

Article

A Double-Layered Seismo-Electric Method for Characterizing Groundwater Seepage Fields in High-Level Waste Disposal

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Abstract

Groundwater seepage plays a critical role in the long-term safety of high-level radioactive waste (HLW) disposal, yet its characterization remains challenging due to the complexity of fractured rock media. This study introduces the Double-Layered Seismo-Electric Method (DSEM) for imaging groundwater seepage fields with enhanced sensitivity and spatial resolution. By integrating elastic wave propagation with electrokinetic coupling in a stratified framework, DSEM improves the detection of hydraulic gradients and preferential flow pathways. Application at a representative disposal site demonstrates that the method effectively delineates seepage channels and estimates hydraulic conductivity, providing reliable input parameters for groundwater flow modeling. These results highlight the potential of DSEM as a non-invasive geophysical technique to support safety assessments and long-term monitoring in deep geological disposal of high-level radioactive waste.

Keywords: groundwater flow velocity and direction; high-level radioactive waste disposal; double-layer seismo-electric effect; 3D seismo-electric seepage field detection; low-permeability rock mass



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1. Introduction

The safe disposal of high-level radioactive waste (HLW) is a major scientific and engineering challenge with critical implications for long-term environmental and human health. Radionuclide migration from deep geological repositories to the biosphere over timescales of thousands of years, primarily through groundwater transport following repository closure and resaturation, is a key concern [1–3]. Therefore, quantifying groundwater seepage velocity and flow direction is essential for evaluating the safety and performance of HLW disposal systems. Numerous hydrogeological techniques have been developed to monitor groundwater under natural flow conditions [4–6]. Among them, isotopic tracer methods are well established, offering high precision in measuring seepage velocity and direction across a wide dynamic range [7–11]. For instance, Gao et al. reported velocity measurements ranging from 0.01 to 100 m/d, with directional errors within $\pm 3^\circ$ [12]. Other recent advances include hydrogeophysical approaches [13–15], direct measurement devices such as the GFD4 seepage meter [16], and fiber-optic distributed temperature sensing (DTS)

applied to fractured rock masses [17]. Conventional methods such as isotopic tracers and packer tests have been widely applied to characterize seepage in fractured rock. However, these approaches are typically invasive, labor-intensive, and restricted to point-scale observations, which limit their ability to capture the spatial heterogeneity of groundwater flow in deep geological repositories. In contrast, the Double-Layered Seismo-Electric Method (DSEM) integrates elastic wave stimulation with electrokinetic response detection, enabling non-invasive, high-resolution imaging of hydraulic pathways. Unlike tracer tests, which require long monitoring periods and may be affected by geochemical reactions, or packer tests, which disturb formation conditions and yield only localized estimates, DSEM directly senses flow-related electrokinetic signals over continuous profiles. This capability allows for the identification of preferential seepage channels and characterization of hydraulic conductivity at scales relevant to repository safety assessments.

For over a century, sonar detection technologies have demonstrated robust performance in underwater structural inspection and geological surveying [18–20]. Modern three-dimensional (3D) acoustic imaging systems enable precise visualization of subsurface structures in turbid or low-visibility aquatic environments, making them valuable for hydraulic infrastructure assessment [21–26]. More recently, the coupling between seismic P-waves and the electrical double layer in saturated porous media—referred to as the Double-Layered Seismo-Electric Method (DSEM)—has attracted considerable attention as a novel geophysical tool for subsurface flow detection [27–37]. This seismo-electric effect provides the theoretical foundation for a newly developed three-dimensional vector seepage field detection technique. By integrating acoustic wave propagation with electrokinetic responses, DSEM allows quantitative determination of groundwater flow velocity, direction, permeability coefficient, and seepage flux in fractured rock masses under in situ conditions.

Conventional methods for seepage characterization, such as isotopic tracer experiments and packer tests, yield valuable point-scale data but are invasive, time-consuming, and spatially limited. In contrast, DSEM offers a non-invasive alternative with broader spatial coverage and higher temporal resolution. Unlike isotopic tracers that require repeated sampling and laboratory analysis, or packer tests that disturb the hydraulic regime during measurement, DSEM enables direct monitoring of groundwater flow without altering subsurface conditions. Unlike isotopic tracers, which require repeated sampling and laboratory analysis, or packer tests, which disturb the hydraulic regime during measurement, DSEM enables in situ monitoring of flow fields without altering groundwater conditions.

Despite recent progress in hydrogeophysics, current techniques still face difficulties in simultaneously delineating seepage pathways and quantifying flow parameters in complex geological settings. A significant research gap remains: the lack of a robust, non-invasive method capable of resolving groundwater seepage fields with sufficient spatial resolution and minimal disturbance. This study addresses this gap by introducing the DSEM framework, which integrates elastic wave propagation with electrokinetic coupling in a stratified configuration. Application of this method to a representative high-level waste (HLW) disposal site demonstrates its capability to delineate preferential flow channels and to provide reliable constraints for seepage modeling, thereby enhancing the methodological toolbox available for groundwater monitoring in nuclear waste safety assessments.

DSEM has been successfully applied in various engineering and environmental contexts, including dam seepage monitoring [38–40], deep foundation pits [41], and subway tunnels [42]. Owing to its precision and adaptability to complex hydrogeological environments, it holds considerable promise for the in situ characterization of groundwater flow in HLW repository investigations. This paper presents the theoretical basis, methodological implementation, and field application of DSEM in the Beishan area. By evaluating

its performance in detecting groundwater seepage under natural conditions, we aim to establish its scientific and technical validity for site selection and safety assessment of HLW repositories.

2. Principles and Methods

To investigate the groundwater seepage field characteristics within the study area, field measurements were conducted at two representative fault zones, Fault F31 in Xinchang and the Shiyuejing fault zone. Given the structural orientation of these faults and their potential control on groundwater flow pathways, five surface boreholes were deployed along Fault F31, and three boreholes were installed within a deep tunnel intersecting the Shiyuejing fault zone. This configuration enabled the acquisition of seepage field parameters across a range of depths, from surface to subsurface, to capture the spatial variability of groundwater flow.

2.1. Principles of the Double-Layer Seismo-Electric Effect

The double-layer seismo-electric effect originates from electrokinetic processes occurring at the solid–liquid interfaces of fluid-saturated porous media. In their equilibrium state, mineral surfaces (particularly clay particles or fracture walls) carry negative charges, which attract compensating cations from the pore fluid to form a diffuse electrical double layer (EDL) (Figure 1a). This equilibrium establishes a stable electrochemical potential distribution at the fluid–solid boundary. When groundwater flows through interconnected pores or fractures under a hydraulic gradient, relative motion occurs between the mobile ions in the fluid and the immobile surface charges. This ion displacement perturbs the charge density within the EDL, producing localized streaming currents and transient potential differences (Figure 1b). The resulting oscillatory charge redistribution generates an alternating electric field, known as the seismo-electric field. The magnitude and propagation characteristics of this field are governed by fracture geometry, connectivity, aperture variability, and fluid content (Figure 1c). Accordingly, the double-layer seismo-electric effect provides a physical basis for in situ detection of groundwater seepage and associated hydrogeological parameters, forming the theoretical foundation of the three-dimensional vector seepage field detection method employed in this study.

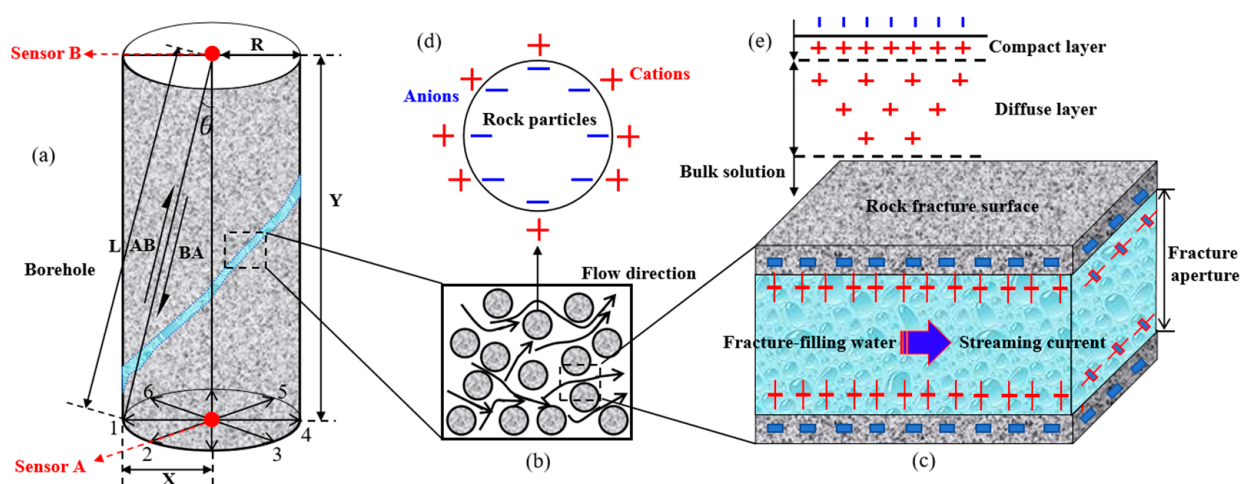


Figure 1. Schematic diagram of double-layer seismo-electric effect. (a) P-wave propagation in homogeneous porous media; (b) water flow transport at the grain scale; (c) seismo-electric effects at the pore scale; (d) surface charge characteristics of rock grains; (e) electrical double-layer structure.

Groundwater flow in saturated porous media induces electrokinetic effects due to the interaction between fluid movement and the electrical double layer at the solid–liquid

interface (Figure 1d). The resulting seismo-electric signals can be detected by an array of seismo-electric sensors, which enables accurate measurement of both the magnitude and spatial distribution of the induced fields. The orientation of the flow-induced signal source is determined through the spatiotemporal distribution of the recorded data. Furthermore, by analyzing the distance and phase difference between the upper electrode (A) and lower electrode (B) aligned along the direction of the seepage-induced signal, a particle velocity equation describing the continuous seepage field is derived (Equation (1)). This formulation provides a quantitative basis for estimating the groundwater velocity field. The experimental setup, including the three-dimensional seismo-electric velocity vector acquisition system, is illustrated in Figure 1e.

$$U = -L^2/2X(1/T_{BA} - 1/T_{AB}) \quad (1)$$

where L is the length of the propagation path of the sound wave between sensors (m); X is the axial component of the propagation path (m); T_{BA} , T_{AB} is the propagation time from the upper electrode (A) and lower electrode (B) (s); and U is the average seepage rate of the fluid through the sound channel between electrode (A) and (B) (m/s).

2.2. Seismo-Electric Logging Based on the Double-Layered Effect

The permeability coefficient is a fundamental hydrogeological parameter for evaluating groundwater migration within fractured rock. When seepage through fractures occurs under laminar flow conditions, Darcy's law is applicable, which establishes a linear relationship between seepage velocity (v) and the hydraulic gradient (i):

$$v = k \cdot i \quad (2)$$

$$v = q/A = k \cdot i \quad (3)$$

where v is the average seepage velocity (m/s), k is the permeability coefficient (m/s), and i is the hydraulic gradient (dimensionless); $i = \Delta h/L$, Δh is the difference in water level (cm); L is the length of infiltration path (cm); q represents the volumetric seepage rate per unit time (m³/s); and A is the cross-sectional area in the vertical seepage direction (m²).

$$q = k \cdot A \cdot \Delta h/l = k \cdot A \cdot i \quad (4)$$

$$Q = v \cdot d \quad (5)$$

where Q represents the section seepage rate (m³/s), which is the seepage velocity (v) of each measuring point multiplied by the water-passing section area (d); and d is the water-crossing section area (m²).

By substituting Equations (2) and (3) into Equations (4) and (5), Equation (6) can be deduced.

$$k = v \cdot d \cdot l / A \Delta h \quad (6)$$

Thus, the groundwater seepage field in borehole fractures can be characterized by integrating three measured quantities: the seepage velocity (v) derived from three-component sonic logging, the propagation time (T) of acoustic waves within the fractures, and the seepage direction obtained from Equation (1). These combined parameters allow quantitative determination of seepage velocity, flow direction, and hydraulic properties along the borehole.

