1. Introduction

Red beds are a widespread type of sedimentary rock, occurring throughout western Europe, western, interior, and eastern United States, and parts of Russia, China, South America, southern Africa, India, and eastern Australia [1, 2]. They typically consist of conglomerate, sandstone, siltstone, and mudstone and are predominantly in red color due to the presence of ferric oxides. Red beds are a complex assemblage of hard and soft rocks of unequal thickness.

As a typical foundation rock mass, red beds are often encountered in large-scale civil engineering. For example, in China, the Gezhouba and Xiangjiaba Dams on the Yangtze River and the Xiaolangdi and Xixiayuan Dams on the Yellow River are all built on red beds [3–6]. In fact, red beds are a kind of dam foundation rock mass that has the most problems in the history of dam construction. According to incomplete statistics, a very high percentage of gravity dams that experienced foundation failures were constructed on red beds [6]. For example, the failure of St. Francis dam, in the
United States, was believed to be caused by the geologic engineering problems of red beds [7]. It was found that after the St. Francis dam was impounded, the gypsum in the conglomerate of the dam foundation was dissolved and the clay cement was softened, which results in the dam foundation scrapped within a very short time. The Bouzey dam in France was also believed to be impacted by the geologic engineering problems of red beds. The dam was found to slip to crash along the clay layer above the cracked red sandstone of the dam foundation [8]. What is more, during the construction of the Mangla Dam in Pakistan, in order to ensure the safety of the project, the original engineering design had to be modified as interlayer shear zones in the clay rock of the dam foundation were newly found [9]. The low strength, the development of interlayer shear zone, and the structural damage caused by the soluble salt corrosion will seriously threaten the safety of large dams. Therefore, it is the prerequisite for the safety guarantee to carry out the research on engineering geological and hydrogeological properties of red beds.

Affected by the depositional environment and the depositional rate, lithology variations are quite common in red beds [10]. For example, a layer of a specific lithology (i.e., sandstone, siltstone, or mudstone) can suddenly disappear or gradually become thinner or thicker in the vertical or horizontal directions. The issue of lithology variations will lead to irregular changes in the proportion of different lithologies that are deposited, thereby changing the characteristics of strength, deformation, and seepage and having an important impact on the evaluation of hardness, weathering, unloading, integrity, and permeability of rock masses.

As far as the authors know, the evaluation of the degree of lithology variations in red beds is almost at the qualitative stage for engineering geology. Simple language or field photos are often used for presentation. For the petroleum geological industry and the field of sedimentology, techniques of lithofacies or lithology analysis that use seismic or geophysical prospecting are quite mature [11, 12]. Based on the theory of geostatistics, commercial or public software have been able to achieve the establishment of lithofacies or lithology models to better predict its three-dimensional spatial distribution [13–16]. Of course, it is possible to directly introduce the mature techniques in the field of petroleum geology and sedimentology to the field of engineering geology. However, it is more meaningful to use common engineering geological practice to explore a kind of method that is more closely related to engineering geological issues.

Boreholes are the most conventional and effective exploration measures to obtain first-hand geological data, which can intuitively provide the geological information of deep rock masses. For giant projects of water conservancy, hydro-power, and civil engineering, it is often requested to drill a large number of boreholes. Based on the valuable data of borehole logs, this paper introduces a statistical method for quantitatively evaluating the degree of lithology variations in layered red beds with depth. The Yellow River Guxian Dam is selected as a field case study, and the proposed statistical method is applied to reveal the general behaviors of lithology variations at the dam site.

