Characterization of Bedrock Hydrogeology for Development of Shallow Geothermal Energy :A Review of Key Technologies and Application Cases

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Research Background

According to global population distribution and bedrock burial depth, that many BHEs are expected to be installed in shallow bedrock [1];

In reviewing related hydrogeology literature, common structures of water conduits and storage median in bedrocks, which are considered to be beneficial in BHE performance and ground heat balance [2-4].

As shown in Fig 1, the shallow bedrock is unique to fissure water and Karst water. The distinct attributes of bedrock hydrogeological conditions significantly impact the heat transfer ability of BHEs, as well as geothermal capacity and thermal balance of underground heat exchange zone.

Existing regional surveys and site investigation tasks are not based on the hydrogeological conditions of shallow bedrock environments. Therefore, the techniques and tools applicable to such environments have not yet been thoroughly reviewed or discussed.

a. Fissure water   b. Karst water

Fig. 1. Types of groundwater in shallow bedrock.

Technical Roadmap

This study begins by examining the attributes of bedrock groundwater and summarizing the objectives and scope of both regional and site-specific investigations. Subsequently, a review is conducted of surface geophysical methods and drilling exploration techniques employed to characterize structural features and discontinuity networks. Application cases of these technologies and tools in geothermal projects are presented to illustrate their practical utility. A comprehensive review and technical guidance for the development of shallow geothermal energy in bedrock areas have been developed.

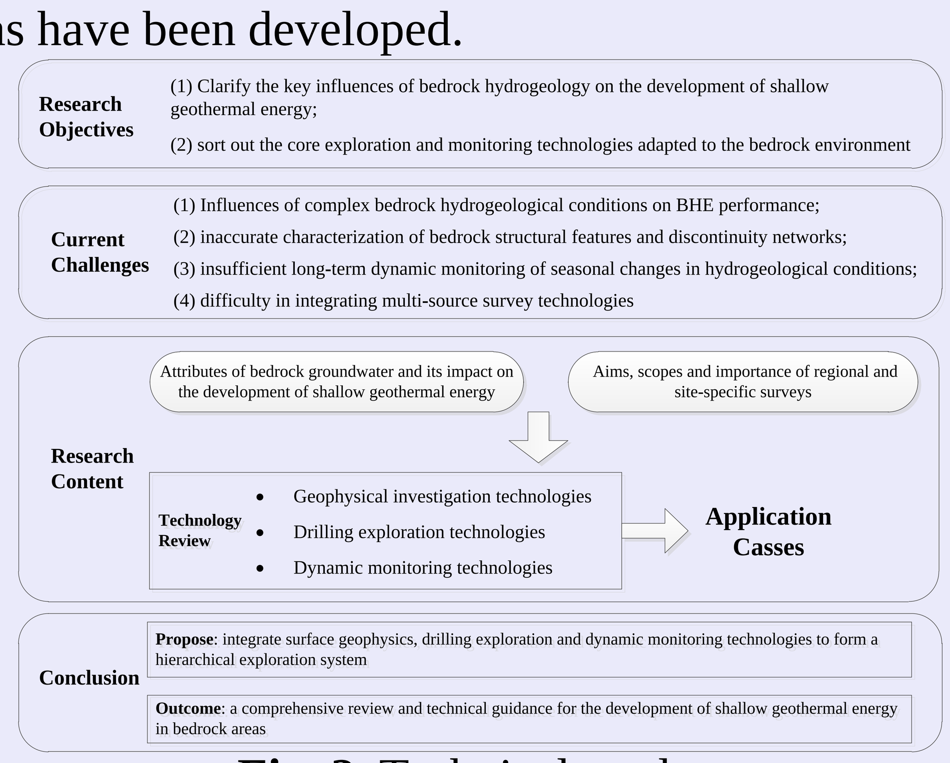


Fig. 2. Technical roadmap.

1.Regional survey

The aim of regional survey is to provide fundamentals for regional planning and layout for possible BHE-based geothermal heating and cooling projects. Identify the conditions and distribution patterns of shallow geothermal energy within the region, and classify suitable areas [5].

