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Characterization of Seepage Velocity beneath a Complex Rock Mass Dam Based on Entropy Theory

Xixi Chen [1,2], Jiansheng Chen [3,4,*], Tao Wang [3,4], Huaidong Zhou [1] and Linghua Liu [1]

1 Department of Water Environment, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; xxchen@hhu.edu.cn (X.C.); hdzhou@iwhr.com (H.Z.); lhliu@iwhr.com (L.L.)
2 College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China
3 Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China; jxalfoudqt@hhu.edu.cn
4 Geotechnical Research Institute of Hohai University, Nanjing 210098, China
* Correspondence: jschen@hhu.edu.cn; Tel.: +86-25-8378-7734

Academic Editor: Raúl Alcaraz Martínez
Received: 24 May 2016; Accepted: 8 August 2016; Published: 11 August 2016

Abstract: Owing to the randomness in the fracture flow system, the seepage system beneath a complex rock mass dam is inherently complex and highly uncertain, an investigation of the dam leakage by estimating the spatial distribution of the seepage field by conventional methods is quite difficult. In this paper, the entropy theory, as a relation between the definiteness and probability, is used to probabilistically analyze the characteristics of the seepage system in a complex rock mass dam. Based on the principle of maximum entropy, an equation for the vertical distribution of the seepage velocity in a dam borehole is derived. The achieved distribution is tested and compared with actual field data, and the results show good agreement. According to the entropy of flow velocity in boreholes, the rupture degree of a dam bedrock has been successfully estimated. Moreover, a new sampling scheme is presented. The sampling frequency has a negative correlation with the distance to the site of the minimum velocity, which is preferable to the traditional one. This paper demonstrates the significant advantage of applying the entropy theory for seepage velocity analysis in a complex rock mass dam.

Keywords: entropy theory; uncertainty and randomness; seepage velocity; fracture flow; complex rock mass dam

1. Introduction

Many rock mass dams have been built worldwide, and they continue to be designed in the valleys of rivers on bedrock, where faults develop broadly. The complex geological structure results in that the seepage system beneath a dam are more stochastic, which has attracted considerable public attention [1,2]. Usually, a dam body is designed to allow a limited amount of uniform seepage; if this amount is exceeded, internal erosion may occur and result in an increase in the local permeability and redistribution of the entire seepage field. Then, hydraulics will lead to the formation of localized seepage zones and even sudden dam failure [3]. Owing to the bed rocks having complex geological conditions and developed faults and fissures, seepage within the fractured rock mass of the dam foundation has a significant impact on the safe operation of the dam. It is a challenge to investigate and model a fractured flow [4–6]. Therefore, statistical techniques, e.g., Monte Carlo simulations, random field theory, and the finite element technique, have been employed [7–9]. Although these techniques allow for the uncertainty to be considered more explicitly, studies of the seepage system in a complex rock mass dam still suffer from major problems such as the small sample sizes and limited information. Therefore, dam leakage investigation through estimating the spatial distribution of the seepage field is quite difficult [10,11].

The seepage velocity, as a proxy for the seepage field, is widely and effectively used to locate seepage areas, because it is obviously larger in the vicinity of seepage zones and regularly decreases in the surroundings. Additionally, it has been extensively used for tracer techniques in boreholes, such as a temperature indication, a conductivity tracer, and an interconnection test [11–15]. The parameters associated with the seepage velocity in the field are estimated either from the hydraulic conductivity obtained from a slug test and the observed head gradient, or by the point dilution method in boreholes [16–19]. However, these conventional methods are only appropriate for the water flow in an unconsolidated layer, and has serious limitations for fractured flow. The dual medium model [20] was introduced into the fractured flow with the conducted fracture as the transmission medium, in accordance with the continuous flow characteristics, and the fractures were connected to the water-conductive medium, but were not water-conductive as a water storage structure. Although the "dual medium" is convenient for a seepage calculation of the fractured rock mass, the so-called water storage structure is not closed, and the water is exchanged slowly with the continuous flow all the time, which causes an increase in the entropy value from the results of the dilution velocity measurement.

