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本期焦点

CURRENT FOCUS

岩土热响应实验已广泛应用到地源热泵系统设计中。本文全面展现了恒温法热响应实验过程，可为地源热泵系统优化设计提供参考，同时也有利于推广恒温法热响应测试方法在地埋管换热器设计中的应用。

CONTENTS

The method of geotechnical thermal response experiment has been widely employed in designs of ground source heat pump system. In this paper, the thermal response experiment process of constant temperature method is presented comprehensively, which can provide reference for the optimization design of ground source heat pump system and promote the application of constant temperature thermal response test method in the design of buried tube heat exchanger.

恒温法热响应实验在地埋管换热器设计中的应用

THE APPLICATION OF THERMOSTATIC THERMAL RESPONSE EXPERIMENT IN DESIGN OF BURIED PIPE HEAT EXCHANGERS

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摘 要：岩土热响应实验已广泛应用到地源热泵系统设计中，其测试获得的岩土热物性参数对地埋管换热器的设计起着关键作用。本文针对河北某一实际工程建立了深度为200 m 的双 U 型垂直地埋管试验井利用恒温法热响应实验，对该试验井进行夏季排热和冬季取热运行工况模拟，获得岩土初始地温、进 / 出水温度变化曲线、单孔换热功率及每延米换热量等参数，进而根据线性模型反演出地层导热系数和热阻等热物性参数。本文全面展现了恒温法热响应实验过程，并对实验结果进行讨论分析，可为地源热泵系统优化设计提供参考，同时也有利于推广恒温法热响应测试方法在地埋管换热器设计中的应用。

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关键词：岩土热响应实验；恒温法；地埋管换热器；地源热泵；岩土热物性

引 言

随着我国加大开发利用清洁能源的力度，地源热泵作为开发浅层地热能的重要技术，得到了蓬勃的发展。地源热泵系统主要利用地埋管换热器将储存在土壤或者岩土里的热量提取出来，通过热泵系统给用户进行供暖或者制冷。然而，地埋管换热器作为地源热泵的核心部件，其换热是个复杂的非稳态过程，其换热特性受地下岩土热物性、地下水文地质条件、换热器材质及回填材质等因素的影响较大 [1]。其中地下岩土的热物性参数对地埋管换热器换热能力起关键作用，尤其是岩土导热系数，岩土导热系数越大，每延米的换热量较大，因此单位孔的换热能力较强 [2]。研究表明，岩土导热系数假如存在 10% 的误差，将会造成地埋管换热器设计长度误差在 4.5%-5%，将会出现不能满足建筑负荷或者造成建筑初投资浪费的现象 [3]。因此获取准确的岩土热物性参数，是设计地埋管换热器的关键依据，同时也保持地源热泵系统良好的经济性和运行的可持续性。

目前岩土热响应实验是获取土壤热物性参数最有效的途径，也是目前较为普遍的方法。自从 1983 年提出利用热响应试验方法来确定土壤热物性参数以来 [4]，国内外学者不断地推广与完善热响应测试方法 [5-6]，现已广泛应用到地源热泵实际工程中。目前，实际工程中应用最广泛的岩土热响应实验方法主要有恒热流法和恒温法 [7]。恒热流法虽然较为普遍，但该方法只能测试排热工况，且模型计算较为复杂且易出现较大误差现象 [8]。为此，我国研究者提出恒温法热响应实验，并对试验装置进行了改进，更为真实的反映地埋管换热器的换热能力和准确的测得岩土热物性参数 [9]。本文以河北省某项工程钻井为例，采用恒温法热响应实验获取试验井岩土热物性，更真实的展示地埋管换热器换热性能，提出并优化地埋管设计，以此为基础进行恒温法热响应实验的推广，同时为实际工程地源热泵地埋管换热器的优化设计提供一定参考依据。

1. 恒温法热响应实验理论方法与测试仪器

1.1 实验原理

岩土热物性参数作为一种热物理性质，无论对其进行放热或是取热试验，其数据处理过程基本相同。恒温法是建立稳定的地埋管换热器运行工况，从而确定地埋管换热器的换热能力的方法。由图 1 可以看出，流体经过电加热器加热（或制冷设备制冷）后，被送入到地下，由于加热（冷却）后的流体温度高于（低于）地下土壤的温度，故在土壤与管道内的流体之间存在热量交换，这样从地下再回到测试仪中的流体温度存在一定的变化，这就是地下土壤的温度响应。在仪器与地下管路相连的地方各设置一个温度传感器，这样就可以采集到管道平均温度的实时数值。在施工现场进行原位热响应测试，可获取综合了现场各种因素的实际结果，能够更准确的预测土壤的热物性，降低参数选取的不确定性，使地埋管换热器的设计更为合理。现场测试时，首先在埋设地源热泵系统地下管路的地面上施钻测试孔，测试孔与常规地埋管规格相同，然后按照实际施工的要求装好管路，填上回填料，然后再连接上热响应实验测试车，进行测试。

1.2 岩土热物性的计算方法

恒温法模拟试验是维持恒定的进水温度，建立稳定的地埋管换热器运行工况，集合供、回水温度温差数据，来确定地埋管换热器的换热能力。如公式 (1)：

$$Q = C\,\rho v \Delta t \tag{1}$$

式中：Q——加热功率，W；

C——水比热容，4.2×10^3 J/(Kg · °C)；

ρ——水密度，1.0×10^3 Kg/m3；

v——流量，m^3/h；

Δ t——进出水温差，°C。

线热源理论是当前大多数地源热泵埋管换热器传热模型的理论基础，其物理意义明确、计算简单方便，广泛应用于地源热泵地下埋管换热器的计算。恒温法热响应测试能直接获得单孔换热功率和延米释热量实测值，在获得测试参数基础上，利用线热源模型进行反演计算，可求得钻孔的平均热传导系数 λ、钻孔热阻 Rb 等参数，其线热源模型计算公式 (2) 如下：

$$T_f = \frac{Q}{4\pi\lambda H} ln(t) + \left[\frac{Q}{H}\left(\frac{1}{4\pi\lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) + R_b\right) + T_{sur}\right] \tag{2}$$

式中：T_f ——平均温度，° C；

A——热量扩散率，m^2/s；

Q——加热功率，W；

H——有效孔深，m；

λ——导热系数，W/(m•K)；

γ——欧拉系数，0.5772；

R_b——导热热阻，m•K/W；

T_{sur}——土壤的初始温度，° C；

r_b——孔的半径，m。

由于载热流体的平均温度与加热时间的自然对数成正比，关系式为 (3)，根据测试结果做出载热流体平均温度与时间对数的关系曲线 (理论上为直线)，确定该曲线的斜率 k，可由公式 (6) 求导热系数，并可推导出公式 (7)，也可在一系列假设的情况下得到。

$$T_f = k\,ln(t) + m \tag{3}$$

式中：

$$k = \frac{Q}{4\pi\lambda H} \tag{4}$$

$$m = \frac{Q}{H}\left(\frac{1}{4\pi\lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) + R_b\right) + T_{\text{sur}} \tag{5}$$

$$\lambda = \frac{Q}{4\pi kH} \tag{6}$$

计算钻孔热阻：

$$R_b = \frac{(C - T_{sur})}{q_c\ H} - \frac{1}{4\pi\lambda_s}\left[\ln\left(\frac{4\alpha}{\gamma_b^2}\right) - \gamma\right] \tag{7}$$

根据公式 (6) 计算延米释热量：

$$q_{c\,释热} = \frac{T_{fmax}(t) - T_{sur}}{T_{f\,试验}} q_{c\,试验} \tag{8}$$

根据公式 (7) 计算延米取热量实测值：

$$q_{h\ 取热} = \frac{T_{fmin}(t) - T_{sur}}{T_{f\,试验} - T_{sur}} q_{c\,试验} \tag{9}$$

式中：C_m——埋管深度范围内土壤的平均比热容，J/(kg ．℃)；

$q_{c\ 试验}$——试验工况时载热流体的单位孔深释热量，W/m；

$q_{c\ 释热}$——释热工况时载热流体的单位孔深释热量，W/m；

$q_{h\ 取热}$——取热工况时载热流体的单位孔深取热量，W/m；

$T_{f\ 试验}$——载热流体试验工况时的平均温度，℃；

T_{fmax}——载热流体释热工作工况时的平均温度，℃；

T_{fmin}——制冷流体取热工作工况时的平均温度，℃。

根据《浅层地热能勘查评价规范》(DZ/T0225-2009) 附录 A，钻孔延米换热量计算公式如下：

$$D = \frac{2\pi L|t_1 - t_4|}{\frac{1}{\lambda_1}\ln\frac{r_1}{r_2} + \frac{1}{\lambda_2}\ln\frac{r_3}{r_2} + \frac{1}{\lambda_3}\ln\frac{r_4}{r_3}} \tag{10}$$

式中：λ_1——地埋管材料的热导率，W/m•k (PE 管为 0.42 W/m•k)；

λ_2——换热孔中回填料的热导率，W/m•k；

λ_3——换热孔周围岩土体的平均热导率，W/m•k；

L——地埋管换热器长度，m；

r_1——地埋管束的等效半径，m，双 U 为管内径 4 倍；

r_2——地埋管束的等效外径，m，等效半径 r1 加管材壁厚；

r_3——换热孔平均半径，m；

r_4——换热温度影响半径，m，取 0.5 m；

t_1——地埋管内流体的平均温度（散热工况取 35 ℃，吸热工况取 4 ℃）；

t_4——温度影响半径之外岩土体的初始温度。

1.3 测试设备

热响应测试装置见图 1，该试验仪主要包括自动控制系统、自动采集系统、电加热设备、制冷设备、水泵、流量计、温度传感器、压力表等设备。表 1 是岩土热响应测试仪器技术指标。

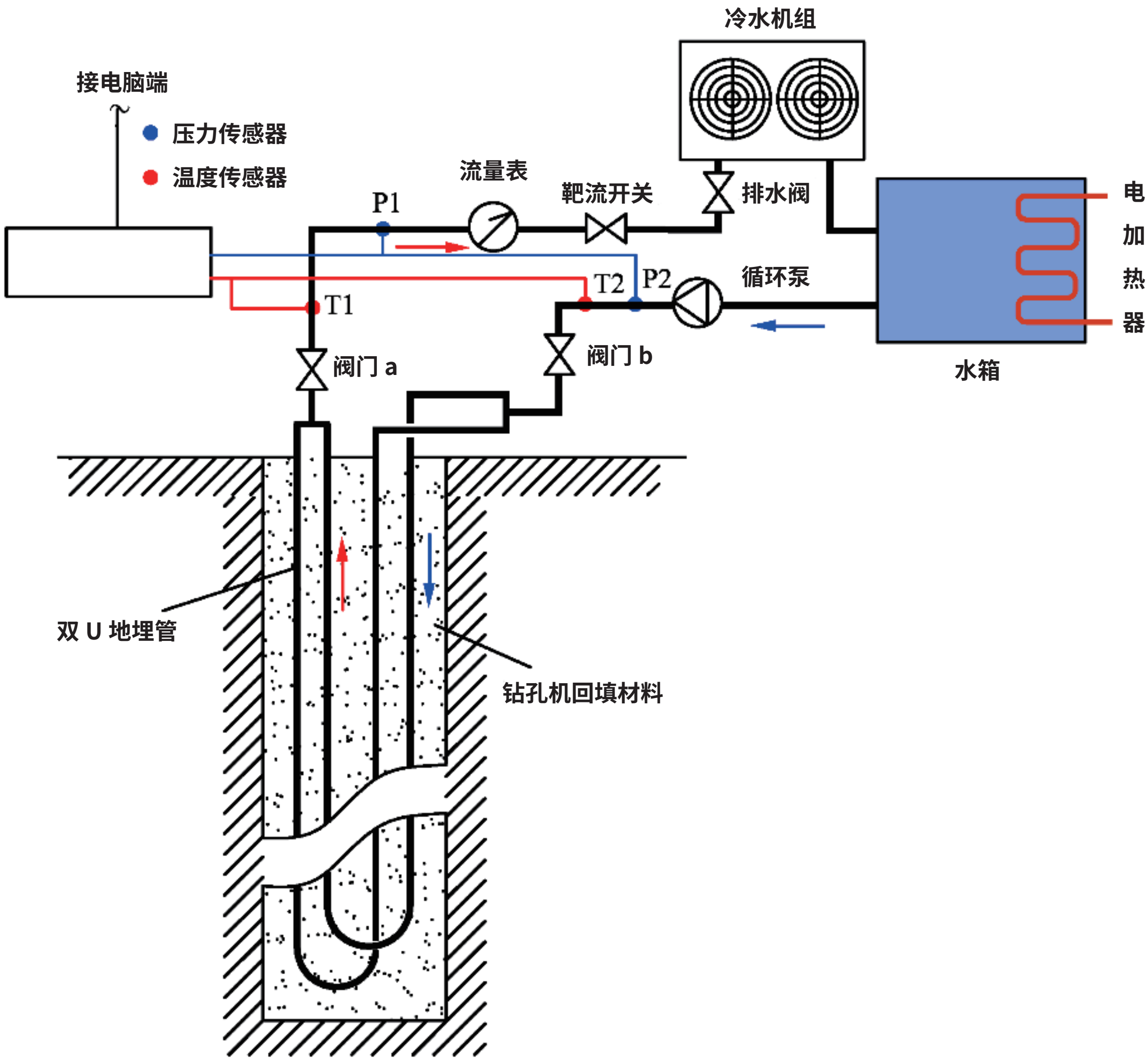

图 1. 恒温法热响应测试装置图

表 1 DR–40 岩土热响应测试仪主要技术指标

仪器名称	仪器测量量程	仪器精度
加热制冷设备	制热功率，制冷功率	/
	36 kW 可调，24 kW 可调	/
循环水泵	流量，最大扬程	/
	1-12 m^3/h 可调，30 m	/
功率传感器	量程	精度
	0-30 A	1.0 级
温度传感器	量程	精度
	-50 ～ +100°C	±0.15 °C
流量传感器	量程	精度
	0 ～ 12 m^3/h	0.5 级
压力传感器	量程	精度
	0 ～ 1.6 MPA	10 PA

2. 场地地质概况及试验井参数

该试验场地，地质构造以太古界斜长片麻岩等变质岩为基底，其上为中生代陆相盆地，自下侏罗统至下白垩统，层序齐全，堆积总厚度 6600 m 以上。钻孔 200 m 深度以内的地层自上而下依次为第四系卵石 (0 m-2.10 m)、第四系含砾亚粘土 (2.10 m-14.52 m)、侏罗系中统后城组砂岩 (14.52 m-20.00 m)、侏罗系中统后城组砾岩 (20.00 m-55.51 m)、侏罗系中统髫髻山组安山岩 (55.51 m-105.47 m)、太古界片麻岩 (105.47 m-200 m)。

水文地质条件：第四系为松散岩类孔隙水，岩性为砂卵砾石、亚砂土和砾石砂等。基岩构造裂隙和孔隙水。片麻岩、砂砾岩和火山岩出露区属基岩裂隙含水层，是工作区最主要的含水层。

试验井深 200 m，0-24 m 井孔径为 325 mm；24-200 m 井孔径为 235 mm。试验井 0-24m 下入 5mm 壁厚 325mm 螺纹钢管。双 U 地埋管换热器为 PE 管 (DN32 mm，内径 26 mm，壁厚 6 mm)，回填材料为中细砂。

3. 恒温法热响应实验结果与分析

测试设备均运行正常，本次共进行了 1 组初始地温测试、1 组夏季工况 (恒温法 35 °C)、1 组冬季工况 (恒温法 4 °C) 共 3 组热响应试验。

3.1 测试工作

根据本工程特点和场地范围，进行地埋管换热器原位热响应测试，试验井采用 PE 管双 U 地埋管换热

器，实际换热孔参数如下：换热孔成孔孔径 235 mm，成孔深度为自然地面以下 203 m。换热器埋设深度 200 m。管道的连接及试压：地埋管出 / 回水口至热响应试验仪管道连接完成后，使用电动打压泵，将管道压力提升至 1.2 Mpa，关闭截止阀，保压 30 min，无压降和渗漏。试压完成后将换热管与测试车连接，用打压泵向系统内注水并打开排空阀排空，检查了各个接头点，无漏水现象。地上管道外裹橡塑保温套做保温处理，厚度约 20mm。水电等外部设备连接完毕后，对测试设备各环节进行了检查，无误后开始运行。

3.2 管内流态判定

《地源热泵系统工程技术规范》第 4.3.9 节指出，地埋管换热器管内流体应保持紊流状态。因此对测试地埋管换热器流态进行判定，一般判定方法为临界雷诺数判别。对于任何管径和任何牛顿流体，判别流态的临界雷诺数却是相同的，其值约为 2000，依据雷诺数计算公式 (11) 及试验相关参数，可知管内循环水流量设置为 1.5 m^3/h

$$Re = \frac{vd\rho}{\mu} = \frac{vd}{\upsilon} \tag{11}$$

式中：Re——雷诺数；

v——流体流速，m/s；

d——管内径，m；

ρ——流体密度，kg/m^3；

μ——流体的动力黏度，Pa•s；

υ——流体的运动粘度，mm^2/s

3.3 初始地温测试

岩土初始地温这一参数是确定岩土热物性的必要参数之一，其准确度直接影响着岩土热阻和岩土导热系数的计算。与此同时，地埋管换热器的平均温度与岩土平均温度的温差是热传递的驱动力，因此岩土的初始地温测定对于地埋管换热器的设计相当重要 [8]。

