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Risk Estimation of River Diversion with Observed Flood: Methodology and Case Study

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Abstract: Due to potential result in loss of human lives and substantial destruction of construction facilities in failure, risk estimation of river diversion is a long-standing problem in water resources planning and management. Despite extensive efforts to effectively tackle this problem during recent decades, the traditional rather inefficient technique of stochastic simulation approaches are limited by modeling assumptions, authenticity of de- signed flood and effectiveness of results in hydropower projects. Accordingly, this article aims at developing a risk estimation method with observed flood model as a remedy to shortcomings of existing common methods. The statistic definition of diversion risk is proposed on the basis of failure mechanism to measure the comprehensive affection of uncertainties. Observed flood and uncertainty of flow discharge along with flood routing process are considered in the estimation process to pro- vide a more reliable result of diversion risk. This approach is demonstrated and discussed for river diversion system of Baima Dam in China and the risk estimation results are recommended for the optimal design of di-version system through comparison with two methods. The presented observed-flood-based asses approach can effectively provide designers and engineers with additional tool to recheck and evaluate risk of the system.

Keywords: *River diversion, Risk estimation, Observed flood, Uncertainty analysis, Outflow discharge, Baima Dam*

1. Introduction

River diversion (RD), as a temporary system in hydropower project, is principally performed to provide a dry and safe site for the construction of permanent works of dam [1,2]. Because the river diversion system (RDS) has more influencing factors, such as the unique large- scale flow conditions, complex inner structure, broad outer connection, and more random confusing factors in the RDS operation process[3]. In practice, most disastrous dam failures occurred in construction period whereas failure of diversion works may impose considerable economic losses and even result fatalities [4]. Due to this high degree of uncertainty and potential destruction, risk estimation is an appropriate response and one of the most critical operations in the construction of large dams[5]. Furthermore, evaluating the risk of river diversion (RRD) accurately and reliably is a sequential and conceptually concise approach, which gives stepwise insight into each phase of the project [6].

The degree of understanding of RD uncertainties will determine the final success or failure of a RDS, or even hydropower project to a great extent [7]. Value estimation of those random variables is based on insufficient information and imperfect knowledge, resulting in various hydrologic and hydraulic uncertainties.

Hydrologic uncertainty impacting upstream flow is the direct reason, which leads to RRD. It was not until the 1970s that researchers started to view RD from the perspective of hydrologic analysis [8]. Early efforts out- lined the concepts of RRD: judged whether upstream flow exceeding the criteria for design flood [9,10]. Calculation techniques for hydrological uncertainty have evolved from highly conceptual methods to practical computing methods, such as classical probability [11, 12], stochastic process [13-15] and artificial neural net-work [3]. These techniques have contributed greatly to the growth of hydrology at both theoretical and application levels. However, these models were concerned mainly on hydrologic uncertainty and ignored other related uncertainties in RDS. So it's unsatisfactory for engineering practice inevitably to some extent [16].

The uncertainty of hydraulics is an important factor in RRD estimation. Despite extensive efforts to effectively tackle this problem during recent decades, first efforts were undertaken to develop more complex integrated models of discharge capacity in the 1980s, which sought to reveal the inherent correlation between up- stream flow and discharge capacity [17, 18]. Afshar [19-21] carried out a first-order second-moment analysis for hydraulic uncertainties and formulated their RD optimization model, which incorporated the uncertainty of the flood magnitude estimator and the hydraulic un- certainties. Jiang [22] applied a mathematic model of stochastic differential equation (SDE) for flood routing and solved the probability density distributions of up- stream water level (UWL). It's basically reflected the complexity of large-scale RDS conditions but it was difficult to obtain SDE solution for different characteristics of flood [23, 24]. Modern computing methods enabled the simulation of different flood sequences [25]. Thus the Monte-Carlo method was used to simulate the design flood and calculate integrated RRD considering hydraulic, hydrologic uncertainty [26]. In this naive approach, the simulative model with design flood was one of the most widely used methods for RRD estimation. Accordingly, numerous improved methods based on Monte-Carlo, such as SDPR [27], FSVA [28] and DITRP [29] and SWAT [30], enjoyed being the dominant technique in RRD.