Entropy, as a measurement of the dispersion or complexity of a system, can be used to study the spatial distribution of the seepage velocity in a fractured rock mass. Since the distribution of fractures in a rock mass is revealed by boreholes, the dilution velocity measurement method can analyze the regional characteristics of the fracture seepage. There is little change in the velocity of a continuous flow in an ideal fracture with a small dispersion and a small entropy value of the velocity; actually, there is a continuous flow through the water storage structure, in which the fissure flow is not closed, with a great variation in the velocity, a large discreteness, and a large entropy value. The entropy value of the dilution velocity in the boreholes reflects the characteristics of the dual medium and can be used to determine the fracture development and seepage characteristics of a local rock mass.

Entropy reflects system complexity, that is, smaller values of entropy indicate greater regularity, and greater values convey more disorder, or randomness [21]. As a measure of information or uncertainty, it is associated with a random variable or probability distribution. Indeed, the principle of maximum entropy (POME)-based distribution is favored over distributions with less entropy among those that satisfy the given constraints; furthermore, the POME has been used to yield a variety of distributions, some of which have found wide applications to environmental and water resources [22–25]. Recently, the POME has been applied to model the vertical distributions of parameters. For instance, Chiu [26–29] has already successfully applied the entropy concept and entropy-maximization principle to model the vertical distributions of the velocity, shear stress, and suspended sediment concentration in an open-channel flow. Marini [30] developed a new entropy-based approach for deriving a two-dimensional (2D) velocity distribution in an open-channel flow, and the values of the derived distribution were in good agreement with the experimentally measured velocities. Greco and Miraudа [31] successfully employed the POME to estimate the entropy parameters, which were tested on a rectangular tilting flume in a laboratory, and introduced a suitable relation between the entropy parameters and the relative submergence in open-channel flows with large-scale roughness.

For a seepage system in a complex rock mass dam as a relatively isolated system, this study aims to employ the theory and concept of entropy to analyze the characteristics of the spatial distribution of the seepage velocity probabilistically, by considering its uncertainties and randomness.

2. Theory

Based on the First Law of Thermodynamics, all natural systems involve spatiotemporal exchanges of the material, energy, and information; the seepage process is no exception. Furthermore, the direction of material, energy, and information exchange is clarified by the Second Law of Thermodynamics, indicating that the entropy in an isolated system would tend to a maximum. In other words, states tend to evolve from ordered, statistically-unlikely configurations, to less-ordered and statistically more probable. The spontaneous reverse occurrence is statistically improbable to the point of impossibility [21]. Based on the Second Law of Thermodynamics, the information entropy theory was developed in the late 1940s, followed by the principle of maximum entropy (POME) in the late 1950s. Since then, these theories have been used in numerous applications in different areas [32–39]. Although the thermodynamic entropy and information entropy are used in different fields of study, they share main properties; for example, both are measures of the disorder in a system.

2.1. Information Entropy

Originating from the thermodynamic entropy, information entropy, as a measure of the dispersion, uncertainty, disorder, and diversification associated with a random variable or its probability distribution, was first introduced by Shannon [40]. A discrete form of entropy $S(X)$ is expressed in terms of the probability as:

$$S(X) = -\sum_{\mathrm{i}} p(X_i)\ln p(X_i) \tag{1}$$

where $p(X_i)$ is the (a priori) probability (mass function) of a system being in state X_i, which is a member of $\{X_i,\ i = 1, 2, \cdots\}$. The entropy for a discrete case must be positive because $p(X_i)$ is a probability. Therefore, $\ln p(X_i)$ is always negative, and it is clear that $S = 0$ if and only if the probability of a certain state is 1 (and that of all other states is 0). If the state variable X is continuous, the entropy is expressed, instead of Equation (1), as:

$$S(X) = -\int p(X)\ln p(X)dX \tag{2}$$

where $p(X)$ is the probability density function (PDF), which can be derived from the cumulative distribution function (CDF) by derivation. Note that $p(X)dX$ is the probability of the state variable being between X and $X + dX$, and $p(X)$ by itself is not a probability; thus, its magnitude may be greater than unity and, therefore, $\ln p$ may be positive. Therefore, the entropy for the continuous distribution, as defined by Equation (2), may become negative, although for a discrete case, it must be positive. The entropy is the average information content per sample datum [26,41,42].