本文岩土初始地温测试方法采用的是无功循环法，在测试前地埋管换热器内已充满水并放置 48 h，在不向换热器加载冷、热量时，利用水泵将水在地埋管内循环流动，直至水温趋于稳定状态且与岩土达到热平衡，此时地埋管内水温即为岩土初始平均温度 [10]。根据临界雷诺数判别，本文测试在 PE 双 U 地埋管内恒定流量是 1.5 m3/h，持续运行 23 h，直至水温达到稳定状态，停止测试 [11]。测试曲线如图所示，进、出水管及平均温度在 16 h 处，基本处于最终稳定状态，进 / 出水管平均温度稳定在 12.2 ℃，即岩土初始地温为 12.2 ℃。

3.4 恒温法岩土热响应实验模拟夏季和冬季实验结果分析

(1) 恒定进水温度为 35 ℃的夏季工况热响应实验

岩土热响应实验模拟夏季工况，设定恒定进水温度 35 ℃，流量 L=1.5 m3/h。测试持续时间为 58 h，

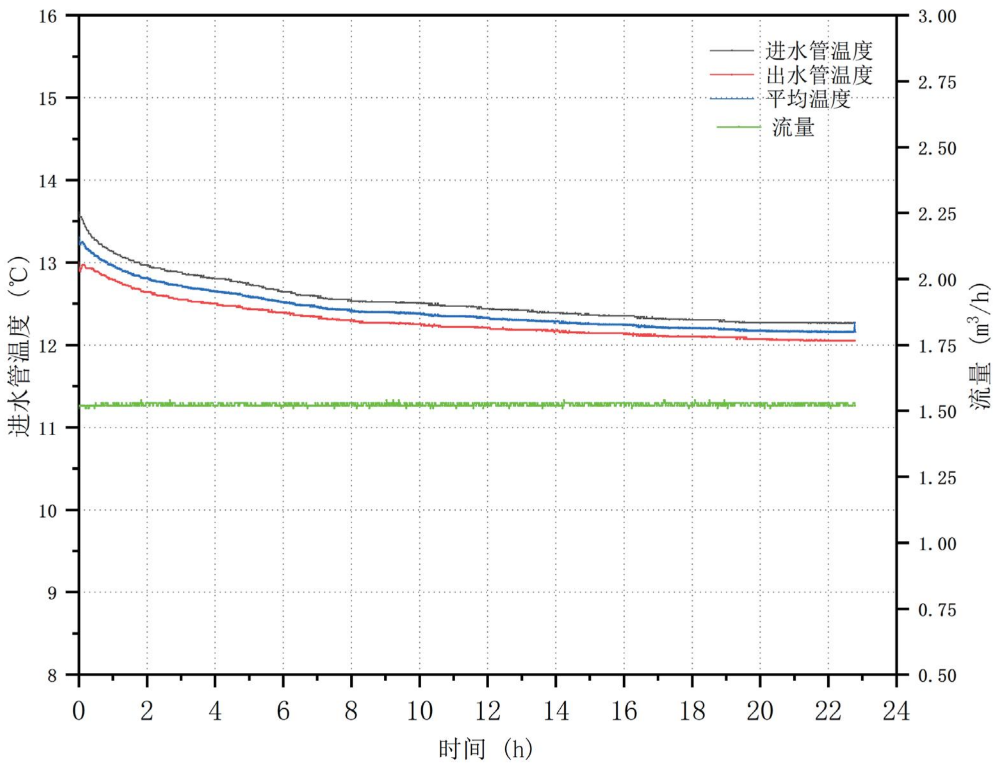

图 2. 地埋管换热器岩土初始地温测试图

稳定时间为 49 h。测试埋管进出水温度、平均温度、流量、功率如图所示。其中图中实时功率，是在恒定温度 (T=35 ℃) 的情况下利用计算的实时温差，根据公式 Q=CmΔT 得到实时的换热量 (即排热功率)。从图中看到，夏季工况运行 9 个小时后，进出口温度趋于稳定，这是由于夏季工况设置进水口温度为 35 ℃，高于岩土初始地温 12.2 ℃，两者温差为 22.8 ℃，需要热响应测试仪加热一段时间维持动态平衡，最后趋于稳定。图中曲线在 7.5 小时前的波动是由于加热箱波动引起。图中显示，进出口温度稳定时间超过 12 h，满足恒温试验条件。

单位每延米换热量是岩土热物性其中重要的一个参数，其能反演导热系数，也直接反映着钻孔换热量能力，是地埋管换热器设计的重要参考依据。如图所示，单位每延米换热量增幅较大，其变化幅度及波动性较为频繁，这是由于夏季工况进水温度 T 为 35 ℃，与周围岩土温差较大，根据傅里叶定律，热量传递速度较大。随着热响应试验进行 10 h 以后，单位每延米换热量趋于稳定状态，这是由于周围岩土温度一定达到了一个动态平衡，热量在周围土壤中的扩散速率减缓，逐渐趋于动态平衡 [12]。当地埋管换热器管内流体与周围岩土达到动态平衡后，会形成热量的堆积增大导热热阻，达到 80 W/m 后，换热趋于稳定，稳定后的每延米换热量为 80 W/m，舍弃前 2.5 h，求得其平均换热量为 84.79 W/m。通过此试验可知，在本试验条件下，恒温法热响应实验进行夏季工况，至少需要 10 h 的温度波动阶段以进入稳定状态，因此恒温法热响应测试需要适当延长试验时间，才使得测试结果较为准确。

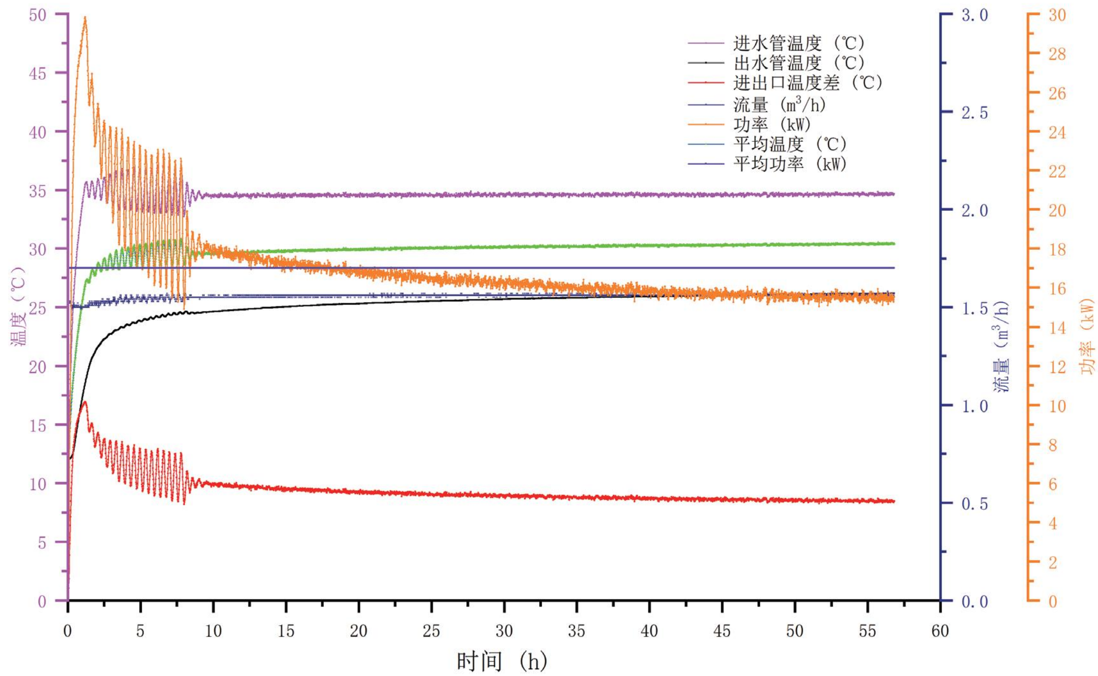

图 3. 地埋管测试孔夏季排热工况下测试成果图

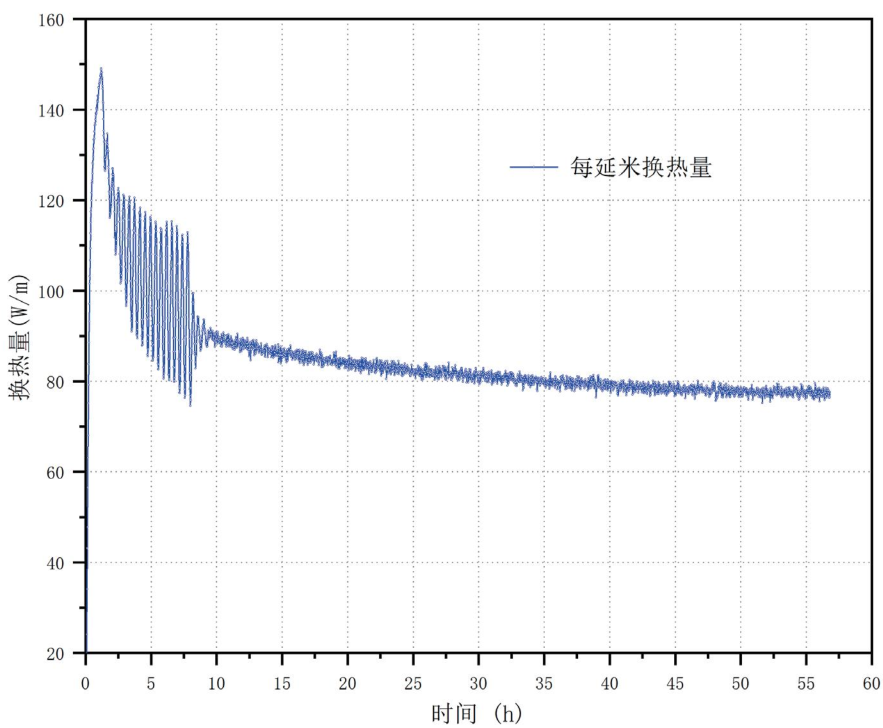

图 4. 地埋管测试孔夏季排热工况下每延米换热量

(2) 恒定进水温度为 4 ℃的冬季工况热响应试验

岩土热响应试验模拟冬季工况，设定进水温度为 4 ℃，流量为 1.53 m^3/h，测试时间约 50 h，系统运行参数如图 5 所示。图中冬季运行功率参照夏季功率计算方法，其曲线变化趋势与图中进 / 出水管温度变化趋势基本吻合，测试孔换热功率为 6.09 kW/ 孔。图中所示，系统运行 26 h 后，进水管温度稳定在 4 ℃，稳定时间接近 24 小时，符合规范要求。

如图所示，进水温度与出水温度变化曲线相对平滑，前 26 h 进 / 出水温度呈现下降趋势，两者温差基本保持在 3.2-3.75 ℃左右 (前 0.5 h 除外)，这是由于岩土热响应测试期间，模拟取热工况下，空调机组自身系统制冷量保持在一个定量及埋管内介质与钻井填料之间非稳态导热造成的，持续与钻孔周围岩土进行换热，进水温度与出水温度持续下降，在 26 h 后达到稳定状态，进水温度保持在 4 ℃。其中系统进入稳定时间需要 26 h，这是由于进 / 出水温差较小和空调机组系统制冷量局限共同作用所致。其中 26 h 处进水温度起伏波动是由空调机组运行波动引起的。

如图所示 6，每延米换热量变化趋势在 26 h 基本处于稳定状态，相较于图 4 夏季工况，稳定时间较长，冬季取热工况下进 / 出水温度差较小，造成其热传递速度较慢，与周围岩土换热量较少，若要达到取热动态平衡，需要较长的时间。与此同时，冬季取热工况下单位延米换热功率表为 30.45 W/ 延米，每延米换热量相比于夏季工况较低，其中一个原因是进出水温差较小引起的，冷量在钻井周围土壤的堆积较慢，使得取热处于变化的过程，冷量堆积一定量后，取热保持恒定。另一个原因是岩土初始地温相对较低，造成进水口温度与周围岩土换热速率较慢。此试验也验证了，岩土初始地温对于地埋管换热器换热能力的影响

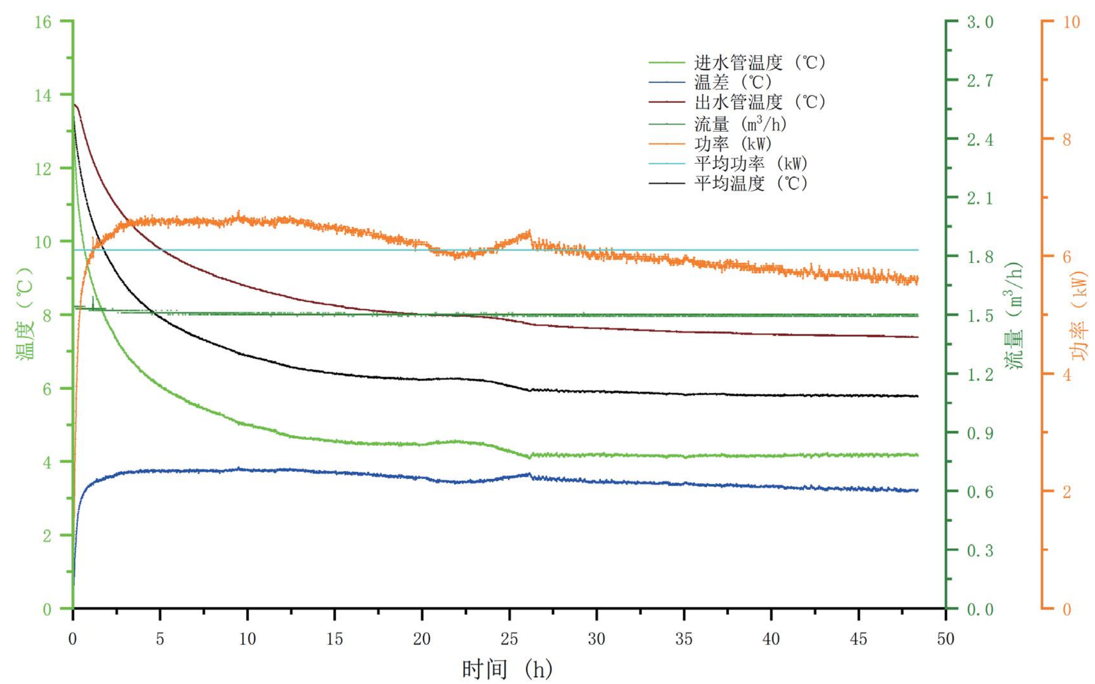

图 5. 地埋管测试孔冬季取热工况下测试成果图

重要性。在本试验条件下，模拟冬季取热工况下，需要 26 h 才能达到稳定状态，相较于夏季工况，稳定时间较长，恒温法热响应实验需要更长时间，才能保证岩土热响应实验测试准确。

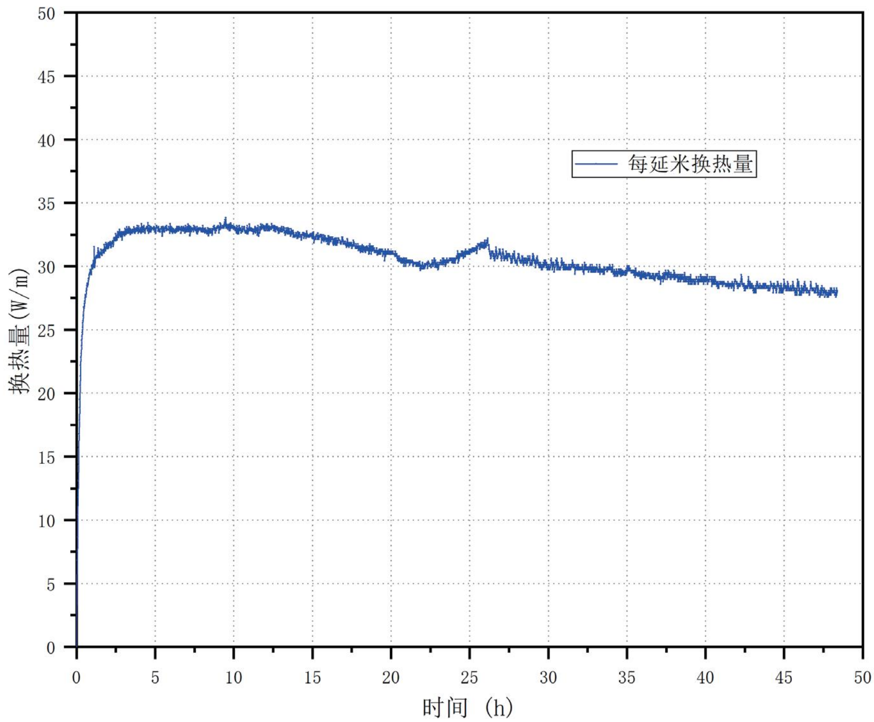

图 6. 地埋管测试孔冬季取热工况下每延米换热量

4. 岩土热物性参数测试结果

通过恒温法岩土热响应实验可较为直观真实的获得钻孔在夏季和冬季工况下单孔换热功率和每延米换热功率参考值。依据测试结果，利用钻孔线性模型，根据公式进行模拟计算可获得岩土热物性导热系数和热阻，PE 管双 U 地埋管换热器实验孔详细测试结果如下：

1) 模拟夏季工况恒定进水温度为 35 °C，流量 1.5 m^3/h 测试条件下，单位延米换热功率参考值为 84.79W/ 延米，单孔换热功率 16.95 kW。

2) 试验孔模拟冬季工况恒定进水温度为 4 °C，流量 1.5 m^3/h 测试条件下，单位延米换热功率参考值为 30.45 W/ 延米，单孔换热功率为 6.09 kW。