2. Study Area

The to-be-built Guxian (Chinese: 古贤) Dam is located at the middle reach of the Yellow River, Northwestern China (Figure 1). As one of the seven major control backbone projects in the mainstream, it has an extremely important strategic position in the Yellow River governance development and the water and sediment regulation system [17–19]. Particularly, as the Guxian Dam is close to the downstream Xiaolangdi Dam, it has a unique geographical advantage in the joint regulation of water and sediment with the Xiaolangdi Dam. The major role of Guxian Dam is to focus on flood prevention and silt reduction, taking into account comprehensive utilization of water resources, irrigation, and power generation. At the feasibility stage, the recommended dam type is the roller-compacted concrete (RCC) gravity dam, with a normal reservoir level of 627 m and a maximum dam height of 215 m [20]. The corresponding total reservoir storage is about 12.6 billion m$^3$. And a power plant of 2100 MW is scheduled to be installed. The Guxian Dam is currently the highest RCC gravity dam under construction and proposed in China.

The Guxian Dam is to be built on red beds of the upper section of the Middle Triassic Ermaying Formation ($T_{2er2}$) and the lower section of the Tongchuan Formation ($T_{3t1}$) (Figures 2 and 3). The lithology in these two formations is dominantly characterized by the greyish and light green sandstone, the dark purple calcareous and argillaceous siltstones, and a small amount of mudstone (Figure 2). Folds and faults are not developed in the dam site. The stratigraphic attitude is generally horizontal. Structural discontinuities are mainly presented in the forms of beddings, joints, and shear zones.

As shown in Figure 3, according to the variations in stratigraphic thickness and percentage of different lithologies, the upper section of the Ermaying Formation ($T_{2er2}$) is finely divided into 11 lithology groups. Among them, 7 groups, i.e., $T_{2er2}^{11}$, $T_{2er2}^{10}$, $T_{2er2}^{9}$, $T_{2er2}^{8}$, $T_{2er2}^{7}$, $T_{2er2}^{6}$, and $T_{2er2}^{5}$, are disclosed in the dam site. Similarly, the lower section of the Tongchuan Formation ($T_{3t1}$) is divided into 2 groups. Among them, the $T_{3t1}^{5}$ group is then divided into 4 subgroups, i.e., $T_{3t1}^{5-1}$, $T_{3t1}^{5-2}$, $T_{3t1}^{5-3}$, and $T_{3t1}^{5-4}$. Due to the intense lithology variations, percentages of sandstone, siltstone, and mudstone in each group differ greatly.

3. Materials

Boreholes are the most conventional and effective exploration measure, which can directly obtain the geological information of deep rock masses. After the completion of drilling, one important work for engineering geologists is to record the authentic first-hand geological information by plotting borehole logs. For the Guxian Dam site, until now, more than 150 boreholes have been drilled and recorded during the past 20 years, in which a total of more than 80 boreholes were drilled at the riverbed (Figure 4), among which 32 boreholes were completed at the stage of preliminary design in the year 2019. By taking account of necessity and economy, the borehole depth at the riverbeds generally does not exceed 150 m,
Figure 1: (a) Location of the Yellow River Guxian Dam and (b) its design sketch rendering after construction. The map of the Yellow River with approximate borders shown in (a) is from the website of https://en.wikipedia.org/wiki/Yellow_River.

Figure 2: (a) Horizontally distributed red beds with (b) strong lithology variations exposed at the Yellow River Guxian Dam site. The lithology is dominated by (c) the greyish sandstone, (d) the dark purple calcareous, and (e) argillaceous siltstones. (a) The Tongchuan T1t1 Formation exposed at the left dam abutment. (b) The Ermaying T2er1 09 Formation exposed at the right dam abutment. (c-e) The Ermaying T2er2 09 Formation disclosed by boreholes at the riverbed.
which indicates that groups of $T_2^{er_2}$, $T_2^{er_2}$, $T_2^{er_2}$, $T_2^{er_2}$, $T_2^{er_2}$, and $T_2^{er_2}$ are disclosed (Figure 3). Note that, as space is limited, in this paper, we only take the red beds at the riverbed as an example. A similar analysis for the dam abutments is not presented.