2.2. Principle of Maximum Entropy

According to the entropy concept, a system tends to maximize its entropy under steady equilibrium conditions under the prevailing constraints. The derivation and justification of the maximum entropy principle were carried out by Jaynes [43], which is presented in treatises by Levine and Tribus [44] and Shore and Johnson [45]. The maximum entropy means the maximum information in the data obtained about the state variable X, which, according to Equations (1) or (2) is, in turn, equivalent to the maximum uncertainty in X before measurement. Intuitively, distributions of higher entropy represent more disorder, more probable and less predictable. The POME that governs a system and the corresponding magnitude of the entropy will depend on the prevailing constraints. When there are no constraints, the POME yields a uniform distribution. As more constraints are introduced, the distribution becomes more peaked and possibly skewed. Therefore, a uniform (a priori) probability distribution over the limits of X should give the maximum entropy. In reality, the probability distribution often cannot be uniform owing to various constraints. The entropy (as defined by Equations (1) or (2)) is a measure of the uncertainty, randomness, or how close an a priori probability distribution is to the uniform distribution. It is zero in a purely deterministic case, in which the probability mass function $p(X_j) = 1$ and $p(X_i) = 0$ for all $i \neq j$.

When the difference between the upstream and downstream pressures is constant and the seepage inside a dam body is in equilibrium, the seepage system can be considered a relatively isolated system. To estimate which state the system is in, according to the entropy concept, the velocity system tends to maximize the entropy. Thus, the maximum entropy principle should be used to model the a priori probability distribution of the possible states of the velocity. Data that can be used to estimate the a posteriori probability distribution by improving the a priori distribution may then be collected. The parameter estimation involved in the process deals with the “residuals” or the deviations in the probability distribution fitted to the data. According to the definition of entropy, this is equivalent to the minimization of the entropy of the probability distribution of the residuals [10], which is an optimization problem. It can be solved using the calculus of variations, and the general form is given by Chiu [26].

3. Derivation of Seepage Velocity Distribution

An uncased borehole in a rock mass can reveal not only a water-conductive fractured zone but also some water-storage structure. Generally, such a water-storage structure is extensively developed in the rock mass, and the stored water is slowly exchanged with the water in the borehole, which influences the velocity by the dilution method. For the situation in which a water-conductive fracture and a water-storage structure are exposed simultaneously, the horizontal seepage velocity reaches a maximum using the dilution method. In fact, there exists a horizontal velocity in the water-storage structure, which is not water-conductive. This causes significant errors in the horizontal velocity. All of these problems can be solved by entropy to some extent. In the case that there is no water-storage structure, the horizontal flow velocity only exists near the water-conductive fracture, with smaller corresponding entropy value, whereas the entropy value of the horizontal velocity is larger when the water-storage structure causes uncertainty.

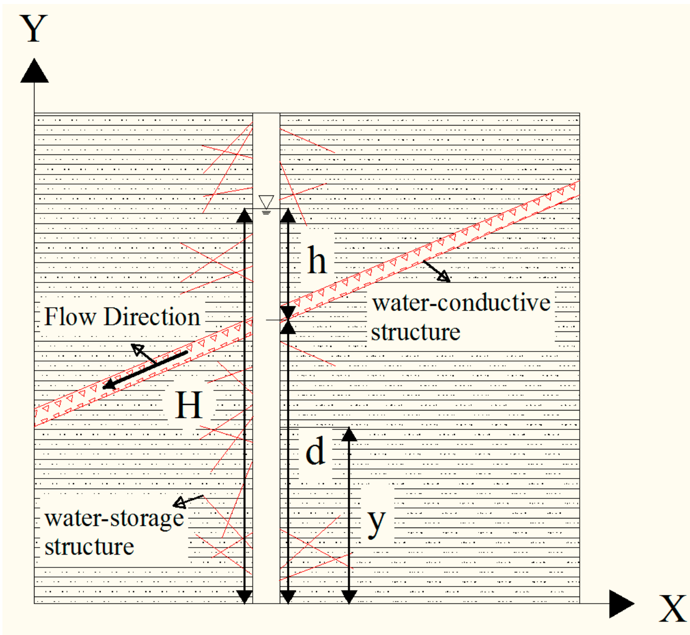

Figure 1. Model diagram of seepage velocity in a borehole.