2.3. Estimation of Seismo-Electric Signals and Statistical Evaluation

To estimate seepage velocity, the propagation times of the seismo-electric signals traveling from borehole A to borehole B (denoted as T_{AB}) and in the opposite direction (T_{BA}) were determined after signal preprocessing. The raw waveforms were filtered using a 20–200 Hz band-pass filter, selected to suppress low-frequency cultural noise and high-frequency instrumental artifacts. The first-arrival times were identified by cross-correlation between source and receiver wavelets, with a picking accuracy of approximately 0.5 ms. Calibration was performed under non-flowing conditions using reference inter-borehole measurements to remove systematic offsets related to instrument delay and acquisition geometry. The seepage velocity was then derived from the travel-time difference ($\Delta T = T_{AB} - T_{BA}$) following the conventional cross-borehole flow measurement principle, where the sign of ΔT indicates the preferential flow direction.

To quantitatively evaluate spatial differences in inferred hydraulic properties (e.g., seepage velocity, hydraulic conductivity) among boreholes drilled into distinct structural domains, the non-parametric Kruskal–Wallis H test was applied [43]. This test is particularly suitable because it does not require the assumption of normal data distribution and is robust to outliers, which are frequently encountered in hydrogeological field datasets.

The Kruskal–Wallis test examines the null hypothesis (H_0) that the median values across k groups are equal, against the alternative hypothesis (H_1) that at least one group has a different median. The procedure is as follows: all N observations from the k groups are pooled and ranked from smallest to largest, with tied values assigned the average of the ranks they would otherwise receive. For each group j ($j = 1, 2, \dots, k$), the sum of ranks (R_j) is calculated. The test statistic H is then computed according to the standard formula (see [43] for details).

$$H = 12/N(N+1) \sum_{j=1}^k \frac{R_j^2}{n_j} - 3(N+1) \quad (7)$$

where n_j is the sample size of the j -th group, R_j is the sum of ranks for the j -th group, $N = \sum n_j$ is the total sample size across all groups.

When tied ranks are present, a correction factor is applied. The corrected test statistic H_c is given by:

$$H_c = H / \left(1 - \sum \left(t_i^3 - t_i \right) / (N^3 - N) \right) \quad (8)$$

where t_i is the number of tied values in the i -th group of ties. Under the null hypothesis, the Kruskal–Wallis statistic H_c approximately follows a χ^2 distribution with $(k - 1)$ degrees of freedom. A p -value smaller than the adopted significance level ($\alpha = 0.05$ in this study) leads to the rejection of H_0 , indicating statistically significant differences in medians among the groups. Following a significant omnibus Kruskal–Wallis test, Dunn’s test with Bonferroni correction was applied for pairwise comparisons to determine which specific groups differed.

This statistical framework was applied to the hydraulic conductivity estimates derived from the DSEM inversion across the four characterization boreholes (Figure 2). The results show that the differences in median hydraulic conductivity values among the boreholes are statistically significant ($p < 0.01$), providing strong evidence for orders-of-magnitude heterogeneity in the seepage field.

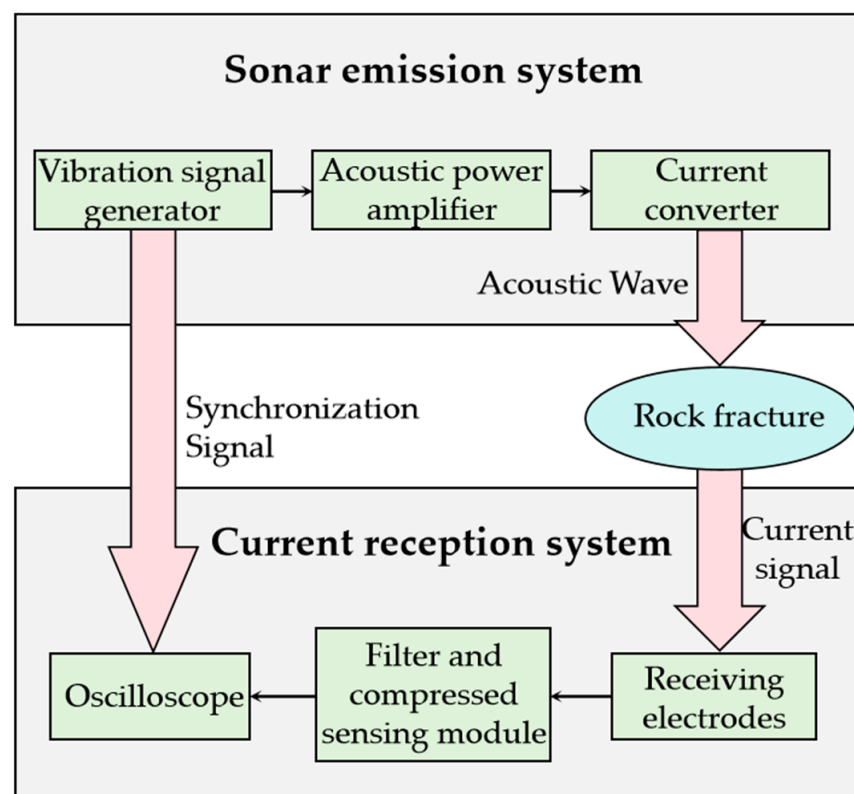


Figure 2. Flow Chart of double-layer seismo-electric effect exploration.

The seismo-electric exploration system (Figure 2) consists of a seismic source, a set of signal-receiving sensors, and a data acquisition unit. The receiving sensors include high-stability polarized electrodes and geophones, which detect both seismic and seismo-electric responses. In practice, seismic waves generated by the source propagate through the subsurface and interact with fluid-bearing fractures or porous layers. At these interfaces, electrokinetic coupling within the electrical double layer induces secondary seismo-electric fields. The returning signals thus contain two components: (i) elastic wave reflections that provide depth information on subsurface structures, and (ii) seismo-electric conversions that are sensitive to the presence and properties of pore fluids. Once transmitted back to the surface, these signals are captured by electrode pairs (Figure 2) and processed through the acquisition system. By applying Equations (1)–(6), the seepage velocity, flow direction, and hydraulic conductivity of the fractured rock mass can be quantitatively estimated. This integrated approach enables the identification of preferential flow pathways and improves characterization of groundwater seepage fields in crystalline rock settings.

3. Hydrogeological Characteristics of the Study Area

The study area is situated within the designated site-selection area for the Xinchang high-level radioactive waste (HLW) disposal facility in the Beishan region, Gansu Province, China. It covers approximately 94 km², extending about 20 km in the east–west direction and 5 km from north to south (Figure 3). The topography of the Beishan region is characterized by elevated terrain in both the north and south, with a relatively lower central zone. The northern boundary is formed by the Beishan Mountains, whereas the southern margin is delineated by the Qilian Mountains. The central portion corresponds to the Hexi Corridor, which trends east–west and consists primarily of low mountains and hills with subdued relief. Climatically, the area belongs to a high-altitude Gobi desert zone and exhibits a typical temperate continental climate. It is marked by arid and windy conditions, low precipitation, and high evaporation. The mean annual temperature ranges from 4.4 °C

to 8.4 °C. The annual precipitation is between 55.1 and 73.1 mm, whereas the mean annual evaporation is extremely high, ranging from 2380.9 to 3538.0 mm.

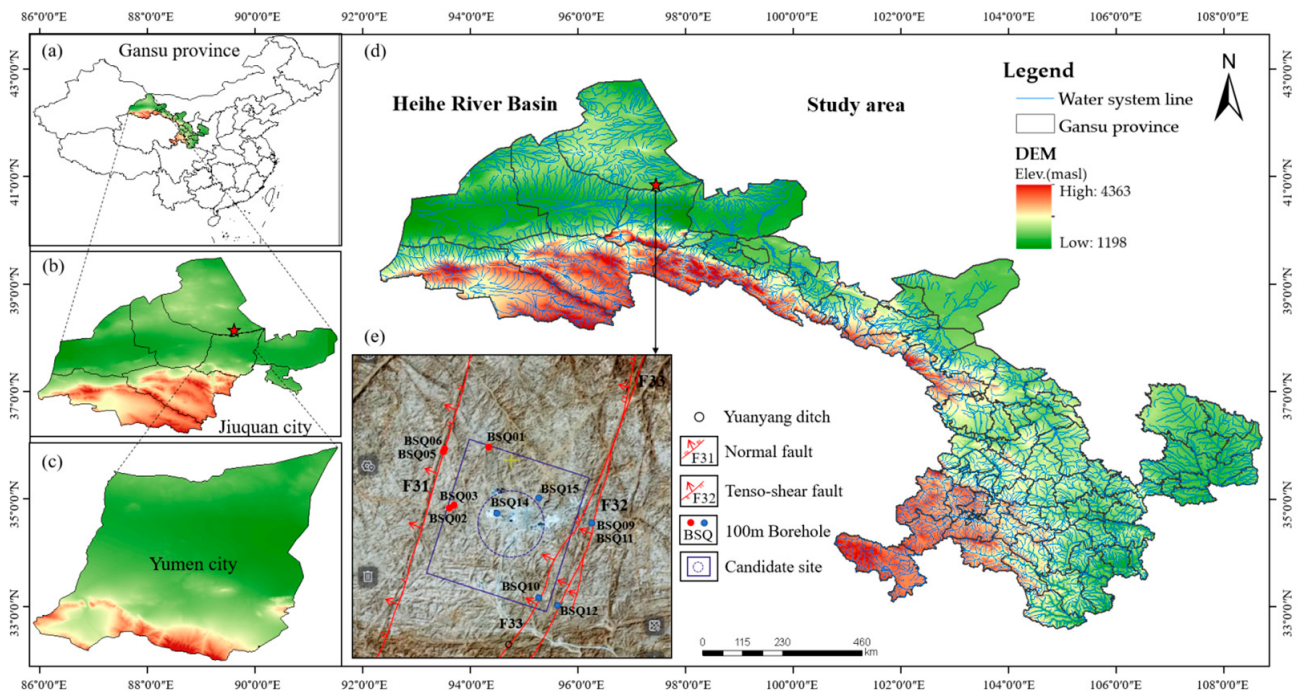


Figure 3. Digital elevation and hydrographic distribution map of the Xinchang site of the underground research laboratory of the high-level radioactive waste repository in Beishan Mountain, Yumen City, Jiuquan City, and Gansu Province. (a) Geographic location of Gansu Province, China; (b) Location of Jiuquan City within Gansu Province; (c) Location of Yumen City within Jiuquan City; (d) Spatial distribution of the Heihe River Basin in Gansu Province; (e) Remote sensing satellite imagery of the Xinchang underground high-level radioactive waste research laboratory.

The groundwater in the study area can be classified into three hydrogeological types according to geomorphological and lithological settings: (i) fractured bedrock groundwater in mountainous regions, (ii) pore–fracture groundwater in valley alluvial–diluvial deposits, and (iii) pore–fracture groundwater in basin alluvial deposits. Among these, fractured bedrock groundwater in mountainous terrains is the most widespread. It mainly occurs as unconfined groundwater within the weathered and fractured upper sections of metamorphic rocks and granites. The depth of the groundwater table varies considerably with topographic relief. In low-lying valleys, the water table is typically shallow, usually less than 5 m. In contrast, in elevated terrains, groundwater levels are deeper, generally ranging from 10 to 40 m. The principal aquifer media are weathered zones and structurally controlled fracture networks within the bedrock, which provide the main water-bearing capacity (Figure 4). The depth of the weathered zone ranges from approximately 30 to 80 m, depending on the degree of weathering and rock type. Groundwater yield is strongly influenced by geomorphology, lithological composition, and fracture density and orientation. As a result, single-well inflows vary greatly, ranging from as low as 10 m³/d to nearly 1000 m³/d. This wide range reflects the pronounced heterogeneity of fractured bedrock aquifers in the study area.