表 2. 岩土热响应试验参数

测试	孔深	初始地温	测试工况	导热系数	热阻	延米换热量	单孔换热量
PE 双 U 地埋管	203	12.27	夏季工况	1.68	0.08	84.79	16.95
			夏季工况	1.01	0.09	30.45	6.09

5. 结论

岩土热响应测试方法能够更直观、真实、准确的获得岩土热物性参数，是地埋管换热器的设计重要参数依据，更好的展现地埋管换热器的换热性能。本文利用恒温法岩土热响应试验方法对钻孔进行了现场热响应测试，主要结论如下：

1）恒温法热响应实验相较于其他测热物性参数试验，能够模拟夏季排热和冬季取热工况，更真实、准确的获取热物性参数，对于地埋管换热器设计更为真实准确，并可以直观获得每延米换热量。

2）恒温法热响应实验真实的模拟了地埋管换热器取热和排热工况，试验证明地埋管换热器在排热工况换热能力比取热工况下高，单位孔换热量高于 10.9 kW/ 孔，也间接验证了岩土初始地温对于地埋管换热器换热能力影响较大。

3）恒温法热响应实验期间夏季排热工况稳定时间比冬季取热工况稳定时间较短，建议进行恒温法试验时延长冬季取热工况时间；进行相关参数计算时，建议舍弃较长的冬季取热工况不稳定数据，可提高试验测试岩土热物性参数准确性。

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让加速地热服务双碳目标成为WGC2023的中国亮点

TO MAKE "ACCELERATING THE DUAL CARBON GOALS THROUGH GEOTHERMAL SERVICES" THE HIGHLIGHT OF CHINA IN WGC2023

作者：郑克棪
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中国获准主办2023年世界地热大会，机会难得。我一直在想：我们应该拿出鲜亮光彩的形象和成果奉献给2023年世界地热大会（WGC2023）。

历届世界地热大会的亮点

国际地热协会1989年成立，1995年首场的世界地热大会在意大利佛罗伦萨举办。在世界地热发电的起源地开启了五年一次世界地热大会系列，大会20厚的5册论文集创造了地热论文集空前的记录。

2000年世界地热大会在日本别府和盛冈举行，61个国家1700多位代表参会，展示了小国土面积的地热发电强项。

2005年世界地热大会在土耳其安塔利亚举行，83个国家1500多位代表参会。会后土耳其地热法实施使地热发电转为突飞猛进。

2010年世界地热大会在印度尼西亚巴厘岛举行，85个国家2500多位代表参会。会后印尼设立地热法使不受矿产资源法限制，地热发电快速增长。

2015年世界地热大会在澳大利亚墨尔本举行，82个国家1600多位代表参会。澳大利亚欠缺水热型地热资源，地热开发较晚，但展示了兆瓦级发电。

2020年世界地热大会在冰岛雷克雅未克举

行，仅举行了线上开幕式，2021 年 3-6 月举行几次线上会议，因全球疫情影响的推迟无疑给大会造成巨大影响。

中国地热的成就与面临任务

中国地热发电虽然起步较早，但现今明显处于落后状态。中国地热直接利用在 1995 年世界地热大会上尚不及冰岛，排名世界第二；但 2000 年世界地热大会以来就始终是中国第一，且越做越强，远超第二、三、四名的总和。中国的地源热泵发展更快，短短 20 多年攀上了世界最高峰，遥遥领先后续名次，他们已无力追回状态。我们就是靠此赢得了 2023 年世界地热大会主办权，我们似乎要给世界地热增添一抹新鲜色彩让世界地热从注视地热发电的传统习俗中得到额外的新感受：原来地热直接利用也可以如此精彩。

地热可为双碳目标切实贡献

借助国家节能减排政策支持可再生能源发展，这些年国内地热利用获得长足进步。但是与其他可再生能源相比，中国地热还没有做强，即使在近几年提倡北方地区冬季清洁供暖的形势下，地热从技术和经济可行性所决定的性价比来看有优势，但地热做出的贡献没有与其优势相匹配，不少场合地热仍然是被舍弃的。

地热可以为碳达峰和碳中和作切实贡献，其力度是显而易见的。

（1）二氧化碳排放率

天然气自诩为清洁能源，只是其碳排放率比煤炭少了一半。但是以同样百万度电的二氧化碳排放作对比，天然气的排放仍是地热（风电、水电、核电）的 31 倍。

（2）能力系数

地热、风电、水电、核电的二氧化碳排放率均属最低档，但他们的能力系数还有差异，地热最高 0.72，水电居中 0.40，风电最低 0.22。太阳能光伏发电的二氧化碳排放率高于地热和风电，且能力系数还是最低 0.14。

（3）碳排综合贡献比较

鉴于上述两大制约因素，我们可以引进“碳排综合贡献数”，设为百万度电的 2 吨与年产百万度电的兆瓦数的乘积。于是得出：煤炭和石油为冠亚军，碳排综合贡献数分别为 20 万和 18 万；天然气为季军 9 万多；接着太阳能为 3 万多；生物质能 1 万多；风电 7 千多；水电 4 千多；地热 2 千多；核电低于 2 千居末位。这就是碳排综合贡献的排序，所以要实现碳达峰、碳中和，天然气不宜多用，核电和地热才是能力最优的上品。

创建 2023 的中国亮点

既往 20 年中国地热在世界地热大会的亮相使中国地热走向了世界，拿下了世界地热直接利用的桂冠，取得如此辉煌成就并非完全由中国地热行业本身的努力，这里有国家政策层面的巨大优惠支持。在这样的基础上，我们可以期望在 2023 世界地热大会再创中国新亮点。

（1）在实现中国碳达峰和碳中和的进程上，让地热作出更大贡献，应该可以成为 2023 世界地热大会的中国亮点。按国家能源局综合司在《关于促进地热能开发利用的若干意见（征求意见稿）》中提出的我国地热能发展目标，到 2025 年地热能供暖（制冷）面积比 2020 年增加 50%。仅此数据与碳达峰目标还相距甚远，我们需要更大努力。

（2）经过去年的地热发电前景百人论坛和媒

体报道，加上今年两会诸多委员和代表提案，业界估计国家对地热发电上网电价的补贴政策可望落实，若如此，则必将迎来我国地热发电的大增长，目前大型国企中核集团、三峡集团等都规划了地热发电项目正在实施。这将有效改变我国地热发电的落后局面。

（3）我们应该遵循地热科学规律，整顿地热管理秩序，热盼设立《地热法》，至少从一刀切关停地热井的行政命令中理清地热管理乱象，由于未从源头找出问题解决，所以既没管好，又添了新问题，甚至在尚未解决的地热多头管理中有地方新添了让城管来管理。这种局面是让国际上看笑话，应该用革新、创新给出一个体面转变的新亮相。

（4）积极办好 2023 世界地热大会从现在做起。迫于疫情影响的世界地热大会 2020+1，采取了积极应对措施，在推迟的 10 月冰岛实体会议前，举行 3-6 月的线上开场，但组委会对这次中方的响应（出错、拖延）不满意。我们应吸取教训，努力改正，挽回形象。

（注：原文刊登于 2021 年 6 月《中国地热》杂志，转载请注明出处）

2021 地热产业企业家论坛暨联盟年会开幕辞

OPENING REMARKS OF THE 2021 GEOTHERMAL INDUSTRY ENTREPRENEURS' FORUM AND ALLIANCE ANNUAL MEETING

尊敬的各位来宾，女士们，先生们：

大家好！

今天，由中国地热与温泉产业技术创新战略联盟（以下简称联盟）、中国煤炭地质总局水文地质局、陕西省煤田地质集团有限公司与徐工基础工程机械事业部共同主办，中矿矿业大学等单位协办和支持的“2021 地热产业企业家论坛暨联盟

年会”将在古老而美丽的历史文化名城徐州隆重召开。大家齐聚一堂，将共同探讨交流我国地热产业发展的新机遇，共同研究行业在碳达峰，碳中和背景下的国家政策、产业创新、技术进步、国际合作等议题。

近年来为促进地热产业快速发展，国家相关主管部门相继发布了多项支持鼓励政策。

2016 年 3 月，《国家能源局关于印发 2016 年能源工作指导意见的通知》提到要积极开发利用地热能、生物质能等新能源。

2017 年 12 月，国土资源部等 3 个部，《关于加快浅层地热能开发利用促进北方采暖地区燃煤减量替代的通知》提出了到 2020 年，浅层地热能在供热（冷）领域得到有效应用，应用水平得到较大提升，在替代民用散煤供热（冷）方面发挥积极作用，区域供热（冷）用能结构得到优化，相关政策机制和保障制度进一步完善，浅层地热能利用技术开发、咨询评价、关键设备制造、工程建设、运营服务等产业体系进一步健全与强化。

2020 年 1 月，全国人民代表大会，《对检查可再生能源法实施情况报告的意见和建议》提到要加强深海、远海风电和深层地热能的研发攻关。

2021 年 2 月，《国家能源局关于因地制宜做好可再生能源供暖工作的通知》提出积极推广地热能开发利用。重点推进中深层地热能供暖，按照“以灌定采、采灌均衡、水热均衡”的原则，根据地热形成机理、地热资源品位和资源量、地下水生态环境条件，实施总量控制，分区分类管理，以集中与分散相结合的方式推进中深层地热能供暖。

2021 年 9 月，国家发改委等八部门联合发布《关于促进地热能开发利用的若干意见》目标：到 2025 年，各地基本建立起完善规范的地热能开发利用管理流程，全国地热能开发利用信息统计和监测体系基本完善，地热能供暖面积比 2020 年增加 50%，在资源条件好的地区建设一批地热能发电示范项目；到 2035 年，地热能供暖面积比 2025 年翻一番。

相关政策的密集出台，必将使行业迎来广阔的发展空间和前所未有的历史机遇，在此基础上联盟也将发挥行业带动引领作用，推动产业相关政策落实，促进行业技术项目合作，提供企业所需各项服务。

本次会议以“地热产业政策、机遇与未来”为主题，以“合作、发展、共创、共赢”为宗旨，解读并分析地热产业宏观经济形势与技术创新引领；探讨浅层、中深层与干热岩地热能开发利用，地热能勘查、设计、钻探、施工、地下水开采与回灌，地热供暖系统的建造、调试、运营与管理，温泉产业发展趋势、项目工程的设计运营等话题。邀请地热行业知名专家学者、政府相关职能部门领导、地热行业需求与供应企业、金融机构等优秀代表共谋发展、交流经验、互通信息，助力地热产业相关单位突破发展瓶颈，搭建形象宣传平台、品牌推广、商务合作的最佳桥梁。

本次大会的顺利召开，得到了各界人士及在座各位的大力支持和信任，在此向你们的到来表示诚挚的欢迎和衷心的感谢，希望本次大会可以为地热产业开发领域的朋友们提供一个获得信息、结交朋友、取得成效的服务平台。使与会来宾在会议上收获满满，在地热能开发利用产业的前进道路上建功立业、再创辉煌。

最后预祝“2021 地热产业企业家论坛暨联盟年会”取得圆满成功。

谢谢大家！

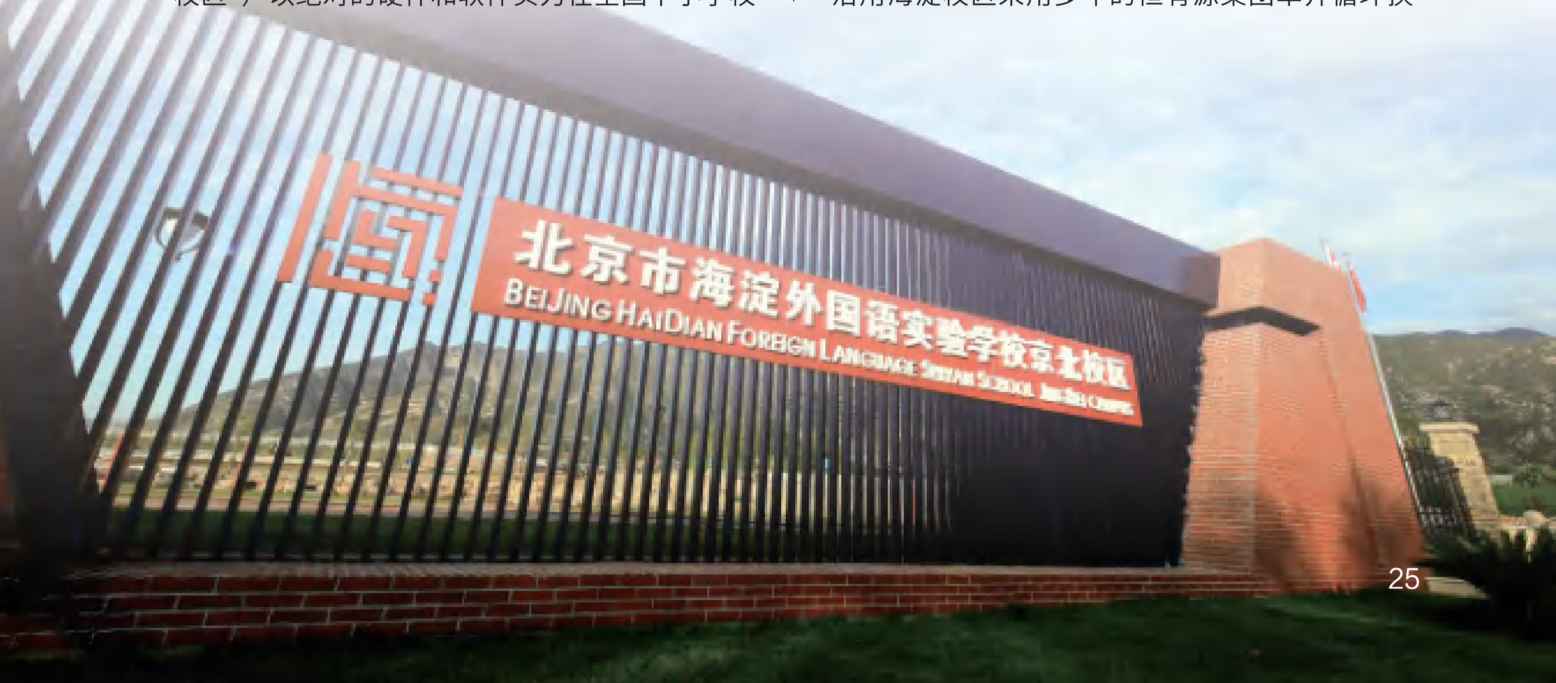
联盟总顾问国务院资深参事代表

王秉忱

海淀外国语及其京北校区：用浅层地热能为孩子们保驾护航的20年

Haidian Foreign Language Academy and its Northern Beijing Campus: 20 YEARS OF PROTECTING OUR CHILDREN THROUGH SHALLOW GEOTHERMAL ENERGY TECHNOLOGY

小生灵云集的动物园，青翠的草地，四季恒温的泳池，设施精良的综合体育中心，专业齐全的冰雪运动中心、滑雪练习场，用实际行动践行“体教融合、艺教融合、科教融合”理念的北京市海淀外国语实验学校京北校区（以下简称“京北校区”）以绝对的硬件和软件实力在全国中小学校中被广为赞誉。作为北京市乃至全国负有盛名的学校，北京市海淀外国语学校京北校区不仅在教学理念上与北京校区一脉相承，在建设环保绿色生态校园方面也继承了北京校区的传统。为了给学生们打造低碳环保舒适的学习环境，京北校区沿用海淀校区采用多年的恒有源集团单井循环换



热地能采集技术给全校冬季供暖，夏季制冷，同时保证了学校的游泳馆和生活用水，节能减排又高效清洁。

一切为孩子们着想。在 20 多年前，海淀外国语学校就开始了环保低碳校园的实践。海淀外国语学校早在 2001 年就已经与恒有源科技发展集团有限公司合作，为学生打造舒适环保的学习环境，恒有源集团的单井循环换热地能采集技术不仅保证学校冬暖夏凉，还提供学校游泳馆和生活 24 小时热水。20 多个春秋的相伴，恒有源集团的单井循环换热地能采集技术持续创新，其成果不仅让师生们切身感受到了环保低碳的舒适，也让学校建设环保校园的决心更加坚定。

以冬奥精神为学生打造冬暖夏凉场馆

成立于 1999 年的北京市海淀外国语实验学校，经过二十多年的已发展成为海淀外国语教育集团，在国内外有多个校区。北京市已建立“两校一园多址”，“两校”指的是北京市海淀外国语实验学校和北京市海淀国际学校，“一园”指的是北京市海淀外国语实验学校附属幼儿园（海淀 / 京北 / 朝阳园），而“多址”指的是海淀和京北两个校区：海淀校区位于北京市海淀区，京北校区坐落在首都北部生态新区，位于河北怀来和延庆两处，与冬奥场馆也是相距咫尺。

从基础设施上看，京北校区的规模和设施齐备，不仅包括各校区都有的动物园、游泳馆、大型室内运动场馆，还针对学校区位特色增加了独有的冰雪特色项目，设置了冰雪运动中心、滑雪练习场、网球馆、羽毛球馆、击剑馆、大型剧场等场馆。不仅如此，集团与北京市射击运动协会达成合作协议，在京北校区建立青少年射击运动中心，从小培养青少年对射击运动的爱好，也为国家级专业运动队提供后备力量，国家体育总局为奥运储备中国国少队人才的冰雪项目基地和网球项目基地也落户于此。更为特别的是，京北校区的学生还能坐着小火车去上学，足见教学环境的优良。

