Heat Transfer Analysis and Calculation for Borehole Heat Exchangers with Groundwater Through-flow inside and outside Wellbore

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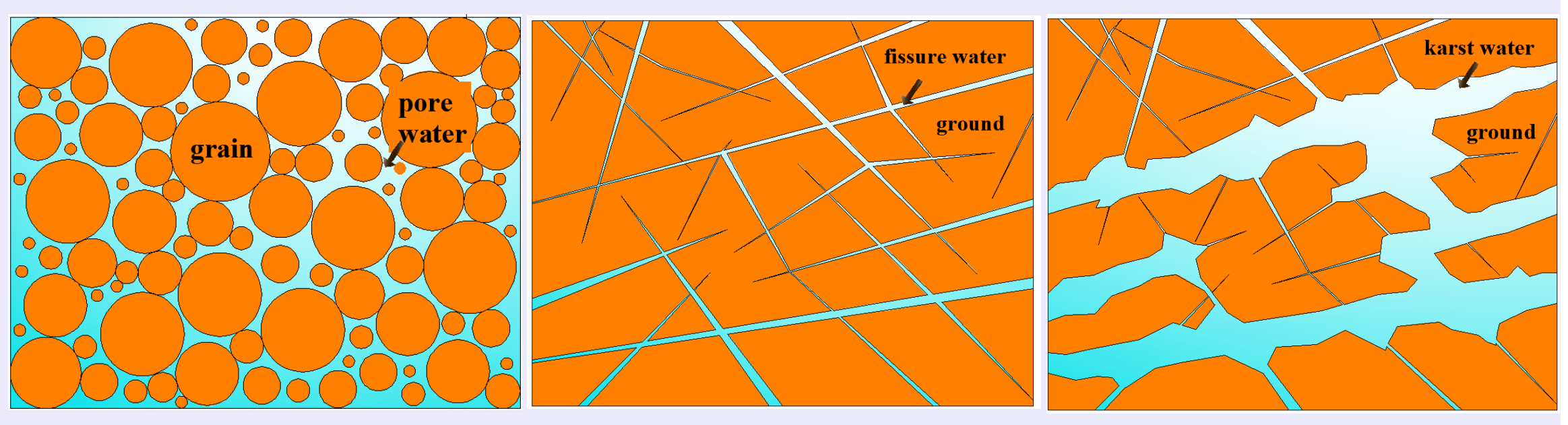
Research Background

According to global population distribution and bedrock burial depth, that many borehole heat exchangers (BHEs) are expected to be installed in shallow bedrocks[1];

Groundwater in bedrock is bedrock fissure water and karst water, which are conduit flow rather than pore water, and often forms concentrated groundwater runoff belts;

Existing research on BHE heat transfer are largely confined to pore flow and homogeneous layers, which significantly differs from the actual hydrogeological conditions in bedrock[2-3];

In existing research , the borehole wall is treated as a boundary, dividing BHE heat transfer into two decoupled parts: steady-state heat transfer inside the borehole and transient heat transfer outside the borehole[4].



a. Pore water b. Fissure water c. Karst water

Fig. 1. Three types of groundwater.

Methodology

This study considers scenarios where groundwater enters the wellbore and flows transversely through it or moves vertically to hydraulically connect multiple aquifers. The integrated heat transfer model inside and outside the borehole.

Through a comprehensive analysis of the BHE heat transfer mechanism, multiple heat transfer pathways along the “U tube → backfill material → rock mass” chain are identified, and a corresponding thermal resistance network model is constructed.