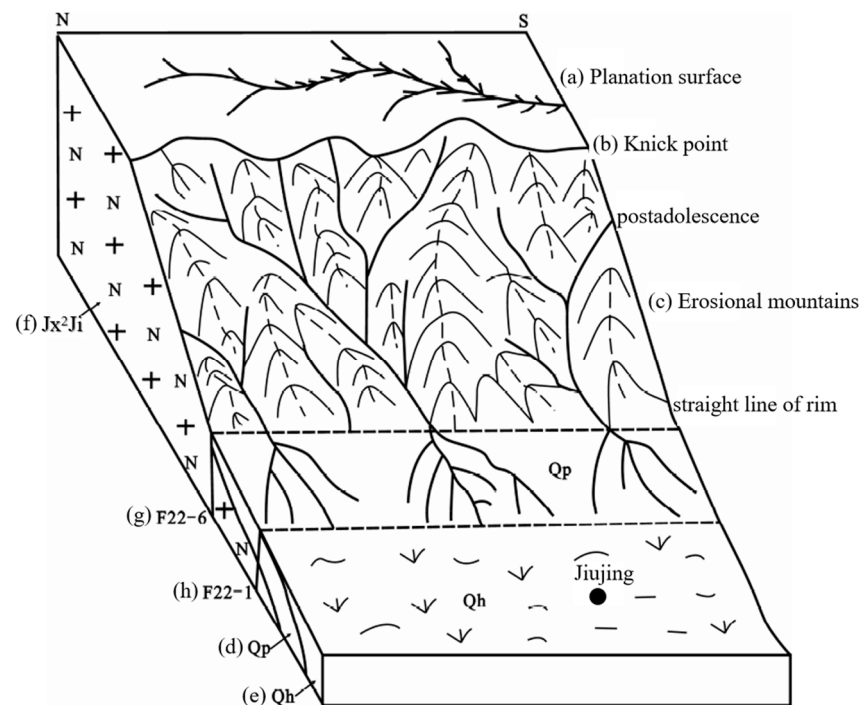


Figure 4. Hydrological conditions of the Xinchang site (according to Guo et al. [36]). (a) Planation surface: a broad, nearly level geomorphic surface formed under long-term tectonic stability of the crust; (b) knickpoint: a location on a river's longitudinal profile where the gradient abruptly increases, typically indicating tectonic uplift or lithological variation; (c) erosional mountains: mountain landforms primarily shaped by long-term erosional processes; (d) Q_p : Pleistocene sedimentary deposits; (e) Q_h : Holocene sedimentary deposits; (f) Jx^2Ji : Lithostratigraphic code for denote the Middle Jurassic Ziliujing Formation, which in the Beishan region is characterized by interbedded sandstone, siltstone, and mudstone.; (g) and (h) F22-6 and F22-1: Fault zones.

In the arid inland basin under investigation, groundwater recharge originates primarily from atmospheric precipitation through vertical infiltration. The region is characterized by arid to hyper-arid climatic conditions, with mean annual precipitation of only 60–80 mm. Consequently, effective groundwater recharge is extremely limited and exhibits pronounced spatial heterogeneity. Precipitation infiltrates through the vadose zone and is preferentially stored in geomorphic depressions, gullies, and structurally controlled fracture zones. These features constitute the principal recharge and storage domains of the groundwater system. A significant portion of the infiltrated water is lost to intense evaporation, particularly in areas with shallow or exposed water tables. The remaining fraction contributes to subsurface runoff, migrating along preferential pathways defined by fractures, gullies, and depressions. This subsurface flow ultimately discharges into terminal basins or other low-lying discharge zones, thereby completing the regional groundwater circulation cycle. Overall, the system exhibits alternating phases of recharge, storage, lateral flow, and discharge, forming a relatively closed, self-regulating circulation system characteristic of inland arid environments.

4. Results

To enhance clarity, the results are presented separately for the Xinchang and Shiyuejing sites. Within each site, the data are organized sequentially by seepage velocity, flow direction, and discharge characteristics. This structure facilitates a systematic comparison of hydrogeological conditions across the two fault zones.

4.1. Surface Borehole Testing in the Xinchang Area

To characterize the natural groundwater seepage vector field and hydraulic gradient field under unified boundary conditions in the candidate site, large-scale data analysis from the seismo-electric seepage measurement method was employed. The processed data were used to generate three-dimensional visualizations of groundwater seepage velocity, flow direction, discharge, and related hydrogeological parameters, thereby providing key input for the quantitative evaluation of groundwater dynamics. Faults F31 and F32 in the Xinchang area are left-lateral strike-slip faults with a northeastward strike. Both faults strike approximately 60° northeast and dip southeast at angles between 70° and 80° . Based on these structural features, the fault zones were subdivided into distinct hydrogeological units for detailed characterization. Five boreholes located within a 100 m radius were selected for 3D seismo-electric seepage tests (Figure 5).

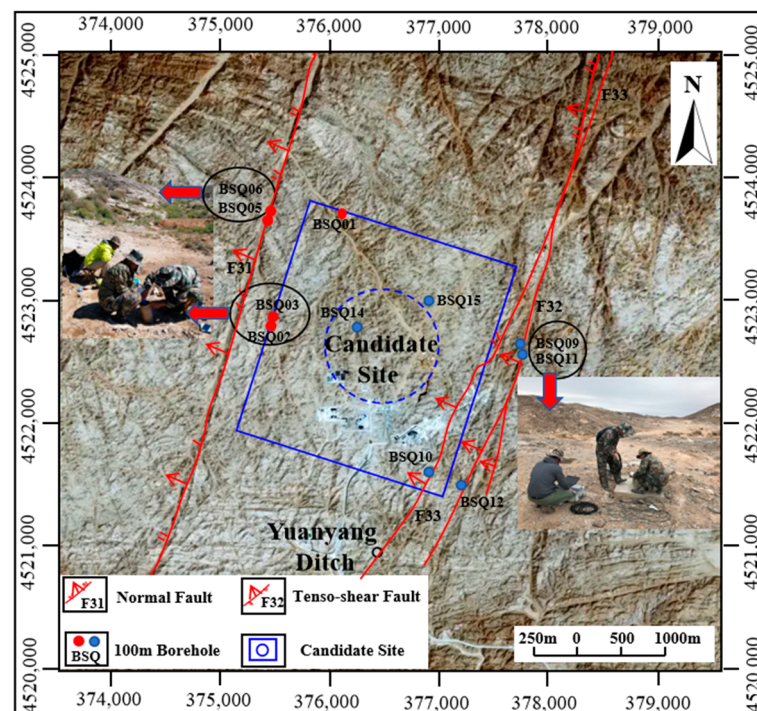


Figure 5. Location of 3D seismo-electric testing boreholes in the Xinchang area. Fault trace is shown in red line. Study area is outlined in blue line. Selected area is indicated by a blue dashed line. Experimental drilling zone is marked in black line.

As shown in Figure 5, five hydrogeological survey boreholes were symmetrically arranged along the hanging wall and footwall of the steeply dipping fault F31. Specifically, BSQ05 and BSQ06 were drilled on the northern side, BSQ03 and BSQ04 on the southern side, and BSQ01 on the eastern segment of the fault. In addition, six monitoring wells were installed to further characterize groundwater seepage across the study area. Among them, BSQ09–BSQ12 are located along the F32 fault zone and represent structurally influenced hydrogeological units, while BSQ14 and BSQ15 were positioned within the candidate repository site, situated in relatively intact granite. This layout allows a representative comparison of seepage behavior between fractured and unfractured rock masses, thereby facilitating analysis of structural controls on groundwater flow dynamics. All hydrogeological boreholes were drilled to depths of approximately 100 m, capturing the seepage characteristics of both fault zones and adjacent low-lying granite terrain. Based on measurements from these boreholes and subsequent three-dimensional seismo-electric data

analysis, the groundwater velocity, flow direction, and discharge were reconstructed across the study area.

Thus, the hydrogeological characteristics revealed by five boreholes in Beishan Mountain and the measurement results of groundwater seepage are displayed. Through the analysis of horizontal seepage velocity and seepage direction in groundwater well tests, the groundwater seepage field in each measurement hole is distinctly recognized, and the relationship between permeability characteristics and recharge and discharge in different geotechnical penetration sections becomes evident. Hence, the seepage distribution curves of each aquifer and groundwater are measured as shown in Figure 6 and Table 1. The solid curves denote model-predicted velocity profiles, while the shaded bands represent the uncertainty range. The velocity scale is shown on the left axis.

The results were visualized as a three-dimensional dynamic seepage field model under unified hydrological boundary conditions. Numerical isocontour maps were then generated, displaying the triaxial velocity components (X, Y, Z), preferential seepage directions, and corresponding discharge fields derived from the inversion process. The integrated hydrogeological characteristics obtained from the five Beishan boreholes, together with groundwater seepage measurements, provide a clear delineation of spatial variability in the seepage field. Horizontal seepage velocities and flow directions obtained from in-well testing further confirm the heterogeneity of groundwater movement, while highlighting the relationship between permeability variations and recharge–discharge processes across different structural and lithological sections. Seepage distribution curves for each aquifer system are presented in Figure 6 and summarized in Tables 1 and A1. In these plots, the solid curves represent model-predicted velocity profiles, whereas the shaded envelopes denote the associated uncertainty ranges. The velocity scale is given along the left axis for quantitative comparison.

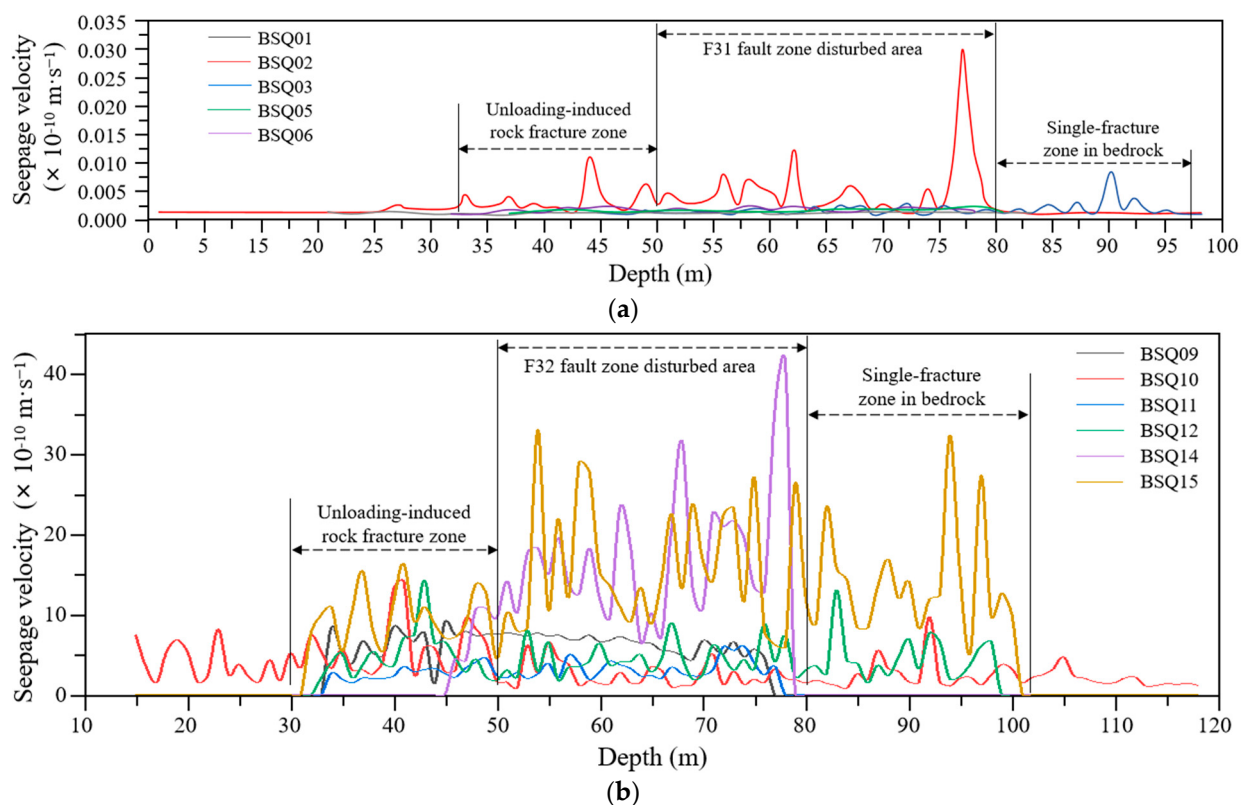


Figure 6. Cont.