据了解，京北校区在建筑设计十分人性化，学生的宿舍、教室、食堂、室内篮球场、游泳馆等场所是彼此相通的，很好地避免了孩子们运动完后一身大汗地在户内外不同温差中切换的情况。不仅如此，学校还为每栋宿舍楼都配备了中央空调和新风系统，冬暖夏凉。

而保证京北校区孩子们的室内环境四季恒定，除了建筑设计外还有一个必不可少的因素：恒有源单井循环换热地能采集技术。由于海淀校区已经使用该技术近 20 年，充分感受到了恒有源单井循环换热地能采集技术带来的巨大优势：冬供暖夏降温，低碳环保，24 小时热水。

海淀外国语学校京北校区一期项目坐落在张家口市怀来县北辛堡镇原乡，建设校区共 6 栋楼，包括 1# 小学部、2# 中学部、3# 海外剧场、4# 综合体育中心、5# 冰雪中心、滑雪大厅等，供暖冷总建筑面积 59292.93 ㎡。自 2019 年 9 月起投入使用。

“一切为了孩子，为了孩子的一切，为了一切的孩子。”宋庆龄先生这三个“一切”不仅成为一代又一代教书育人者的座右铭，也是每个有担当者义不容辞

的责任。作为浅层地热能行业的领军企业，恒有源集团在建设北京市海淀外国语京北校区时更是秉承了这三个“一切”的理念，集中公司上下合力，利用浅层地热为孩子们的每个春夏秋冬护航。

室内四季如春 让孩子们学习更舒适

滑雪、滑冰、射击、击剑、骑马，京北校区的孩子们在学校可以享受全方位的素质教育。打造舒适的学习环境，是校方和恒有源集团共同的责任。该项目依据学校区域内建筑物功能，采用恒有源地能热泵环境系统，系统共设置 4 个冷热源集中机房、1 个集中换热站及 22 口恒有源单井循环换热地能采集井，采用地能集中供给，各机房独立运行的方式，可满足建筑物的冬季供暖、夏季制冷、全年提供生活热水及泳池加热的需求。

无论室外天气如何变幻，室内四季每日如春。通过恒有源地能热泵环境系统，根据室外环境温度，各建筑室内温度可以在 18°C -26°C之间随意调节，分别满足冬季和夏季对室内环境舒适度的要求。生活热水系统供水温度设置 40-45°C，24 小时不间断供水。

节能环保年替代电厂电煤 1844 吨

在依山傍水的京北校区不仅有包罗万象的课堂，还有学生们处处可以感受到的环保低碳践行理念。在舒适的基础上更环保低碳是项目的初衷。计算项目每年冬季供暖总用电量为 226.78 万度。与电锅炉供暖相比每年节电 551.8 万度，节省电煤 184 吨；减排与直接供暖锅炉比，每年节煤 90.4 吨，减少排烟量 10 万标立方米，减排二氧化碳 236.8 吨，减排二氧化硫 0.3 吨。

项目每年夏季制冷总用电量为 50.89 万度，比传统中央空调系统节电量约为 17.11 万度电。因不采用冷却塔，没有水的蒸发损失，每年节水 396 吨。

经过运行分析计算，该项目耗电量平均为冬季供暖和热水 38.2kW•h/ ㎡（含 1400 人的生活热水），夏季 8.6 kW•h/ ㎡（夏季余热回收免费制热水和辅助制冷），全年供暖、制冷和提供生活热水共耗电量为 46.8kW•h/ ㎡，按照居民电价 0.52 元 / kW•h 计算，全年运行费用为 24.4 元 / ㎡（146 天供热，200 天热水，365 天泳池加热，90 天制冷）。

恒有源的地能热泵技术节约费用超四成

该项目利用单井循环换热地能采集技术采集地表下百米以内深度的土壤、砂石、地下水中蕴含的低于 25°C的低温热能，与成熟的热泵技术相结合，为建筑物供暖、制冷、提供生活热水。技术使用过程中没有水的消耗，对地下水无污染，不会产生潜在地质灾害。

系统制冷产生的热量可直接通过热泵机组实施热回收用作制备生活热水或用于泳池池水加热，实现系统能量的循环利用。同时，项目实现了原创技术的完全市场化，参考以往类似项目实际运行情况并结合本项目特点，在没有获得任何项目相关补贴的情况下，可实现项目的低成本运营。年均运行费用 24.4 元 / ㎡，较张家口市 2018 年发布执行的张家口市非居民（学校）供热价格 44.1 元 / ㎡（建筑平米）节约 44.7%。

目前，京北校区三期也正在建设规划中，未来将开展与中国科学院、中国农业科学院等北京各大科研院所的战略合作，打造充满科技感的未来科学城，让孩子们不仅可以仰望星空，还能共同探索世界。而恒有源单井循环换热地能采集技术也会继续与海淀外国语学校携手并进，合力为孩子们打造更加环保舒适的教学环境，利用浅层地热在孩子们前行的路上保驾护航。

东南沿海干热岩资源成因模式探讨及勘查进展

DISCUSSION AND PROGRESS-TRACKING OF THE FORMATION MODEL OF DRY HOT ROCK RESOURCES IN THE SOUTHEAST COASTAL AREA

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摘　要：干热岩资源是地热资源的重要组成部分，绝大部分以开采地壳中中生代以来中酸性侵入岩体中所蕴含的热量为主。东南沿海地区是我国最主要的高放射性花岗岩分布区，发育大面积的中生代酸性花岗岩体，是寻找干热岩的良好靶区。本文通过研究东南沿海大地构造背景、区域大地热流分布、地壳厚度、居里面埋深及新构造等条件，分析了东南沿海干热岩资源的赋存背景，对福建地区是否存在干热岩进行了探讨，并通过控热构造分析提出了东南沿海干热岩资源的成因模式，初步建立了东南沿海干热岩成藏的三元聚热模型，总结了漳州、惠州等地区的干热岩资源靶区勘查进展，相关研究可为今后我国东南沿海地区干热岩勘查评价提供了基础。

关键词：干热岩；东南沿海；成因模式；勘查进展

引 言

干热岩（Hot Dry Rock-HDR）是地热资源的重要赋存形式，指地层深处（一般指地下3～10km）存在的没有水或蒸汽的致密的热岩体。干热岩分布广泛，是未来地热开发的主要方向。据麻省理工学院2006年报告，只要开发美国3500~7500m深度2%的干热岩资源储量，就将达到260000 EJ，是美国2005年全年能源消耗总量的2600倍，有极大的开发潜力。据初步估算，中国大陆3~10km深处干热岩资源总计为2.5×1025J，相当于860万亿吨标煤，若能采出2%，即相当于中国2015年全国一次性能耗总量的4000倍。

干热岩地热发电与核能、太阳能或其它可再生能源发电相比，尽管目前技术尚未成熟，但作为重要的潜在能源，已具备了一定的商业价值。到目前为止，中国干热岩资源开发及其技术研究十分薄弱，特别是干热岩资源评价、靶区选择、关键技术研究和示范工程建立，亟需缩小与发达国家间的差距，紧跟国际步伐，发现和掌握适合我国地质情况的干热岩资源，力求在不久的将来在利用研究领域中有我国的一席之地。目前我国在青海共和盆地已发现品质较高的干热岩体，东南沿海正在开展干热岩勘查研究工作。

目前，干热岩资源的开发绝大部分以开采地壳中中生代以来中酸性侵入岩体中所蕴含的热量为主。东南沿海地区是我国最主要的高放射性花岗岩分布区，发育大面积的中生代酸性花岗岩体，花岗岩中富含U、Th、K等放射性元素，其放射性元素的衰变热是重要的热源，在壳源产热和幔源产热均理想的情况下花岗岩分布区的大地热流值可超过100μW/m2，在覆盖层理想的地方，可以获取理想的干热岩资源。同时，作为我国主要的能源消费地区，长期以来东南沿海地区就是煤、电、油等异常短缺的地区，能源的绝大部分要依靠区外调进。经济的高速增长，特别是大量高耗能工业的发展，使该地区能源消耗增长过快，更加剧了能源供应的紧张，干热岩资源的开发利用可为本地提供后备能源基地，具有重要的意义。

1 干热岩资源赋存地质背景

东南沿海地区尤其是赣、粤、闽三省具有大规模的不同时期的花岗岩分布，这些花岗岩体岩石类型多样、形成时代各异，具有复杂的源区和地质演化特征，并与深部断裂带密切相关，另外，区域内具有大规模的不同时期的沉积盆地产出，这些优越的地质条件都为区内干热岩热量的生产和保存提供了极有利的条件。

1.1 大地构造背景

地热、地震、火山以及断裂的分布，都严格受控于大地构造特征。东南沿海位于亚洲大陆东部边缘南段，全区分布有大量的晚中生代火山-侵入杂岩，是濒太平洋地区构造-岩浆带的重要组成部分。　晚中生代以来太平洋板块俯冲以及菲律宾板块的碰撞对控制整个亚洲大陆东部的古新世以至第四纪岩浆-火山活动至关重要，这直接关系到东南沿海地区是否具有类似台湾的高温地热资源。

现今台湾海峡地区P波层析成像的结果证明，

现今东南沿海地区以欧亚大陆与菲律宾板块的碰撞挤压作用为主。菲律宾板块的 NW 向挤压作用在漳州地区以至东南沿海地热系统的形成起到了重要作用。根据台湾海峡地区 1964-1996 年地震记录及运动学指示，欧亚板块下插在菲律宾板块之下，以及菲律宾板块位于台湾地区之下引起的碰撞，是形成地区内地震的主因，区域主应力方向与板块俯冲碰撞方向一致。

1.2 地球物理揭示的深部热结构

1.2.1 地壳厚度特征

从东南沿海地壳厚度分布图上看（图 1），东南沿海地壳厚度分布特征与地势分布相近，由西南地区向东南沿海地区地壳厚度逐渐变薄，至福州 - 广州一带地壳厚度已小于 30km。东南沿海地区从内陆到沿海，除金华 - 福州一带存在北东向整体地壳厚度增厚，基本呈现出由厚至薄的趋势变化。

按照地壳厚度变化特征，以北海 - 戴云山 - 杭州一带为界，可以将东南沿海地区划分为两个带，以西为东南沿海地壳厚度增厚带，以金华 - 福州的北东向地壳厚度加厚为特征，以东为东南沿海地壳厚度陡坡带，以地壳厚度向沿海急剧变薄为特征。

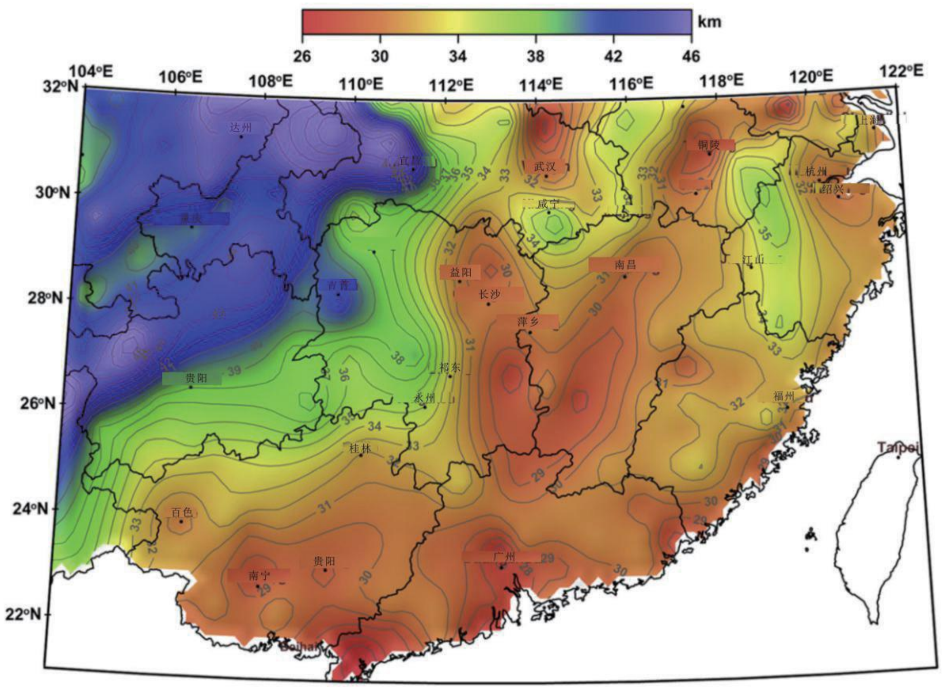

图 1 提取浅层地热能的单井循环系统概述

1.2.2 地震波速

引起 P 波波速下降的地质因素是多种多样的，例如可能是破碎带，由于裂隙增多孔隙增大使 P 波速度减小；岩石孔隙压力、温度和含水性质的变化也可以使 P 波速度明显减小，此外地壳中存在部分熔融

的物质也会降低 P 波速度。福建地区地震折射剖面 YCA 和 L3 所揭示的漳州盆地地区深部构造表明，该地区属深部结构异常带。在漳州市正下方深度 10.2km 以下的地壳中上部存在速度小于 5.8km/s 的 P 波低速体（图 2）。也有可能由于这个地区的莫霍面深度只有 29km 左右，又有 NW 向张性深断裂，因此壳内的热源可能不断得到地幔热源的补充。从而引起局部地区地热异常。此深度的低速体从江西南部至福建沿海均有发现，说明区域大地构造背景的统一性和连续性。

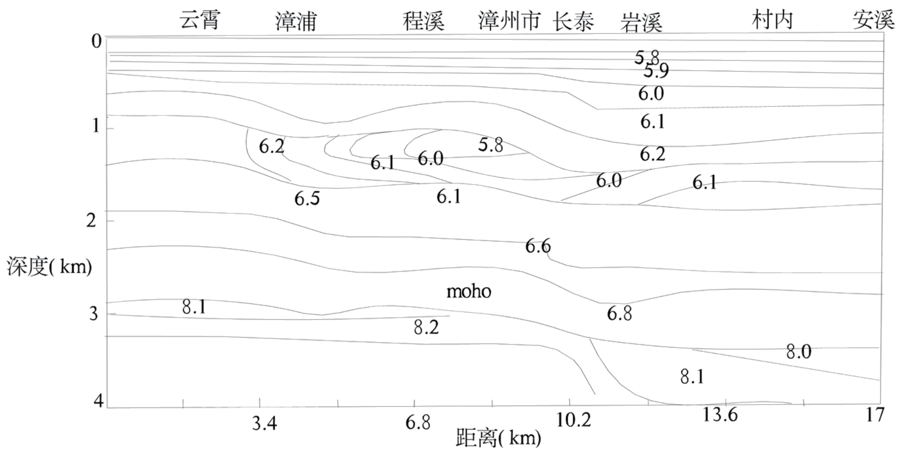

图 2 YCA 测线 P 波波速等值线剖面图

根据电性结构差异可以解译出，现今东南沿海地区岩石圈层从西向东逐渐减薄，结合浅部变形表现可以推断出，岩石圈经历了一定程度的伸展作用（图 3）。软流圈层位的流动推动了岩石圈的伸展，同时在莫霍面深度局部融熔形成一系列壳幔混合带，地壳浅部则形成一系列铲状伸展、拆离断层，断层上部为脆性，下部逐渐过渡呈脆韧性已至韧性，与壳幔混合带相沟通。地球物理显示在中上地壳据地表约 15km 处存在低速层，且层位从江西南部到福建沿海均有分布，该层位可能代表着中地壳的部分熔融岩浆体，或中下地壳韧性流动层。

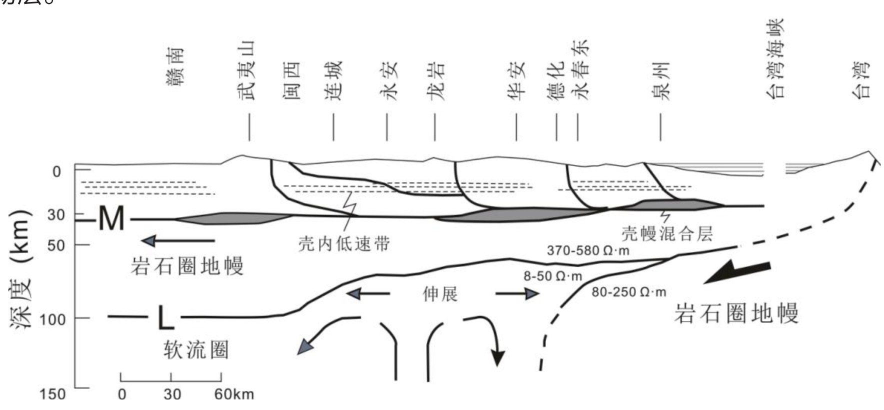

图 3 江西南部 – 福建 – 台湾综合地球物理剖面图

1.2.3 热流值

大地热流值是表征地壳热状态的一个综合参数，是干热岩资源赋存分布的重要地热地质指标之一。我国东南沿海地区大地热流值整体上受大地构造背景影响明显（图 4）：西北侧的盆地区整体构造活动较稳定，表现为较低的大地热流值，而靠近板块接触带的东南海岸一带，则表现为较高的大地热流值。在整体由西向东热流值逐渐升高的趋势下，局部的深部热结构控制了大地热流值的高低。从图 4 中可以看出福建福州、漳州以及广东阳江 - 茂名一带大地热流值达到最高，热流值达到 95μW/m^2 以上。