In an infinite dam body, for simplicity of analysis, the seepage velocity in a borehole with relatively small diameter only varies with the longitudinal distance in the one-dimensional case (Figure 1). For the maximum velocity occurs at where a seepage passage exists, it is assumed that the distance from the water level to the minimum velocity (the bottom) is H, and the distance from the water level to the maximum velocity is h. Let d denote the distance from the location of the maximum velocity to the minimum velocity (the bottom). The velocity is divided into two parts: the upper part (UP) with the distance h, and the other is the lower part (LP) with the distance d. Let $v_{\max}$ and v_0 denote the maximum and minimum velocity respectively, and v denotes the velocity at an arbitrary location in the lower part, accordingly, y denotes the distance from the corresponding above-mentioned arbitrary location to the bottom in vertical distance. The (time-averaged) velocity monotonically decreases in the vertical direction in the lower part, which is analogous to the velocity distribution in an infinitely wide open-channel flow [28]. Owing to the similar variation in the velocity with depth in both parts, the velocity variation in the lower part is discussed for simplicity. The velocity is less than v at any location the distance is less than y. Assuming that all values of y between zero and d are equally likely, it can be stated that the probability of the velocity being equal to or less than v is y/d, or that the cumulative distribution function $F(v)$ is:

$$F(v) = \frac{y}{d} \tag{3}$$

The probability density function $f(v)$ is:

$$f(v) = \frac{dF(v)}{dv} = (d\frac{dv}{dy})^{-1} \tag{4}$$

It should be noted that $f(v)dv$ is the probability of the velocity being between v and $v + dv$, and, therefore, the density function $f(v)$ itself is not a probability. The density function $f(v)$ to be identified must satisfy the constraints:

$$\int_{v_0}^{v_{\max}} f(v)dv = 1 \tag{5}$$

where $v_{\max}$ is the maximum value of v where $y = d$, whereas v_0 is the minimum value of v that occurs at the bottom where $y = 0$. An additional constraint pertinent to the velocity distribution is the mean value of v, which may be expressed as:

$$\int_{v_0}^{v_{\max}} vf(v)dv = \overline{v} \tag{6}$$

where $\overline{v}$ is the (depth-averaged) mean velocity.

To identify the probability density function $f(v)$, the entropy maximization principle may be applied. The function $f(v)$ that maximizes the entropy:

$$S(v) = -\int_{v_0}^{v_{\max}} f(v)\ln f(v)dv \tag{7}$$

subject to the constraints of Equations (5) and (6) can yield:

$$f(v) = e^{\lambda_1 - 1}e^{\lambda_2 v} \tag{8}$$

where λ_1 and λ_2 are parameters (Lagrange multipliers).

The substitution of Equation (8) into Equations (5) and (6) yields:

$$e^{\lambda_1 - 1} = \lambda_2(e^{\lambda_2 v_{\max}} - e^{\lambda_2 v_0})^{-1} \tag{9}$$

$$\overline{v} = (v_{\max}e^{\lambda_2 v_{\max}} - v_0 e^{\lambda_2 v_0})(e^{\lambda_2 v_{\max}} - e^{\lambda_2 v_0})^{-1} - \frac{1}{\lambda_2} \tag{10}$$

The substitution of Equation (9) into Equation (7) gives the entropy:

$$S(v) = -\int_{v_0}^{v_{\max}} f(v)\ln f(v)dv = -\lambda_1 + 2 - v_{\max}e^{\lambda_1 - 1 + \lambda_2 v_{\max}} + v_0 e^{\lambda_1 - 1 + \lambda_2 v_0} \tag{11}$$

which shows the relation of the entropy with parameters λ_1 and λ_2. The cumulative distribution function $F(v)$ can be derived from Equation (12):

$$F(v) = \int f(v)dv = \int_{v_0}^{v} e^{\lambda_1 - 1}e^{\lambda_2 \tau}d\tau = \frac{e^{\lambda_1 - 1}}{\lambda_2}(e^{\lambda_2 v} - e^{\lambda_2 v_0}) \tag{12}$$