With the deepening of the understanding on the geological conditions at the dam site, improvements were made to the field borehole logging since the preliminary design stage in the year 2019. On the one hand, we paid special attention to carefully distinguish the harder calcareous siltstone and the softer argillaceous siltstone or mudstone. On the other hand, to more accurately describe the lithology variations, we narrowed the minimum length of logging segment from 100 cm to 10 cm to improve the logging resolution. In the years before 2019, for lithology segments of length less than 100 cm, we often treated them as interbeds, which is not favorable to finely describe the lithology variation. Therefore, a total of 1300 lithology segments were logged for the 50 boreholes drilled before the year 2019. In contrast, more than 3200 lithology segments were logged for the 32 boreholes drilled in the year 2019. In fact, this also indicates the high degree of lithology variations of the Guxian Dam foundation at the riverbed. As a result, in the current study, we choose to only use the high-resolution lithology logs recorded in the year 2019 for analysis. Note that the lithology logs ever drilled before the year 2019 were also analyzed, which are

![Figure 3: Geological cross section of the Guxian Dam axis. Note that the lithological column on the left and the interlayered shear zones are not precise descriptions but are schematic representations based on actual field data. $Q_{eol}^{2+3}$ refers to Quaternary Middle-Upper Pleistocene loess. $Q_{al+dl}^{2+3}$ refers to Quaternary Middle-Upper Pleistocene alluvium and slope deposits. $Q_{al}^4$ represents the Quaternary Holocene alluvial deposits. $T_2^{t_1}$ represents the lower part of the Middle Triassic Tongchuan Formation. $T_2^{er_2}$ represents the lower part of the Middle Triassic Ermaying Formation.](image1)

![Figure 4: Schematic diagram showing boreholes ever drilled at the Yellow River Guxian Dam site.](image2)
shown in Figure S1 in the supplementary material. The overall trends of the two are consistent, but there are some differences, which are believed to be caused by the accuracy of the borehole logging resolution. The coarser resolution may ignore some thin-layer lithology variations.

4. Method

As red beds are deposited in layers, theoretically, the lithology disclosed by boreholes in the same layer can be used as random variables for statistical analysis. Red beds are mostly a kind of layered strata with a certain inclination. In order to accurately characterize the lithology variations within the same layer or stratum, borehole elevations need to be corrected according to the stratigraphic attitude to facilitate the following data batch processing. This process involves four steps of attitude calculation, reference point selection, distance calculation, and elevation modification (Figures 5(a) and 5(b)).

Obtaining the reliable information of stratigraphic attitude (usually presented in the form of $\alpha \beta$, where $\alpha$ is the dip direction and $\beta$ is the dip angle) is important for the evaluation of lithology variations. Methods such as the field measurement by a geological compass and the indoor calculation by the knowledge of space analytic geometry and the remote sensing images are commonly used [21, 22]. For the Guxian Dam site, as the stratum inclination or dip angle $\beta$ is tiny, the results by the geological compass and the remote sensing images are of great variability and uncertainty. Here, we choose to use the borehole logs of a typical stratum to fit its plane equation in three dimensions. The coefficients of the plane equation are then used to calculate the stratigraphic attitude. As a result, the calculated stratigraphic attitude of the Guxian Dam site is $307^\circ \pm 0.5^\circ$.

The reference point is commonly selected at the boundary of the study area, but it can also be selected according to the purpose of the work (Figure 5(b)). For example, former geological investigations of the Guxian Dam site show that there are differences in lithology on the left and right sides of the riverbed. Note that the dip angle is $0.5^\circ$, and the dip direction is approximately perpendicular to the Yellow River. Although the dip angle is very tiny, given the width of the river bed is about 400 m, the elevation difference of the same stratigraphic layer at the two sides of the riverbed can be 3–4 m. For the current study of a resolution of 0.1 m, it will bring a relatively large error. Therefore, in order to discern appreciable differences of the same stratigraphic layer between the left half and right half of the riverbed, we selected the middle point of the dam axis $I(x_0, y_0)$, as the reference point. And boreholes should be modified according to this reference point. Thus, we can make a comparative study of the same stratigraphic layer at the two sides of the riverbed.