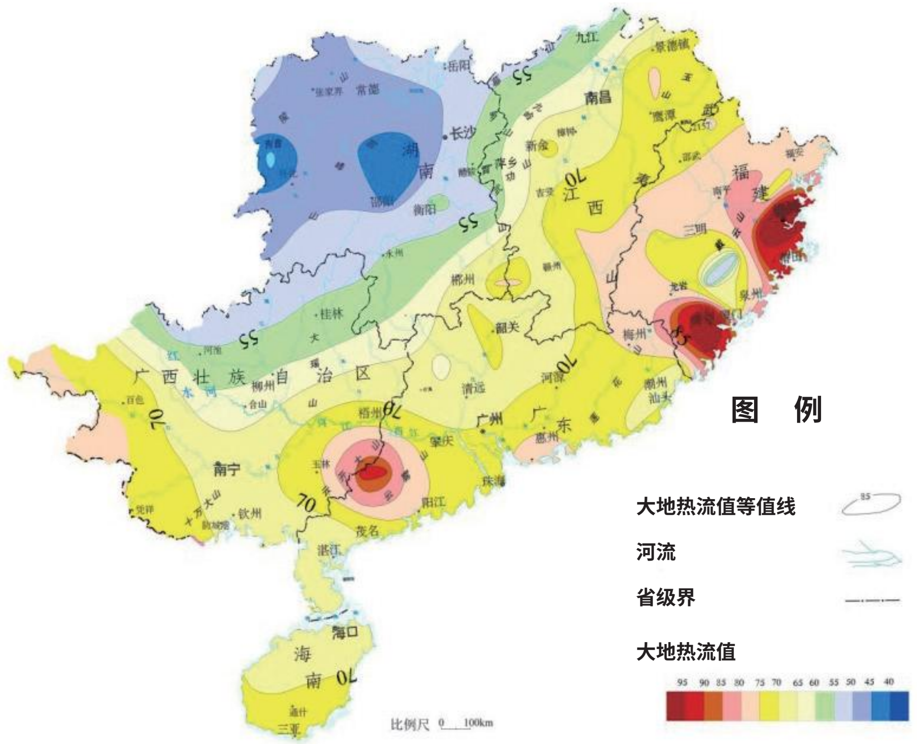

图 4　我国东南沿海地区大地热流值等值线图

2 东南沿海干热岩成因模式探讨

2.1 关于福建地区是否存在干热岩资源的争论

2.1.1 认为存在干热岩资源

由近南北向的九龙江深大活动断裂与近东西向的深切割西溪活动断裂共同形成的漳州盆地至九龙江口东西向地热异常走廊，面积约 2000km^2，地应力集中，地壳较薄，中地壳有高温热储分布，下地壳可能有巨大岩浆房存在，干热高温热储条件是福建省大陆上最具开发前景的地区。

滕吉文等认为福州盆地、漳州盆地恰处在太平洋板块与欧亚板块碰撞、挤压、俯冲与消减的聚集地带。壳幔结构特异，上地壳中存在低速层，特别是漳州盆地在低速层中局部地带呈现出透镜状低速体，故有理由推断地下有热储的存在。漳州 - 长泰之间尚存在一条贯穿地壳、直抵上地幔顶部的深、大断裂带，它可

能构成深部物质向上的运移通道，即热能的补给途径。

2.1.2 认为不存在干热岩资源

万天丰等对福建岩石圈热状态进行研究，认为福建不具备可用于发电的干热岩开发条件。根据计算，即使在深部温度较高的漳州地区，5km深度方可达到 194.6°C，德化为 187.6°C，其他地区均不足 180°C。按照上述温度，想要开发福建干热岩内的人工热储，需要技术条件大幅度提高，降低施工成本才有可能。

廖志杰从福建所处板块构造背景认为，福建地壳上部不可能出现岩浆热源的温度条件 [17]。人工爆破地震所发现的低速层，分布比较稳定，不可能是融熔或半融熔层所造成，而是由于岩石破碎所造成，即由闽台铲状活动断裂系或滑脱面所致，闽台低角度活动断裂系在沿海地区的埋深正好为十余公里。廖志杰等认为福建出现的大规模水热活动异常是由于福建地区自新近纪以来受到菲律宾大洋板块来自东南的强烈挤压，使相对脆性的、固结的闽台地区陆壳产生铲状断层系统，断裂网格发育，使丰沛的大气水渗入地下深处，吸收岩石中的热量，由于水头压力差和密度差，地下水可沿断裂，特别是北西向张剪性断裂，排出地表或储存于地表附近，构成大量深循环水热对流系统。它们主要是低温和中温的温水储，当循环深度大时也可以形成高温的热水系统。在这种地热地质条件下，形成可开采干热岩系统难度较大，想要获得 150°C以上高温岩体，需要寻找上覆较厚盖层的花岗岩体。

2.2 区域控热系统分析

2.2.1 热源机制

地表热流值结果显示，东南沿海地区比陆内南岭地区要高，地表热流值作为各种热源（含地幔热、岩浆热、构造热、放射性元素衰变热等）在地表的直接反应，其值大小在很大程度上反映了深部热源的综合情况。前人对东南沿海地区开展了大量的花岗岩研究工作，通过对区内不含铀矿的花岗岩进行单位体积生热率统计，结果见表 1。统计结果表明，东南沿海所有的结晶岩石类型中，花岗岩具有最宽的单位体积生热率变化范围（0.9-10.9 μW/m^3）和最高的平均单位体积生热率（4.11 μW/m^3）。表中的数值显示相对其它类型岩石，花岗岩具有显著高的单位体积生热率。其中，燕山期尤其是燕山晚期花岗岩具有最高的平均单位体积生热率（6.4 μW/m^3），显著高于晋宁期、加里东期和印支期花岗岩的平均单位体积生热率，而且数据亦显示花岗岩形成时代越新，平均单位体积生热率。因此，东南沿海地区地区的花岗岩尤其是燕山期花岗岩具有显著高的单位体积生热率，为干热岩资源的形成提供了良好的生热条件。庞忠和根据地热和水文地球化学模拟结果，显示漳州地区幔源热贡献率大约 60%，而放射性元素衰变生热贡献率大约 40%。周珣若等根据漳州岩体的元素和同位素地球化学特征模拟，也发现地幔在花岗岩体中的物质贡献率超过 60%，与林乐夫等研究结果基本一致。上述研究表明，漳州地区花岗岩体中既有地幔热贡献，也有地壳物质贡献，但以地幔热贡献为主。

表 1 东南沿海地区不同时期基底岩石的单位体积生热率

花岗岩体形成时代	平均单位体积生热率（μW/m^3）
晋宁期花岗岩	3.1
加里东期花岗岩	3.3
印支期花岗岩	3.9
燕山早期花岗岩	5.2
燕山晚期花岗岩	6.4

2.2.2 导热通道

东南沿海地区出露的花岗岩与区域几条主要断裂带密切相关，如萍乡 - 桂林断裂带，龙岩 - 大埔 - 海丰断裂带，赣江断裂带，茶陵 - 广昌断裂带，梧州 - 四会隐伏断裂带和长乐 - 南澳断裂带等，花岗岩通常产出在断裂带的交汇区域。花岗岩尤其是燕山期花岗岩分布具有特定的展布方向特征，燕山早期及印支期花岗岩以东西向展布为主，而燕山晚期花岗岩则具有显著的北东向展布特征。此外，花岗岩的年龄趋势具有自西向东、自内陆（南岭地区）向沿海地区年轻化的趋势。同时，花岗岩与各种类型的沉积盆地密切共生。此外，每一期与造山作用相关的花岗岩实际上都有两个年龄峰值，较老年龄的花岗岩一般形成于同碰撞造山时期，形成于挤压环境下，而较年轻年龄的花岗岩一般形成于后造山期，形成于伸展环境下。这种形成环境的变化，可能伴随着能量和物质的转移。

一般而言，温泉分区界线与大型构造线相当，温泉的出露与主干断裂，虽未有直接关系，但与次一级断裂构造关系较密切，例如福建漳州盆地，平和宫仔前 - 芗城盘谷、九湖新塘 - 漳州地热田 - 郭坑黄坑 - 长泰雪美、东泗松岭 - 角美田里 - 集美后溪、厦门癸官湖 - 翔安东山等温泉，在 NE 走向上分别连续出露 2-4 个温泉，宫仔前 - 盘谷、新塘 - 漳州 - 黄坑 - 雪美，东泗 - 田里 - 后溪、癸官湖 - 五缘湾 - 东山等温泉出露均呈北东向排列，反映地下热水的热源主要受 NE 向构造控制；然而从单个温泉出露地段分析，它们主要出露于 NE 向与 NW 向构造的交汇处，工作区 NW 向构造为区域最新构造，地下水的连通性、富水性相对较好，为地下热水提供主要补给来源及径流通道，说明了断裂具有良好的导热作用。

因此，东南沿海地区由于具有深断裂的存在，局部熔融或深部热流的热能可以通过深断裂更直接传递至浅部，因此会形成地温等值线的上扬，深断裂与浅部张性断裂交汇周围往往具有温泉出露。

2.2.3 储热盖层

为了保存好基底热量，防止大气降水渗入冷却岩体，需要在基底之上覆盖有低导热率的盖层，这种盖层通常主要是沉积岩（沉积物）或火山岩，有时候也可以是合适厚度的风化壳层。标准一维稳态方程模拟显示，在其它物理参数相同的条件下，在大约 5km 深度处，有沉积盖层覆盖的花岗岩基底比没有沉积物盖层的温度要高 30-40℃，由此可见盖层对于干热岩热量保持的重要性。

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2.2.4 热储层

东南沿海地区干热岩热储层以高放射性花岗岩体为主。放射性生热是岩石圈内热的主要来源之一，U、Th 和天然放射性同位素 40K 是主要的生热元素。东南沿海地区绝大部分区域都处于高生热率范围。尤其是广东全省及江西南部、福建南部地区的大面积花岗岩出露，生热率背景超过了 2.8μW/m^3，如此大面积的高生热率区域在全球大陆实属罕见。根据东南沿海地区现有的钻孔测温推算，东南沿海地区地温梯度为 20-40℃/km，以 180℃作为干热岩资源起步温度，可以初步得出东南沿海热储层埋深普遍大于 5km，而广东惠州黄沙洞、福建漳州、琼北等地热梯度较高地区，热储层埋深约为 4-5km。

根据以上关于东南沿海区域控热系统的分析，笔者认为东南沿海可能的干热岩资源需具备以下三元聚热模式，即酸性岩体放射性生热，断裂导

热加之盖层保热的成藏模式，如图 5 所示。

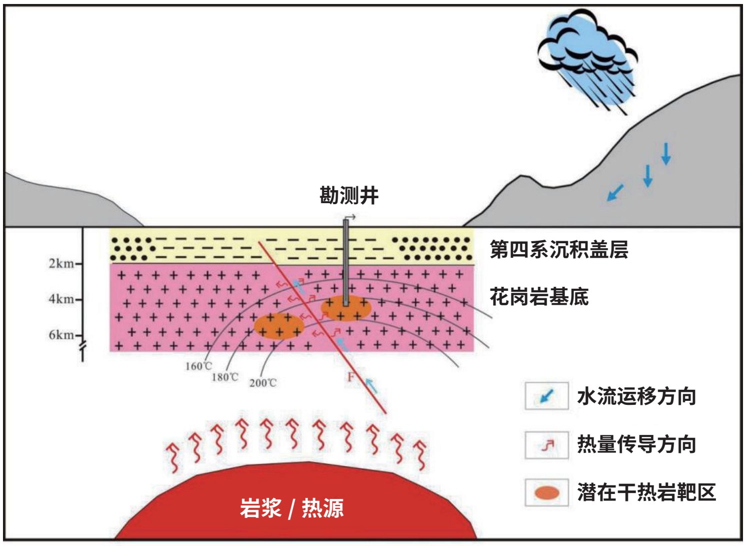


图 5 东南沿海干热岩资源成藏的三元聚热模式图

4 东南沿海干热岩资源重点靶区勘查进展

4.1 漳州地区

漳州地区是我国东南沿海典型地热异常区，漳州地区出露温泉大多为 40-80°C，水温高于 60°C的温泉有 13 处，是我国中低温温泉中水温最高的。在水热异常的背景下，通过地热调查、地球物理勘查与地热钻探，对漳州龙海地区深部干热岩赋存特征进行了调查研究。结果显示，区内普遍缺失侏罗纪以后至第四纪以前的地层，下部为燕山期花岗岩体侵入，地表为第四纪更新世冲洪积层覆盖，厚度大于 20m（图 6）。

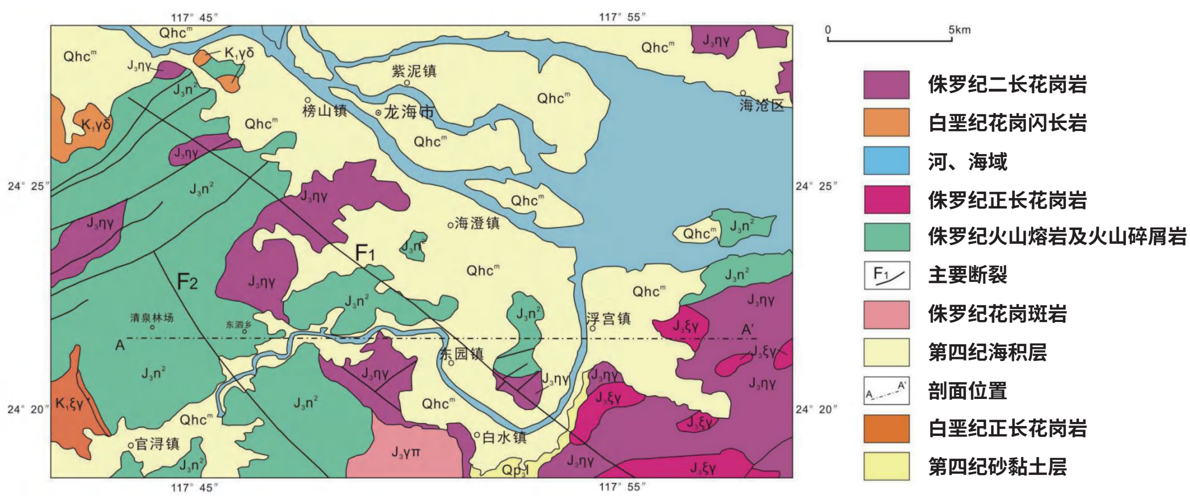
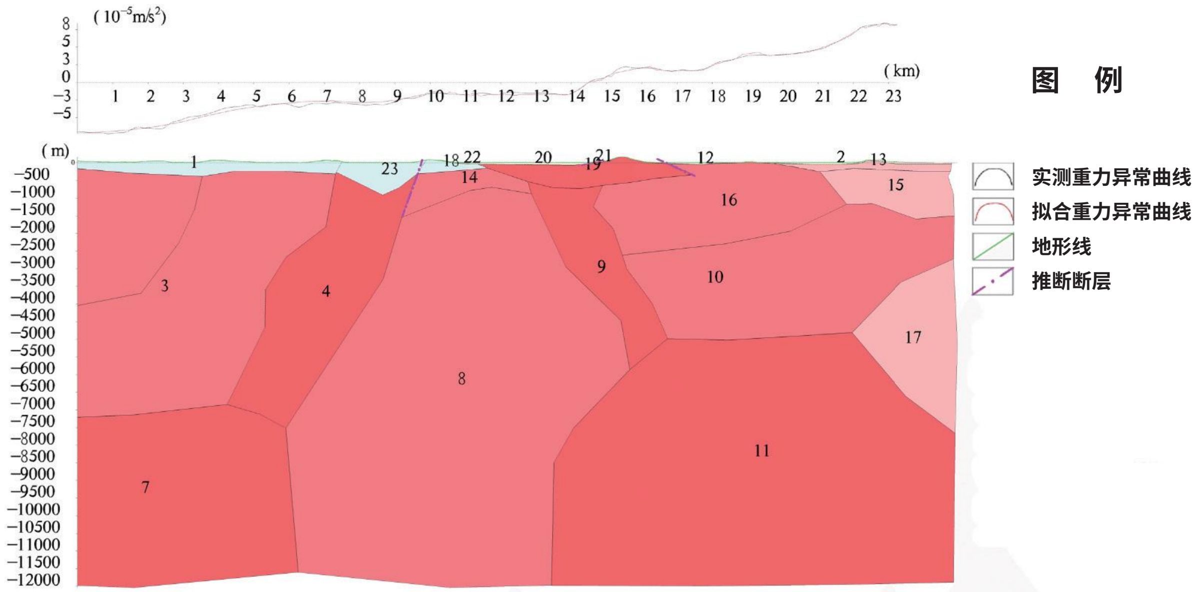


图 6 漳州地区地质简图（A–A’为物探综合剖面）

从物探综合解译结果（图 7）可以看出，区内存在大范围的花岗岩侵入，推测第 4、9、19 岩体为第三期 γ52（3）c 岩体，其他花岗岩体为更早期的；第 13、15 及 17 为花岗闪长岩体。在剖面的东部及西部 7 公里以下存在较大范围的低阻体（第 7 及 11 岩体），推断为半融熔岩体。



1、2.59 侏罗系凝灰岩
2、1.81 第四系
3、2.62 花岗岩
4、2.62 花岗岩
5、2.62 花岗岩
6、2.58 花岗岩
7、2.62 花岗岩
8、2.62 花岗岩
9、2.61 花岗岩
10、2.62 花岗岩
11、2.62 花岗岩
12、1.81 第四系
13、2.68 花岗闪长岩
14、2.61 花岗岩
15、2.68 花岗闪长岩
16、2.61 花岗岩
17、2.68 花岗闪长岩
18、2.6 侏罗系凝灰岩
19、2.61 花岗岩
20、1.81 第四系
21、1.81 第四系
22、1.81 第四系
23、2.56 侏罗系凝灰岩