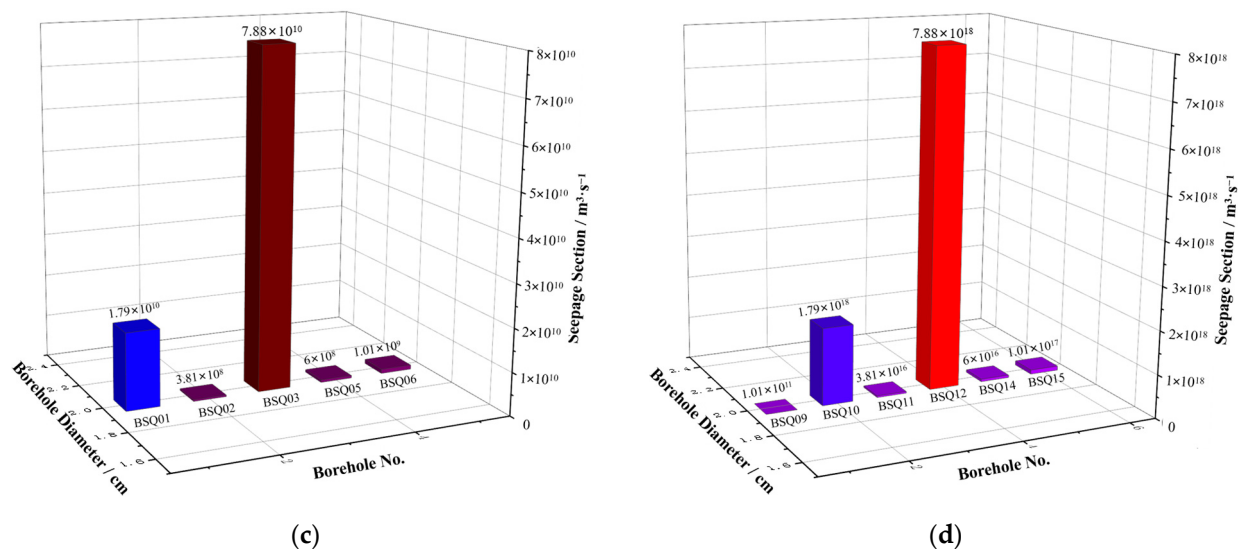


Figure 6. Seepage velocity curve and depth distribution curve of seismo-electric holes in Beishan area. (a) Distribution of seepage velocity curves from 3D seismo-electric measurements at boreholes BSQ01–BSQ06; (b) distribution of seepage velocity curves from 3D seismo-electric measurements at boreholes BSQ09–BSQ15; (c) cross-sectional flow rates at boreholes BSQ01–BSQ06 from 3D seismo-electric measurements; (d) cross-sectional flow rates at boreholes BSQ09–BSQ15 from 3D seismo-electric measurements.

Table 1. Hydrogeological parameters of monitoring wells in the Beishan site.

Borehole No.	Average Velocity (m/s)	Maximum Velocity (m/s)	Minimum Velocity (m/s)	Average Permeability Coefficient (m/s)	Maximum Permeability Coefficient (m/s)	Minimum Permeability Coefficient (m/s)	Seepage Section	Seepage Direction
BSQ01	7.01×10^{-6}	8.37×10^{-5}	3.53×10^{-8}	8.09×10^{-9}	9.66×10^{-8}	3.95×10^{-11}	1.79×10^4	97–156
BSQ02	1.50×10^{-7}	3.54×10^{-6}	5.29×10^{-9}	3.53×10^{-10}	8.34×10^{-9}	1.25×10^{-11}	3.81×10^2	151–245
BSQ03	2.63×10^{-5}	3.31×10^{-4}	6.24×10^{-8}	6.36×10^{-8}	8.01×10^{-7}	1.51×10^{-10}	7.88×10^4	152–246
BSQ05	1.33×10^{-7}	4.51×10^{-6}	4.12×10^{-9}	2.30×10^{-9}	7.76×10^{-8}	7.09×10^{-11}	6.00×10^2	125–216
BSQ06	2.23×10^{-7}	5.33×10^{-6}	4.28×10^{-9}	4.90×10^{-9}	1.17×10^{-7}	9.4×10^{-11}	1.01×10^3	135–223
BSQ09	6.49×10^{-10}	9.09×10^{-10}	1.34×10^{-10}	3.9×10^{-9}	5.46×10^{-9}	8.04×10^{-10}	1.38	175–224
BSQ10	3.22×10^{-10}	1.42×10^{-9}	8.4×10^{-11}	4.65×10^{-10}	2.06×10^{-9}	1.19×10^{-10}	1.70	108–155
BSQ11	3.07×10^{-10}	6.08×10^{-10}	1.48×10^{-10}	1.84×10^{-9}	3.65×10^{-9}	8.88×10^{-10}	6.83×10^{-1}	187–231
BSQ12	4.61×10^{-10}	1.43×10^{-9}	1.45×10^{-10}	2.77×10^{-9}	8.55×10^{-9}	8.7×10^{-10}	1.55	126–168
BSQ14	1.61×10^{-9}	4.16×10^{-9}	4.19×10^{-10}	9.55×10^{-10}	2.46×10^{-9}	2.48×10^{-10}	2.73	160–214
BSQ15	1.37×10^{-9}	3.31×10^{-9}	4.48×10^{-10}	1.18×10^{-9}	2.84×10^{-9}	3.84×10^{-10}	4.78	145–193

Note: 1. Table 1 shows v-seepage velocity (m/s); k-permeability (m/s); and q-seepage rate (m^3/s). 2. The velocity and direction outlined in the table were measured on-site. 3. The seepage section rate is the sum of the seepage velocity of each measurement point multiplied by the width of the water-passing section. 4. The seepage direction is NN (north–north).

Figure 6a,b present the visualized results, comparing bar charts of single-borehole seepage rates with three-dimensional spherical representations of spatial seepage for five measurement boreholes in the study area. The seepage discharge at each measurement point was estimated by multiplying the measured seepage velocity by an estimated effective cross-sectional width of 50 m per borehole. The total calculated seepage discharge across the measured area is $9.87 \times 10^1 \text{ m}^3/\text{s}$. The individual contributions are: $7.88 \times 10^1 \text{ m}^3/\text{s}$ for borehole BSQ03, $1.79 \times 10^1 \text{ m}^3/\text{s}$ for BSQ01, $1.01 \text{ m}^3/\text{s}$ for BSQ06, $6.00 \times 10^{-1} \text{ m}^3/\text{s}$ for BSQ05, and $3.81 \times 10^{-1} \text{ m}^3/\text{s}$ for BSQ04. Notably, BSQ03 alone accounts for approximately 79.8% of the total seepage, with a flow rate over two orders of magnitude larger than that of the lowest-flowing borehole, BSQ04, as illustrated in Figure 6a. These results indicate a highly uneven distribution of groundwater seepage, with lower discharges observed in the northern and western zones and higher discharges in the southern and eastern zones.

Figure 6b provides detailed spatial seepage information, where the sphere diameter is proportional to the volumetric seepage, and the color represents the magnitude of the seepage rate. Based on these data, a seepage contour map was generated to delineate the spatial distribution and boundaries of the seepage field.

The distribution curves of seepage velocity with respect to measured elevation for the five measuring boreholes are shown in Table 1 and Figure 6c,d. It is evident that borehole BSQ03 exhibits the highest seepage velocity, followed by notable velocity anomalies observed in borehole BSQ01. The average seepage velocities of the boreholes, ranked from highest to lowest, are: BSQ03, BSQ01, BSQ06, BSQ02, and BSQ05.

At the Xinchang site, velocity profiles derived from boreholes BSQ01–BSQ15 exhibit pronounced spatial heterogeneity (Figure 7a). Borehole BSQ03 recorded the highest seepage velocities, ranging from 1×10^{-10} to 5×10^{-8} m/s, corresponding to zones of enhanced fracture development. Flow directions, depicted using rose diagrams (Figure 7b, Tables 1 and A2), are predominantly oriented from northwest to southeast. The integrated seepage discharge map further reveals localized preferential flow paths along the F31 fault zone.

To estimate volumetric groundwater seepage discharge, an effective lateral width of 50 m was assigned to each borehole. This assumption was based on borehole logs and core inspections, which indicated that hydraulically active fracture zones typically extend 40–60 m laterally within the rock mass. Previous hydrogeological investigations at the Beishan site have employed similar lateral widths for fractured granite aquifers in comparable structural settings. To assess the sensitivity of this assumption, the lateral width was varied between 30 m and 70 m. The recalculated discharge varied by approximately $\pm 28\%$ relative to the baseline. Importantly, the spatial pattern of seepage and the relative contribution of each borehole (notably BSQ03) remained unchanged. This demonstrates that the main conclusions regarding seepage heterogeneity and preferential flow paths are robust to variations in the assumed section width.

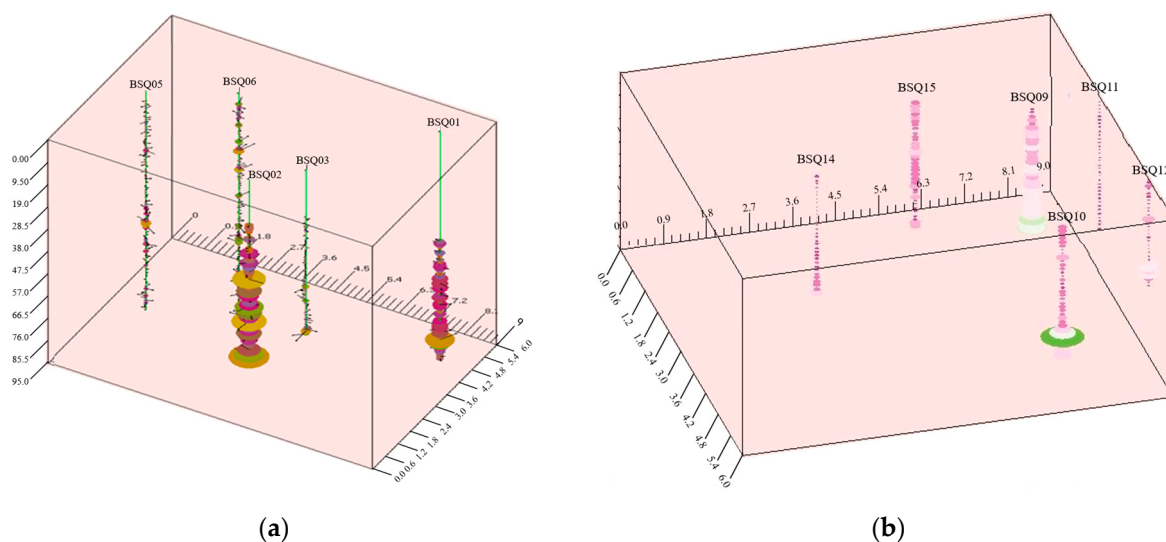


Figure 7. Cont.

