu-Jiuxian Karst System (CJKS) of Taian City in Shandong Province. It is demonstrated that this method was rational and feasible and was suitable for decision making of water authorities and governments.

2 Method

2.1 Establishment of the Criterion Model of GLW

An observation well cluster would be selected for analysis. It is stipulated that the selected wells should: (1) have monitoring data with a long-term time series which is more than 15 years; (2) have high quality monitoring data with the deficit no longer than half a year; and (3) be equally distributed in the area.

The percentile of long-term monitoring data for each observational day was calculated with the centile of 5, 25 and 75. The criterion model of GLW is established by the percentile curves of the whole hydrological year consist of minimum curve, 5 centile curve, 25 centile curve and 75 centile curve.

2.2 *Establishment of the Criterion for GLW of Karst Collapse*

It is proven that the karst collapse is initiated commonly due to the rapid fluctuation of groundwater level around the roof of the bedrock in covered karst areas in northern China [6]. The criterion for GLW of karst collapse can be established with the expression h ± i (m), where h is the roof of karst bedrock, i the threshold of water level wave of karst collapse initiation according to mechanism research or experiences.

2.3 *Evaluation of GLW for Single Observation Well*

The comprehensive judgment criterion model for single observation well would be elaborated as follows: (1) area above centile 75 curve is safe area; (2) area between centile 25 and 75 curve is green area; (3) area between centile 5 and 25 curve is blue area; (4) area between minimum curve and centile 75 curve is orange area; (5) area beneath minimum curve is red area; and (6) area between the threshold i is red area overlapping other types of areas. The GLW for single observation well can be obtained by verifying the designated area in the criterion model of updated monitoring data. It is necessary that the criterion model be updated every year in each hydrological year.

2.4 *Issue of Warning*

Warning divisions for the entire area that are based on the geological hazard susceptibility partitions will be determined by the combination of GLW results of observation well clusters and illustrated. A warning should be issued for different divisions, respectively, as well as suggestions such as reducing groundwater abstraction amount or more circumspect on karst collapse hazard.

3 Verification

3.1 Study Area

The Chengqu-Jiuxian Karst System (CJKS) is located in and to the southeast of the urban area of Taian City in Shandong Province. The CJKS is a monoclinic karst system [7] with an area of 112 km^2. The system is restrained and divided by faulted structures and stratigraphic, the main in which are Cambrain-Ordovician stratum. The depth of the aquifer is about 70–80 m. The aquifer has karst grown strongly and good water retention properties as the flow of a single-well can be up to 1000–5000 m^3/d. This system contains two water-rich areas—Chengqu and Jiuxian, both of which have been developed to groundwater-source locations. The main recharge of the karstic groundwater consists of inter-aquifer flow from Quaternary deposits through "skylights", lateral flow and surface water from the Muwhen River in the south. The flow path is from east to west in the east side of the Daidaoan Fault and from north to south in the west. Groundwater discharges to surface or Quaternary around Jiuxian village and Xujiapu village at the southernmost area of CJKS in natural station. Groundwater abstraction formed wells are currently the most important discharge. The Quaternary deposits overlaying on CJKS are thicker from northeast to southwest with a depth of 0–40 m.

The Chengqu groundwater-source location was constructed in the 1950s. The abstraction amount was up to the peak of $5–6 \times 10^4$ m/d during 1982. Karst collapses were initiated by overexploitation. Abstraction from the water supply company was prohibited in 1993 and from enterprises had been reduced to 2.1×10^4 m/d since 2012. The Jiuxian groundwater-source location was set up for operation in 1982 by the water supply company. The peak pumping amount was about 5×10^4 m/d around 2002. Karst collapse occurred in a large area soon afterwards. Although the pumping was presently limited, there still are more than 100 wells for municipal water supply and rural drinking and irrigation supply in the location with the abstraction amount up to 5×10^4 m/d during extreme drought.