The next step is to calculate the plane distances between the boreholes and the reference point in the dip direction. To facilitate the batch processing, we use the reference point $I(x_0, y_0)$ as the coordinate origin, the strike as the abscissa, and the dip direction as the ordinate, to establish a plane coordinate system. By means of the coordinate rotation (Equations (1a) and (1b)), the geodetic coordinates of each borehole $(x, y)$ can be converted into the plane coordinates of stratigraphic attitude $(x', y')$. In this way, the ordinate of the borehole $y'$ in the new plane coordinate system can be regarded as the distance between the borehole and the reference point in the dip direction.

\[
x' = (x - x_0) \cdot \cos (-\alpha) - (y - y_0) \cdot \sin (-\alpha) + x_0, \tag{1a}
\]
\[
y' = (x - x_0) \cdot \sin (-\alpha) + (y - y_0) \cdot \cos (-\alpha) + y_0, \tag{1b}
\]

where $\alpha$ is the dip direction rotated in the clockwise direction.

With the information of the distance and stratigraphic attitude, the elevation difference $\Delta h$ between the borehole and the reference point can be calculated based on the basic knowledge of trigonometric functions. The elevation modification can be performed according to the following equation:

\[
h' = h + \Delta h = h - \tan (\beta) \cdot y', \tag{2}
\]

where $h$ and $h'$ are the borehole elevation before and after modification, respectively. Note that a positive (or negative) value of $y'$ means that the borehole is lower (or higher) than the reference point and its elevation should be compensated (reduced).

After the elevation modification, we can statistically analyze the borehole logs and plot the percentage curve of a specific lithology with elevation or depth. This process involves the steps of data discretization, data statistics, and curve plotting (Figures 5(a) and 5(c)). First, the borehole logs of lithology segments should be spatially discretized in the vertical direction. The resolution of discretization is determined by data quality and study purposes. For example, for the Guxian Dam site, borehole logs recorded before the year 2019 are of a low resolution in meters, so one-meter resolution is selected for the discretization, while for borehole logs recorded in the year 2019, as the logging resolution is 0.1 meter, a finer resolution of 0.1 meter can be set for the discretization. After discretization, for a given elevation, we should count the total number of boreholes $N$, the number of boreholes with the specific lithology $M$, and use the formula $M/N \cdot 100\%$ to calculate the percentage of the specific lithology. Finally, we plot the percentage curve of the specific lithology with depth.

In fact, the lithology statistical method proposed in this paper is similar to that of Lugeon test in previous studies [4, 23, 24]. They both are statistical analysis of rock mass properties at a given modified elevation and then plot the depth-dependent curves. The difference is that this paper is a percentage analysis of a specific lithology, while previous studies mainly focused on the average Lugeon values and permeability.

5. Results

Using the method introduced in former sections (Figure 4), we plotted the hard rock percentage curve with depth for the Guxian Dam foundation at the riverbed. Note that, in this study, we differentiate the hard and soft rocks only based on...
the rock types by the in situ observations of borehole logs. That is, we classify the rock types of feldspar sandstone, fine sandstone, and conglomerate into hard rocks and the rock types of calcareous siltstone, argillaceous siltstone, and mudstone into soft rocks. According to the laboratory test results of the project feasibility study, the saturated uniaxial compressive strengths (SUCSs) of sandstone in the dam foundation range from 79 to 115 MPa with an average value of

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**Figure 5:** (a) Flow chart of plotting a percentage curve of a specific lithology, which involves seven steps of attitude calculation, reference point selection, distance calculation, elevation modification, data discretization, data statistics, and curve plotting. The former four steps are visually illustrated via (b), and the last three steps are visually expressed via (c) in a case of hard rocks.
95.4 MPa. The SUCSs of calcareous siltstone range from 35.5 to 100.5 MPa with an average value of 65.9 MPa. The SUCSs of argillaceous siltstone or mudstone range from 36.4 to 66.1 MPa with an average value of 46.7 MPa. Therefore, we can generally conclude that SUCSs of hard rocks are larger than 60 MPa, and SUCSs of soft rocks are smaller than 60 MPa. The horizontal axis of the curve is the percentage of hard rocks, and the vertical axis is the elevation. In theory, the summation of percentages of hard and soft rocks should be 100%.