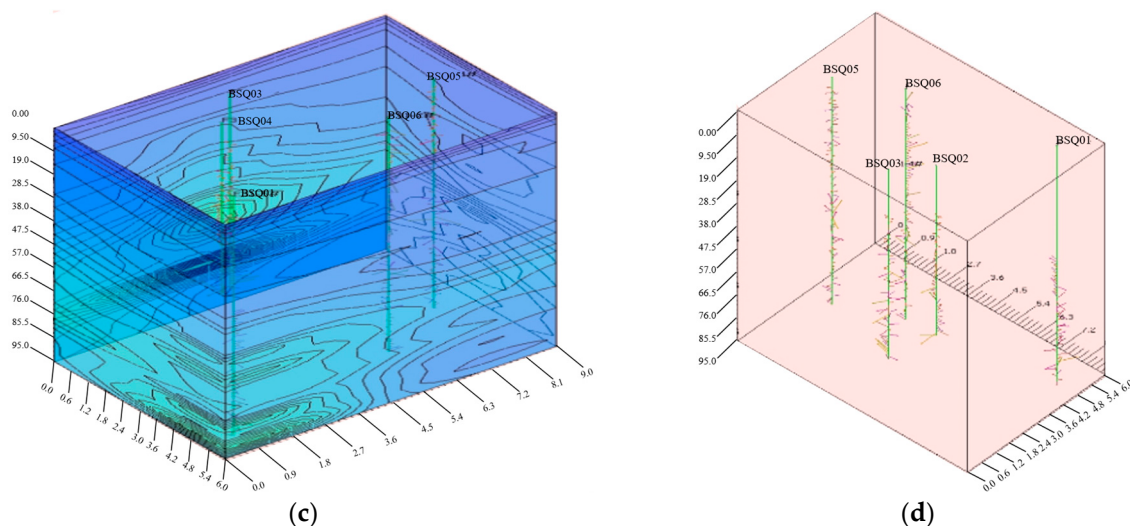


Figure 7. Results of 3D seismo-electric vector velocity and spatial distribution of measurement boreholes BSQ01-BSQ06 in Xinchang area (The colors in the figure indicate both the magnitude and direction of the velocity vectors, as well as their spatial distribution.). (a) Histogram distribution of seepage rates of seismo-electric holes; (b) spatial distribution map of seepage measured by seismo-electric; (c) Seepage velocity map at the boundary of the seepage field; (d) groundwater flow direction inferred from each measurement borehole.

Figure 8 shows the primary directions of natural groundwater seepage across boreholes BSQ01-BSQ05 at the Beishan site. In the figure, the arrow lengths represent seepage velocities, and the orientations indicate flow directions. The dominant seepage trend is from northwest to southeast. Integrating these measurements with drilling and logging data allows a more detailed characterization of the groundwater flow field within the fracture zone. To evaluate whether the observed velocity variations among boreholes are statistically significant, a Kruskal–Wallis non-parametric test was performed on the velocity datasets from BSQ01-BSQ06. The results reveal significant differences among boreholes ($H = 19.6, p < 0.01$), indicating that the observed two-orders-of-magnitude variability reflects genuine hydrogeological heterogeneity associated with fracture development rather than random fluctuations.

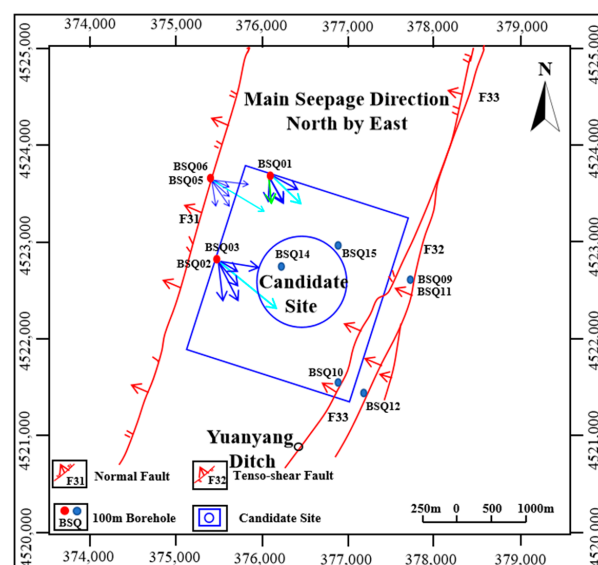


Figure 8. Ichonography of groundwater seepage direction in the Xinchang area. The arrow lengths of different colors correspond to the magnitudes of groundwater seepage velocities, while their orientations indicate the directions of flow.

4.2. Underground Tunnel Testing in the Shiyuejing Fault

The Shiyuejing fault exhibits structural characteristics similar to the faults F31 and F32 in Xinchang. These faults are left-lateral strike-slip normal faults with a general strike of 60° northeastern, dipping southeast at an angle of 70°–80° (Figures 3 and 9). The faults F31 and F32 investigated in Xinchang primarily characterize near-surface groundwater seepage (0–100 m depth), whereas the Shiyuejing fault investigation provides insights into deep subsurface seepage behavior. To examine these characteristics, three shallow hydrological boreholes, located approximately 10 m apart within the Shiyuejing tunnel, were selected for hydrogeological seismo-electric seepage measurements. Positions of the seismo-electric measurement holes (SW1, SW2, and SW3) are shown in Figure 9.

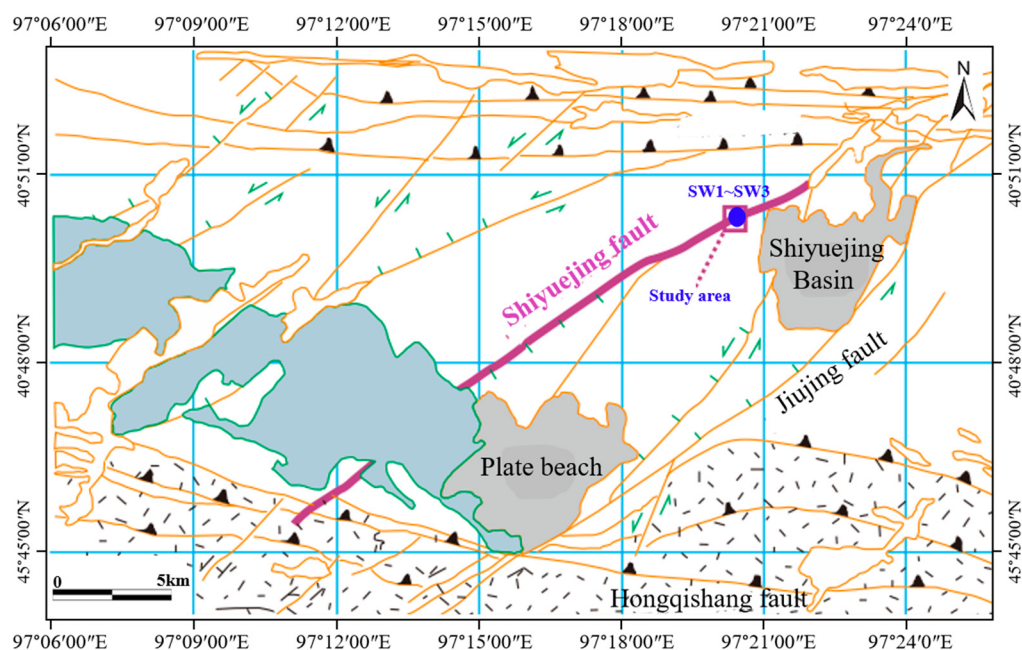


Figure 9. Location of 3D seismo-electric testing boreholes in Shiyuejing fault. The green arrow represents the movement direction of the fault's upper plate relative to the lower plate; Brown lines denote the Shiyuejing fault; Orange lines indicate other faults; Light gray areas correspond to plateaus and basins; Light green areas represent granite.

Figure 10 presents a column chart showing the distribution of seepage flow rates across the three monitored boreholes, corresponding to a total measured flow of $1.77 \times 10^{-3} \text{ m}^3/\text{s}$. As summarized in Tables 2 and A3, borehole SW3 shows the highest seepage flow rate, indicating relatively higher permeability or close connectivity to major flow pathways within the fractured rock mass. Borehole SW1 exhibits a moderate flow rate, whereas SW2 records the lowest, suggesting lower permeability or weaker hydraulic connectivity. The observed variations in flow rates among the boreholes reflect heterogeneity in the local fracture network and rock mass properties. Factors such as fracture density, aperture, connectivity, and orientation relative to the regional hydraulic gradient likely contribute to these differences. The consistency between quantitative seepage measurements and the spatial arrangement of the boreholes confirms the reliability of the detection method and enhances understanding of groundwater migration in low-permeability fractured rock.

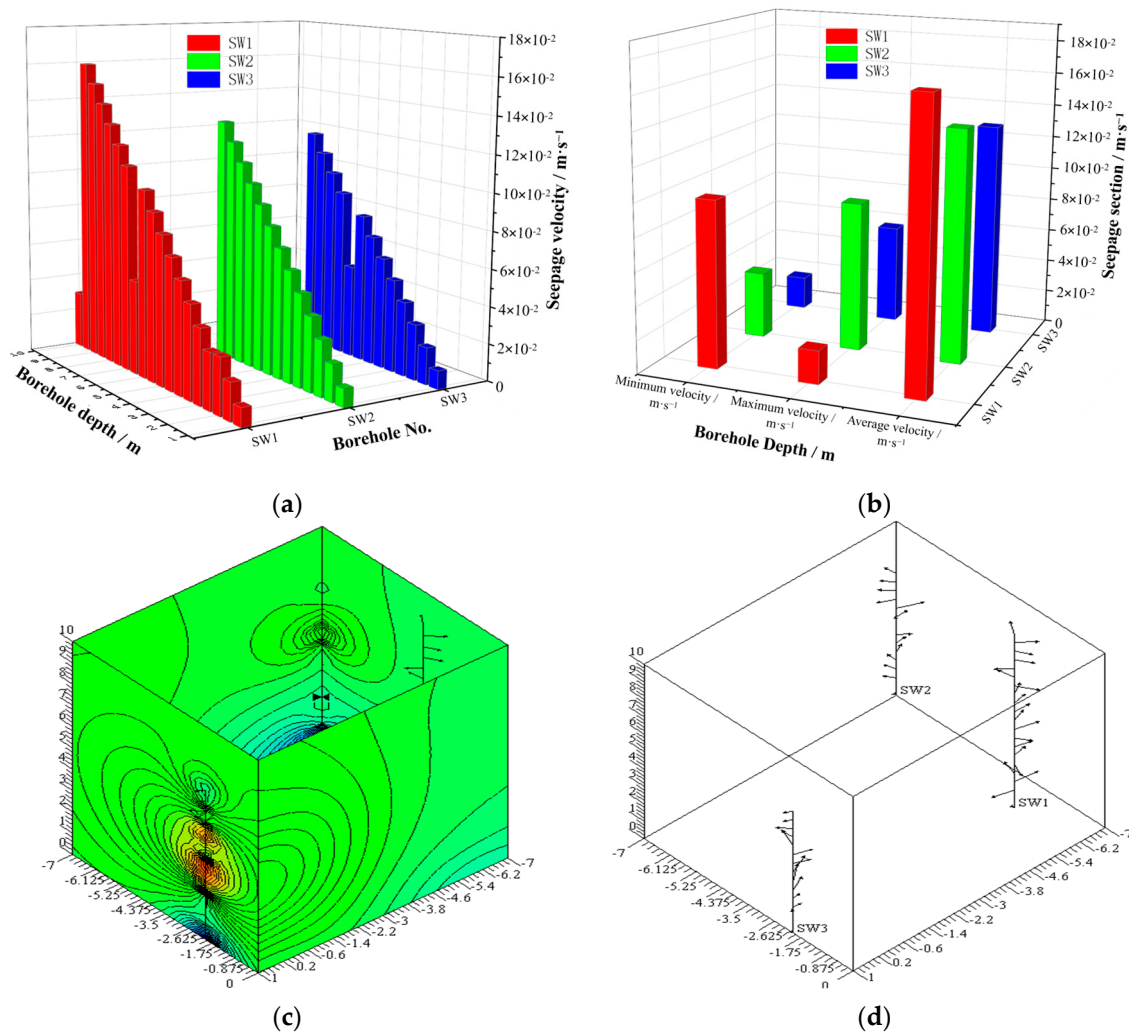


Figure 10. Cross-section seepage, permeability coefficient, velocity contour maps and seepage direction distributions of testing holes in Shiyuejing fault. (a) Seepage velocity distribution of seismo-electric boreholes; (b) seepage section and velocity curve; (c) three-dimensional contour map of the seepage velocity field; (d) detailed three-dimensional spatial distribution of groundwater flow directions.