However, the conventional RRD methods are limited by modeling assumptions, authenticity of design flood and effectiveness of RRD results. First of all, owing few RRD models have considered the correlation of flood peak and volume, the randomness of combination between them, the typical discharge hygrograph of de- sign flood selected in course of computation of design flood often cannot represent the flood feature in this basin [12]. In addition, the tradition RRD models are derived on the inadequate assumption that RDS would withstand catastrophic natural flood and the flood peak and volume follow a Pearson III distribution, while the characteristics of runoff yield and concentration have been changed by anthropoid activities. Last but not least, as RD is a temporary structure, the flood hydrographic characteristics in RD period are much different from the operation period of hydropower project while the stochastic simulation models are not designed specifically for RRD applications. Inevitably, these tools cannot ensure design flood keep consistent with flood feature and RRD results are not efficient and cost-effective in representing risk conditions in the field of RDS. Consequently, the statistical characteristics of flood in RD period desire to be validated and the effectiveness of RRD results with design flood remains to be inspected in development [31].

2. Statement of the work:

Accordingly, this article aims at developing a RRD estimation method with observed flood model as a remedy to shortcomings of existing common methods. The model accounts for the inherent and parameter hydrologic uncertainties as well as hydraulic uncertainties along with flood routing process. Firstly, the definition of RRD is proposed according RDS failure mechanism to measure the comprehensive affection of uncertainties. Then, the characteristics of hydraulics uncertainty are presented with consideration of hydraulic parameters to generate a series of discharge capacity corresponding to water level. After the observed flood routing follows annual highest UWL (AHUWL) sequence calculated. At last, experience frequency is analyzed to avoid dependence on the sample of RRD results. Meanwhile a curve with minimum fitting errors is selected according to the principle of interpolation and curve fitting. And the RRD result of corresponding design flood level is obtained from the curve.

The presented approach is proved to overcome the two principal demerits of RRD with design flood approaches. Firstly, in contrast to the RRD approaches with design flood, this model keeps hydrological features more consistent with characteristics of actual flood. Secondly, it provides a more authentic result which reflects much more reliable RDS uncertainties and potential security conditions. These two functional merits can appreciably contribute to the robustness and performance of the presented approach making it a suitable alternative for the risk estimation of real-world diversion system. The applicability and performance of the method is illustrated with real case study of rechecking RRD results of Baima Dam, to be constructed on the Wujiang River in the west of China.

3. Methodology:

3.1. Definition of RRD:

Uncertainties are inevitable in design and management of RDS [4]. The risk involved in RDS is a consequence of the interaction of several random and uncertain variables [32,33]. Ang and Tang [34] distinguished two broad types of uncertainties:

- Uncertainty associated with natural randomness of the underlying phenomenon such as natural variability of flood flows;
- Uncertainty associated with imprecision in our pre- diction of reality such as uncertainty in estimation of Manning's roughness coefficient during design phase.

These uncertainties may be integrated to define the RRD. The RDS under these uncertainties including inherent and parameter hydrologic and hydraulic uncertainties is subject to failure and it fails once the UWL exceeds a fixed threshold [35]. Mathematically, RRD(R) can be defined as the probability that UWL exceeding the retention structure elevation during the period of cofferdam construction and operation [26, 36, 37]:

$$R = prob\left(Z_{up} > H_{upcoffer}\right) \tag{1}$$

Where, Z_{up} =UWL; $H_{upcoffer}$ = retention structure elevation.

The historical flood investigation is applied to calculate UWL sequence by a modified formulation presented in Chapter 3.3. For design standard of RDS, the retention structure elevation is always considered as a constant quantity. Statistic result through comparison with UWL sequence and retention structure elevation is proposed to measure the comprehensive affection of uncertainties for the RRD.

3.2. Discharge capacity risk approach:

Uncertainty of hydraulic parameters is the main factor affects discharge capacity (DC) of RDS, which is generally expressed by Manning equation in the form [38]:

$$q = \frac{1}{n} A^{\frac{5}{3}} \chi^{\frac{-2}{3}} S^{\frac{1}{2}} \tag{2}$$

In which n =roughness coefficient; A = flow area; χ = hydraulic radio; and S = channel slope.