As shown in Figure 6, due to the drastic variations in lithology, the percentage of hard rocks fluctuates with depth. When the curve approaches 100%, it shows that the lithology is statistically dominated by hard rocks at the current elevation. Conversely, it is dominated by soft rocks. Here, we define that the bulges whose percentages of hard rocks tend to the right side of 100% are crests and the sags which tend to the left side of 0% are troughs. With the help of the fluctuation of the curve, we can find some fundamental behaviors of lithology variations for the Guixian Dam foundation at the riverbed.

The hard rock percentage curve, in the T2er210, T2er29, T2er210, and T2er29 groups, is generally characterized by one significant crest or trough with minor fluctuations locally, indicating that the lithology in these groups is much uniform and of a low degree of variation. In contrast, the curve fluctuates strongly in the T2er25 and T2er24 groups and is characterized by several significant crests and troughs, which indicates that the lithology in these two groups is nonuniform and of a high degree of variation. Moreover, the curve in the T2er210, T2er29, T2er210, and T2er29 groups is generally distributed to the left side with values less than 50%, indicating that these groups are mainly dominated by soft rocks. In contrast, the curve in the T2er25 and T2er24 groups is generally approaching to the right side of 100%, indicating that these two groups are dominated by hard rocks. Therefore, the degree of lithology variations for each group differs greatly.

The hard rock percentage curves basically coincide on two sides of the riverbed and are of quite similar behaviors (Figures 6(a) and 6(b)). However, if carefully observed, we can find that some differences exist (Figure 6(c)). For example, the curve of the left riverbed is higher than that for the right. More specifically, the curve of the left riverbed is generally more to the right than that of the right riverbed, especially in the ranges from 435 to 450 m. The value is 1, it means that the lithology variations are statistically uniform without variations (0 means only soft rocks and 100% means only hard rocks). When the value of the hard rock percentage is 50%, it means the lithology varies seriously and that the hard rock and the soft rock are statistically half. Based on the above perceptions, in order to quantitatively characterize the degree of lithology variations in dimensionless and normalized values from 0 to 1, we introduced a lithology variation index (LVI). Its mathematical expression is as follows:

\[
LVI = \frac{HRP}{50\%}, \text{ when } HRP \leq 50\%, \quad (3a)
\]

\[
LVI = \frac{|100\% - HRP|}{50\%}, \text{ when } HRP \geq 50\%, \quad (3b)
\]

where HRP is the hard rock percentage and 50% is the hard rock percentage with the most serious lithology variation. The value of LVI ranges from 0 to 1. When the value is 0, it means that the lithology at the current elevation is uniform and there are no variations, i.e., only soft or hard rocks. When the value is 1, it means that the lithology variations may be serious, i.e., the hard rock and the soft rock are statistically half. Note that the same value of LVI may give two different hard or soft rock percentages. For example, a LVI value of 0.5 can mean that the hard rock takes 25% or the soft rock takes 25%.