Table 2. Data of 3D seismo-electric test boreholes in Shiyuejing fault.

Borehole No.	SW1	SW2	SW3
Average velocity (m/s)	6.72×10^{-10}	7.27×10^{-10}	1.02×10^{-9}
Maximum velocity (m/s)	8.94×10^{-10}	1.26×10^{-9}	1.63×10^{-9}
Minimum velocity (m/s)	5.76×10^{-10}	6.03×10^{-10}	5.91×10^{-10}
Seepage section (m/s)	6.39×10^{-1}	4.73×10^{-1}	6.60×10^{-1}
Seepage direction	200–326	138–251	176–271

Note: 1. In Table 2, the velocity and direction in the table are measured in situ. 2. The section seepage rate is the sum of the seepage velocity of each measuring point multiplied by the width of the water-passing section. 3. The seepage direction is north–north.

As shown in Figure 10c,d, the measured average seepage velocities for the boreholes in the Shiyuejing fault zone display a clear decreasing trend from SW2 to SW3. Specifically, the average velocity for SW2 was 7.28×10^{-10} m/s, followed by SW1 at 6.72×10^{-10} m/s, while the lowest velocity was observed in SW3, at 1.02×10^{-10} m/s. Overall, seepage velocities across SW1–SW3 ranged from 1×10^{-10} to 1×10^{-9} m/s. Directional analysis indicates that groundwater predominantly flows from northeast to southwest, consistent with the regional

hydraulic gradient. The markedly lower seepage velocity in SW3 suggests a localized zone of lower permeability, likely caused by less-developed fracture networks or a more compact rock matrix. In contrast, the higher velocities in SW1 and SW2 imply enhanced flow pathways, potentially associated with more extensive fracturing or increased porosity. These observations demonstrate significant spatial heterogeneity in hydraulic conductivity across the tested boreholes and underscore the necessity of site-specific hydrogeological characterization when evaluating groundwater migration in low-permeability fractured rock formations.

4.3. Comparison of Seepage Velocity Curves and Core Analyses

- As illustrated in Figure 11, a comparison between permeability coefficients derived from well-logging measurements in boreholes BSQ05 and BSQ06 and those obtained from corresponding core analyses indicates systematically higher values in the borehole sections. This discrepancy is mainly attributed to the fractured and weakly cemented rock intervals represented by the cores in the tested zones. Such structural heterogeneities are likely to promote preferential groundwater flow, thereby enhancing local permeability. To further substantiate these interpretations, integration with borehole imaging data obtained from downhole micro-camera (micro-TV) inspection is recommended. Correlating seepage characteristics with direct observations of fracture networks would provide a more accurate representation of subsurface flow behavior. This combined approach would improve the characterization of groundwater transport mechanisms in fractured crystalline rock and increase the reliability of permeability estimations in low-permeability environments.

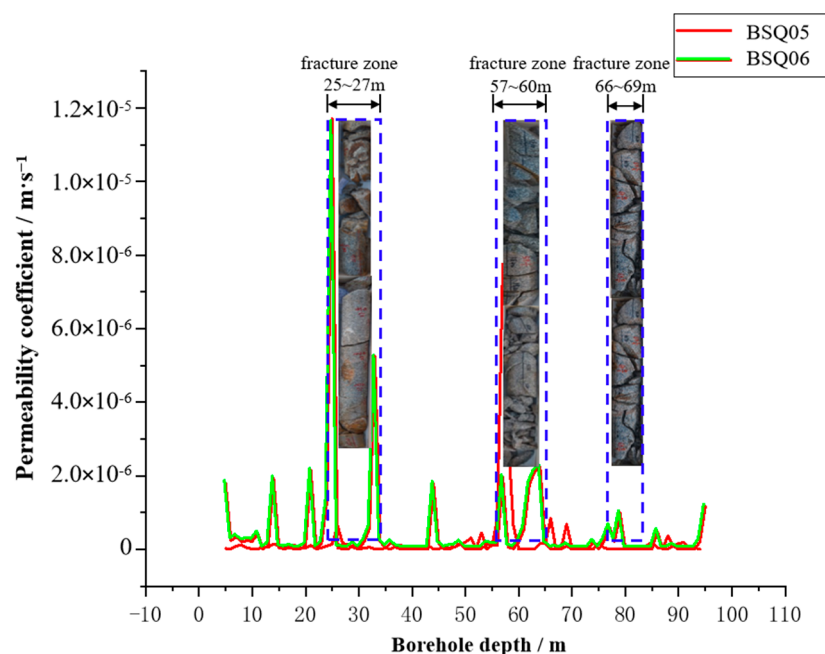


Figure 11. Comparison of permeability coefficients and cores of holes BSQ05 and BSQ06, the blue dotted line indicates zones where the permeability coefficient exhibits a sudden increase, corresponding to rock masses that are relatively fragmented and characterized by well-developed fractures.

- Figure 10c,d shows the three-dimensional distribution of seepage velocity vectors at discrete measurement points within the natural groundwater field, obtained through DSEM measurements validated against hydrogeological logging from three boreholes along the Shiyuejing tunnel. Figure 10c presents the three-dimensional vector field, whereas Figure 10d shows the dominant planar seepage directions for each

borehole. In both figures, the length of each arrow represents seepage velocity magnitude, while its orientation indicates flow direction. The results reveal a consistent northeast–southwest trend in the primary groundwater seepage direction. This directional pattern reflects the structural and hydraulic controls exerted by regional faults and fracture networks, which govern preferential flow pathways in the low-permeability rock mass. The uniformity of seepage directions among boreholes further indicates a coherent regional hydraulic gradient, thereby supporting the reliability of the DSEM-based seepage detection method. These findings are crucial for understanding subsurface fluid dynamics in the Shiyuejing fault zone and for providing valuable input to the long-term safety assessment of potential high-level radioactive waste disposal at the Beishan site.

- Through comparison and verification of seepage velocity measurements obtained from borehole TV imaging and three-dimensional acoustic scanning in boreholes SW1–WS3 (Figure 12), it is evident that seepage velocity ranges from 5.76×10^{-10} m/s to 8.94×10^{-10} m/s, with pronounced values observed at depths of 1.5 m, 4.5 m, 7.0 m, and 9.5 m. The area delineated by the blue dashed line corresponds to a zone where the permeability coefficient exhibits a marked increase, consistent with the highly fractured core of the Shiyuejing fault. The area outlined by the green dashed line shows a lower degree of rock fragmentation compared with the blue-delineated zone, suggesting that it lies within the influence zone of the Shiyuejing fault rather than its core. The area marked by the red dashed line indicates relatively intact rock cores with only minor fractures, implying that this section is located at a considerable distance from the core region of the Shiyuejing fault. Analysis of the borehole TV records further reveals that fracture planes are preferentially developed at depths where higher groundwater velocities are detected, indicating a strong spatial correlation between fracture occurrence and seepage flow.

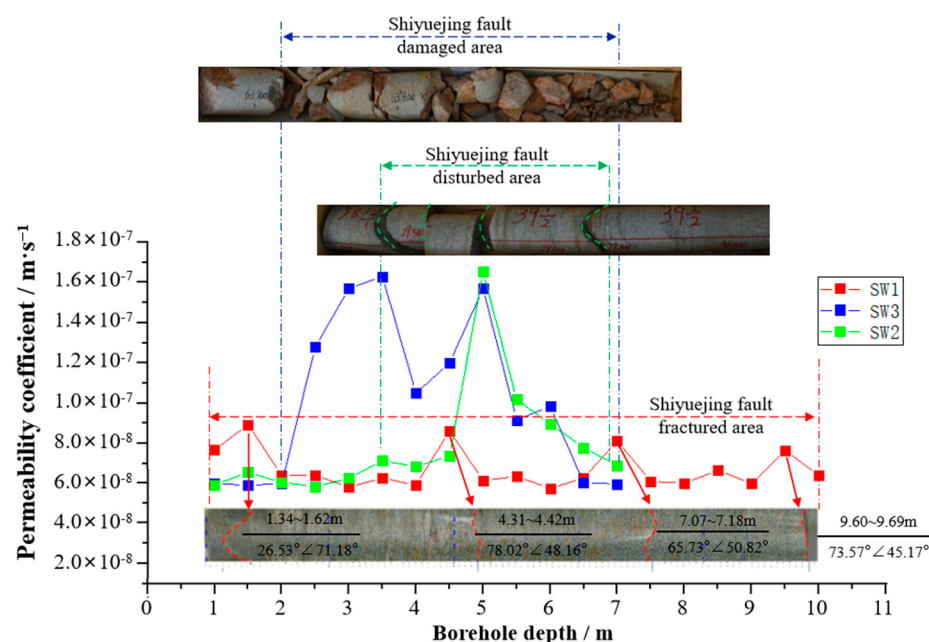


Figure 12. Comparison of seepage velocity curves and cores of SW1–SW3 boreholes in Shiyuejing fault. The region enclosed by the blue dotted line corresponds to a damaged zone characterized by a pronounced increase in the permeability coefficient; The region delineated by the green dotted line exhibits a lower degree of rock fragmentation relative to the damaged zone; The region marked by the red dotted line stands for fractured area.

5. Discussion

The Double-Layered Seismo-Electric Method (DSEM) provided key hydrogeological parameters at the Xinchang site, including groundwater seepage velocity and flow direction within shallow fractured rock and across major fault zones (F31 and Shiyuejing). The obtained data provide a robust foundation for understanding groundwater dynamics in the context of high-level radioactive waste (HLW) disposal site evaluation.

At present, the majority of hydrogeological boreholes at the site extend to depths of 0–100 m, meaning that most available observations and measurements are restricted to the shallow subsurface. However, regional geological and hydrogeological investigations suggest that the lithology at greater depths (500–700 m) is predominantly massive granite, with limited structural complexity and relatively homogeneous properties. Based on these findings, the measured seepage parameters in the shallow section may serve as a reasonable approximation for deeper zones, providing a valuable reference for modeling groundwater flow at potential repository depths.

Compared with conventional hydrogeological techniques such as packer tests, the Double-Layered Seismo-Electric Method (DSEM) demonstrates clear advantages in operational efficiency, spatial coverage, and interpretive capability. The method substantially reduces logistical complexity and field time while enabling accurate in situ determination of seepage velocity, flow direction, and fracture hydraulic conductivity. These capabilities enhance the quantitative assessment of subsurface flow regimes, particularly in low-permeability, fractured crystalline rock where traditional approaches are often limited.

Prior to field application, calibration tests were conducted in a laboratory flume containing fractured granite blocks under controlled hydraulic gradients. The measured velocities agreed with Darcy's law predictions within $\pm 5\%$. In addition, repeatability was evaluated through five replicate measurements at borehole BSQ03, yielding a coefficient of variation of 6.8%. An error propagation analysis, which considered uncertainties in travel-time measurements ($\pm 0.1 \mu\text{s}$) and sensor spacing ($\pm 0.5 \text{ mm}$), showed that the overall uncertainty in velocity estimation remained within $\pm 12\%$. These findings confirm the robustness and reliability of the method.

Furthermore, the technology facilitates spatial mapping of seepage fields across multiple boreholes, enabling a more integrated understanding of hydrogeological processes and anisotropy in fracture-dominated aquifers. The results confirm that the 3D seismo-electric approach is technically feasible and scientifically valuable for characterizing groundwater systems in high-level waste (HLW) disposal site investigations. Accordingly, it provides a promising tool for improving the precision of seepage field analysis and supporting safety assessments for long-term waste containment.