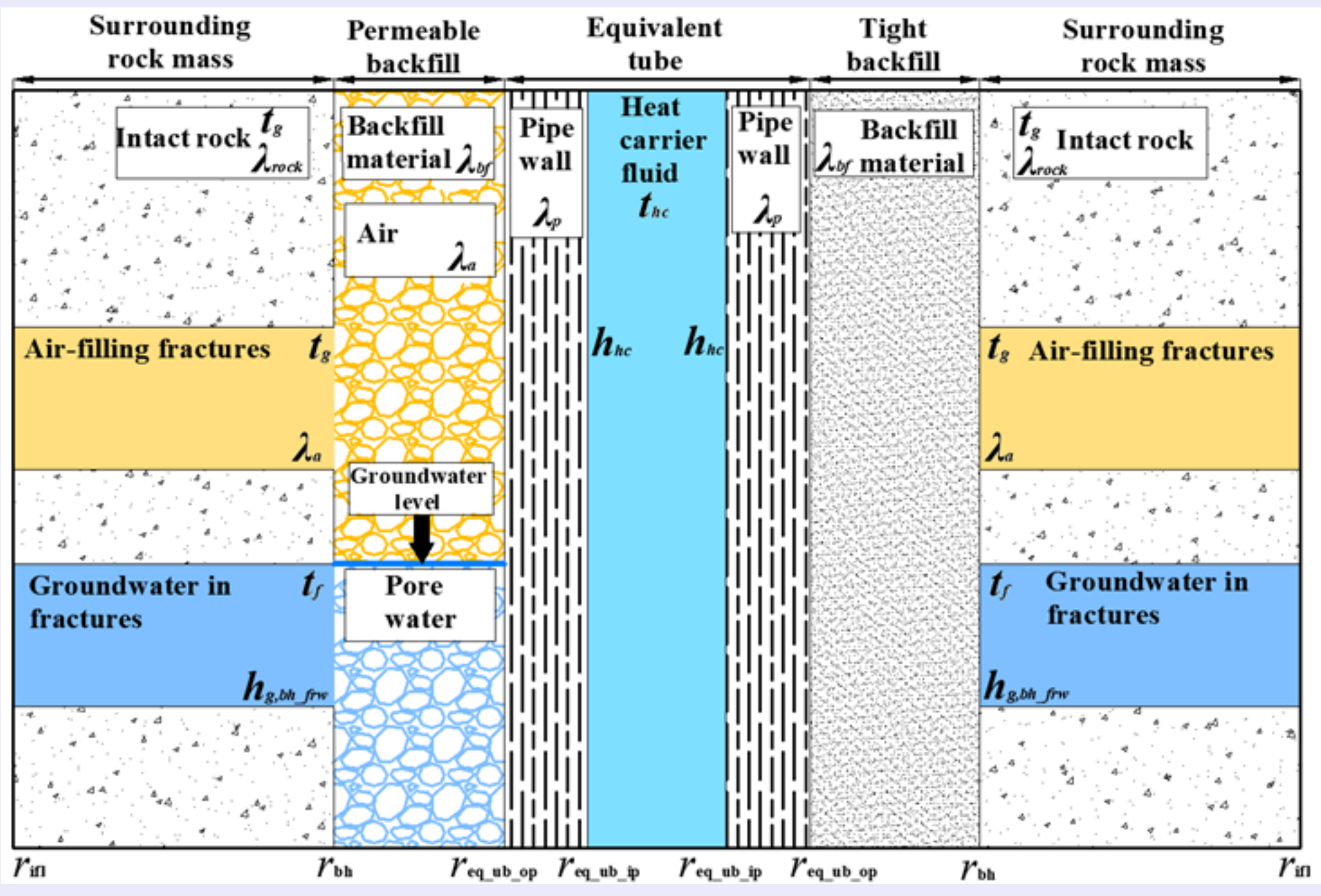


Fig. 2. Schematic diagram of heat exchange under different borehole backfilling methods.