Conduct a preliminary feasibility assessment for regional project development based on factors such as economy, sustainability, and environmental impact.

2. Site investigation tasks

The purpose of site assessment is to determine geothermal and construction conditions, calculate borehole heat transfer power (single and cluster), support feasibility study and design phases of BHE projects, and propose development [6]. It can thus be seen that regional survey emphasizes identification at macro-level, whereas project site investigation focuses on implementation at micro-level.

Research Content

1.Geophysical Investigation

Geophysical exploration infers the physical properties and geometric features of geological bodies by analyzing their natural or artificially induced physical fields. For borehole projects in unconsolidated layers, geophysical exploration is not a work must to do, due to their homogenous and stable properties. However, in bedrock dominated-regions, due to the complex structures and heterogeneous properties, the benefit of geophysical exploration is pronounced.

Application Cases:

The case site is located in Guiyang, Guizhou Province, China. The region is a typical karst environment. The two low-resistivity anomalies in Profile 1 and the low-resistivity anomaly in Profile 2 correspond to Anomaly Zone 1 in Fig. 3, suggesting possible small-scale karst development. The two elliptical low-resistivity anomalies in Profile 3 fall within Anomaly Zone 2 in Fig. 3, likely representing mechanically weak layers filled with water in fractured zones.

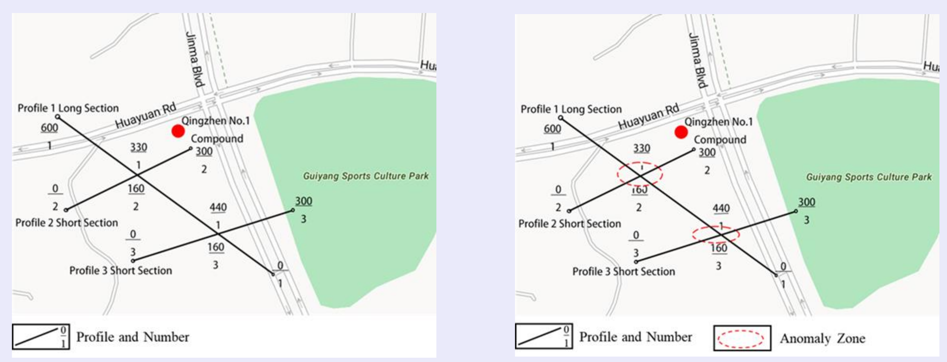


Fig. 3. Layout of at three profiles at the case site and Overall anomaly interpretation of the case site.