3.2 Results

Seven observation wells were selected along with the groundwater flow direction in CJKS (Table 1). Monitoring frequency is 3/month or 6/month. The percentile curve, including minimum 5, 25 and 75, were illustrated as the criterion model using long-term monitoring data. The roof of bedrock h for each observation well was from drilling data. Karst collapse intensively occurred when the water level was fluctuating around the roof of bedrock when the inter-aquifer recharge was occurring [6]. Therefore, $h \pm 2$ m is determined to be the karst collapse warning criterion. According to the established comprehensive judgment criterion model, GLW for every observation well was obtained by taking the monitoring water level

Table 1 Information of selected observation wells and GLW for June 5, 2016

ID	Depth	Time series	Frequency/ month	h ± i(m)	Water level June 5, 2016	GLW for single well on June 5, 2016
201	294.77	1997–2015	3	130.57 ± 2	118.54	Safe area
206	150.26	1990–2015	6	126.79 ± 2	118.82	Safe area
208	100.03	1990–2015	6	118.14 ± 2	112.66	Green area
212	175.00	1990–2015	6	109.19 ± 2	124.49	Safe area
225	294.77	1990–2015	3	110.41 ± 2	107.68	Green area
230	120.90	1990–2015	3	117.14 ± 2	115.85	Red area
236	150.05	1990–2015	3	132.44 ± 2	109.97	Red area

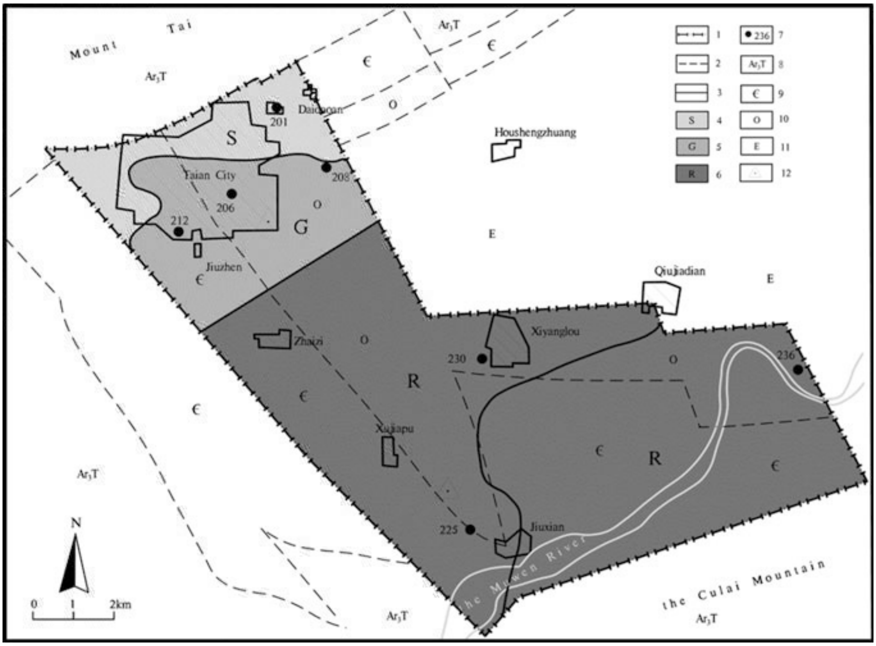

Fig. 1 Groundwater warning division of CJKS in June 5, 2016. 1-Study area boundary, 2-Stratigraphic boundary, 3-Warning divisions boundary, 4-Safe area, 5-Green area, 6-Red area, 7-Observation wells with ID, 8-Metamorphic rocks group, 9-Cambrian stratum, 10-Ordovician stratum, 11-Eogene stratum, 12-Groundwater-source location

on June 5, 2016 for example. Then the warning division of the whole study area was illustrated based on the geological hazard susceptibility partitions of Taian City (Fig. 1).

4 Conclusion

In this study, a method for groundwater level warning (GLW) in covered karst areas was put forward. The method was based on statistics of percentile and groundwater warning of karst collapse. This approach was verified in a typical study area of Taian City in Shandong Province. The study area identified as Chengqu-Jiuxian Karst System (CJKS) is a typical covered karst system in northern China where groundwater overexploitation coexists with serious karst collapse. The basis of this verification is a reasonably comprehensive groundwater observation net. Results showed that the warning divisions can be illustrated with four partitions in the study area including one safe area, one green area and two red areas on June 5, 2016. It is indicated that the method promoted is reasonably clear and easy to calculate. The verification result corresponds to the fact of the study area and powerfully sustains the method to be used for other locations in northern China.