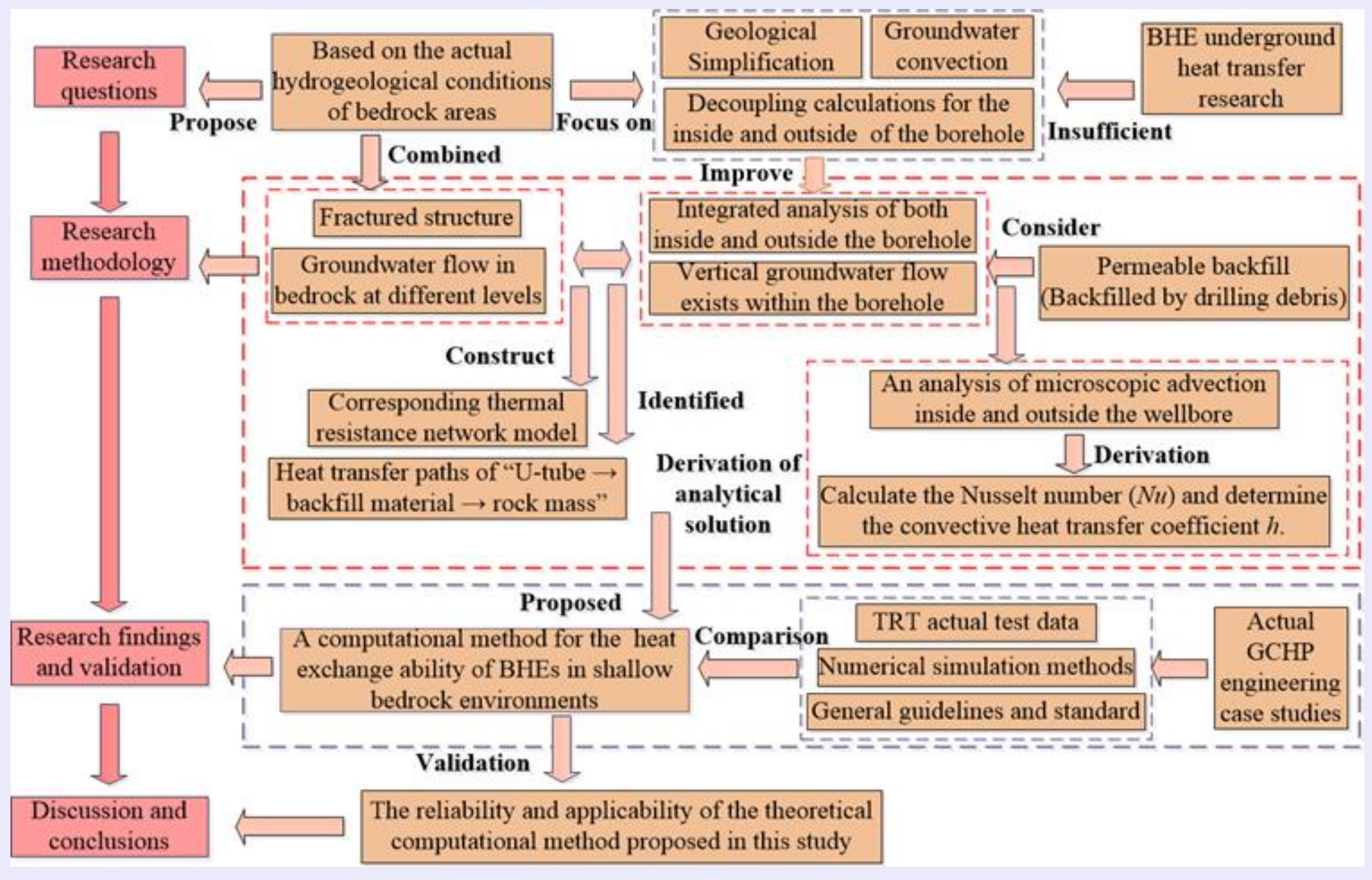
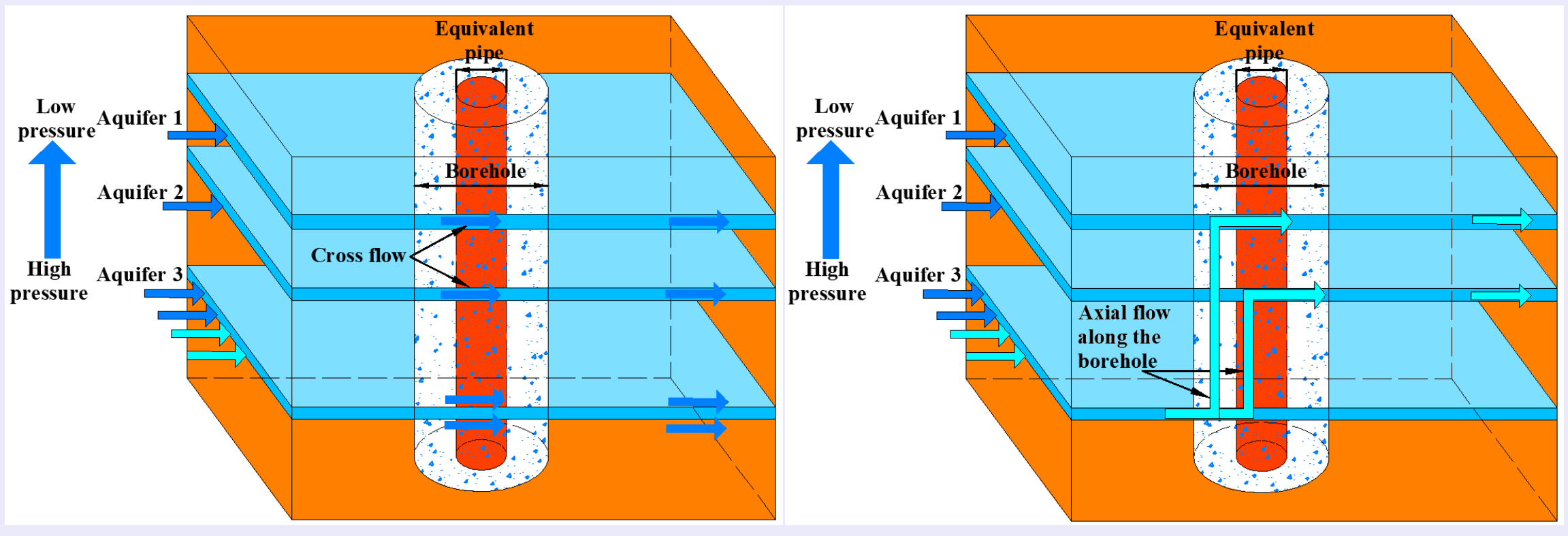


Fig. 3. Methodology and Technical Roadmap.

An integrated thermal resistance network when groundwater flow and hydraulic connectivity exist simultaneously inside and outside the borehole.

The contribution of advection induced by groundwater through-flow to the heat exchange of BHEs is included.

Calculation methods of the Nusselt number (Nu) and heat transfer coefficient (h) corresponding to different flow patterns of groundwater inside the borehole.



a. Cross flow b. Axial flow along the borehole

Fig. 4. Schematic diagram of groundwater flow tendency in a borehole penetrating multiple confined aquifers with different hydraulic heads.

Model Derivation

1.**Permeable backfill model:**

In the permeable backfill model, the portion of the backfilled borehole below the groundwater level allows groundwater to flow into the borehole through the pores of the backfill.