Then, the equation of the spatial distribution of the seepage velocity as a function of the depth is expressed as:

$$v = \frac{1}{\lambda_2}\ln[\frac{\lambda_2}{e^{\lambda_1-1}}F(v) + e^{\lambda_2 v_0}] = \frac{1}{\lambda_2}\ln[(e^{\lambda_2 v_{\max}} - e^{\lambda_2 v_0})\frac{y}{d} + e^{\lambda_2 v_0}] \quad (13)$$

where the parameters λ_2 can be obtained from Equation (10). To simplify the calculation, let $m = \lambda_2 v_{\max}$; Equations (10) and (13) become Equations (14) and (15), respectively:

$$\frac{\overline{v}}{v_{\max}} = (e^m - \frac{v_0}{v_{\max}}e^{m\cdot\frac{v_0}{v_{\max}}})(e^m - e^{m\cdot\frac{v_0}{v_{\max}}})^{-1} - \frac{1}{m} \quad (14)$$

$$v = \frac{v_{\max}}{m}\ln[(e^m - e^{m\cdot\frac{v_0}{v_{\max}}})\frac{y}{d} + e^{m\cdot\frac{v_0}{v_{\max}}}] \quad (15)$$

The parameters v_0, $v_{\max}$, λ_2, $\overline{v}$, and m can be determined from the measured data; then, they are substituted into Equation (15) to obtain the distribution equation of the seepage velocity as a function of depth. It demonstrates that the seepage velocity in each part has a logarithmic distribution.

4. Tests and Results

The actual field data for a dam in the Ling'ao reservoir is used to test the distribution equation of the seepage velocity derived above. The reservoir has a designed seepage velocity of 8.64×10^{-3} m/d, and it suffers from heavy water leakage according to the field survey and study. Sixteen boreholes were drilled along the axis of the dam crest in 2007, and the horizontal seepage velocity of the water in each borehole in situ was measured using a point dilution method. According to the results of an investigation, three concentrated seepage passages were found beneath the dam. Accordingly, three boreholes numbered Bo+125, Bo+275, and Bo+425, which are influenced by these three concentrated seepage paths, are chosen for the field case studies.

The dam lies in the low hills landform in the coastal area, where there are great topographical changes and several faults. Daya Bay located southeast of the dam, and the PaiYa Mountain of NE-SW extension is northwest, the peak of which is 707.60 m high. Loose quaternary deposits with few outcrops of bedrock are frequently encountered throughout the dam area, primarily on the steep slopes, hillsides, and hilltops outside the wadis. These loose quaternary deposits mainly consist of residual deposits, blunt diluvium, and slope diluvium. Its main lithology is that of a fine-grained feldspar quartz sandstone, siltstone, and quartz conglomerate with thick-bedded and inconspicuous bedding. Based on the drilling survey, a cross-section geological map of the dam site is shown in Figure 2. The first dam-filling soil is characterized by silty clay containing numerous grains of fine sands and small numbers of crushed stones colored bronze and yellowish-brown. The second exhibits siltstone weathered from quartz sand with a high regional residual strength and a shaped core. The third is characterized by strongly weathered quartz sandstone with more fractures, as indicated by the cinereous color and the fact that the rock core is fragmentized or stumpy rock, and the particle size is about 1–5 cm thick. The fourth is intermediately weathered quartz sandstone, with developed fissures, and the fissure surface is disseminated by iron-manganese. The last presents weakly weathered quartz sandstone with less fracture, with a cinereous color and a 10–25 cm cylindrical rock core [11].

The raw profile values of the seepage velocity are obtained at depth intervals of 1 m for each borehole. As stated above, each borehole is divided into two parts at demarcation point (the maximum velocity), and the parameters d, v_0, $v_{\max}$, and $\overline{v}$ in each part are obtained from the measured data, which are substituted into Equations (9), (10) and (14) to determine the values of m, λ_2, and λ_1. Finally, the seepage velocity distribution as a function of the depth is obtained. To quantitatively evaluate the goodness of fit of the computed distribution of the seepage velocity, the statistical measure of error and the mean error (MR) are used. The error is the absolute value of the difference of the measured value from the correspondingly computed value at each point, and the MR is the average value of the error. The values of these parameters in each part of the three boreholes are listed in Table 1.