图 7 龙海地区重力和大地电磁联合反演推断解释剖面

在地球物理解译的基础上，选择完整花岗岩体，在龙海东泗乡开展了干热岩科学钻探，钻探深度为 4000m。完钻后总共进行了三次测试，每次 3 组，第一次为 0-2500m，第二次为 0-3350m，第三次为 0-4000m，结果见图 8。从图中可以看出，第一次测井温度比另外两次温度均低约 3°C，第 2 次和第 3 次测井温度曲线重合度较高，这表明第 1 次测井温度尚未达到平衡状态，测试结果偏差较大，第 2 次和第 3 次测井井温已经达到平衡，测井温度即为实际地层温度，结果更加可信。本次测井与 3350m 测井结果较为接近，4000m 深处温度最高约为 109°C，在预测温度范围之内。

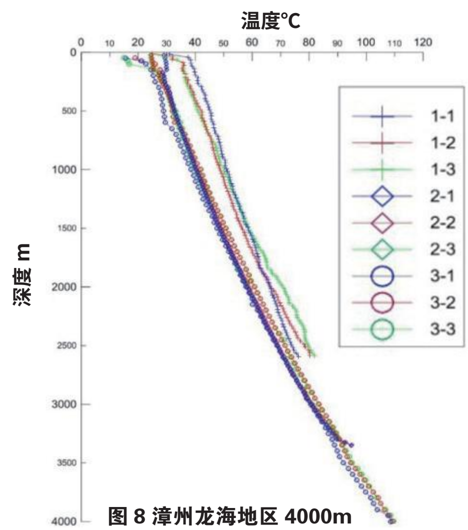


图 8 漳州龙海地区 4000m 井深井温度曲线

利用 TOUGH2 软件进行地温场演变模拟，为了减少数值计算带来的误差，在平面上采用泰森多边形进行剖分，限定单个网格最大面积为 10000m^2；垂向上采用等距剖分方法，每 200m 一层，共计 40 层，网格总计 39680 个。模型中的一些相关参数见表 2。热储主要为花岗岩，据测井资料和岩芯热导率测试，并结合经验值，确定其热导率为 3.4 W/（m•K），孔隙度为 0.01，渗透率为 1×10-17 m^2。断裂存在硅化现象，其热导率高于普通热储，为 5.5 W/（m•K）。

表 2 模型主要参数表

模型部分	孔隙度	渗透率 m^2	热导率 W/（m · K）
热储	0.01	1×10^{-17}	3.4
浅部断裂	0.05	1×10^{-12}	5.5
深部断裂	0.02	1×10^{-17}	5.5

模型的初始压力采用静水压力 $P=P0+\rho_{水}\cdot g\cdot h$ 计算，其中 P 为目标网格压力，Pa；P0 为大气压，Pa；g 为重力加速度，N/kg；h 为网格中心点深度。采用 2500m 以浅的测温数据做线性拟合得到：$T=23.403+0.0186\cdot Z$，式中 T 为温度，°C；Z 为深度，m。以此作为模型的初始温度条件。

研究区深部地温分布模拟结果见图 9。从图中可以发现，深部热量主要沿断裂传导至浅部，可以见到明显的地温等值线凸起现象。模型预测 5100m 地层温度能够达到 140°C。

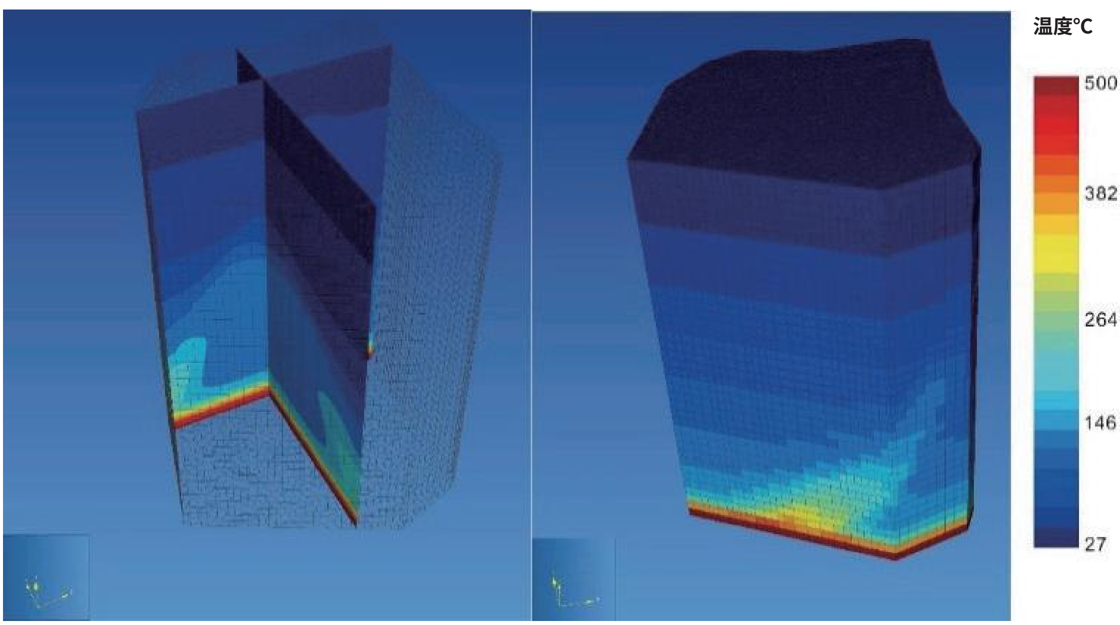


图 9 研究区深部地温分布图

4.2 惠州黄沙洞地区

惠州黄沙洞地区在区域上属华南板块，华夏陆块南部，处于河源深断裂带的南东侧约 30km，紫金—博罗深断裂带的南东侧约 12km，莲花山深断裂带北西侧约 40km。研究区出露地层包括震旦系老虎塘组（Z2lh）、寒武系牛角河组（n）、泥盆系老虎头组（D1-2l）、帽子峰组（D3C1m）、石炭系测水组（C1c）和第四系黄岗组（Qp3hg），研究区北西侧为大点顶岩体（J1D），岩性为细中粒黑云二长花岗岩。

根据重力反演剖面（图 10），可见基底埋深在 4 ～ 9km 起伏，研究区基底构造十分发育，主要表现为北东向和北西向互相切割。这些大断裂控制岩体侵入和地层沉积，矮陂岩体是沿着断裂交汇部位侵入。研究区基底是由早古生界震旦纪变质岩结晶基岩组成。

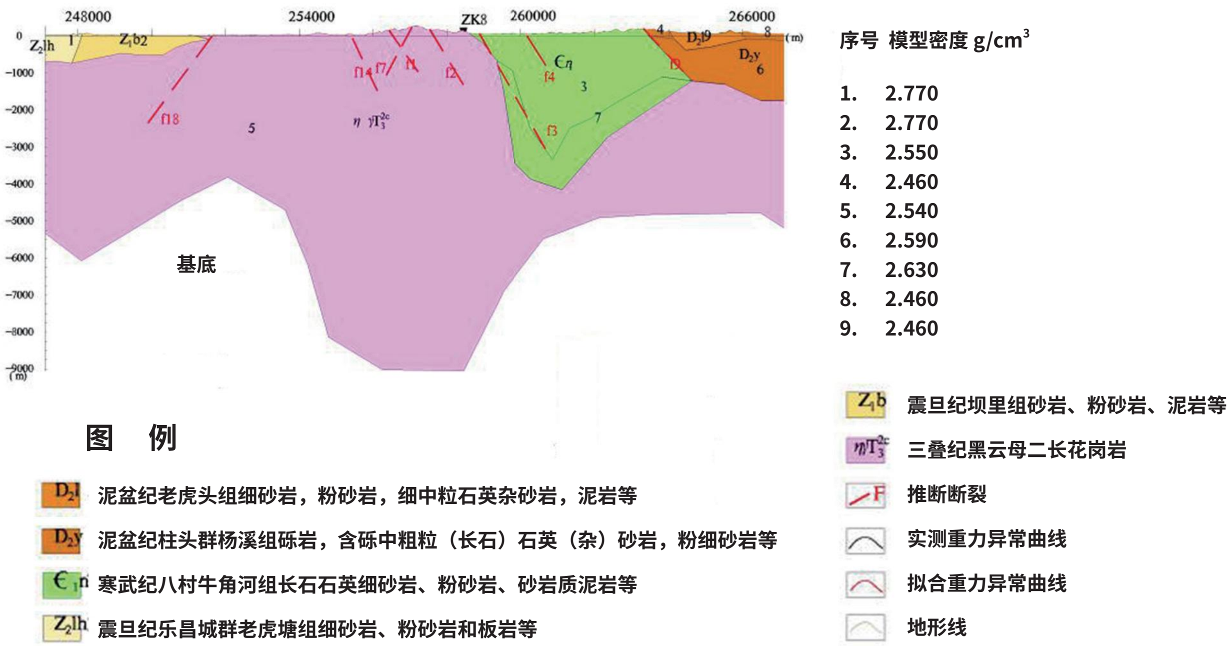


图 10 研究区重力反演剖面

采用 CSAMT 方法进行浅部断裂探测，共布置测线 4 条，编号分别为 L1 线、L2 线、L3 线、L4 线，L1 线与 L3 线呈 NW 向，L2 线与 L4 线呈 NE 向。将音频大地电磁 L2 和 L4 线联合解译可以看出，存在对应的低阻体通道，位于 L3 线东侧（图 11）。投影到图 12 上，通道为 NW 向，且 L2 线反映出的低阻体通道范围小于 L4 线，因此，可以推断该低阻体通道由南向北逐渐减小，将其定义为 T1。

将音频大地电磁 L1 和 L3 线联合解译可以看出，存在对应的低阻与高阻体分界线（T2），位置与 L4 线大致重合（图 12）。投影到图 12 上，通道为 NE 向，与地表 NE 向断裂带（F2-F4）方向一致，位于马儿寨断裂 F3 与川龙凹断裂 F4 断裂之间。可以推断 F3 断裂与 F4 断裂是低阻与高阻的分界线在地表的反映。

根据图 14 中物探解译 T1 和 T2 与地质条件对应关系，可以看出温泉区 NW 向出露的温泉 / 地热井基本位于低阻通道 T1 上，因此，T1 推测为温泉 / 地热井的控热导水构造。此外，根据构造地质调查，T1

范围内地层发育 NW 向断裂，角度高倾，可作为断裂存在的证据。对于区域应力而言，区域主应力 61 方向为 NW-SE 向挤压（温泉区内可见轴面走向 245°背斜褶皱），NW 向作为最小应力 63 方向应为拉张性质，也与 T1 导水通道的作用相符。

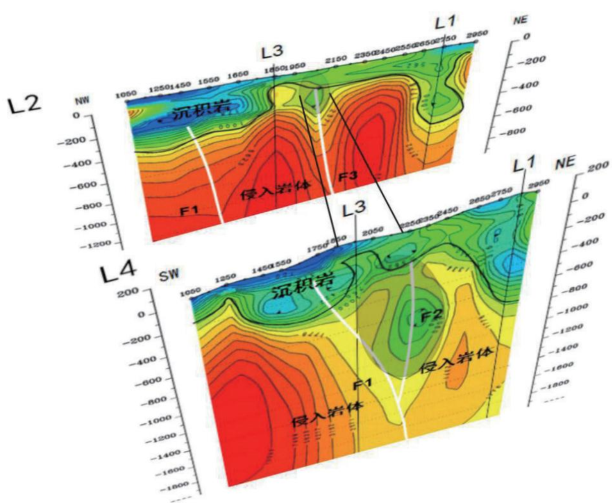


图 11 L2 和 L4 测线联合解译图

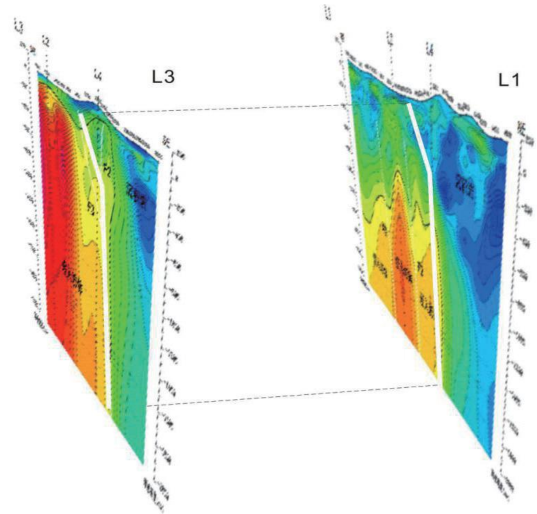


图 12 L1 和 L3 测线联合解译图

从前述论证总结得出，黄沙洞地热田的热成因模式为深部热源沿 NE 向压扭性断裂带 T2（F2-F4）传导至浅部，遇到 NW 向张性低阻通道 T1，以流体为介质将热传递至地表，形成温泉。按照此热成因模式，钻探孔位选择原则为位于压扭性断裂带 T2 北西侧下盘，且位于张性低阻通道 T1 中（图 13）。考虑到 T1 从 SE 向 NW 逐渐变小，可能断裂（热）传递逐渐减弱，因此选择相对靠近 T2 导热断裂带的位置。

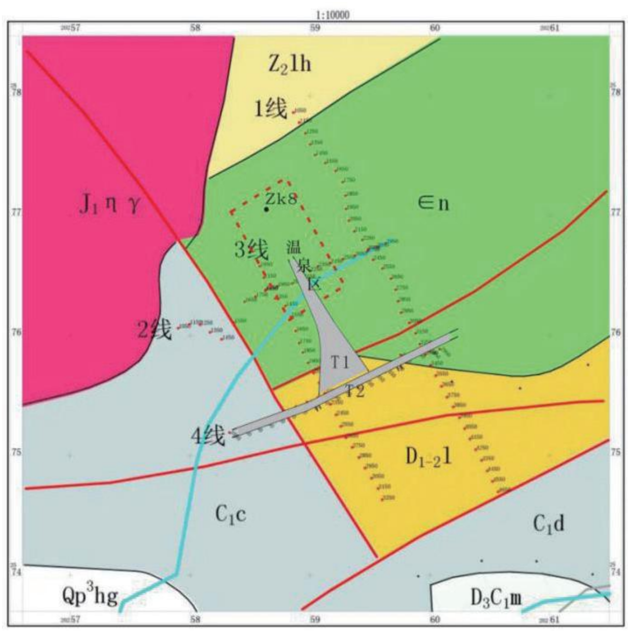


图 13 研究区地质简图及物探解译成果图

钻探进尺深度为 3009m，从 2017 年 11 月 29 日开始施工，钻探总进尺为 3009m，钻孔于 1560m 深处成功揭穿沉积盖层，进入下部隐伏花岗岩体，上覆沉积盖层岩性从浅至深依次是砂岩、千枚状页岩、炭质板岩、构造角砾岩及硅化石英砂岩，钻获了一套典型的变质程度从浅至深的变质序列。根据钻井测温曲线，2900m 温度达到 127.5℃（图 14），2400-2500m 段和 2750-2800m 段温度出现突变，结合钻井漏失出水情况分析，这两处突变应是两段含水层产出高温热水引起温度升高所致。根据 0-3000m 地温特征，可以预测继续钻进至高温无水深度，将具有良好的干热岩资源勘查开发潜力。

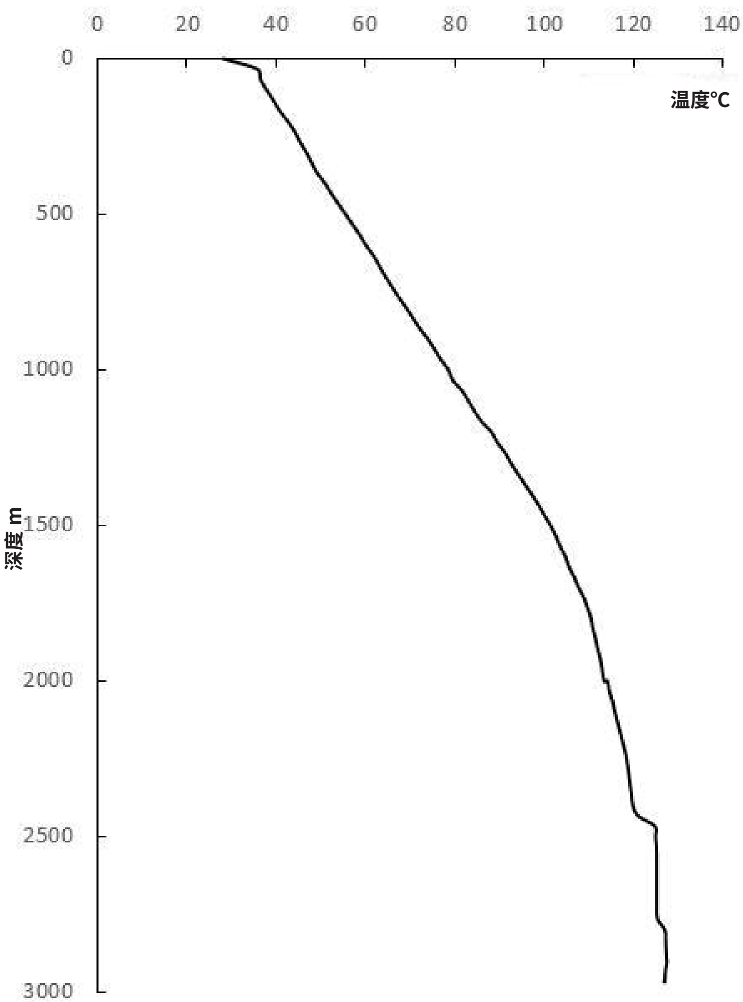


图 14 惠州惠热 1 井地温测温曲线

5 结论与建议

（1）东南沿海地区干热岩具有酸性岩体放射性生热，断裂导热加之盖层保热的三元聚热模式，燕山晚期花岗岩生热率可达 6.4 μW/m3，是壳源热源的主要组成部分；区域性断裂构造作为导热通道沟通深部热源与浅地表，将深部热量传导至浅部；沉积盖层对酸性岩体放射性生热和断裂导热起到盖层保温作用，一定程度上阻碍了热量的散逸。

（2）东南沿海干热岩重点靶区包括福建漳州、惠州黄沙洞地区，其中漳州地区由于缺乏必要的盖层，4000m 深处获得温度为 109℃；惠州黄沙洞地区具有约 1500m 的沉积盖层，北东向深断裂为导热通道，钻井于 2900m 深度达到 127.5℃，是惠州地区目前同深度的最高温度。

（3）目前，酸性岩体放射性生热及断裂导热对干热岩的热量贡献多少尚不清楚，此外东南沿海的沉积盖层普遍保热效果相对较差，因此，建议下一步开展关于三元聚热模式中各聚热因素的热量贡献进行研究，结合区域地质构造背景，建立更为精细的模式指标值。

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THE APPLICATION OF THERMOSTATIC THERMAL RESPONSE EXPERIMENT IN DESIGN OF BURIED PIPE HEAT EXCHANGERS

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Abstract

Geotechnical thermal response experiments have been widely used in the design of ground source heat pump systems, and the geotechnical thermophysical parameters obtained play a key role in the design of buried pipe heat exchangers. In this paper, a 200-m deep double U-shaped vertical buried-pipe test well is created for a practical project in Hebei Province, where the thermostatic thermal response experiment is used to simulate the operation conditions of heat removal in summer and heat extraction in winter of the test well. Parameters such as initial ground temperature, incoming / outgoing water temperature curve, single hole heat exchange power and heat exchange per linear meter are obtained, followed by deducing the thermal physical parameters such as thermal conductivity and

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thermal resistance of formation according to linear models. In this paper, the experimental process of thermal response by the constant temperature method is fully demonstrated, and the experimental results are discussed and analyzed, which can provide reference for the optimal design of ground source heat pump systems. The results are also conducive to popularizing the application of the thermal response test by constant temperature methods in the design of buried pipe heat exchangers.