It may flow transversely across the U tube and exit through the same fracture on the right side; alternatively, it may flow vertically inside the borehole and then exit through another fracture with a lower hydraulic head.

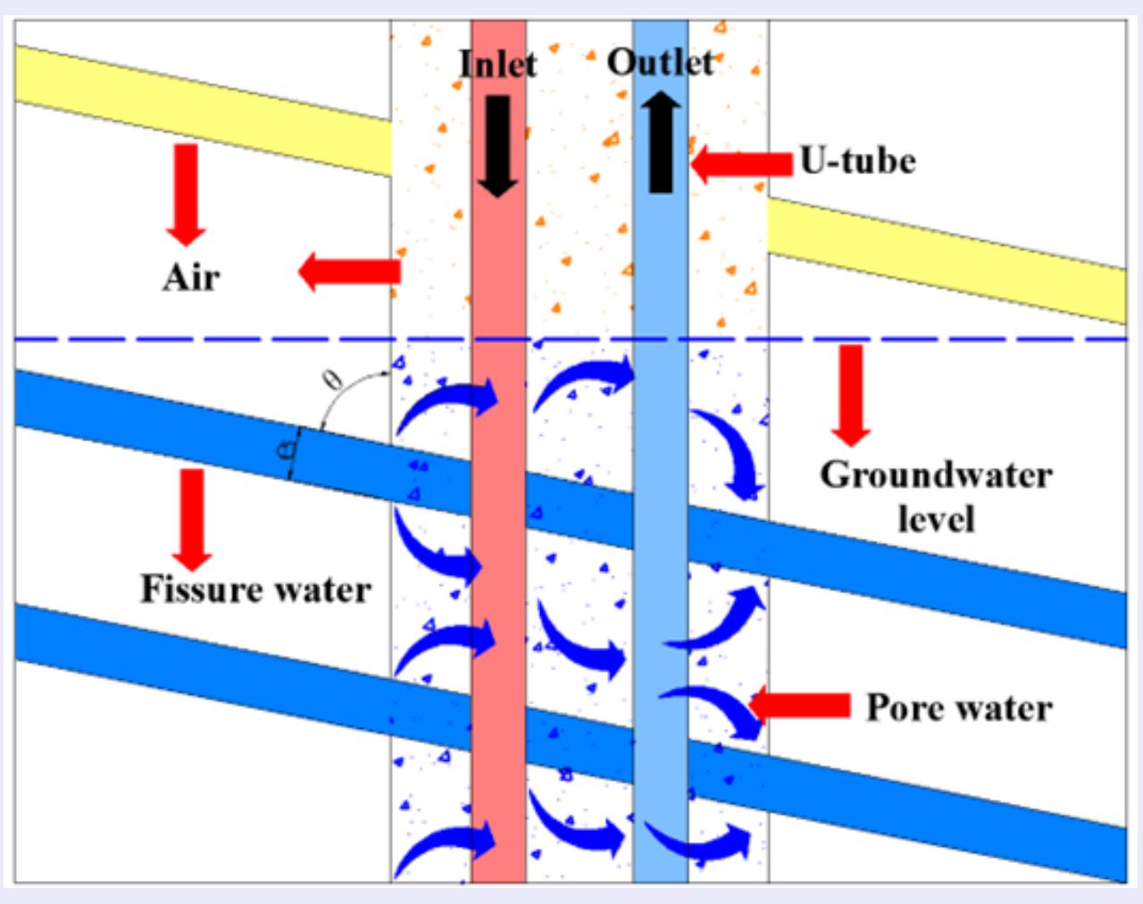


Fig. 5. Schematic diagram of the contact area between groundwater in fracture *i* and the borehole under permeable backfilling conditions.