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Flow Chocking Characteristics of Leak-Floor Flip Buckets

Shu-fang Li and Ji-wei Yang

Abstract Leak-floor flip bucket is a new type of flip bucket recently proposed. It has the advantages of decreasing flow choking on the bucket in small flow regimes and improving energy dissipation by a typical long-narrow nappe. However, if the structure parameters are designed unreasonably, flow choking may also occur on the bucket if the impact location of the lower jet trajectory is too near to the base of the structure, and will threaten the safety of the dam. The purpose of this paper is to study the critical conditions when flow choking begins to disappear or appear on the leak-floor flip bucket, during the increasing and decreasing discharge regimes, respectively. Five leak-floor flip bucket models were conducted, and one circular-shaped flip bucket was prepared for comparison. The critical conditions were investigated under a systematic variation of the approach flow depth, gap width and gap length. It concludes that the critical Froude numbers are primarily influenced by the relative bucket height and the area ratio of the gap; empirical equations for the prediction of critical conditions are obtained and conformed to the test data reasonably.

Keywords Leak-floor flip bucket · Flow choking · Critical condition
Dissipater

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1 Introduction

Ski jumps are a major element of high dam spillways or tunnel outlet for its satisfactory energy dissipation, especially when the velocity is larger than about 15–20 m/s [1, 2]. Many types of flip buckets were designed as ski jump generators. After the traditional continuous circular-typed (CCT) flip bucket [3–6], a series of different types of energy dissipaters such as slit-type flip bucket [7], triangular-shaped flip bucket [8–10] and deflector dissipaters [11] were proposed. However, a significant disadvantage of the mentioned bucket is the increased level of local flow choking, which is the breakdown of supercritical flow and a local hydraulic jump due to small approach Froude number and the presence of the bucket. When flow choking occurs, the water flow on the bucket is unstable, the jet trajectory impinges almost vertical and causes significant scour at the toe of the dissipater. Further, the choking makes the hydrodynamic and fluctuation pressures on the sidewalls much greater, thus flow choking must be carefully checked.

Leak-floor (LF) flip bucket has firstly been proposed by Deng [12] (Sichuan University, China) in 2009 to improve flow choking, energy dissipation and impact location. It is made up of a curved bed and two side walls, with a gap in the center axis of the bed, and that the length of the two beds which connect the two side walls can be designed to be the same or different, and the bed may be curved or distorted. As its plan view is like a swallowtail, it is also called the swallowtail-type flip bucket. Figure 1a gives a specific LF flip bucket with an equal side wall length proposed by Deng [12]. The LF flip bucket mainly has three advantages as a dissipater: (1) it can decrease flow choking on the bucket and reduce the incipient ski-jump discharge; (2) it makes the water jet diffuse in the longitudinal direction due to the existence of the gap, and reduces the pressure that effects on the side walls; and (3) by changing the length of the two side walls or the bed forms, it can adjust the jet direction into the downstream water flexibly, and adapt to complex terrain conditions to protect the banks of the downstream river.

The LF flip bucket has firstly been used in the right spillway tunnel of Jinping I hydropower project in China [13], and is also being used in the testing stage of Nam Ngiep II spillway [14]. In 2015, Deng [15] studied the flow pattern, the formation and the mechanism of the LF flip bucket based on experiments and numerical simulation. Until now, several questions have so far not been systematically addressed, such as flow choking characteristics, cavitations, energy dissipation, and so on. Although the flow choking characteristic is somewhat not as important as the other problems, the research on it will fill in the gaps in the systematic study of LF flip bucket. In this paper, the flow choking characteristics of LF flip bucket are experimentally investigated. As a preliminary research, this paper only considered a simple condition with equal side bucket length and an axis symmetric gap as shown in Fig. 1b.