Keywords：Geotechnical Thermal Response Experiment; Thermostatic Method; Buried Pipe Heat Exchanger; Ground Source Heat Pump; Geotechnical Thermal Properties

Introduction

As China increases its efforts to develop and utilize clean energy, ground source heat pumps are flourishing as an important technology for developing shallow geothermal energy. Ground source heat pump systems mainly use buried tube heat exchangers to extract the heat stored in the soil or rock-soil, to heat or cool environments through heat pump systems. However, as the core component of a ground source heat pump, heat exchange is a complex non-stationary process, and its characteristics are influenced by the thermophysical properties of underground rock-soil, subsurface hydrogeological conditions, heat exchanger materials, and backfill materials [1]. The thermophysical properties of the subsurface geotechnical parameters play a key role in the heat exchange capacity of buried pipe heat exchangers, especially regarding geotechnical thermal conductivity. Generally, the greater the geotechnical thermal conductivity, the greater the heat exchange per linear meter and heat exchange capacity per unit hole are [2]. Research has shown that if there is a 10% error in the thermal conductivity of the rock-soil, there will be a 4.5%-5% error in the design length of the buried pipe heat exchanger, which does not meet the requirements of building load and causes a waste of initial investment in the construction [3]. Obtaining accurate geotechnical parameters is therefore a key precondition for the design of buried pipe heat exchangers, as well as maintaining good economic and sustainability of ground source heat pump systems.

Geotechnical thermal response tests are currently the most common and effective methods to obtain thermophysical properties of soil. Since 1983, when the thermal response test method was proposed to determine thermophysical properties and parameters of soil [4], domestic and foreign scholars have continuously promoted and improved the thermal response test method [5-6], which is now widely used in practical engineering applications of ground source heat pumps. At present, the most widely-used geotechnical thermal response test methods in applied engineering are the constant heat flow and the constant temperature methods [7]. Although the constant heat flow method is more commonly used, it can only test thermal discharge conditions, and the complex model calculation is prone to large errors [8]. For this reason, researchers in China have proposed the thermostatic method of thermal response experiments and improved the test setup to reflect the heat exchange capacity of the buried pipe heat exchanger in a more realistic manner, accurately measuring the geotechnical thermophysical parameters [9]. In this paper, an engineering drilling well in Hebei Province is used as an example to obtain the geotechnical thermophysical properties of the test well. On the basis of using the thermostatic thermal response experiment to more realistically demonstrate the heat exchange performance of buried pipe heat exchangers, propose and optimize the buried pipe design, and promote the thermostatic thermal response experiment, this paper aims to provide reference for the optimized design of the buried pipe heat exchanger for ground source heat pumps in practical projects.

1. Theoretical Method and Test Apparatus for Thermostatic Thermal Response Experiments

1.1 Experimental Principles

Geotechnical thermophysical parameters are a thermophysical property for which the data process is essentially the same for both exothermic and heat extraction tests. The thermostatic method is a method of establishing stable operating conditions for the buried tube heat exchanger and thus determines the heat exchange capacity of the buried tube heat exchanger. As can be seen in Figure 1, the fluid is heated by an electric heater (or cooled by a refrigeration device) and then sent underground. As the temperature of the heated (cooled) fluid becomes higher (lower) than the temperature of the subsurface soil, there is an exchange of heat between the soil and the fluid in the pipe, causing a change in the temperature of the fluid from subsurface and back into the tester, which amounts to the temperature response of the subsurface soil. A temperature sensor is placed at each point where the instrument is connected to the underground pipeline so that a real-time value of the average pipeline temperature can be collected. In-situ thermal response testing at the construction site provides access to actual results that integrate various factors at the site, enabling a more accurate prediction of the thermal properties of the soil, reducing uncertainty in the selection of parameters, and making the design of the buried pipe heat exchanger more justified. For the on-site test, test holes are first drilled in the ground where the underground piping for the ground source heat pump system is buried, with the same specifications as conventional buried pipes. Then, piping is installed and filled with backfill in accordance with the actual construction requirements, before connecting to the thermal response test vehicle during testing.

1.2 Calculation Method of Geotechnical Thermal Properties

The thermostatic simulation test maintains a constant inlet water temperature, establishes a stable operating condition for the buried pipe heat exchanger, and brings together the supply-and-return water temperature difference data, so as to determine the heat exchange capacity of the buried pipe heat exchanger. As in equation (1):

$$Q = C\,\rho v \Delta t \qquad (1)$$

Where: Q - Heating power, W;

C - Specific heat capacity of water, $4.2\text{x}10^3$J/(Kg°C);

ρ - Water density, 1.0×10^3Kg/m^3.

v - Flow rate, m^3/h.

Δt - Temperature difference between incoming and outgoing water, °C.

The linear heat source theory is the theoretical basis of most current heat exchange models for buried tube heat exchangers in ground source heat pumps. The theory is clear in physical significance, simple and easy to calculate, and widely adopted in the calculation of underground buried tube heat exchangers for ground source heat pumps. The thermostatic thermal response test can directly obtain the heat exchange power of a single hole and the measured value of the linear meter heat release. On the basis of the test parameters obtained, the linear heat source model is used to carry out inversion calculations, which can obtain the average heat exchange coefficient of the borehole λ, the borehole thermal resistance Rb, and other parameters. The linear heat source model calculation formula (2) is as follows:

$$T_f = \frac{Q}{4\pi\lambda H} ln(t) + \left[\frac{Q}{H}\left(\frac{1}{4\pi\lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) + R_b\right) + T_{sur}\right] \qquad (2)$$

Where: T_f - Average temperature, °C;
A - Heat diffusivity, m^2/s;
Q - Heating power, W;
H - Effective hole depth, m;
λ - Thermal conductivity, W/(m-K) ;
γ - Euler coefficient, 0.5772;
R_b - Thermal conductivity resistance, m-K/W;
T_{sur} - Initial temperature of soil, °C;
r_b - Radius of hole, m.

As the average temperature of the heat-carrying fluid is proportional to the natural logarithm of heating time, the relationship is (3). A curve of the average temperature of the heat-carrying fluid juxtaposing against the logarithm of the time (theoretically a straight line) is made from the test results, and the slope k of this curve is determined. The thermal conductivity can be found from equation (6), and equation (7) can be derived, also under a series of assumptions.

$$T_f = k\,ln(t) + m \tag{3}$$

Where:

$$k = \frac{Q}{4\pi\lambda H} \tag{4}$$

$$m = \frac{Q}{H}\left(\frac{1}{4\pi\lambda}\left(ln\left(\frac{4a}{r_b}\right) - \gamma\right) + R_b\right) + T_{\text{sur}} \tag{5}$$

$$\lambda = \frac{Q}{4\pi kH} \tag{6}$$

Calculation of the thermal resistance of the borehole:

$$R_b = \frac{(C-T_{sur})}{q_c\,H} - \frac{1}{4\pi\lambda_s}[\ln\left(\frac{4\alpha}{\gamma_b^2}\right) - \gamma] \tag{7}$$

Calculation of the liner heat release according to equation (6):

$$q_{c\;heat\;release} = \frac{T_{fmax}(t) - T_{sur}}{T_{ftest}} q_{c\;test} \tag{8}$$

Calculate the measured value of the linear heat extraction according to equation (7).

$$q_{h\;heat\;extraction} = \frac{T_{fmin}(t) - T_{sur}}{T_{f\;test} - T_{sur}} q_{c\;test} \tag{9}$$

Where: C_m - Average specific heat capacity of the soil over the depth range of the buried pipe, J/(kg.°C);

$q_{c\ test}$ - Heat release per unit pore depth of the heat-carrying fluid at the test condition, W/m;

$q_{c\ heat\ release}$ - Heat release per unit pore depth of the heat-carrying fluid at the heat release condition, W/m;

$q_{h\ heat\ extraction}$ - Heat extraction per unit pore depth of the heat-carrying fluid at the heat extraction condition, W/m;

$T_{f\ test}$ - Average temperature of the heat-carrying fluid at the test condition, °C;

T_{fmax} - Average temperature of the heat-carrying fluid at the heat-release working condition, °C;

T_{fmin} - Average temperature of the cooling fluid during the heat extraction working condition, °C;

According to Appendix A of the Specifications for the Evaluation of Shallow Geothermal Energy Reconnaissance (DZ/T0225-2009), the formula for calculating the heat exchange of borehole linear meter is as follows

$$D = \frac{2\pi L|t_1 - t_4|}{\frac{1}{\lambda_1}\ln\frac{r_1}{r_2} + \frac{1}{\lambda_2}\ln\frac{r_3}{r_2} + \frac{1}{\lambda_3}\ln\frac{r_4}{r_3}} \tag{10}$$

Where: λ_1 - Thermal conductivity of buried pipe material, W/m•k (PE pipe is 0.42W/m•k);

λ_2 - Thermal conductivity of backfill in heat exchange hole, W/m•k;

λ_3 - Average thermal conductivity of rock-soil around heat exchange hole, W/m•k;

L - Length of buried pipe heat exchanger, m;

r_1 - Equivalent radius of buried tube bundle, m, double U is 4 times of inner diameter of pipe;

r_2 - Equivalent outer diameter of buried pipe bundle, m, equivalent radius r1 plus pipe wall thickness;

r_3 - Average radius of heat exchanger holes, m;

r_4 - Influence radius of heat exchange temperature, m, take 0.5m;

t_1 - Average temperature of the fluids in the buried pipe (35°C for heat dissipation and 4°C for heat absorption);

t_4 - Initial temperature of rock-soil outside the temperature influence radius.

1.3 Test Equipment

See Figure 1 for the thermal response test device. The device mainly includes the automatic control system, automatic acquisition system, electric heating equipment, refrigeration equipment, water pump, flowmeter, temperature sensor, and pressure gauge, among other equipment. Table 1 is the technical index of geotechnical thermal response testing instruments.

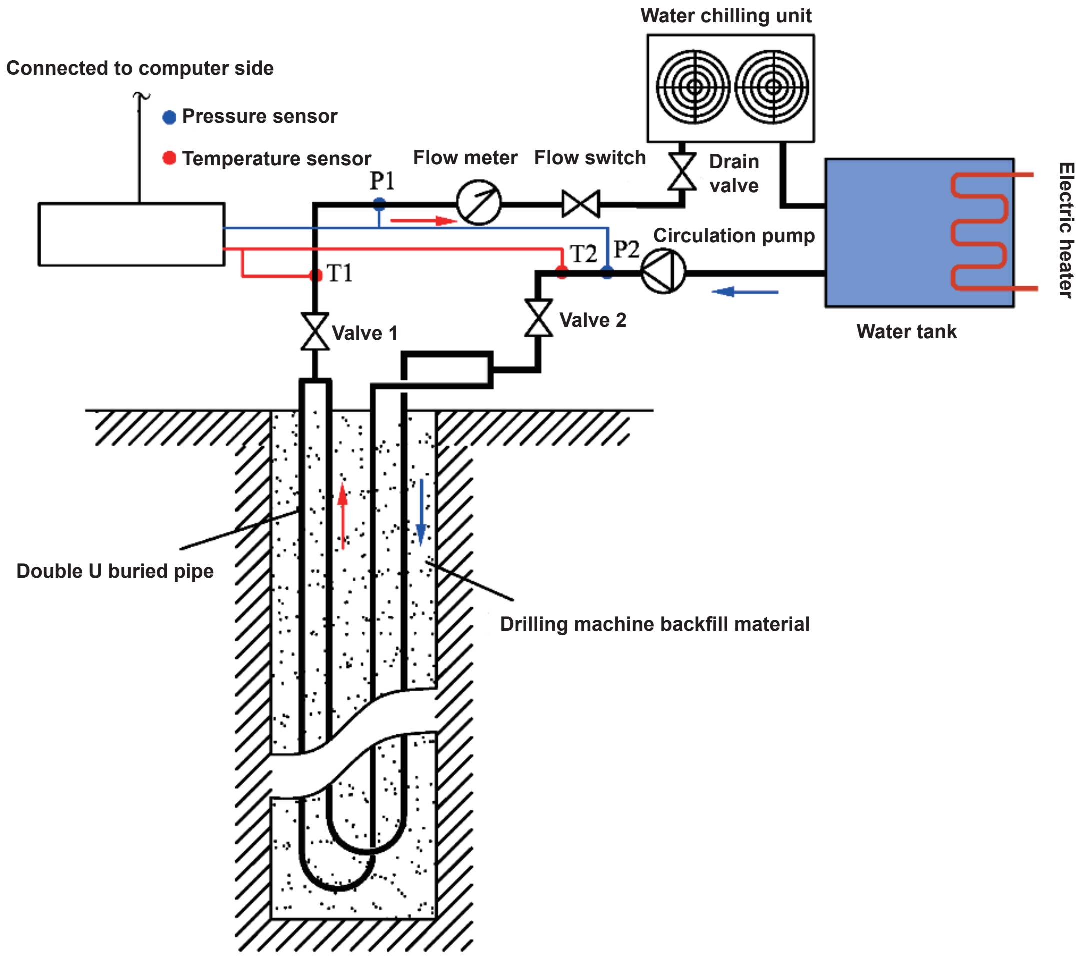

Figure 1. Diagram of devices for the thermostatic thermal response test

Table 1 Main technical indexes of the DR-40 geotechnical thermal response tester

Devices	Measuring range	Precision
Heating and refrigerating equipment	Heating power	Refrigerating power
	36 kW adjustable	24kW adjustable
24kW adjustable	Flow	Maximum lift
	1-12 m^3/h adjustable	30 m
Power sensor	Measuring range	Precision
	0-30 A	1.0 grade

Devices	Measuring range	Precision
Temperature sensor	Measuring range	Precision
	-50 ～ +100°C	±0.15 °C
Flow sensor	Measuring range	Precision
	0 ～ 12 m^3/h	0.5 grade
Pressure sensor	Measuring range	Precision
	0 ～ 1.6 MPA	10 PA

2. Geological Characteristics of Site and Test Well Parameters

The geological structure of the test site is based on metamorphic rocks such as Archaeozoic plagiogneiss, on which is a Mesozoic continental basin with complete sequences from Lower Jurassic to Lower Cretaceous. The total accumulation thickness is over 6,600m. The strata within 200m depth from top to bottom are Quaternary pebbles (0m - 2. 10m), Quaternary gravelly loam (2.10m - 14. 52m), Jurassic Zhongtong Houcheng Group sandstone (14.52m - 20. 00m), Jurassic Zhongtong Houcheng Group conglomerate (20.00 m - 55.51m), Jurassic Tiaojishan andesite (55.51m - 105. 47 m), and Archean gneiss (105.47m - 200m).

Hydrogeological conditions: the Quaternary is filled with water from loose-pore rocks, and the lithology shows sandy gravel, sub-sandy soil and gravel sand. Structural fissures and pore water are contained in the bedrock. Gneiss, glutenite and volcanic rock outcropping areas are present in the bedrock fissure aquifer, the most important aquifer in the working area.

The depth of the test well is 200m, the diameter of the 0~24m-deep well is 325 mm, and the aperture of the 24~200m-deep well is 235mm. The 325mm threaded-steel pipe with a 5mm wall thickness is put into the 0~24m-deep test well. The double-U buried pipe heat exchanger is made of PE pipe material (DN 32mm, inner diameter 26mm, wall thickness 6mm), and the backfill material is made of medium fine sand.