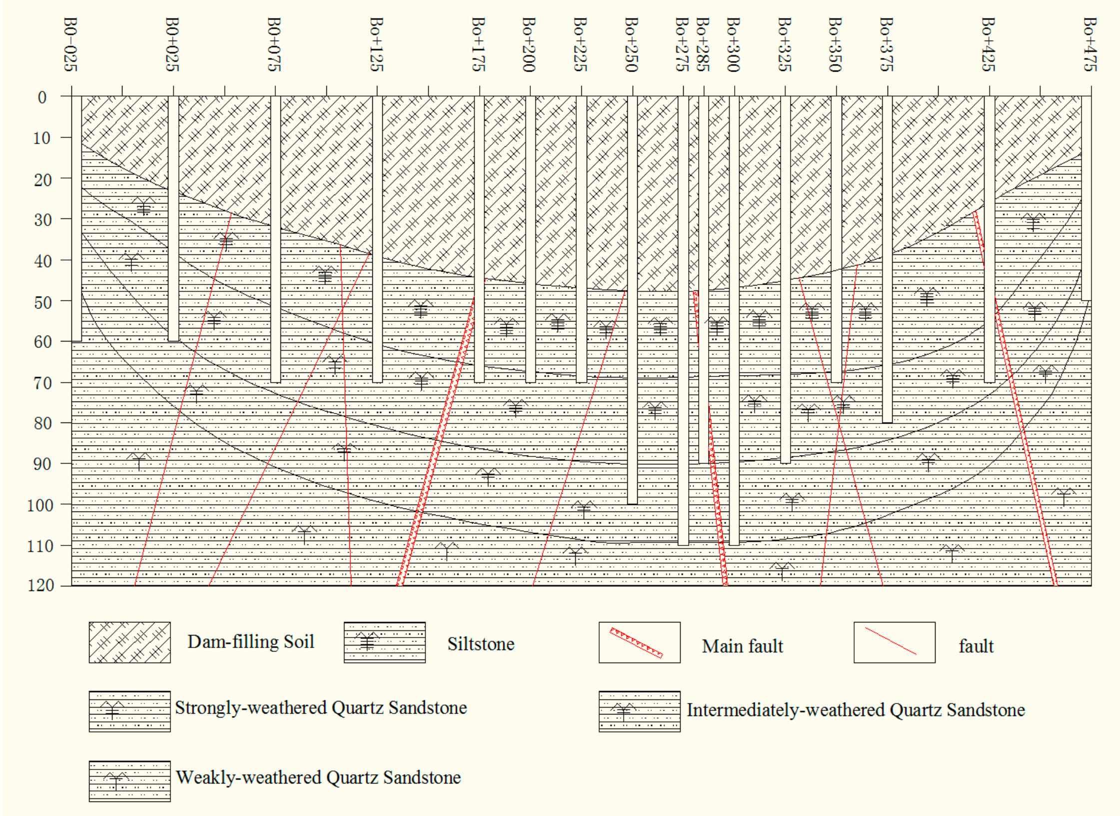

Figure 2. Cross-section geological map of the dam site.

Table 1. Values of the relevant parameters. The MR is the mean error.

Borehole	Bo+125$_{UP}$	Bo+125$_{LP}$	Bo+275$_{UP}$	Bo+275$_{LP}$	Bo+425$_{UP}$	Bo+425$_{LP}$
d	26	31	36	45	15	14
v_0	0.0018	0.0016	0.0096	0.0089	0.0040	0.0018
$v_{\max}$	0.2955	0.2955	0.1189	0.1189	0.2275	0.2275
$\overline{v}$	0.1444	0.1306	0.0613	0.0471	0.0986	0.0497
λ_1	0.3072	2.5700	3.3083	4.0258	4.0021	2.9249
λ_2	−0.5915	−2.5147	−2.9000	−17.7206	−19.7375	−4.1805
m	−0.1748	−0.7431	−0.3448	−2.1069	−4.4909	−0.9512
$S(v)$	−1.2175	−1.2379	−2.0618	−2.1668	−2.0181	−1.5003
MR	0.0327	0.0201	0.0185	0.0125	0.0162	0.0183

The computed seepage velocity distribution as a function of the depth and the measured data in these three boreholes are plotted in Figure 3. Meanwhile, the error of the computed seepage velocity distribution to the measured data at each measurement point is plotted against the depth in Figure 4. The computed seepage velocity distribution is a good fit to the measured data with a relatively small MR, as shown in Table 1.