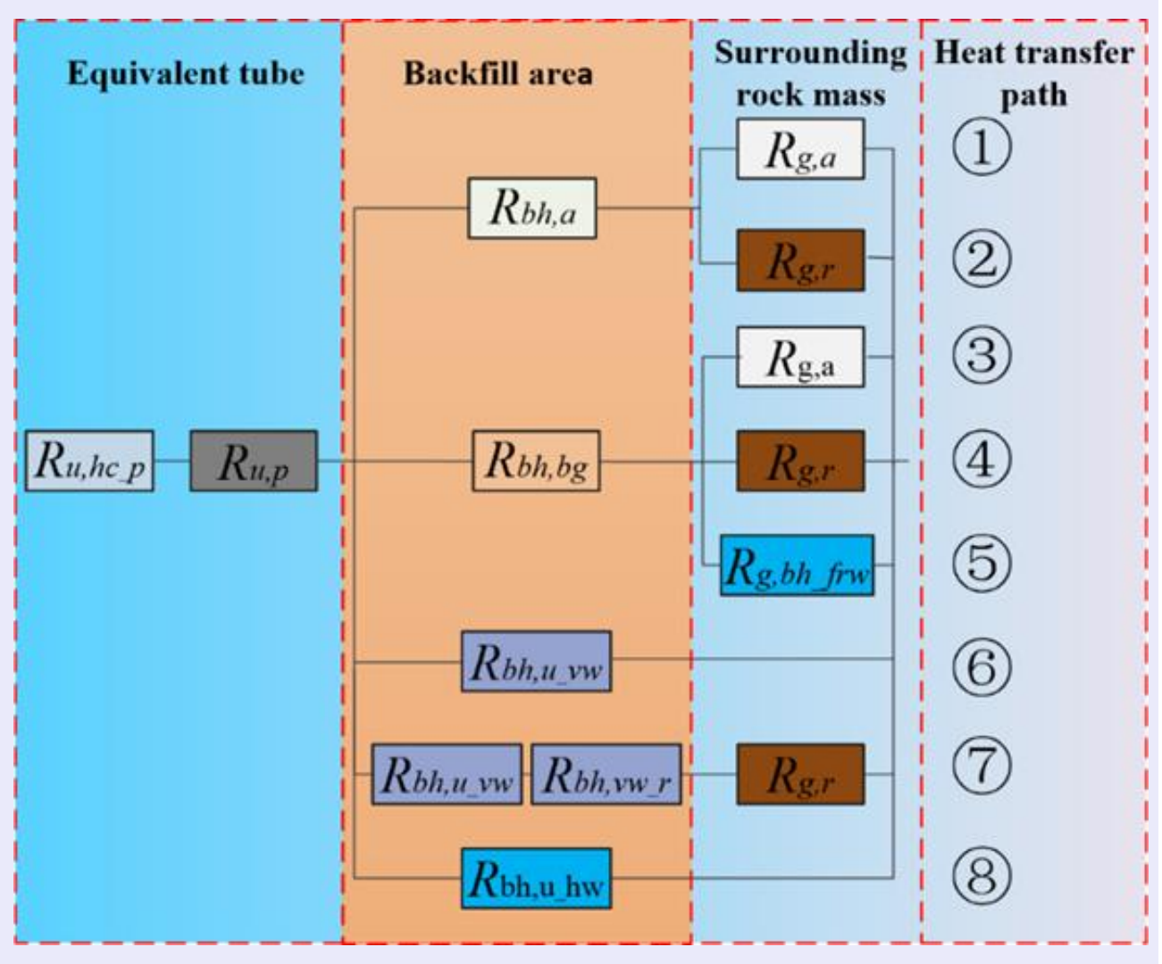


Fig. 6. Thermal resistance network under permeable backfilling conditions.

2.**Tight backfill model:**

The backfill material in the tight backfill model (Figure 7) has low porosity and permeability, meaning it contains neither fissure water nor air-filled pores. Convective heat transfer only occurs at the intersection where the water-conducting fracture *i* meets the borehole wall. The heat exchange in other areas is conducted through heat conduction.