Using Equations (3a) and (3b), we obtained the LVI with depth at the riverbed based on Figure 6 and quantitatively evaluated the degree of lithology variations at different elevations (Figure 7). Figure 7 shows that although the LVI values of the T2er24, T2er29, and T2er24 groups fluctuate locally, their overall values are small and the degree of lithology variations is low. In comparison, the LVI values of the T2er210 and T2er29 groups fluctuate strongly. Specifically, in the elevations of 450-465 m, 420-440 m, and 380-400 m at the left riverbed and of 465-420 m and 380-390 m at the right riverbed, the LVI are of large values and the degree of lithology variations is high. In view of the fact that LVI can quantitatively estimate the degree of lithology variations, it can be used as an important index to supplement the traditional methods such as Q-Rating, Rock Mass Rating (RMR) systems, and
the geological strength index (GSI) when performing rock mass classifications in red beds [25–27]. This will be one of the key study points of LV1 in the future.

6.2. Trilithology Percentage Curve. Although the calcareous and argillaceous siltstones belong to the category of soft rocks, due to the difference in cementing materials (i.e., calcareous or argillaceous cement), their engineering geological properties are still different. It is necessary to distinguish between these two similar lithologies.

Using the data of borehole logs recorded in the year 2019, we obtained the depth-dependent percentage curves of sandstone and calcareous and argillaceous siltstones via the same method of plotting the hard rock percentage curve (Figures 8(a) and 8(b)). Note that due to a very small amount and a similar behavior with argillaceous siltstone, we combined the mudstone and argillaceous siltstone in the data processing. In theory, the summation of percentages of sandstone and calcareous and argillaceous siltstones should be 100%.

As shown in Figures 8(a) and 8(b), the percentages of calcareous and argillaceous siltstones are relatively close, but slightly dominated by the calcareous siltstone. However, at some specific elevations such as 420 m, 372 m, 360 m, and 345 m, the percentages of argillaceous siltstone are relatively high, which may lead to a continuous distribution over a large area at the riverbed. As the argillaceous siltstone has well-developed bedding planes and low shear strength, these elevations might constitute a weak and potential shear sliding surface of the Guxian Dam foundation, which should be paid high attention to the designation or analysis of antislip stability of gravity dam.

Figures 8(a) and 8(b) also provide an insight into the reasonable determination of physical parameters of the dam foundation rock mass. For example, former in situ tests in the Guxian Dam site showed that for slightly weathered or fresh rock masses, the cohesion of sandstone is 1.75 MPa and the internal friction angle is 53.5°; the cohesion of calcareous siltstone is 1.5 MPa and the internal friction angle is 50°; the cohesion of argillaceous siltstone is 1.3 MPa and the internal friction angle is 47.7°. By jointly using the percentages and shear strength parameters of the three lithologies, weighted parameters of cohesion and internal friction varying with depth can be obtained (Figures 8(c)–8(f)), which are critical for the antisliding stability analysis of the Guxian gravity dam. In comparison to traditional methods, the shear strength parameters shown in Figures 8(c)–8(f) synthesize the contributions of the three lithologies and fluctuate with depth, which is superior to the only use of the information on one single lithology. Note that values of cohesion and internal friction are for slightly weathered or fresh rock masses. In Figures 8(c)–8(f), the moderately weathered rock masses of elevations higher than 450 m are not plotted.

Moreover, as fractures or discontinuities are poorly developed in the calcareous or argillaceous siltstone, it can be regarded impermeable. Figures 6 or 8(a) and 8(b) show that in elevations of 405–415 m, 380–390 m, and 350–360 m, three thick sections of a high percentage of siltstones can be found. These sections might be regarded as the bottom boundary when designing the grouting curtain of the dam foundation.

6.3. Shear Zones. The shear zone is a major engineering geological problem often encountered in the construction of...
dams, which directly affects the design, investment, and construction period [5, 6, 28]. Identifying the spatial distributions of shear zones in the dam foundation is of great significance. For the Guxian Dam site, using methods of core drilling, borehole image television, geological exploration tunnel, and ground surface investigation, 12 shear zones with different elevations and properties are disclosed (Figure 3). These shear zones are generally developed along with the stratum with obvious traces of displacement. Some have further evolved into muddy interlayers under the influence of groundwater. Typical field photos of specific shear zones are exhibited in Figure S2 in the supplementary materials.