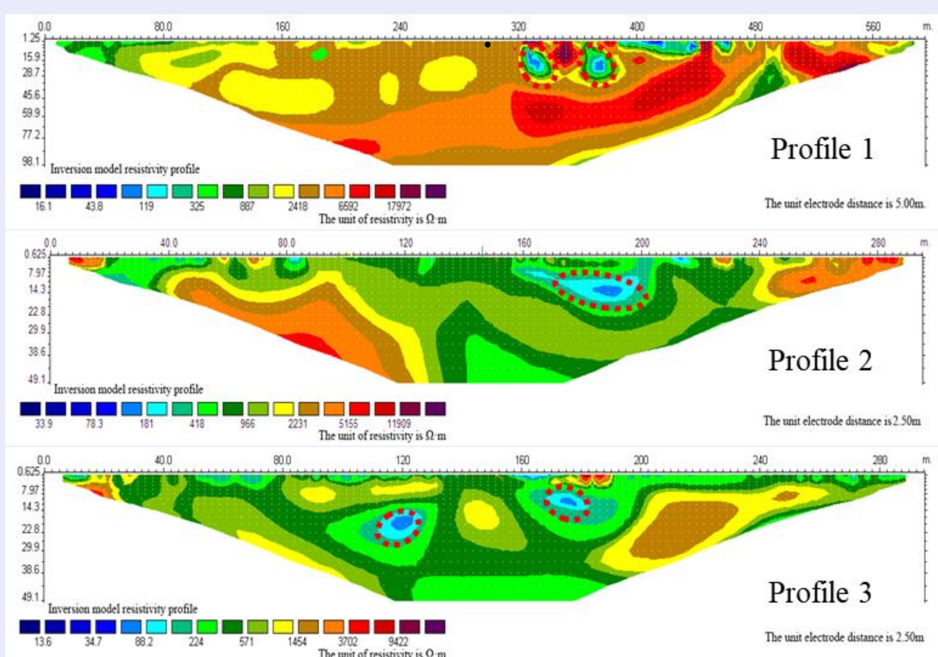


Fig. 4. Apparent resistivity image of Profile 1 to Profile 3.

2.Drilling Exploration

The standard procedures for drilling exploration in various projects do not significantly differ. However, due to the heterogeneity and anisotropy of groundwater in bedrocks, the arrangement of exploration boreholes considers the following aspects:

Areas where hydrogeological conditions are poorly understood and urgently require exploration; Areas with insufficient hydrogeological parameter data where pumping and injection tests are urgently needed; Areas where the quantity, quality, water level, and temperature of groundwater are unclear and need to be determined urgently; Areas requiring verification of results from geological analyses and geophysical interpretations.

Borehole televiewer comprises acoustic and optical televiewers. Optical images directly show lithology, fractures, foliation, bedding, and their relationships. The best approach combines acoustic and optical imaging with integrated interpretation.

Application Cases:

The case site is located in Kaili, Guizhou, China, where the outcrop is Cambrian dolomite. Drilling results for exploration borehole 2 are as follows:

0-2.10m, Quaternary: backfill soils and clays.

2.10-121.2m, Loushanguan Formation of Cambrian: grey to light grey, thin to medium-bedded dolomite and silty dolomite. The rock mass is highly fractured and loosely structured due to tectonic joints. Intermittent karst fissures occur at depths of 21.3–44.7 m and 72.4–83.6 m, with apertures of 2–8 cm, and contain fissure water.

3. Dynamic Monitoring

Water table and ground temperature

The seasonal fluctuations of groundwater content influence the GCHP system operation. Additionally, construction of nearby projects can alter the groundwater flow field.

Through data monitoring, changes in geothermal capacity can be understood, risks of thermal imbalance can be identified, and the operating duration of the heat pump can be adjusted accordingly.

Flow rate and direction

Determining the groundwater flow velocity and direction can provide a basis for accurately calculating the heat transfer of borehole and analyzing thermal balance. The tracer method is not suitable for accurately depicting the flow characteristics of bedrock groundwater; therefore, other advanced approaches such as the particle image velocimetry (PIV) and thermal pulse methods are needed.

Slug test

In current standards and specification, slug tests are only required in groundwater heat pump projects and not required at BHE-based projects at regions with thick Quaternary layers.

Application Cases:

A dynamic groundwater table and temperature monitoring system (Fig.5) was installed in a primary school campus in the city of Tongren, Guizhou Province, China. The lithology of the project site is limestone. At a GCHP project site in Guiyang, China, the PIV intelligent groundwater measurement system (Fig.6) was employed to measure the groundwater flow velocity and direction at the site. These observations confirm the strong seasonal dependence of groundwater levels on local precipitation patterns.