To ensure independent validation of the seismo-electric measurements, we conducted complementary hydrogeological tests in a subset of boreholes. In borehole BSQ03 within the Xinchang fault zone and borehole SW2 within the Shiyuejing fault zone, conventional packer tests were performed. The measured permeability coefficients ranged from 2.1×10^{-8} to $6.5 \times 10^{-8} \text{ m/s}$, consistent with the values inferred from DSEM. In addition, an isotope tracer experiment using deuterium-enriched water was conducted in borehole SW2. The tracer breakthrough curves indicated average groundwater velocities ranging from 1.0×10^{-10} to $1.0 \times 10^{-9} \text{ m/s}$, which closely matched the velocities derived from seismo-electric velocity vector measurements (6.7×10^{-10} – $1.0 \times 10^{-9} \text{ m/s}$). These comparative benchmarks confirm that the seismo-electric method provides reliable and reproducible estimates of groundwater flow parameters, in close agreement with established hydrogeological techniques.

Most boreholes investigated in this study reach depths of approximately 100 m, whereas the planned repository will be located at depths of 500–700 m. This extrapo-

lation is supported by lithological logs and previously published deep-core investigations from the Beishan area [35,36], which demonstrate that massive, low-permeability granite with limited fracturing extends to depths of at least 700 m. These findings indicate that the seepage characteristics identified in shallow boreholes are likely representative of deeper geological horizons, and the velocity estimates obtained at 0–100 m provide a reasonable proxy for hydraulic conditions expected at repository depths.

Despite its demonstrated advantages, several limitations should be acknowledged. The current implementation assumes relatively uniform section widths and homogeneous fracture connectivity, which may oversimplify the natural heterogeneity of fractured media. Moreover, uncertainties arise from the sensitivity of the seismo-electric response to fracture aperture distributions and anisotropic hydraulic properties. These factors may lead to discrepancies between predicted and actual seepage fields, particularly in highly heterogeneous disposal sites. Future work should incorporate stochastic fracture models and sensitivity analyses to further evaluate these uncertainties.

The seepage velocities and flow directions derived from the DSEM are generally consistent with estimates based on Darcy's law and independent hydrogeological parameters. This agreement demonstrates the methodological consistency of DSEM and confirms its technical feasibility for in situ characterization of groundwater seepage in fractured, low-permeability crystalline rock. Despite these advantages, several limitations must be acknowledged. The current implementation assumes relatively uniform borehole sections and homogeneous fracture connectivity, which may oversimplify the inherent heterogeneity of fractured media. In addition, uncertainties stem from the sensitivity of the seismo-electric response to variations in fracture aperture and anisotropic hydraulic properties. Such factors may cause discrepancies between predicted and actual seepage fields, particularly in highly heterogeneous disposal environments. Future studies should incorporate stochastic fracture network modeling and systematic sensitivity analyses to better quantify and reduce these uncertainties.

6. Conclusions

This study applied the Double-Layered Seismo-Electric Method (DSEM) to characterize groundwater seepage fields at a potential high-level radioactive waste disposal site. The main findings are as follows:

- Measurements from five deep boreholes in the Xinchang fault zone revealed that groundwater seepage velocity and direction, as well as the derived seepage maps, exhibit highly heterogeneous distributions in both horizontal and vertical sections. These patterns are consistent with the regional geological structure, and abrupt changes in seepage velocity correspond closely to the development of structural fractures. Seepage velocity varied by approximately two orders of magnitude between boreholes BSQ03 and BSQ04. Within borehole BSQ03, the difference between the maximum and minimum velocities across the vertical profile spanned nearly four orders of magnitude. The dominant seepage direction in borehole BSQ01 was from northwest to southeast.
- At the Shiyuejing fault, three-dimensional velocity vector distributions obtained from boreholes SW1, SW2, and SW3 showed that the seepage field is characterized by a dominant flow direction from northeast to southwest. The seepage velocities in these boreholes were on the order of 10^{-10} m/s. Overall, DSEM successfully quantified groundwater seepage, yielding velocities ranging from 1×10^{-10} to 5×10^{-8} m/s and flow directions consistent with regional hydraulic gradients.
- Based on distribution maps derived from five boreholes in Xinchang and three boreholes in the Shiyuejing fault zone, the dominant seepage directions in the F31, F32,

and Shiyuejing faults are controlled by the orientation of fracture development, with the influence most pronounced in the fault F31. Moreover, groundwater velocity and discharge increase with depth in zones of intensive fracture development, consistent with borehole observations. Preferential flow channels are aligned with major fracture zones, confirming that structural heterogeneity is the primary control on seepage distribution.

- The permeability coefficient of the rock mass in the pre-selected area of the high-level waste disposal repository is approximately 1×10^{-10} m/s. Hydrological data indicate that the hydraulic gradient in this section is about 1%. According to Darcy's law, the corresponding seepage velocity is calculated as 1×10^{-10} m/s, which is consistent with experimentally measured values, thereby validating the feasibility of the method. Furthermore, the seepage parameters derived from DSEM show strong agreement with Darcy's law-based estimates, demonstrating the reliability and applicability of the method in complex fractured media.

Overall, the results highlight the potential of DSEM as a non-invasive, scientifically reliable, and robust tool for enhancing safety assessment and long-term monitoring in the deep geological disposal of high-level radioactive waste.

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Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: Author Guoping Du was employed by the company Nanjing Emperor-dam Engineering Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HLW	High-level radioactive waste
BSQ	100-meter-deep borehole in the Beishan mountainous region
SW	Hydrogeological boreholes in the Shiyuejing fault exploratory trench
3D	Three-dimensional

Appendix A

Table A1. Seepage parameter measurements from boreholes BSQ01 to BSQ06 at the Beishan site, measuring flow velocity (m/s) and flow rate (m³/s).

Depth (m)	BSQ01	BSQ02	BSQ03	BSQ05	BSQ06
50	1.21×10^{-7}	9.66×10^{-7}	3.47×10^{-5}	1.14×10^{-7}	8.52×10^{-9}
51	3.53×10^{-8}	5.21×10^{-8}	1.96×10^{-5}	1.84×10^{-7}	5.95×10^{-9}
52	3.94×10^{-6}	2.89×10^{-8}	7.49×10^{-6}	1.56×10^{-8}	9.85×10^{-9}
53	6.46×10^{-7}	9.52×10^{-9}	1.17×10^{-5}	2.66×10^{-7}	9.54×10^{-8}
54	9.69×10^{-8}	9.91×10^{-9}	3.14×10^{-5}	8.50×10^{-9}	6.90×10^{-8}
55	1.11×10^{-6}	1.90×10^{-8}	7.96×10^{-5}	6.90×10^{-8}	5.37×10^{-8}
56	3.42×10^{-7}	6.79×10^{-7}	2.54×10^{-6}	4.90×10^{-7}	5.34×10^{-8}
57	7.90×10^{-6}	7.02×10^{-8}	6.14×10^{-5}	4.51×10^{-6}	8.93×10^{-7}
58	8.60×10^{-6}	1.38×10^{-8}	4.62×10^{-5}	1.80×10^{-6}	3.13×10^{-8}
59	3.41×10^{-6}	3.68×10^{-8}	3.29×10^{-5}	3.80×10^{-7}	1.04×10^{-8}
60	7.16×10^{-7}	1.37×10^{-8}	1.31×10^{-5}	4.75×10^{-9}	8.97×10^{-8}
61	6.76×10^{-7}	6.67×10^{-8}	1.22×10^{-4}	9.48×10^{-9}	2.56×10^{-7}
62	4.25×10^{-6}	4.06×10^{-8}	3.10×10^{-6}	7.16×10^{-9}	8.07×10^{-7}
63	1.66×10^{-5}	3.75×10^{-8}	1.81×10^{-5}	8.05×10^{-9}	9.65×10^{-7}
64	7.83×10^{-7}	9.63×10^{-8}	1.40×10^{-5}	9.97×10^{-8}	1.02×10^{-6}
65	1.70×10^{-5}	4.11×10^{-8}	2.58×10^{-5}	9.66×10^{-8}	6.75×10^{-8}
66	6.84×10^{-6}	5.81×10^{-8}	5.58×10^{-5}	4.95×10^{-7}	9.60×10^{-9}
67	1.44×10^{-5}	7.84×10^{-8}	4.08×10^{-5}	4.39×10^{-9}	1.25×10^{-8}
68	5.64×10^{-7}	5.48×10^{-7}	9.34×10^{-7}	3.04×10^{-8}	6.07×10^{-9}
69	1.11×10^{-7}	3.54×10^{-6}	2.02×10^{-5}	4.01×10^{-7}	4.70×10^{-8}
70	7.30×10^{-6}	7.80×10^{-7}	6.18×10^{-6}	9.79×10^{-9}	4.84×10^{-9}
Average velocity (m/s)	7.01×10^{-6}	1.50×10^{-7}	2.63×10^{-5}	1.33×10^{-7}	2.23×10^{-7}
Maximum velocity (m/s)	8.37×10^{-5}	3.54×10^{-6}	3.31×10^{-4}	4.51×10^{-6}	5.33×10^{-6}
Minimum velocity (m/s)	3.53×10^{-8}	5.29×10^{-9}	6.24×10^{-8}	4.12×10^{-9}	4.28×10^{-9}
Average permeability coefficient (m/s)	8.09×10^{-9}	3.53×10^{-8}	6.36×10^{-8}	2.30×10^{-9}	4.90×10^{-9}
Maximum permeability coefficient (m/s)	9.66×10^{-8}	8.34×10^{-9}	8.01×10^{-7}	7.76×10^{-8}	1.17×10^{-7}
Minimum permeability coefficient (m/s)	3.95×10^{-11}	1.25×10^{-11}	1.51×10^{-10}	7.09×10^{-11}	9.4×10^{-11}
Seepage section	1.79×10^4	3.81×10^2	7.88×10^4	6.00×10^2	1.01×10^3
Seepage direction	97–156	151–245	152–246	125–216	135–223

Table A2. Seepage parameter measurements from boreholes BSQ09 to BSQ15 at the Beishan site, measuring flow velocity (m/s) and flow rate (m³/s).

Depth (m)	BSQ09	BSQ10	BSQ11	BSQ12	BSQ14	BSQ15
15		7.44×10^{-10}				
16		3.46×10^{-10}				
17		1.49×10^{-10}				
18		5.32×10^{-10}				
19		6.87×10^{-10}				
20		5.37×10^{-10}				
21		1.59×10^{-10}				
22		2.43×10^{-10}				
23		8.19×10^{-10}				
24		2.47×10^{-10}				

Table A2. Cont.