If RD structure is adopted as open diversion channel with trapezoid section, the outflow discharge can be mathematically written as follows:

$$q = \frac{\left[(\omega + mh)h\right]^{\frac{5}{3}}}{\left(\omega + 2h\sqrt{1+m^2}\right)^{\frac{2}{3}}} \frac{\sqrt{s}}{n} \tag{3}$$

Where, h = depth of water; m = slope coefficient; and w =bottom width of open diversion channel.

Due to existing hydraulic uncertainties, the RDS outflow discharge is not a single-valued deterministic quantity and the dominant characteristic of hydraulics uncertainty is usually only applied by stochastic simulation and probability model inversion. In this article, integrated risk distribution mechanism (IRDM) method [39] is used to quantify these epistemic uncertainties and Triangular distribution is assumed for RDS discharge capacity. Thus, the mathematical formulation of the DC risk is developed as follows:

$$F(q) = \begin{cases} 0, & q \le a \\ \dfrac{(q-a)^2}{(b-a)(c-a)}, & a < q \le b \\ 1, & q > c \end{cases} \tag{4}$$

Where, b = mean value of RDS outflow discharge; a and, c = minimum and maximum favorable values for outflow discharge, respectively.

3.3. Observed flood routing:

Considering the relationship between RDS and cascade hydropower stations , controlling discharge capacity is an effective way to reduce RRD for the upstream stations [40, 41]. The reservoir formed by upstream cofferdam has a significant action of flood detention due to regulation function of reservoir (Fig.1). In order to acquire UWL sequence, the observed flood series are calculated by flood routing.

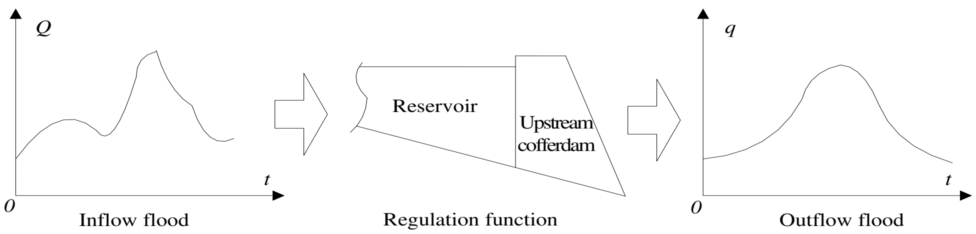

***Fig.1** Regulation function of reservoir formed by upstream cofferdam*

The process of storage and outflow discharge in RDS is developed by water balance equation:

$$\frac{Q_1 + Q_2}{2}\Delta t - \frac{q_1 + q_2}{2}\Delta t = V_2 - V_1 \tag{5}$$

In which Q_1 =initial inflow; Q_2 =inflow in time Δt; q_1 = initial outflow; q_2 = outflow in time Δt; V_1 =initial water storage; and V_2 = water storage in time Δt .

Regarding observed flood, Q1 and Q2 are known, V1 and q1 are initial conditions, V2 and q2 are unknown. Time differential equation can be rewritten by differentiating Δt in flood regulating calculation as the following formula:

$$\frac{dV(t)}{dt} = \left[Q(t) - q(H,t)\right] \tag{6}$$

The initial conditions are estimated as follows:

$$\begin{cases} q(t_1) = Q(t_1) \\ H(t_1) = h(q(t_1)) \\ V(t_1) = V(H(t_1)) \\ Q(t_i) = C_i \ (i = 1, \cdots, \mathrm{n}) \end{cases} \tag{7}$$

Where, C_i is a known value, and the boundary conditions are defined as follows:

$$\begin{cases} q = q(H) \\ V = v(H) \end{cases} \tag{8}$$

Therefore, the functional relation between q and V is determined according to discharge capacity of diversion structure ($H-q$ curve) and storage capacity of reservoir ($H-V$ curve):

$$q = f(V) \tag{9}$$

The period of flood is defined as t ∈ [0, T], and it is dispersed to n small periods (the stability of arithmetic can be assured on the condition that n is big enough):

$$t_i = \frac{i}{n}T \quad (i = 1, 2, \cdots, n) \tag{10}$$

The flood hygrograph of outflow discharge is derived after unknown parameters of water balance equation are solved by dichotomy. Then the maximum DC and homologous AHUWL are obtained. The flowchart of regulating calculation is shown in Fig.2.