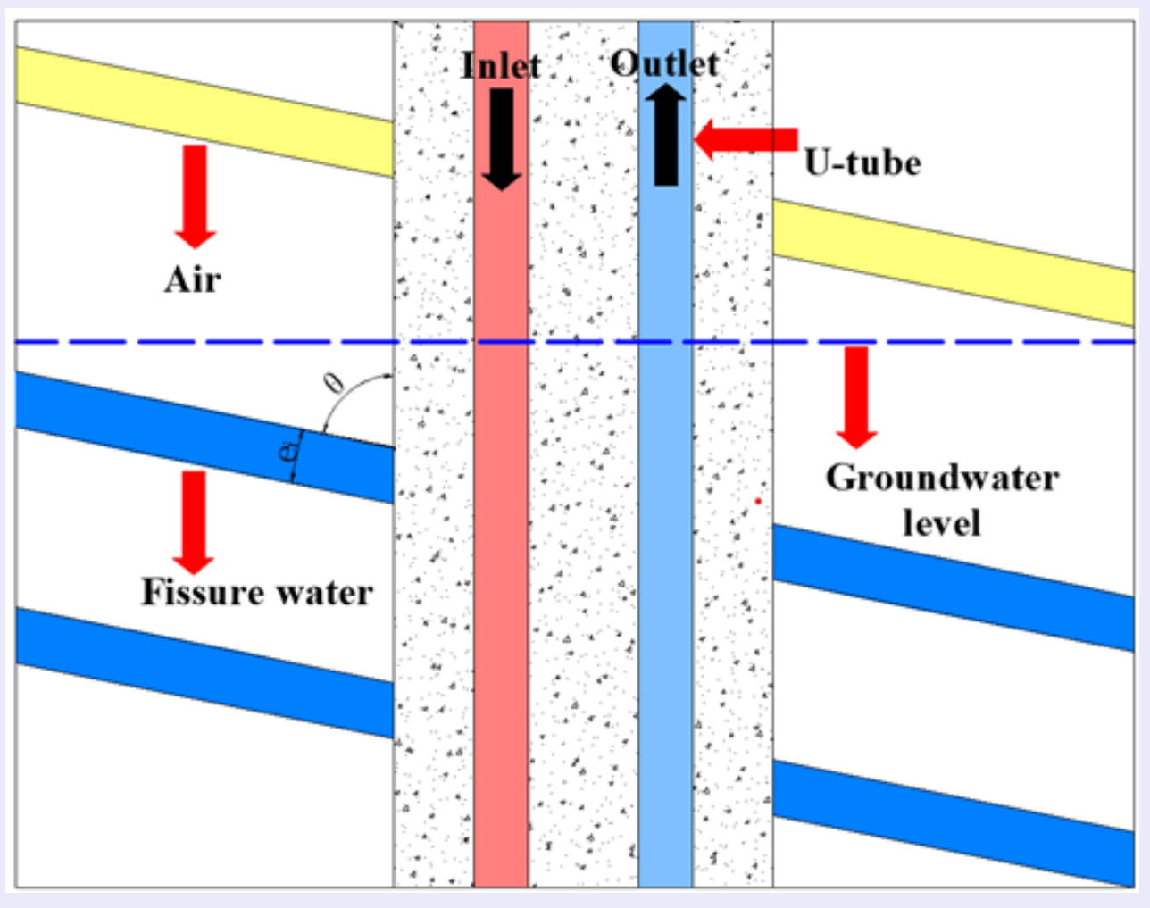


Fig. 7. Schematic diagram of the contact area between groundwater in fracture *i* and the borehole under tight backfilling conditions.

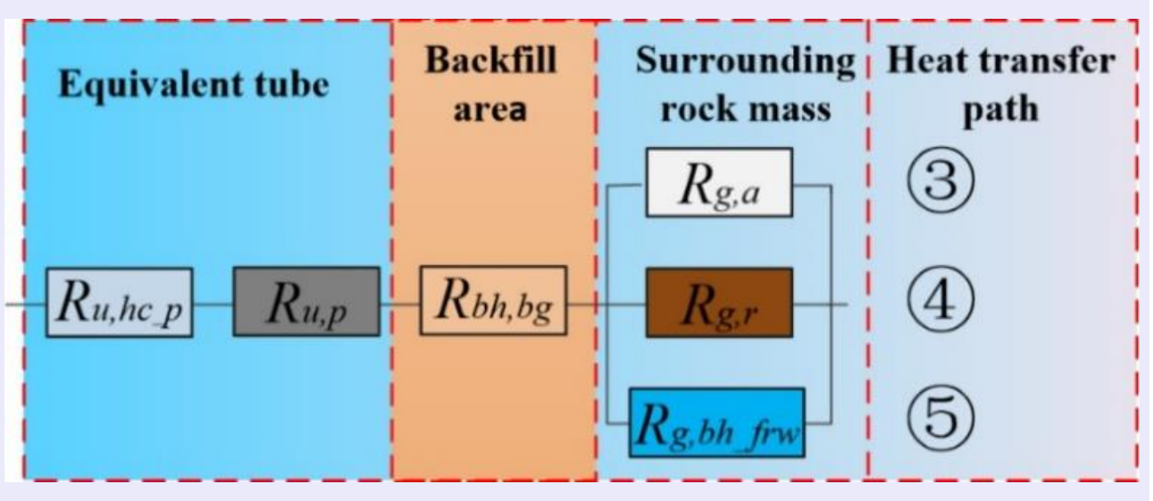


Fig. 8. Thermal resistance network under permeable backfilling conditions.

Results and Discussion

This study compiles hydrogeological and TRT data from a total of 18 boreholes placed in bedrock layers, across 8 GCHP project sites located in Guizhou, China, a typical region with shallow-buried bedrock.

ZK1 to ZK9 is primarily dolomite; ZK10 to ZK15 is primarily limestone; ZK16 to ZK18 is mainly sandstone. The thermal property parameters of 18 boreholes and the in-situ TRT test results are used for subsequent verification.

1.General standard calculation methods and TRT tests are used for verification:

The calculated permeable backfill values proposed in this study are highly consistent with the TRT measured values, especially in dolomite formations.

This is because the permeable backfill model incorporates the crucial heat transfer pathway of advection within the borehole, thus improves calculation accuracy.