Depth (m)	BSQ09	BSQ10	BSQ11	BSQ12	BSQ14	BSQ15
25		3.83×10^{-10}				
26		2.19×10^{-10}				
27		1.61×10^{-10}				
28		4.37×10^{-10}				
29		1.73×10^{-10}				
30		5.19×10^{-10}				
31		3.32×10^{-10}				
32		7.41×10^{-10}				7.7×10^{-10}
33		5.41×10^{-10}		2.09×10^{-10}		9.94×10^{-10}
34	8.44×10^{-10}	3.27×10^{-10}	2.73×10^{-10}	4.06×10^{-10}		1.09×10^{-9}
35	5.16×10^{-10}	5.68×10^{-10}	1.95×10^{-10}	5.25×10^{-10}		5.41×10^{-10}
36	3.91×10^{-10}	3.05×10^{-10}	1.48×10^{-10}	2.1×10^{-10}		1.06×10^{-9}
37	6.71×10^{-10}	3.1×10^{-10}	2.09×10^{-10}	3.67×10^{-10}		1.55×10^{-9}
38	5.17×10^{-10}	2.59×10^{-10}	2.01×10^{-10}	5.41×10^{-10}		8.06×10^{-10}
39	4.86×10^{-10}	4.27×10^{-10}	2.03×10^{-10}	3.85×10^{-10}		5.39×10^{-10}
40	8.54×10^{-10}	1.32×10^{-9}	2.34×10^{-10}	3.58×10^{-10}		1.15×10^{-9}
41	7.53×10^{-10}	1.42×10^{-9}	3.54×10^{-10}	7.06×10^{-10}		1.64×10^{-9}
42	6.64×10^{-10}	2.59×10^{-10}	2.86×10^{-10}	7.47×10^{-10}		9.21×10^{-10}
43	7.76×10^{-10}	5.95×10^{-10}	3.14×10^{-10}	1.43×10^{-9}		1.1×10^{-9}
44	1.34×10^{-10}	5.85×10^{-10}	3.29×10^{-10}	6.41×10^{-10}		8.87×10^{-10}
45	9.09×10^{-10}	2.86×10^{-10}	2.65×10^{-10}	6.63×10^{-10}		7.1×10^{-10}
46	7.42×10^{-10}	3.02×10^{-10}	2.19×10^{-10}	4.6×10^{-10}	4.46×10^{-10}	7.21×10^{-10}
47	7.91×10^{-10}	9.51×10^{-10}	3.32×10^{-10}	2.81×10^{-10}	4.19×10^{-10}	8.79×10^{-10}
48	7.36×10^{-10}	8.2×10^{-10}	4.04×10^{-10}	4.46×10^{-10}	1.07×10^{-9}	1.38×10^{-9}
49	7.53×10^{-10}	6.45×10^{-10}	4.56×10^{-10}	2.18×10^{-10}	1.08×10^{-9}	1.26×10^{-9}
50	7.57×10^{-10}	1.62×10^{-10}	2.41×10^{-10}	1.73×10^{-10}	9.56×10^{-10}	4.48×10^{-10}
51	7.73×10^{-10}	1.59×10^{-10}	2.13×10^{-10}	3.1×10^{-10}	1.42×10^{-9}	1.03×10^{-9}
52	7.52×10^{-10}	8.4×10^{-11}	2.73×10^{-10}	2.15×10^{-10}	1.02×10^{-9}	7.98×10^{-10}
53	7.35×10^{-10}	6.19×10^{-10}	2.03×10^{-10}	8.04×10^{-10}	1.77×10^{-9}	8.43×10^{-10}
54	7.69×10^{-10}	2.72×10^{-10}	2.6×10^{-10}	2.87×10^{-10}	1.83×10^{-9}	3.31×10^{-9}
55	7.29×10^{-10}	6.56×10^{-10}	3.92×10^{-10}	6.61×10^{-10}	1.5×10^{-9}	1.06×10^{-9}
56	7.43×10^{-10}	4.48×10^{-10}	2.1×10^{-10}	1.78×10^{-10}	1.96×10^{-9}	2.2×10^{-9}
57	6.9×10^{-10}	3.74×10^{-10}	4.99×10^{-10}	3.45×10^{-10}	1.38×10^{-9}	1.21×10^{-9}
58	6.85×10^{-10}	1.17×10^{-10}	3.94×10^{-10}	3.5×10^{-10}	1.26×10^{-9}	2.9×10^{-9}
59	7.42×10^{-10}	1.75×10^{-10}	1.9×10^{-10}	4.19×10^{-10}	1.83×10^{-9}	2.78×10^{-9}
60	6.63×10^{-10}	1.4×10^{-10}	2.86×10^{-10}	6.44×10^{-10}	1.21×10^{-9}	1.55×10^{-9}
61	6.78×10^{-10}	1.35×10^{-10}	4.18×10^{-10}	3.67×10^{-10}	9.63×10^{-10}	1.36×10^{-9}
62	7.27×10^{-10}	2.79×10^{-10}	3.71×10^{-10}	4.12×10^{-10}	2.35×10^{-9}	1.09×10^{-9}
63	6.77×10^{-10}	1.46×10^{-10}	3.27×10^{-10}	4.15×10^{-10}	1.84×10^{-9}	9.09×10^{-10}
64	6.47×10^{-10}	1.53×10^{-10}	2.33×10^{-10}	5.02×10^{-10}	6.57×10^{-10}	1.34×10^{-9}
65	6.4×10^{-10}	3.51×10^{-10}	2.4×10^{-10}	2.84×10^{-10}	1.02×10^{-9}	8.79×10^{-10}
66	5.54×10^{-10}	3.04×10^{-10}	2.04×10^{-10}	4.47×10^{-10}	7.25×10^{-10}	1.44×10^{-9}
67	5.42×10^{-10}	9.3×10^{-11}	3.45×10^{-10}	9.01×10^{-10}	2.09×10^{-9}	2.26×10^{-9}
68	4.9×10^{-10}	1.18×10^{-10}	2.62×10^{-10}	4.79×10^{-10}	3.18×10^{-9}	1.32×10^{-9}
69	4.37×10^{-10}	1.19×10^{-10}	2.33×10^{-10}	1.94×10^{-10}	1.36×10^{-9}	2.38×10^{-9}
70	6.76×10^{-10}	3.03×10^{-10}	2.41×10^{-10}	2.51×10^{-10}	1.08×10^{-9}	1.68×10^{-9}
71	6.01×10^{-10}	5.07×10^{-10}	3.06×10^{-10}	6.19×10^{-10}	2.27×10^{-9}	1.42×10^{-9}
72	5.06×10^{-10}	1.25×10^{-10}	6×10^{-10}	4.87×10^{-10}	2.1×10^{-9}	2.24×10^{-9}
73	6.61×10^{-10}	2.96×10^{-10}	5.51×10^{-10}	3.05×10^{-10}	2.17×10^{-9}	2.33×10^{-9}
74	4.71×10^{-10}	1.28×10^{-10}	6.08×10^{-10}	4.4×10^{-10}	1.96×10^{-9}	1.16×10^{-9}
75	5.7×10^{-10}	1.94×10^{-10}	4×10^{-10}	3.17×10^{-10}	1.34×10^{-9}	2.72×10^{-9}

Table A2. Cont.

Depth (m)	BSQ09	BSQ10	BSQ11	BSQ12	BSQ14	BSQ15
76	4.59×10^{-10}	1.51×10^{-10}	2.46×10^{-10}	8.88×10^{-10}	1.28×10^{-9}	7.98×10^{-10}
77		3.23×10^{-10}	3.55×10^{-10}	4.09×10^{-10}	3.57×10^{-9}	6.25×10^{-10}
78		2.04×10^{-10}		7.46×10^{-10}	4.16×10^{-9}	5.91×10^{-10}
79		1.88×10^{-10}		2.19×10^{-10}		2.65×10^{-9}
80		1.47×10^{-10}		3.08×10^{-10}		1.21×10^{-9}
81		1.82×10^{-10}		3.61×10^{-10}		9.07×10^{-10}
82		1.43×10^{-10}		2.6×10^{-10}		2.35×10^{-9}
83		1.14×10^{-10}		1.31×10^{-9}		1.58×10^{-9}
84		8.4×10^{-11}		4.2×10^{-10}		1.43×10^{-9}
85		2.63×10^{-10}		3.9×10^{-10}		8.38×10^{-10}
86		1.89×10^{-10}		1.45×10^{-10}		8.35×10^{-10}
87		5.54×10^{-10}		3.68×10^{-10}		1.35×10^{-9}
88		3.29×10^{-10}		2.39×10^{-10}		1.69×10^{-9}
89		2.89×10^{-10}		4.68×10^{-10}		1.2×10^{-9}
90		1.61×10^{-10}		6.98×10^{-10}		1.42×10^{-9}
91		1.54×10^{-10}		3.21×10^{-10}		8.26×10^{-10}
92		9.72×10^{-10}		7.71×10^{-10}		1.19×10^{-9}
93		1.6×10^{-10}		6.55×10^{-10}		1.24×10^{-9}
94		1.08×10^{-10}		1.93×10^{-10}		3.24×10^{-9}
95		2.05×10^{-10}		2.3×10^{-10}		1.46×10^{-9}
96		2.15×10^{-10}		3.88×10^{-10}		5.36×10^{-10}
97		1.22×10^{-10}		6.06×10^{-10}		2.74×10^{-9}
98		2.44×10^{-10}		6.61×10^{-10}		9.82×10^{-10}
99		3.78×10^{-10}				1.27×10^{-9}
100		3.24×10^{-10}				9.9×10^{-10}
101		1.51×10^{-10}				
102		2.17×10^{-10}				
103		2.5×10^{-10}				
104		3.2×10^{-10}				
105		4.73×10^{-10}				
106		2.37×10^{-10}				
107		2.06×10^{-10}				
108		1.64×10^{-10}				
109		1.43×10^{-10}				
110		1.51×10^{-10}				
111		2.1×10^{-10}				
112		2.18×10^{-10}				
113		1.07×10^{-10}				
114		1.15×10^{-10}				
115		1.37×10^{-10}				
116		1.28×10^{-10}				
117		1.43×10^{-10}				
118		1.18×10^{-10}				
Average velocity (m/s)	6.49×10^{-10}	3.22×10^{-10}	3.07×10^{-10}	4.61×10^{-10}	1.61×10^{-9}	1.37×10^{-9}
Maximum velocity (m/s)	9.09×10^{-10}	1.42×10^{-9}	6.08×10^{-10}	1.43×10^{-9}	4.16×10^{-9}	3.31×10^{-9}
Minimum velocity (m/s)	1.34×10^{-10}	8.4×10^{-11}	1.48×10^{-10}	1.45×10^{-10}	4.19×10^{-10}	4.48×10^{-10}
Average permeability coefficient (m/s)	3.9×10^{-9}	4.65×10^{-10}	1.84×10^{-9}	2.77×10^{-9}	9.55×10^{-10}	1.18×10^{-9}
Maximum permeability coefficient (m/s)	5.46×10^{-9}	2.06×10^{-9}	3.65×10^{-9}	8.55×10^{-9}	2.46×10^{-9}	2.84×10^{-9}
Minimum permeability coefficient (m/s)	8.04×10^{-10}	1.19×10^{-10}	8.88×10^{-10}	8.7×10^{-10}	2.48×10^{-10}	3.84×10^{-10}
Seepage section	1.38	1.70	6.83×10^{-1}	1.55	2.73	4.78
Seepage direction	175–224	108–155	187–231	126–168	160–214	145–193

Table A3. Seepage parameter measurements from boreholes SW1 to SW3 at the Beishan site, measuring flow velocity (m/s) and flow rate (m³/s).

Depth (m)	SW1	SW2	SW3
1	7.68×10^{-10}	6.08×10^{-10}	6.02×10^{-10}
1.5	8.94×10^{-10}	6.47×10^{-10}	5.91×10^{-10}
2	6.42×10^{-10}	6.15×10^{-10}	6.01×10^{-10}
2.5	6.42×10^{-10}	6.03×10^{-10}	1.28×10^{-9}
3	5.83×10^{-10}	6.28×10^{-10}	1.57×10^{-9}
3.5	6.28×10^{-10}	6.82×10^{-10}	1.63×10^{-9}
4	5.92×10^{-10}	6.64×10^{-10}	1.05×10^{-9}
4.5	8.63×10^{-10}	6.96×10^{-10}	1.20×10^{-9}
5	6.16×10^{-10}	1.26×10^{-9}	1.57×10^{-9}
5.5	6.37×10^{-10}	8.69×10^{-10}	9.16×10^{-10}
6	5.76×10^{-10}	7.94×10^{-10}	9.85×10^{-10}
6.5	6.28×10^{-10}	7.22×10^{-10}	6.05×10^{-10}
7	8.13×10^{-10}	6.67×10^{-10}	5.98×10^{-10}
7.5	6.11×10^{-10}		
8	6.03×10^{-10}		
8.5	6.67×10^{-10}		
9	6.00×10^{-10}		
9.5	7.66×10^{-10}		
10	6.42×10^{-10}		
Average velocity (m/s)	6.72×10^{-10}	7.27×10^{-10}	1.02×10^{-9}
Maximum velocity (m/s)	8.94×10^{-10}	1.26×10^{-9}	1.63×10^{-9}
Minimum velocity (m/s)	5.76×10^{-10}	6.03×10^{-10}	5.91×10^{-10}
Seepage section (m/s)	6.39×10^{-1}	4.73×10^{-1}	6.60×10^{-1}
Seepage direction	200–326	138–251	176–271

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