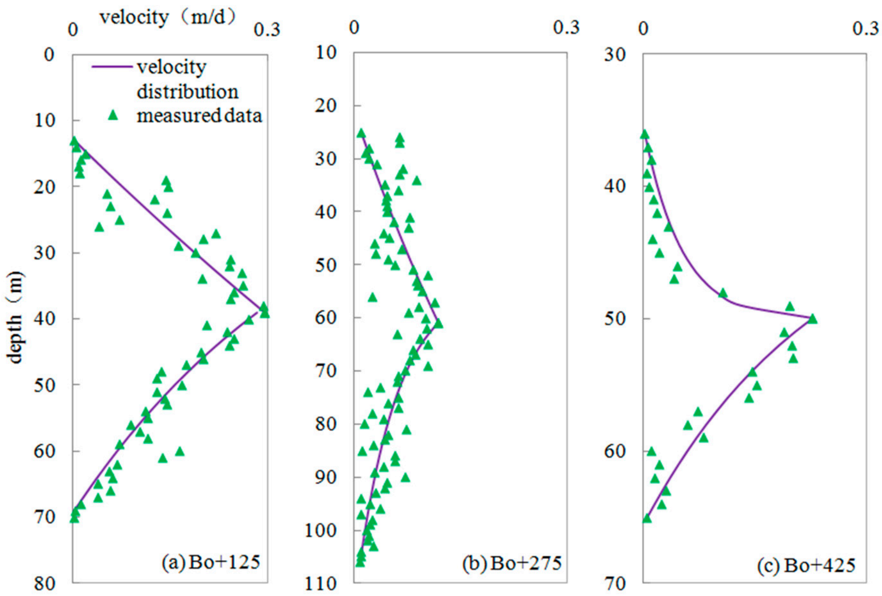

Figure 3. Comparison between the computed seepage velocity distribution and the measured data in (**a**) Bo+125, (**b**) Bo+275, and (**c**) Bo+425.

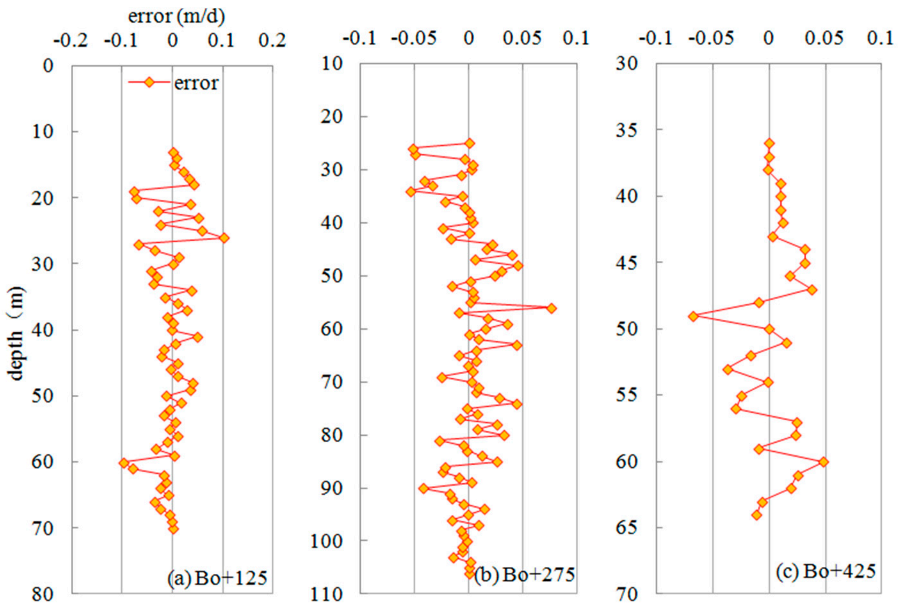

Figure 4. Deviation of the computed seepage velocity distribution from the measured data at each measured point in (**a**) Bo+125, (**b**) Bo+275, and (**c**) Bo+425.