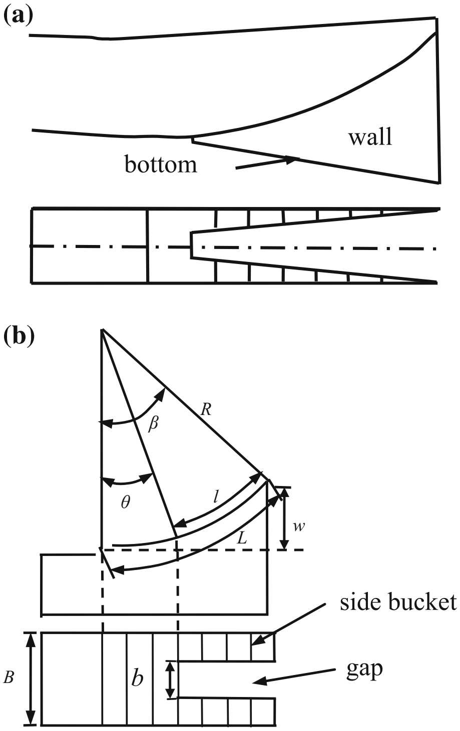


Fig. 1 Schematic view of leak-floor flip bucket **a** proposed by Deng [12]; **b** the present research

2 Experimental Setup

The experiments were conducted in a rectangular channel as described by Wu et al. [16]. It involved a horizontal approach channel to simplify the research. It is 1.25 m long, 0.15 m wide and 0.38 m high. Water was pumped from a laboratory sump to a water tank and then entered the horizontal approach channel. The maximum pump capacity was 400 Ls^{-1}, and the working head was about 1.50 m.

The discharge Q was measured by discharge measurement weir at the end of the tail water channel. The flow depth in the scope of 0.04 m $\leq h_o \leq$ 0.18 m was controlled by a radial sluice gate, which separates the pressure and the free-surface flow section at the inlet of the channel, approach Froude number $Fr = v_o/(gh_o)^{1/2}$ was generated by the jet box and the average approach flow velocity $v_o = Q/bh_o = q/h_o$ (q is the unit discharge), was adjusted by the working head.

The test model, made of Perspex, including five LF flip buckets inserted at the end of the channel, and one circular-shaped bucket was tested for comparison. Figure 1b gives a schematic view of LF flip bucket, where the width B = 0.15 m, the side bucket radius R = 0.50 m and deflection angle $\beta = 45°$ were fixed. The gap deflection angle θ and the gap width b was changed for $\theta = 0°$, 15° and 30°; b = 0.03, 0.05

Table 1 Test program with basic parameter variation

Cases	*b* (m)	θ (°)	*S*	h_o (m)
M1	0	0	0	0.04, 0.07, 0.10, 0.18
M2	0.05	30	0.11	
M3	0.05	15	0.22	
M4	0.05	0	0.33	
M5	0.03	0	0.20	
M6	0.07	0	0.47	

and 0.07 m, with the gap area ratio coefficient $S = lb/BL$ changed accordingly. Table 1 lists the experimental cases and geometric parameters in this paper, in which case M1 is a CCT flip bucket, and cases M2 to M5 are LF flip buckets.

3 Observations of Flow Choking

Figure 2 shows flow choking regimes for all the cases. From visual observations, several aspects can be derived: for the CCT flip bucket of case M1, a hydraulic jump occurs on the bucket, associated with significant air entrainment at the air-water interface, water depth on the bucket increasing dramatically and even part of the turbulent roller climbs over the side walls, the outlet flow flapping sharply, with a jet trajectory impinges almost vertical at the toe [2]. This situation must be avoided in practical engineering because it will endanger the hydraulic structure's foundation; As for the LF flip bucket, case M2 has almost the same flow choking regime as M1 except it is a little weaker, and has a small fin below the nappe because of the small gap on the bucket bed and a small part of water flow from the gap; as for case M3, when the gap deflection angle is decreased to $\theta = 15°$, a fully developed hydraulic jump still exists on the bucket, but the surface turbulence is much weaker than M1 and M2, and the fin extends longitudinal along the gap; when decrease θ to 0° as is the case for M4 (Fig. 2d), there is only a little water block near the bucket outlet. If seen from the plan view (Fig. 3), it can be found that, shock waves intersect on the axis when the water flow direction changed by the gap; observations from Fig. 2e, f found that, when the gap width is decreased to $b = 0.03$ m, a slight surface hydraulic jump appears again; but if the gap width is enlarged to $b = 0.07$ m, the hydraulic jump is then replaced by shock waves once again. It can be obtained from the experiments that the shock wave height is decreased with the increasing of the gap width b.