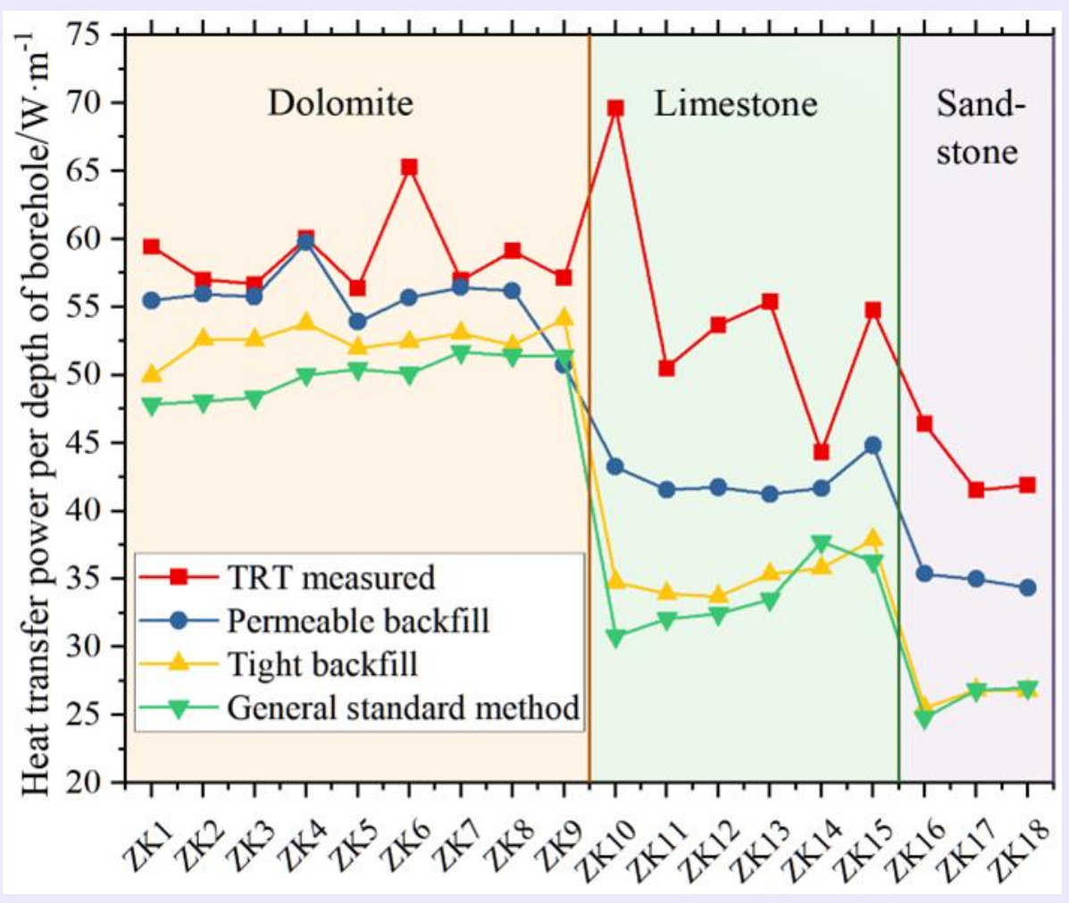


Fig. 9. Comparison among TRT measured values, general standard method, and analytical results by the proposed model (permeable backfill and tight backfill).

2. Analyze the reliability of various calculation methods in dolomite formations:

The TRT measured values exhibit a clear increasing trend with rising inflow. The method proposed in this study also shows a similar trend, but the general standard method exhibits an opposite trend.