According to Table 1, the maximum entropy obtained by the Bo+125, followed by that of Bo+425, and minimum entropy is achieved by Bo+275. The results indicate that velocity dispersion of the boreholes Bo+125, Bo+425 and Bo+275 decrease successively, which is consistent with Figure 3. Although the fissure in Bo+275 is fully developed, the main fracture location has not been revealed by the borehole. Moreover, the fissure in Bo+125 is weakly developed, and the fracture location is well disclosed. The separate entropy of the lower part and the upper part of Bo+125 and 275 are similar, however entropy of lower part of the Bo+425 is much larger than the upper, which may be due to different distribution of soil filling. The upper part of Bo+425 is the dam-filling soil, and water can be approximated as Darcy Flow in unconsolidated layer in most areas; thus, the obtained data have less velocity discreteness and smaller entropy value. In contrast, the lower part of Bo+425 is fractured, the data have a larger velocity discreteness and a bigger entropy value, as a result of the approximation of the fracture flow and the uncertainty in the water storage structure caused by water exchange. On the basis of the above judgment, this area is a concentrated leakage area, and certain measures should be taken for prevention.

With the seepage velocity distribution law given by Equation (13), the velocity measurements between the location of the minimum and the maximum values according to a uniform density function $f(y) = 1/d$ (i.e., the velocity in each distance interval dy has an equal probability of being measured) should result in a set of velocity data distributed according to the density function given by Equation (8). This means that greater velocity values have greater probabilities of being measured. If the entire range of velocity is to have equal probabilities $[f(v) = 1\Big/(v_{\max} - v_0)]$ of being measured, the sampling scheme should be based on Equation (16):

$$f(y) = \left[(v_{\max} - v_0)(de^{\lambda_2 v_0}e^{\lambda_1 - 1} + \lambda_2 y)\right]^{-1} \tag{16}$$

which can be derived from Equation (13) integrated with Equation (8) and the above two equations. According to Equation (16), the sampling frequency increases with the decreasing y. That is, the smaller velocity is, the larger the sampling frequency, which means more samples should be taken to better evaluate the distribution of the seepage velocity when the velocity is small. The sampling scheme is obviously preferred to the traditional one with equal distance intervals.

5. Conclusions

Based on entropy theory, the characteristics of the seepage velocity in a complex rock mass dam are probabilistically analyzed by considering its uncertainties and randomness. The results are in agreement and appropriate, which demonstrates the great advantage of applying entropy theory for a seepage velocity analysis. The conclusions are summarized as follows:

(1) The equation for the spatial distribution of the seepage velocity of a complex rock mass dam as a function of the depth is derived; the distribution is logarithmic from the location of the maximum velocity to the minimum velocity; (2) the derived equation of the seepage velocity distribution is tested and compared with actual field data, and the results demonstrate that it is a good fit to the measured data with a relatively small mean error; (3) according to the entropy of the flow velocity in boreholes, rupture and the leakage degree of the dam are estimated, which provides a new idea and method for leakage in rock mass; and (4) a new sampling scheme, in which the sampling frequency varies with y as expressed in Equation (16), is introduced; this scheme is preferable to the traditional one with equal distance intervals. It demonstrates the great advantage of applying the entropy theory for seepage velocity analysis for rock rupture degree estimation.

It is assumed that the seepage velocity only varies with depth; however, it also changes in the transverse direction resulting in a 2D case. Therefore, further studies of the characteristics of the seepage velocity distribution in a 2D case are needed in the near future. In addition, there exists a certain limitation for the method proposed in this paper, which is the study of the rock mass fracture degree using entropy of velocity in boreholes. It is requested that boreholes reveal the position of a rock fracture, or the deviation is unavoidable. The method also needs to be verified with a related study in the future, and further work for development of quantitative research.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (51578212), the 973 Program of China (2012CB417005) and the Postgraduate Research and Innovation Projects in Jiangsu Province (KYZZ-0141).

Author Contributions: The work presented in the paper corresponds to a collaborative development by all authors. Xixi Chen and Jiansheng Chen conceived and designed the experiments; Tao Wang performed the experiments. Xixi Chen and Tao Wang analyzed the data; Jiansheng Chen, Huaidong Zhou and Linghua Liu contributed modification of the paper. Xixi Chen wrote the paper. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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