In conclusion, the flow choking regimes of LF flip bucket can be divided into three types by visual observation: strong hydraulic jump (SHJ) (Fig. 2a, b), weak hydraulic jump (WHJ) (Fig. 2c, e) and shock wave (SW) flow choking (Fig. 2d, f).

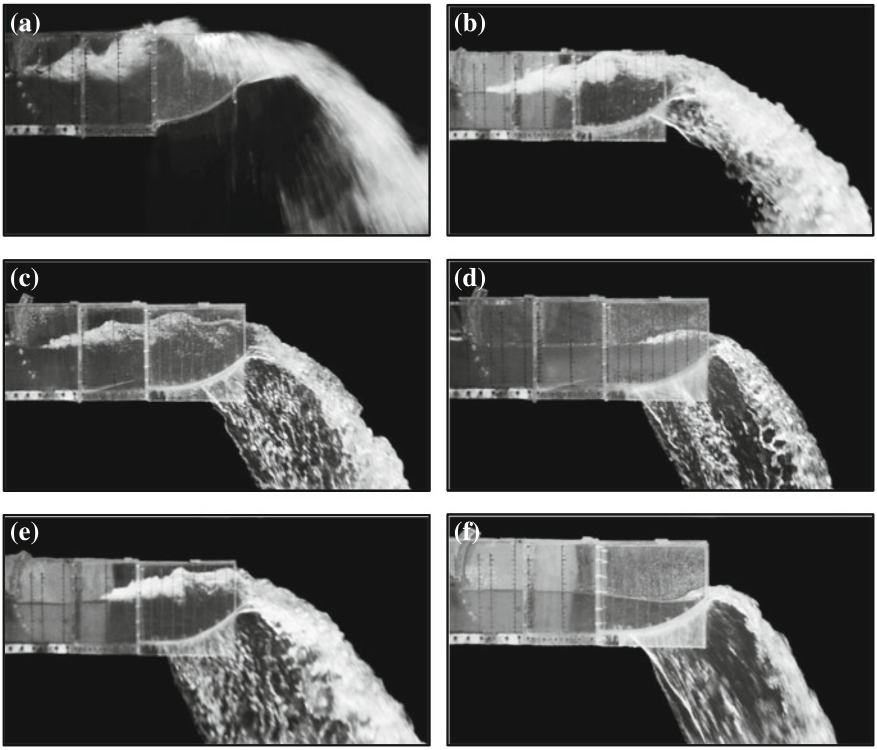


Fig. 2 Flow choking **a** M1: $b = 0$ m, $\theta = 0°$, $Fr = 1.97$; **b** M2: $b = 0.05$ m, $\theta = 30°$, $Fr = 1.91$; **c** M3: $b = 0.05$ m, $\theta = 15°$, $Fr = 1.54$; **d** M4: $b = 0.05$ m, $\theta = 0°$, $Fr = 1.22$; **e** M5: $b = 0.03$ m, $\theta = 0°$, $Fr = 1.64$; **f** M6: $b = 0.07$ m, $\theta = 0°$, $Fr = 1.11$

Fig. 3 Plan view of shock waves for M4: $h_o = 0.04$ m

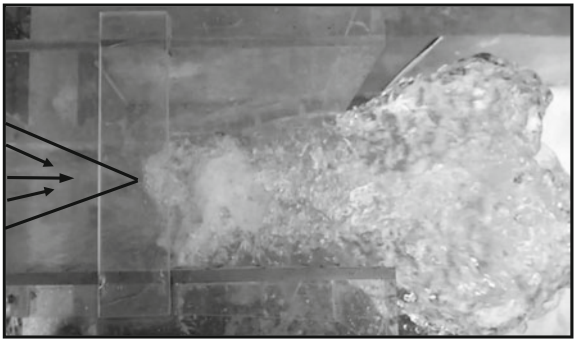


Table 2 Experimental observations of flow choking regimes

Cases	h_o (m)	Flow choking types
M1	0.04–0.18	SHJ
M2	0.04–0.18	SHJ
M3	0.04–0.18	WHJ
M4	0.04–0.10	SW
	0.18	WHJ
M5	0.04–0.18	WHJ
M6	0.04–0.18	SW

The first two situations need special consideration in hydraulic operation, but the last can be ignored. Table 2 lists all the flow choking cases in the experiments.