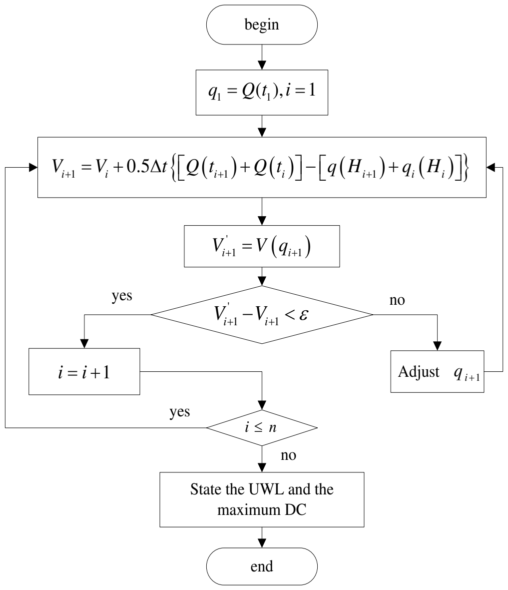

Fig. 2 Flowchart of flood routing

3.4. RRD with observed flood approach:

Rivers hydrological features differ in thousands ways, especially on the variation of runoff yield and concentration under the impact of human activities. The traditional RRD approaches with design flood which de- scribed hydrological characteristic with Pearson III can't adapt to this change and is unable to meet the needs of RRD estimation.

With the development of on-line monitoring technique for hydrology and water resources, observed flood data which interestingly exhibits the practical value of information is available and enable to overcome limitations of design flood. That is, the more information we have with regard to different aspects of the RRD estimation, the more authentic results we can obtain to reflect the safety level of RDS.

Owing to the existing merits about observed flood for a robust and dependable RRD approach, the observed flood series are applied to calculate UWL sequence. Simultaneously, discharge capacity risk model generates a series of uniformly distributed outflow floods which represent the different characteristics of hydraulic uncertainties under different conditions. Thus, observed flood and discharge capacity uncertainty along with flood routing process are considered in the estimation process to provide a more authentic distribution of UWL sequence (Fig.3). Thereafter, statistical analysis of obtained sequence is counted with experiential distribution function :

$$F_n(Z) = \begin{cases} 0, & Z < Z_{(1)} \\ \frac{k}{n}, & Z_{(k)} \le Z \le Z_{(k+1)},\ k = 1, 2, \cdots, n-1 \\ 1, & Z \ge Z_{(n)} \end{cases} \qquad (11)$$

Where, $Z_1, Z_2, \cdots, Z_n$ are total samples, and $Z_{(1)} < Z_{(2)}, \cdots, < Z_{(n)}$ are observed values of order statistics.

According to the definition of diversion risk, the RRD with observed flood is rewritten as follows:

$$P_f(D) = 1 - P(Z \le D) = 1 - F_n(D) \qquad (12)$$

In RRD with observed flood approach, frequency analysis is employed to extend N -d insufficient existing data in order to probabilistically estimate rarely occurring events the magnitudes of which are beyond those that have been observed. The first step in utilization of this method is selection of an appropriate weir height which is crucial to the RRD estimation. Thereafter, considering this fixed value of AHUWL distribution, the RRD corresponding to weir height are determined. Generally, a curve with minimum fitting errors is always selected and output directly by computer from KPearsonts tird curves which possess different abnormal coefficients according to the principle of interpolation and curve fitting [42]. After the frequency analysis follows Pf(D) correction of R(D).

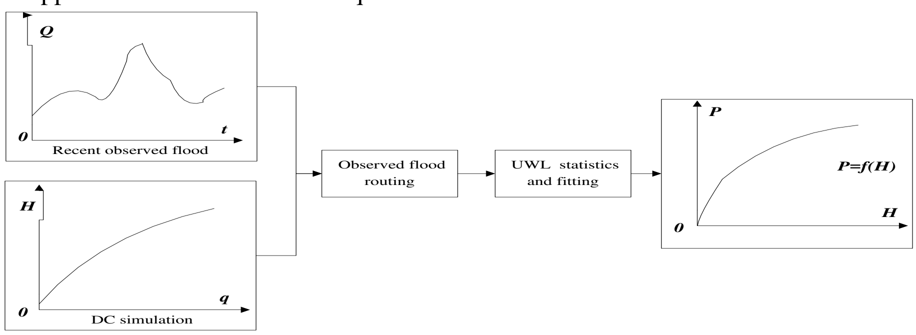

Fig. 3 Calculation process of RRD with observed flood

Meanwhile, in order to minimize representative affection of observed flood and understand the risk deeply from various angles, the RRD with design flood R(D) is emulated and calculated with traditional RRD method. Because failure of RDS may potentially result in loss of human lives and substantial destruction of construction facilities, the RRD results from the two methods are compared and analyzed to measure safety level of RDS (Fig.4).