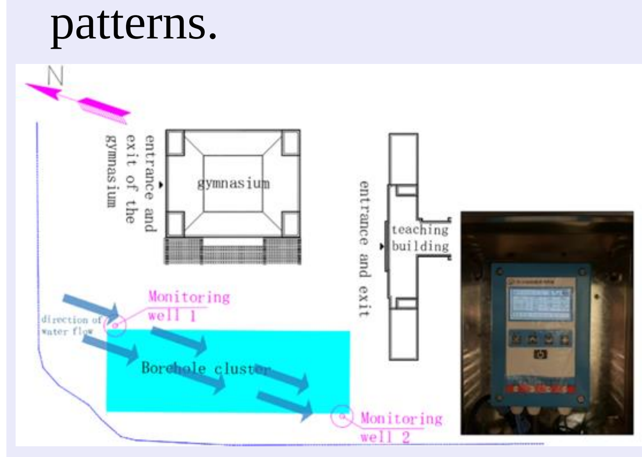
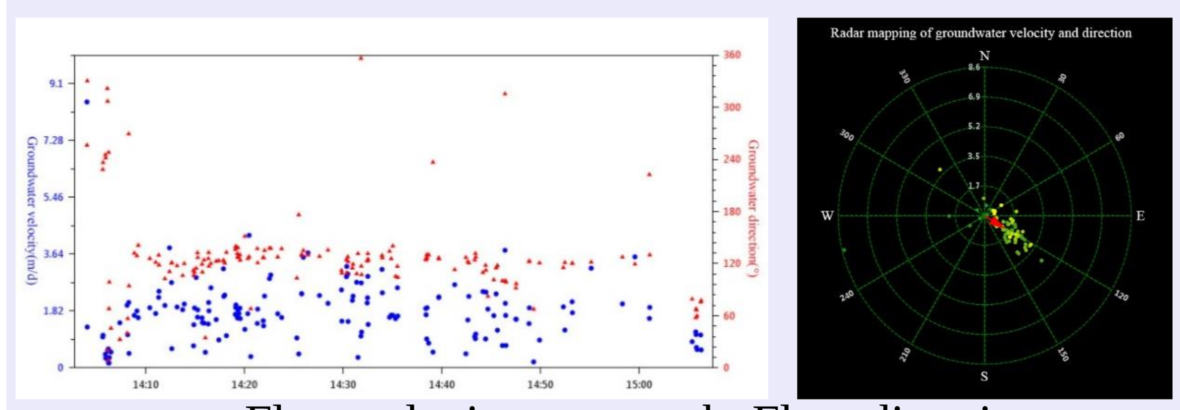


Fig. 5. Location of the monitoring wells.

Fig. 6. The smart PIV groundwater measurement system.



a. Flow velocity   b. Flow direction

Fig. 7. Groundwater flow velocity and direction observed by the PIV method.

Conclusion

Integrated investigation and survey technical path

1. In the regional investigation phase

Existing data→ Data-sparse area surveys→ Geophysical exploration for structure identification→ Representative drilling verification→ Monitoring wells for long-term observation→ Basic data→ Pre-feasibility and investment decisions.

2. In the site evaluation phase

Detailed geophysical investigation→ Identify aquifers, fractures, karst caves→ Assess thermal properties, BHE heat transfer ability, drilling difficulty→ Determine suitable areas for BHE placement→ Conduct drilling surveys→ Ascertain stratigraphic structure, geological features, groundwater characteristics→ Delineate stable stratigraphic zones and provide boreholes for TRT→ Perform borehole imaging, PIV, slug tests→ Establish long-term monitoring network→ Support thermal imbalance risk prediction and operational optimization.

References

[1] Pei, P., Sun, J., Liu, Y., et al. Properties of borehole heat exchangers in shallow bedrock: Insights and perspectives based on project data and rock mass characteristics, Journal of Energy Storage, 130(2025)117463, 2352-152X.

[2] Wang, M. Groundwater and Geological Environment in Karst Areas of Guizhou Province, Geology Press, Beijing, 2015.

[3] Hudson, J., Harrison, J. Engineering Rock Mechanics: An Introduction to the Principles, Applied Mechanics Reviews, 55 (2) (2002), 113-113.

[4] Guo, C. Karst Multi-media Environment and Karst Groundwater System, Chemical Industry Press, 2006.

[5] Liu, Y., Pei, P., Tian, X. Classification of closed-loop GCHP suitability via governing mechanism of hydrogeological attributes: Case Research in Karstic Terrain, Guiyang, China, Geothermics, 136 (2026)

[6] Deng, F., Pei, P. Evaluation of the Site Suitability for Shallow Geothermal Development under Complicated Geological Conditions, Building Energy Efficiency, 50 (12) (2022), 111-118.