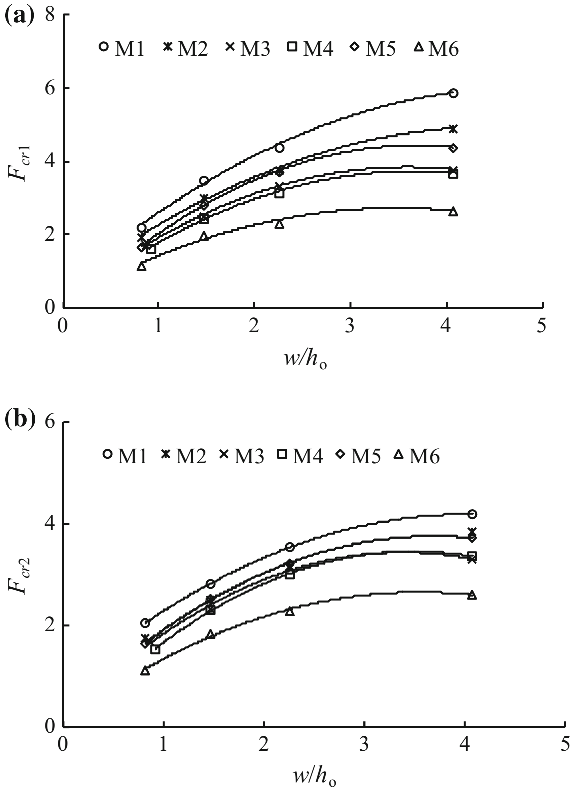
Similarly, as with the CCT flip bucket, flow choking also occurs in the decreasing discharge regime, and it is just the opposite process as the increasing discharge regime. As the decreasing discharge process is always less important [17] in the hydroelectric operation, it will not be discussed here.

4 Critical Flow Choking Froude Number

The flow choking characteristics can be defined by the critical Froude number F_{cri}, where $i = 1$ and 2 represent that flow choking completely disappeared in the increasing discharge regime and appeared in the decreasing discharge regime, respectively. From Heller's [4] result it can be obtained that the relative bucket height w/h_o is the main influence parameter of the flow choking characteristics for the CCT flip bucket, and it can be noted from Wu's [16] experimental results that the outlet width, the contraction angle and the approach flow depth are important in the critical flow choking Froude number of the slit-type flip bucket. As for the LF flip bucket, the relative bucket height w/h_o and the area ratio $S = lb/LB$ are considered as the main parameters influencing the flow choking characteristics.

The critical Froude numbers F_{cri} were recorded during experiments. The experimental results were plotted as F_{cri} versus w/h_o (Fig. 4a, b). It can be found that both F_{cr1} and F_{cr2} are increasing with w/h_o, and F_{cr1} is obviously larger than F_{cr2}. This is reasonable as w enhances the flow depth choked on the bucket and a larger momentum is needed to push the choked flow jump out of the bucket. Otherwise, the depth below the hydraulic jump increases with the flow depth h_o and it is relatively easy to push the hydraulic jump out of the bucket. This is similar to the result of the CCT flip bucket proposed by Heller [4]. It can be obviously observed that the critical Froude numbers of the LF flip buckets are much smaller

Fig. 4 Critical Froude numbers versus w/h_o: **a** increasing discharge regime; **b** decreasing discharge regime



than the corresponding CCT flip buckets (Fig. 4). Figure 5a, b relate to F_{cr1} and F_{cr2} versus the gap area ratio parameter S for LF flip buckets of cases M2 to M6. Both F_{cr1} and F_{cr2} are decreased with S when w/h_o are fixed.