For the Guxian Dam site at the riverbed, 10 shear zones of JQD03-JQD12 are identified by boreholes (Figure 6). Figure 9 gives the information of JQD03-JQD09 shear zones disclosed by boreholes. Borehole disclosure probability (BDF) is a parameter to describe the possibility of the existence of a shear zone. Mathematically, it is equal to the number of boreholes disclosing the shear zone divided by the total number of boreholes. Among them, JQD04, JQD05, and JQD06 shear zones have a stable distribution and a good continuity with borehole disclosure probability more than 80%. In contrast, JQD03, JQD07, and JQD08 shear zones are sporadically distributed and generally have a poor continuity with borehole disclosure probability ranging from 20 to 50%. As the JQD10, JQD11, and JQD12 shear zones are deeply buried and disclosed by few boreholes of a poor statistical significance, we do not make a further discussion on them here.

Engineering geomechanics clarifies that the shear zones are the geomechanical result of the interlayer shear force caused by the buckling of strata under the effect of horizontal crust stress [5, 6]. The development of shear zones requires specific lithology conditions. For instance, for stratified hard rocks with high strengths, the shear force generated during the buckling maybe much lower than their yield strength and will not lead the hard rocks to shear and be destroyed. In contrast, the shear zones are more likely to be developed at the contact interface of stratified soft and hard rocks. The crests and troughs in the hard rock percentage curve approximately characterize the contact interface. More precisely, the crest is a manifestation of a sandwich-like structure with a layer of hard rocks sandwiched by two layers of soft rocks. And the trough is a manifestation of a sandwich-like structure with a layer of soft rocks sandwiched by two layers of hard rocks. The crest and trough in the hard rock percentage curve might be used to show some characteristics of shear zones.

In Figure 6, we can find that, generally, within the location of a specific shear zone, significant troughs can always be found on two sides of the riverbed. In particular, for the JQD08 shear zone, the hard rock percentage curve shows that no troughs are found at the right riverbed, which indicates that the JQD08 shear zone is poorly developed at the right riverbed. This corresponds well to the geological investigation results of the shear zones shown in Figure 9(f). This phenomenon implies that the troughs in the hard rock
percentage curve can be used as a tool to predict or identify the shear zones.

In addition, we obtained the hard rock percentages of the crest and trough within the locations of JQD03-JQD09 shear zones from Figure 6 and calculated their borehole disclosure probability on two sides of the riverbed via Figure 9. We found that for these key shear zones, their borehole disclosure probabilities have a good linear relationship with the hard rock percentages of the crest (Figure 10), but a poor relationship with those of trough or the difference between...
Shear Zone 3  Shear Zone 4
(a)       (b)

Shear Zone 5  Shear Zone 6
(c)       (d)

Shear Zone 7  Shear Zone 8
(e)       (f)

Shear Zone 9
(g)

- Shear zone not disclosed by boreholes
- Shear zone disclosed by boreholes

Figure 9: Spatial distributions of typical shear zones disclosed by boreholes. Altogether, 67 boreholes with different depths are chosen for analysis. This is because due to the very small thickness, shear zones are hard to be precisely detected by drilling cores. Instead, borehole image televisions are applausive. For these 67 boreholes, borehole image televisions are used to record the lithology and to identify the shear zones.
the crest and trough. This shows that the spatial distribution of the shear zone is more related to the hard rocks at the contact interface of stratified soft and hard rocks. This phenomenon implies that the crests in the hard rock percentage curve can be used as a tool to predict the degree of development of shear zones.

7. Conclusions

Characterizing lithology variations in red beds is of an important engineering significance and academic value. In this paper, we proposed a statistical method to quantitatively evaluate the degree of lithology variations in layered red beds with depth. The core of this method is to use borehole logs as random variables for statistical analysis and involves seven steps of attitude calculation, reference point selection, distance calculation, elevation modification, data discretization, data statistics, and curve plotting.