With the purpose of estimating comprehensive RRD accurately and ensuring security of construction, usually the bigger value is taken as diversion risk for the optimal design of RDS

$$R = \max\{R(D), \overline{R}(D)\} \qquad (13)$$

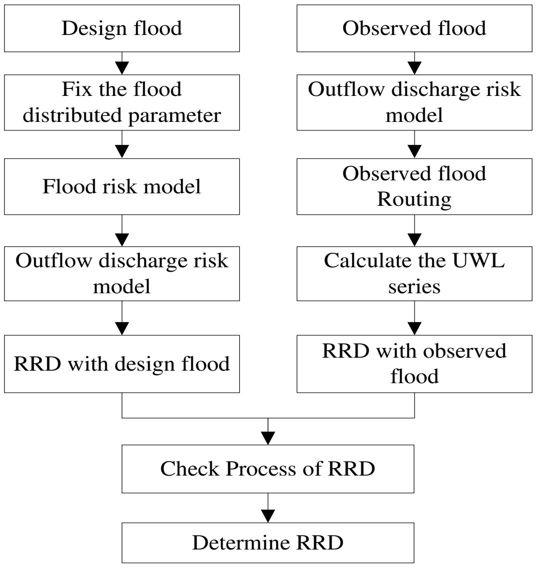

***Fig. 4** Check process of RRD*

4. Case Study:

The objective of this case study is to demonstrate the capability of the proposed RRD model for solving the risk review problem, namely, risk estimation of temporary RDS of Baima Dam. In what follows, some general facts on Baima Dam and temporary RDS are first presented. Then, the mathematical formulation of the problem is described and the proposed model is applied. Thereafter, a comparison between the two RRD results is followed by RRD on design flood. Finally, thorough analysis and interpretation of results are presented and performance and merits of the model are discussed.

4.1. Baima dam and temporary RDS:

Baima Dam, currently under construction, is located in the west of China in Chongqing with installed capacity of 385 MW. With a height of 87.5 m and a crest elevation of 205.5m, it will be the highest concrete dam on the Wujiang River once completed. The dam is classified as a concrete gravity type on large II scale and impounds a reservoir capacity of 3.72×10^{8} m^3. The long valley which hosts the dam has an extremely narrow V-shape. The primary purposes of the dam are generating hydroelectric energy, controlling floods and safety measures in downstream of the dam.

The layout of diversion works of Baima Dam comprises roller earth-rock upstream and downstream cofferdams (Fig.5). The design upstream water level is 188.5m. Due to complexity of geological condition and interaction of a large number of tangible and intangible factors, discharge work is adopted as opened diversion channel with trapezoid section and bottom elevation of 150m.

The relation between storage capacity and UWL is realized with the exploration and survey. In accordance with the original curve of the trend for the extension and interpolation, storage capacity with different UWL are illustrated in H − V curve (Fig.6).