Considering all of the parameters above, a combined parameter $K = (1-S)(w/h_o)$ was proposed and Fig. 6a, b relate to F_{cr1} and F_{cr2} versus K, in which, the dashed line represents results of $h_o = 0.04$ m, and the solid line represents $h_o = 0.07$, 0.10 and 0.18 m. For $h_o = 0.04$ m, the data can be expressed as:

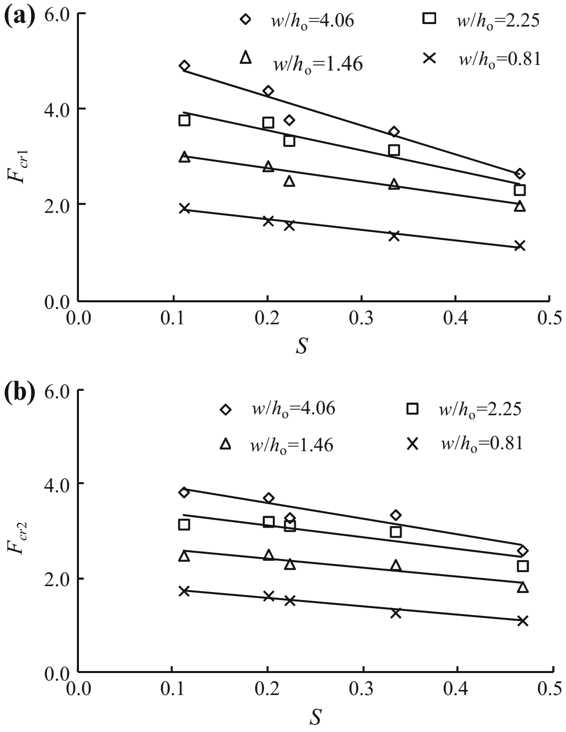
$$F_{cr1} = 1.63K - 0.93 \tag{1}$$

$$F_{cr2} = 0.79K + 1.01 \tag{2}$$

with the correlation coefficients $R^2 = 0.95$ for F_{cr1} and $R^2 = 0.92$ for F_{cr2}.

For cases when $h_o = 0.07$, 0.10 and 0.18 m, the critical Froude number can be expressed as:

Fig. 5 Critical Froude numbers versus S: **a** increasing discharge regime; **b** decreasing discharge regime



$$F_{cr1} = 2.37K^{0.75} \tag{3}$$

$$F_{cr2} = 2.16K^{0.66} \tag{4}$$

with both correlation coefficients $R^2 = 0.97$.

The limitations of the above equations are $0 \leq S \leq 0.5$ for the bucket gap area ratio and $0.8 \leq w/h_o \leq 4.1$ for the relative bucket height.

Figure 7 is the comparisons of the calculated critical Froude number F_{cric} by Eqs. (1)–(4) with the experimental results; the dotted lines represent the ranges of 10% error. The results show that the error is mostly less than 10% and Eqs. (1)–(4) have high precision in the critical flow choking Froude number.

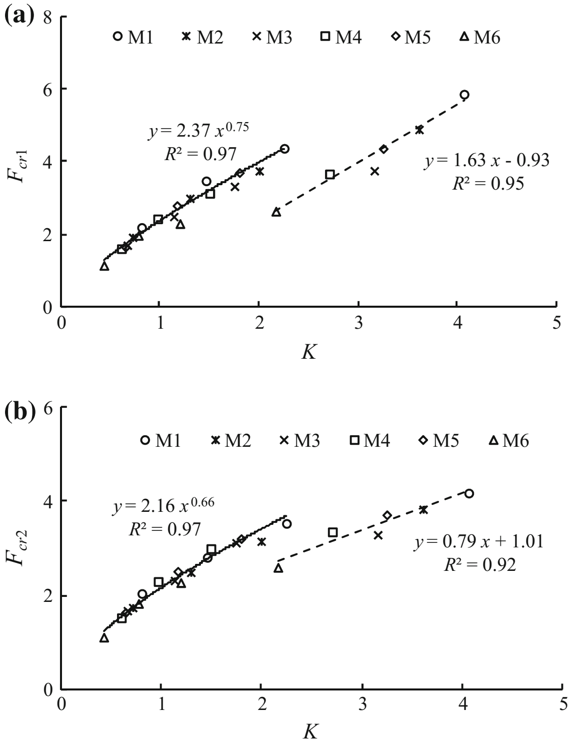


Fig. 6 Critical Froude number versus $K = (1-S)(w/h_o)$: **a** Increasing discharge regime; **b** decreasing discharge regime

5 Discussions

Scale effects may exist when the approach flow depth is too small, such as when $h_o = 0.04$ m, resulted in a different relationship of F_{cri} and K, thus Eqs. (1) and (2) actually have no practical meanings and just for reference only. Equations (3) and (4) can be expressed in a uniform format as:

$$F_{cri} = a_i \left(\frac{w}{h_0} (1 - S) \right)^{b_i} \tag{5}$$

where $a_1 = 2.37$, $b_1 = 0.75$ for F_{cr1} and $a_2 = 2.16$, $b_2 = 0.66$ for F_{cr2}.