We applied this method to the Yellow River Guxian Dam. Its borehole logs ever recorded were used to plot the percentage curve of hard rocks, which effectively reveals the general behaviors of lithology variations of the Guxian Dam site at the riverbed. We found that the degree of lithology variations for each lithology group differs greatly. The lithology in the \( T_{2er2}^5 \) and \( T_{2er2}^6 \) groups is much uniform and of a low degree of variation, while in the \( T_{2er2}^{10} \) and \( T_{2er2}^9 \) groups it is nonuniform and of a high degree of variation. The general behaviors of lithology variations on two sides of the Guxian Dam riverbed are quite similar but still with some differences. The percentage of hard rock for the left riverbed is higher than that for the right. The lithology on two sides of the riverbed for the same elevation may be just the opposite. The thick \( T_{2er2}^{10} \) can be finely divided into two subgroups and the \( T_{2er2}^9 \) groups into three subgroups.

On the basis of the hard rock percentage curve, we introduced a lithology variation index (LVI) to quantitatively characterize the degree of lithology variations, which can be used as an important index to supplement the traditional methods such as Q-Rating, Rock Mass Rating (RMR) systems, and the geological strength index (GSI) when performing rock mass classifications in red beds. We also plotted the vertical percentage curve of sandstone and calcareous and argillaceous siltstones, which can provide basic geological data for the determination of the physical parameters of the dam foundation rock mass, the identification of potential shear sliding surface, and the search for an impervious grouting bottom. Moreover, we found that the locations of shear zones are well represented in the form of troughs in the hard rock percentage curve and that the development of shear zones has a good linear relationship with the corresponding crest in the hard rock percentage curve.

Note that, in this paper, we only use the red beds in the Yellow River Guxian Dam as a field case study. In fact, the proposed method has a very wide range of applications. As long as the rock mass has the interbedded property of a complex assemblage of hard and soft rocks of unequal thickness, it is generally applicable.
Data Availability

Borehole data used in this paper are available from the authors upon request.

Additional Points

Highlights. (1) We introduce a statistical method for evaluating the degree of lithology variations in layered red beds with depth by using data of borehole logs. (2) We introduce the lithology variation index to quantitatively characterize the degree of lithology variations. (3) We plot the trilithology percentage curve of sandstone and calcareous and argillaceous siltstones with depth. (4) We use the hard rock percentage curve to show some characteristics of interlayered shear zones. (5) The to-be-built Yellow River Guxian Dam is introduced as a field case study.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors’ Contributions

All authors contributed to this manuscript. Qing-Bo Li was responsible for the conceptualization, methodology, formal analysis, draft in Chinese, and project administration. Jun-Zhi Wang was responsible for the conceptualization, methodology, formal analysis, draft in English, reviewing, and editing. Gui-Jun Wang was responsible for the methodology, formal analysis, draft in Chinese, and project administration. Qing-Liang Liu was responsible for the formal analysis, draft in Chinese, and funding acquisition. Chang-Bin Yan was responsible for the methodology, formal analysis, reviewing, and editing.

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Supplementary Materials

Figure S1: percentages of hard rocks fluctuating with depth at the riverbed. (a) Left riverbed; (b) right riverbed; (c) the two-side riverbeds. The shadows give the locations of each shear zone identified by borehole image television. Different from Figure 6, the plots in Figure S1 are based on the lithology data recorded before the year 2019, and the vertical resolution of Figure S1 is 1 m. The overall trends of Figure 6 and Figure S1 are consistent, but there are some differences, which are believed to be caused by the accuracy of the borehole logging resolution. Figure S2: typical pictures of the JQD06 shear zone disclosed by (a) the geologic adit beneath the Yellow River, (b) the borehole cores, and (c) the borehole television image. (Supplementary Materials)

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