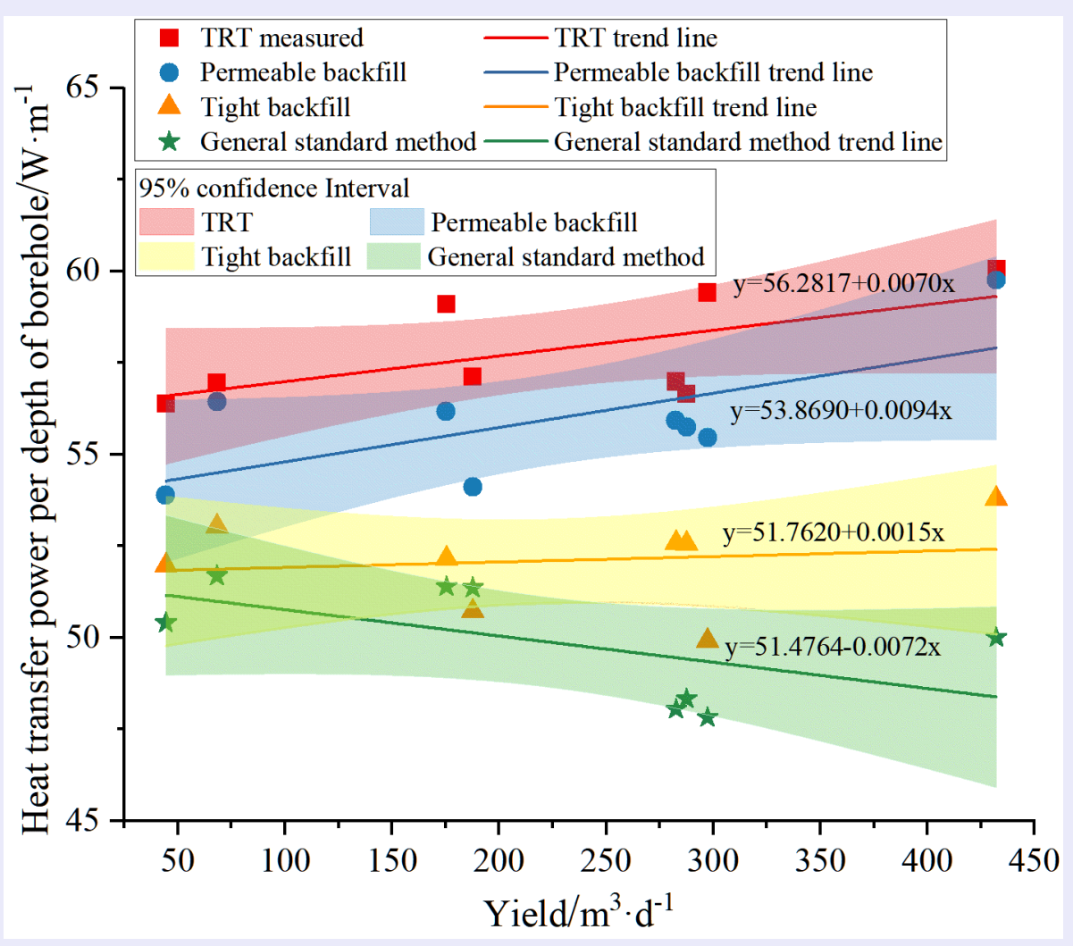


Fig. 10. Comparison of results from the TRT measured values, general standard, permeable, and tight backfill methods in dolomite.

This indicates that the general standard method is not suitable for BHE systems under bedrock hydrogeology conditions. The two are in high consistent, thereby verifying the reliability of the calculation method proposed in this study. The two are in high consistent, thereby verifying the reliability of the calculation method proposed in this study.

3. Validation by numerical simulation:

As show Fig.11 , the numerical simulation values are larger than these by the other methods. A deviation of up to 5% is acceptable. The results obtained by the theoretical calculation method proposed in this study are closer to the TRT measured values.

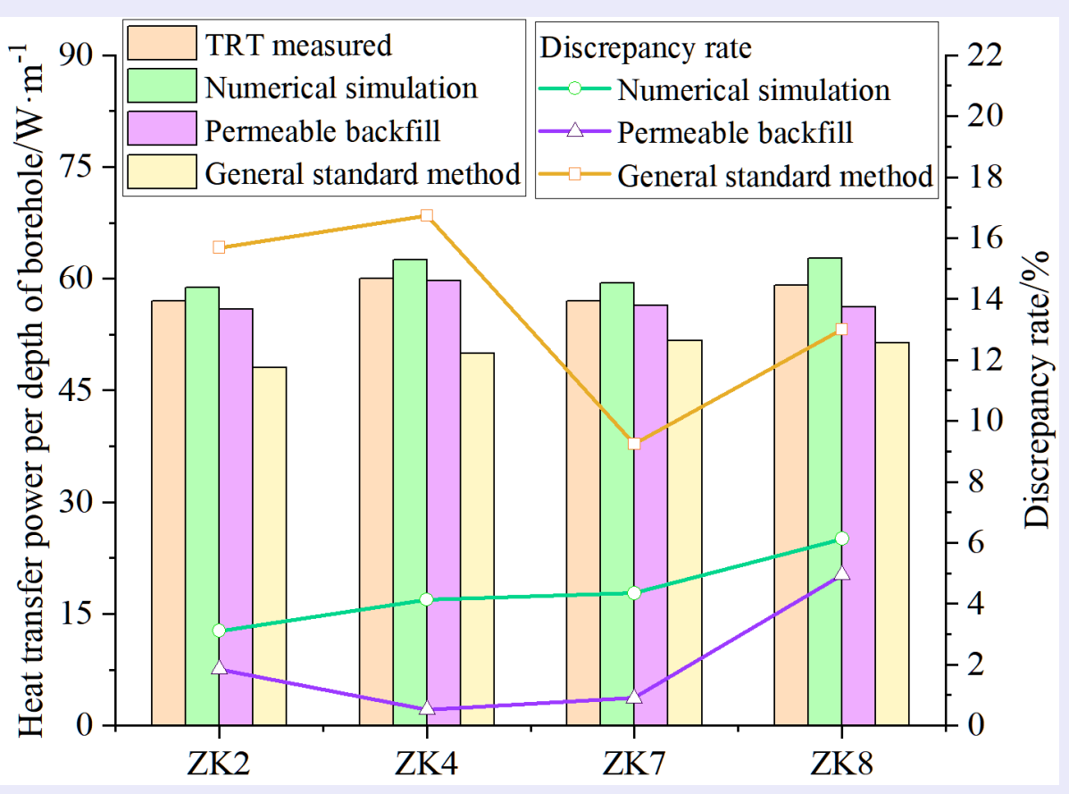


Fig. 11. Comparison of heat transfer power values obtained by the four methods (TRT, numerical simulation, permeable backfill model, general standard method).

Conclusion

The main conclusions drawn from all these work are:

- In the permeable backfill model, the heat transfer pathways and the thermal resistance network account for advection within the borehole, which improves calculation accuracy;

- Compared with the TRT measured data, especially in dolomite formations. The errors are within 5% and are even smaller than those from numerical simulation;

- This work holds significant importance for enabling more precise design of BHE systems in bedrock formations;

References

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