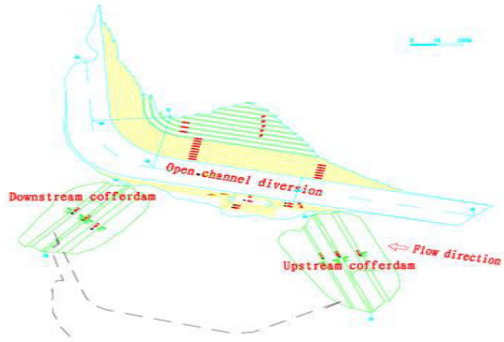

***Fig.5** Layout of diversion works*

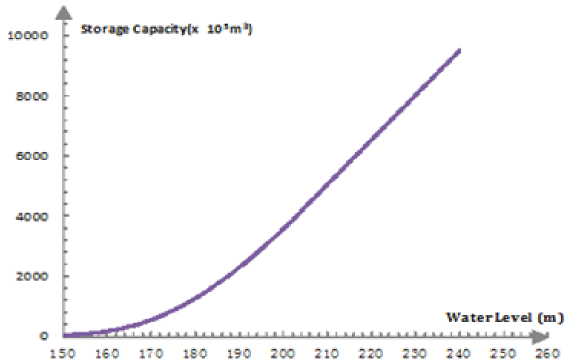

***Fig.6** H − V curve*

4.2. Model Implementation and results:

The opened diversion channel used in this article is on the right bank of its dam site, with bottom width w =70 m, slope coefficient m1 = 1:0.5 when below elevation of 285m, m2 = 1: 1.0 when above elevation of 285m (Appendix A).

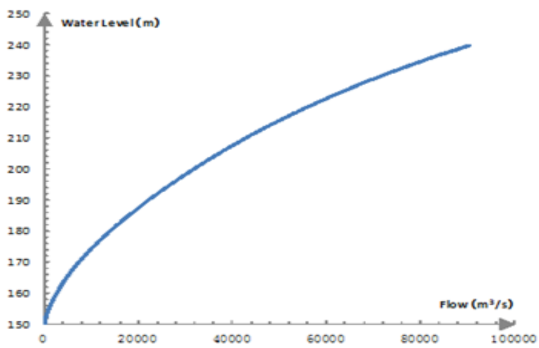

***Fig.7** H − q curve*

According to hydraulic parameters, discharge capacity with different UWL is depicted by Eq.3 in H−q curve (Fig.7). On the ground of observing and analyzing massive engineering practice and operation, the distribution parameters of DC in this case study given by Eq.4 is defined as a = 0.95q, b = 1.0q, c = 1.05q. According to H−q curve and H−V curve, the functional relation between UWL, reservoir storage and out- flow discharge is determined (Appendix B). In this case study, to get stochastic sequences of DC, the with the method of Monte-Carlo [25]. The random parameters of DC are sampled in distribution with the method of Monte-Carlo [25]. The observed flood data the method of Monte-Carlo [25]. The random parameters random parameters of DC are sampled in distribution are the 54-year annual historical flood process of the Wujiang River. Combined with 54-year observed flood and DC sequences, AHUWL series (Tab.1) are obtained with flood routing according to H − q curve and H – V curve. The frequency analysis for AHUWL series clearly indicates that six AHUWL exceed design level (188.5m), and RRD is estimated about 11.11% with experiential distillation function given by Eq.11. In addition, the results of a series of goodness-of-fit tests on 54-year AHUWL series indicate that Pearson III distribution has the best fit. Moreover, theoretical frequency curve is proposed and distribution parameters of fitting method are worked out as Z_c =179.07m, C_y =0.04, C_s=−0.1, C_s/C_y =−2.40. (Fig.8) illustrates RRD is fixed as 10.26% corresponding to design flood level (188.5m).

Table 1 **:** *AHUWL series at dam site with observed flood*

No	AHUWL	No	AHUWL	No	AHUWL	No	AHUWL	No	AHUWL	No	AHUWL
1	189.01	10	173.16	19	176.45	28	190.17	37	182.87	46	185.60
2	175.39	11	166.75	20	176.73	29	177.03	38	170.11	47	189.48
3	166.77	12	178.47	21	190.32	30	178.71	39	172.79	48	172.17
4	182.73	13	176.98	22	173.16	31	170.31	40	185.68	49	191.01
5	168.12	14	178.84	23	169.53	32	181.28	41	188.37	50	185.49
6	188.67	15	172.30	24	179.98	33	178.58	42	175.43	51	170.16
7	177.76	16	169.53	25	165.17	34	183.33	43	186.32	52	181.87
8	182.20	17	185.61	26	188.16	35	183.70	44	172.05	53	177.45
9	173.15	18	178.25	27	185.98	36	187.39	45	180.92	54	182.37

4.3. RRD with design flood:

Considered with type and size of dam, height of coffer- dam and storage capacity, the grade of RD structures is regulated of temporary four according to “Specification for construction planning of hydropower engineering”[43]. Hygrographs of floods with different re- turn periods are illustrated in Appendix C. Statistical properties of five parameters of design flood are given in Tab.2.