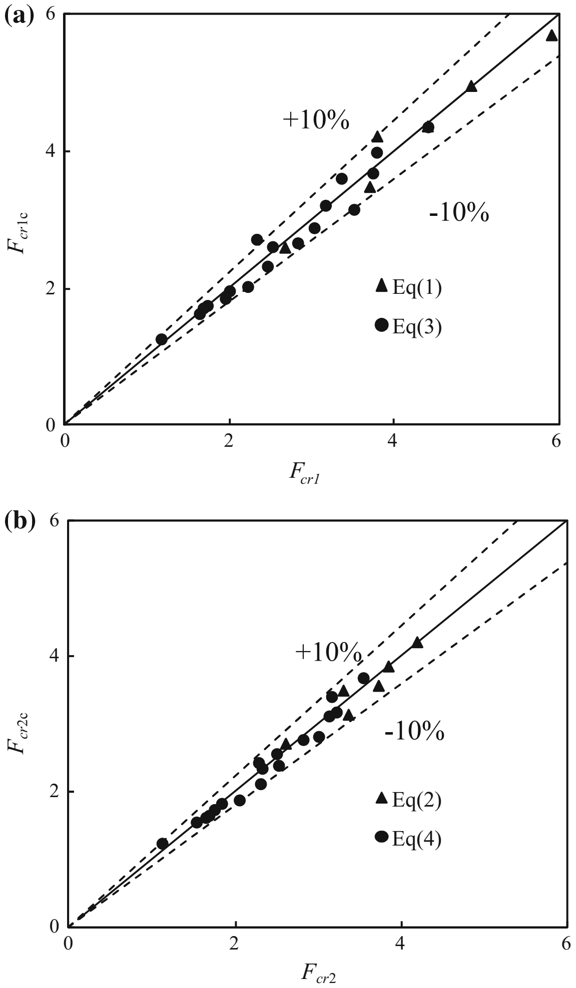


Fig. 7 Comparisons between the measured (*x*-axis) and calculated (*y*-axis) critical Froude number: **a** increasing discharge regime and F_{cr1c} is calculated by Eq. (1) and Eq. (3); **b** decreasing discharge regime and F_{cr2c} is calculated by Eqs. (2) and (4)

The experimental data of the CCT flip bucket was also included in Fig. 6 while considering $S = 0$. This represents that the critical flow choking Froude number, for both LF flip bucket and the CCT flip bucket, has the same tendency with Eq. (5).

From the experiments, it can be shown that the flow choking decreased with S but increased with w/h_o. Besides, it also can be concluded that when $S \geq 0.33$ and $w/h_o \leq 0.81$, or $S \geq 0.47$ and $w/h_o \leq 4.06$, only slightly a weak shock wave appeared, and these situations are far-fetched to be called flow choking, can be considered as reasonable situations in practical engineering. In addition, the design standard suggested that $4 \leq R/h_o \leq 10$ for CCT flip bucket [18]. Then, considering from the aspect of avoiding flow choking, the LF flip bucket can be designed as $S \geq 0.33$ and $w/h_o \leq 0.81$, or $S \geq 0.47$ and $w/h_o \leq 4.06$. Additionally, the trajectory distance must be avoided being too close to cause scour at the toe of bucket.

6 Conclusions

Flow choking regimes and critical conditions of LF flip buckets are explored experimentally. The critical flow choking Froude numbers F_{cr1} and F_{cr2} are focused on and empirical equations to calculate them are obtained. Comparisons between the empirical equations and the test data showed that the paper's equations are reasonable in critical flow choking prediction, both for LF and CCT flip buckets, and can be used for hydraulic design as a preliminary estimation. Furthermore, a preliminary design standard of $S \geq 0.33$ and $w/h_o \leq 0.81$, or $S \geq 0.47$ and $w/h_o \leq 4.06$ for LF flip bucket was proposed from the consideration of avoiding flow choking.

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