According to the relation between UWL, reservoir storage and outflow discharge, the AHUWL, maximum outflow discharge and flood control capacity are worked out after design flood routing (Tab.3).

Table 2: *Design flood parameters*

Design Parameter	Value
Design flood frequency P	10%
Flood peak Q_m	20900
Mean μ	13700
Coefficient of variation C_v	0.38
Coefficient of skewness C_s	1.33

On this basis, UWL sequence with consideration of hydrological uncertainties is gotten if hydrological random parameters are introduced into design flood routing process. What’s more, UWL sequence with consideration of hydraulic uncertainties as well as hydrological uncertainties is obtained if hydraulic parameters and discharge capacity of random parameters are also put into routing procedure.

Table 3 **:** *Routing results with design flood*

Return period (*year*)	AHUWL (*m*)	Maximum outflow discharge (*m3/s*)	Maximum storage (×108*m*3)
10	188.49	20827.07	2.12

Generally, the traditional RRD models with design flood have evaluated uncertainties with flood of Pearson III and DC of triangular distribution. Then flood series and DC sequences are simulated with Monte-Carlo method. Simultaneously, a statistic for RRD is acquired after design flood routing in different cases. Statistical properties of RRD with design flood are given in Tab.4 on the different conditions.

The RRD results range from 9.26% to 9.43% considering random factors condition, which is acceptable comparing with frequency standard of design flood.

Table 4 **:** *RRD with design flood*

Random factor	Design UWL	Simulative UWL	RRD
Hydrologic	188.5	188.2	9.43%
Hydrologic and hydraulics	188.5	188.1	9.26%

4.4 Comparison between the two RRD results:

The RRD results are calculated with observed flood and design flood respectively. It shows that RRD results with the two methods are dissimilar. Comparatively, the former keeps more consistent with characteristics of hydrological features due to observed flood and reflects a more reliable result of RRD, while the latter is more convenient to calculate RRD with design flood and requires less observation hydrology information of historical flood. Actually, the core concepts of both the two methods are mainly to ascertain the distribution of AHUWL in front of cofferdam while the only difference in calculating AHUWL process is flood sequence used in flood routing.

Due to large scale of the project, expected damages are very diverse and severe during the operating period of cofferdam (usually 3 to 5 years). In such circumstances the observed flood in recent period poses great influence on RDS. Hence the higher RRD of 10.26% is recommended for risk-cost optimization of RD structures in this case. In the light of above analysis, application of the presented approach might be a justifiable and viable alternative for the risk estimation of RDS.

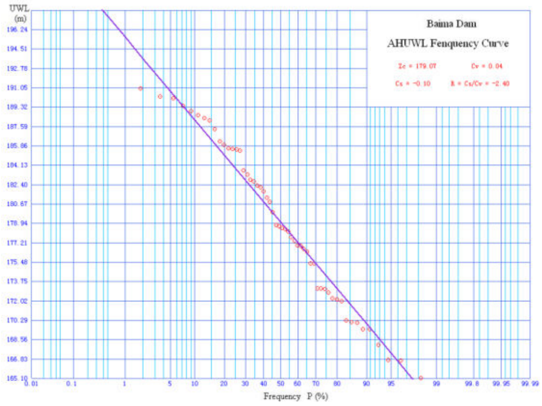

Fig.8 *Frequency curve of AHUWL at dam site*

5. Conclusion:

Application of conventional RRD simulative approaches to practical estimation of RDS uncertainties is shown to suffer from some shortcomings. A RRD estimating method with observed flood model was developed in this article for the recheck of RRD in response to these limitations. Contrary to RRD approaches with design flood, this model keeps hydrological features more consistent with characteristics of actual flood. Hence, RRD results with observed flood reflect much more reliable RDS uncertainties and potential security conditions.

Thus, this approach allows methodological incorporation of simulative estimation into a structured quantitative model. This conceptually straightforward and practically efficient observed-flood-based asses framework provides designers and engineers with additional tool rechecking and evaluating RRD which is very helpful in making realistic decisions.

The applicability of the proposed model was demonstrated on risk estimation of temporary RDS of Baima Dam. The RRD is calculated for DC uncertainty with flood routing consideration. The results are acceptable and reveal that the diversion scheme is appropriate to the engineering.

6. Acknowledgements:

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