3. Results and Analysis of the Thermal Response Experiment by the Constant Temperature Method

All the test equipment were in normal conditions. Three groups of thermal response tests were carried out, with one group of initial ground temperature test, one group of summer work conditions (constant temperature method 35°C), and one group of winter work conditions (constant temperature method 4°C).

3.1 Test Preparation

Based on the characteristics of this project and the scope of the site, an in-situ thermal response test of the buried pipe heat exchanger is carried out. A PE pipe double-U buried pipe heat exchanger is used in the test well. The parameters of the heat exchange hole are as follows: the hole diameter is 235mm, and the hole depth is 203m below the natural ground. The buried depth of the heat exchanger is 200m. Pipeline connection and pressure test: after the pipeline connection from the water outlet/inlet of the buried pipe to the thermal response tester is completed, the electric pressure pump is raised to the pipeline pressure at 1.2Mpa. The stop valve is closed and the pressure is kept for 30 min without pressure drop and leakage. After the pressure test is completed, the heat exchange pipe is connected to the test vehicle, water is injected into the system with the pressure pump, and the emptying valve is opened for drainage. All joint points are checked, and there is no water leakage. The above-ground pipeline is wrapped with a rubber and plastic insulation sleeve with a thickness of about 20mm for insulation treatment. After the connection to external equipment for water and electricity is completed, all links in the test equipment are checked, after which the operation begins.

3.2 Determination of Flow State in Pipe

Section 4.3.9 of Engineering and Technical Specifications for Ground Source Heat Pump Systems points out that the fluid in the buried pipe heat exchanger should keep turbulent flow. Therefore, the critical Reynolds number is generally used to judge the flow state of the tested buried pipe heat exchanger. For any pipe diameter and Newtonian fluid, the critical Reynolds number to judge the flow state is the same at about 2000. According to Reynolds number calculation formula (11) and test-related parameters, it can be known that the circulating water flow rate in the pipe is set to 1.5 m^3/h

$$Re = \frac{\mathrm{v}d\rho}{\mu} = \frac{\mathrm{v}d}{\upsilon} \qquad (11)$$

Where: Re - Reynolds number;

v - Fluid flow rate, m/s;

d - Inner diameter of the pipe, m;

ρ - Fluid density, kg/m^3;

μ- Dynamic viscosity of fluid, Pa•s;

υ - Kinematic viscosity of fluid, mm^2/s

3.3 Initial Ground Temperature Test

The initial ground temperature of rock-soil is one of the necessary parameters to determine the thermophysical properties of the rock-soil, and its accuracy directly affects the calculation of thermal resistance and thermal conductivity of the rock-soil. At the same time, the temperature difference between the average temperature of ground heat exchanger and rock-soil is the driving force of heat transfer. Hence, the measurement of initial ground temperature of rock-soil is very important for the design of ground heat exchangers [8].

In this paper, the initial ground temperature test method of rock and soil adopts a reactive power cycle method. Before the test, the buried pipe heat exchanger is filled with water and placed for 48h. When the heat exchanger is not loaded with coldness and heat, the water is circulated in the buried pipe by the water pump until the water temperature becomes more stable and reaches thermal balance with rock-soil. At this point, the water temperature in the buried pipe is taken to be the initial average temperature of rock-soil [10]. According to the critical Reynolds number, the constant flow rate in PE double-U buried pipe is 1.5m^3/h, and it runs continuously for 23h until the water temperature reaches a stable state, where the test is stopped [11]. The test curve is shown in the figure. The average temperature of the inlet and outlet pipes is generally in the final stable state at 16h, and the average temperature of the inlet/outlet pipes is stable at 12.2°C. Hence, the initial ground temperature of rock-soil is determined to be 12.2°C.

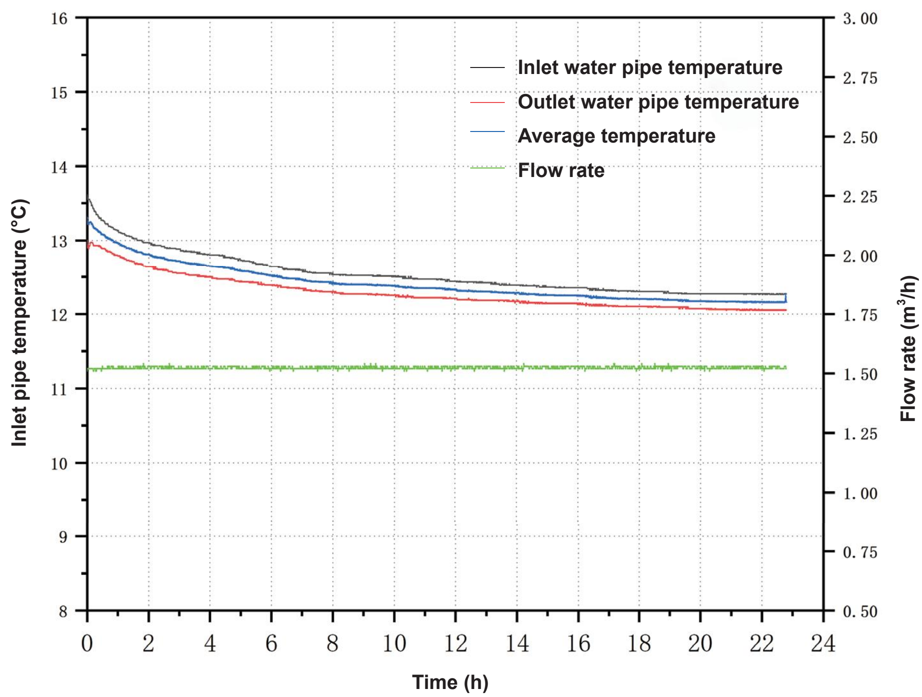

Figure 2. Initial ground temperature test diagram of rock–soil for buried pipe heat

3.4 Analysis of the Results of the Thermostatic Geotechnical Thermal Response Experiment Simulating Summer and Winter Conditions

(1) Thermal response experiment for summer working conditions with a constant 35 °C inlet water temperature

The thermal response of rock and soil experiment simulates the working condition in summer, setting the constant inlet temperature at 35°C and the flow rate at L=1.5 m^3/h. The duration of the test was 58h and the stability time was 49h. Test the inlet and outlet water temperature, average temperature, flow rate and power of buried pipe are as shown in the figure. The real-time power in the figure obtains real-time heat transfer (i.e., heat removal power) according to the formula $Q=Cm\Delta T$ by using the calculated real-time temperature difference at a constant temperature (T=35 °C). It can be seen from the figure that after 9 hours of operation in summer, the inlet and outlet temperature stabilizes, due to the fact that the inlet temperature is set at 35 °C in summer, which is 12.2 °C higher than the initial ground temperature of rock and soil. The temperature difference between them is 22.8 °C, which requires the thermal response tester to heat for a period of time to maintain dynamic balance before finally stabilizing. The fluctuation of the curve in the figure before 7.5h is caused by the fluctuation of the heating box. The figure shows that the temperature stabilization time of inlet and outlet exceeds 12h, which meets the constant temperature test conditions.

The heat exchange per unit per linear meter is one of the most important parameters in the thermal properties of rock-soil, which can directly reflect the thermal conductivity and heat exchange capacity of the borehole. It is hence an important reference for the design of buried pipe heat exchangers. As shown in the graph, the heat exchange rate per unit per linear meter increases significantly and the magnitude and volatility of the changes becomes more frequent, due to the 35°C inlet water temperature T during summer working conditions and the greater temperature difference between the surrounding rock and soil. The heat transfer rate is greater according to Fourier’s law. As the thermal response test proceeds for 10h, the heat exchange per unit per linear meter stabilizes, caused by surrounding rock-soil temperatures which must have reached a dynamic equilibrium. The slow-down in the rate of heat diffusion in the surrounding soil gradually tends to a dynamic equilibrium [12]. After the dynamic equilibrium is reached between the fluid inside the buried pipe heat exchanger and the surrounding rock-soil, heat buildup will be formed to increase the thermal conductivity resistance, reaching 80 W/m. Discarding the first 2.5h, the average heat exchange is obtained as 84.79 W/m. Through this test, it can be seen that under present test conditions, the thermostatic thermal response experiment for summer working conditions needs at least 10h of temperature flunctuations before stabilization. Therefore, the thermostatic thermal response test needs to be extended to make the test results more accurate.

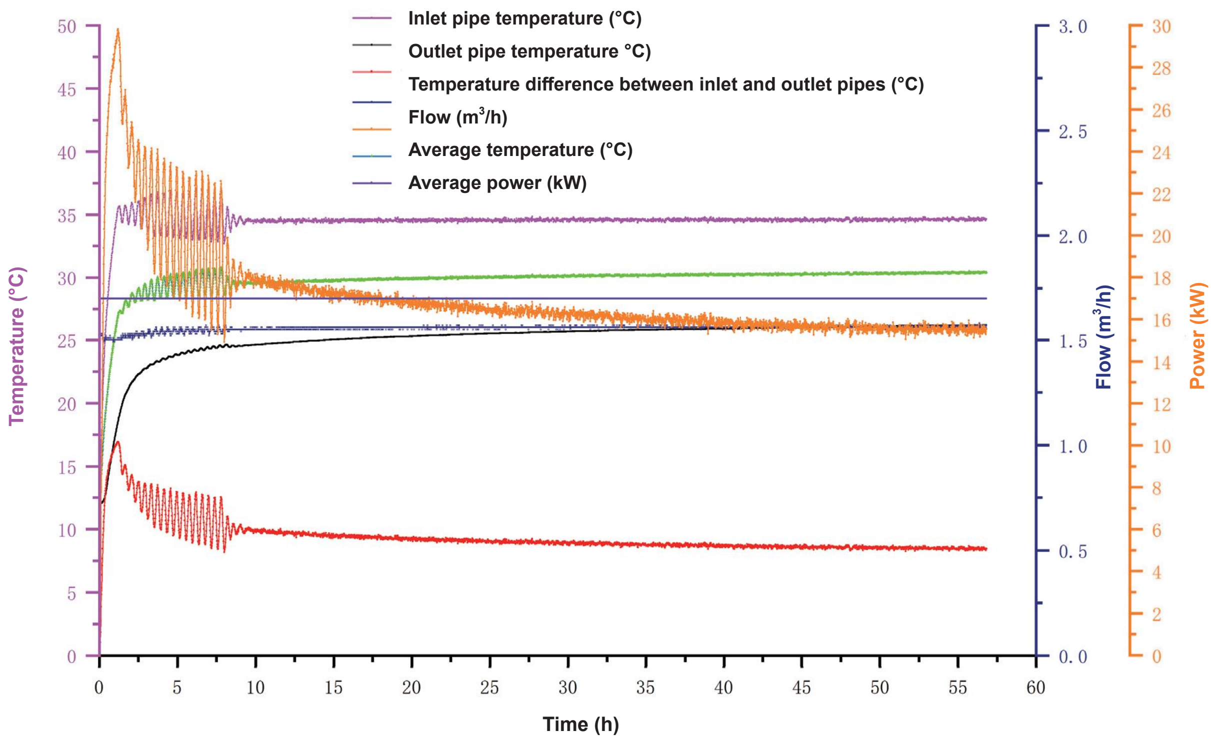

Figure 3. Test results of buried pipe test hole in summer working condition of heat removal

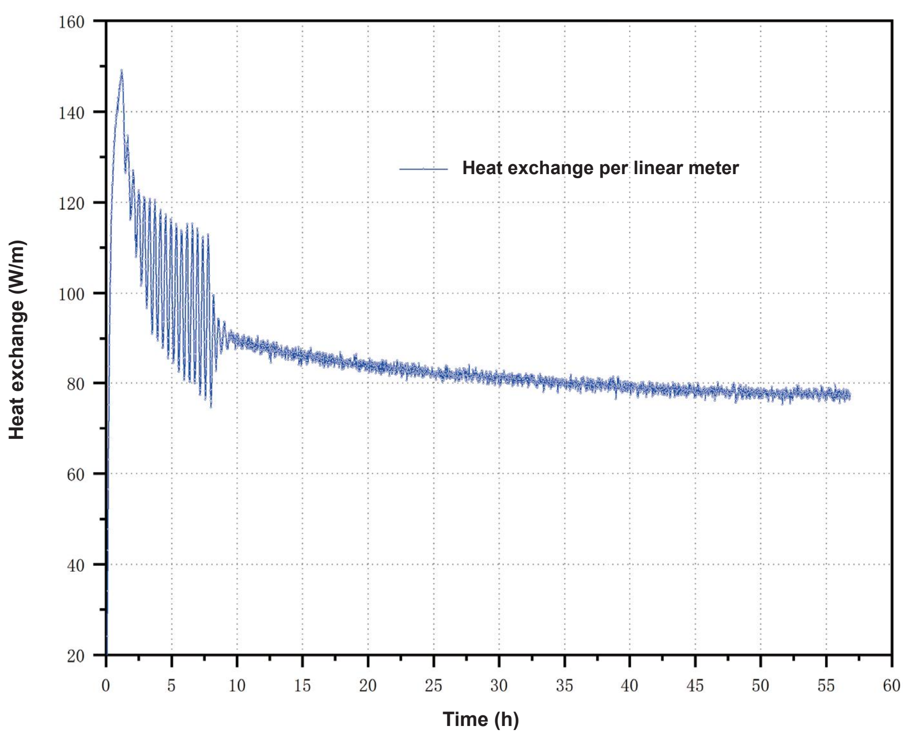

Figure 4. Heat exchange of buried pipe test hole in summer working conditions of heat removal

(2) Thermal response experiment for winter working conditions with a constant inlet water temperature of 4°C

The geotechnical thermal response test simulates winter working conditions, and sets the inlet water temperature at 4°C, flow rate at 1.53m^3/h, and test time at about 50h. The operating parameters of the system are shown in Figure 5. The summer power calculation method is referred in the calculation of winter operation power, its curve change trend is generally consistent with the temperature change trend of the inlet/outlet pipe, and the heat exchange power of the test hole is at 6.09kw/hole. As shown in the figure, after the system runs for 26 hours, the temperature of the inlet pipe stabilizes at 4°C. The stability time is close to 24 hours, which meets the specification requirements.

As shown in the figure, the change in the curves of inlet and outlet water temperatures are relatively smooth, showing a downward trend in the first 26 hours. The temperature difference between them is approximately kept at 3.2-3.75°C (except for the first 0.5h). This is because during the thermal response test of rock-soil under the simulated heat extraction working condition, the cooling capacity of the air-conditioning unit is kept at a fixed amount, and the unsteady heat conduction between the medium in the buried pipe and the drilling packing causes the heat exchange between the air-conditioning unit and the rock-soil around the borehole continu-

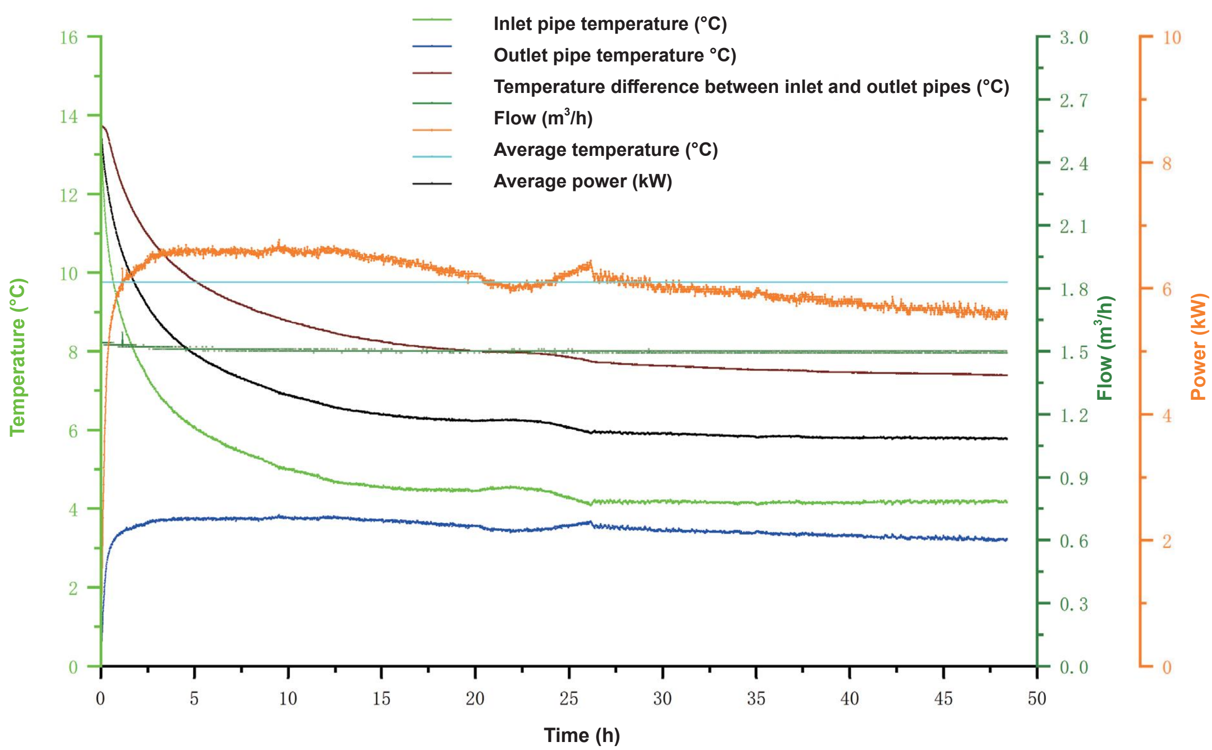

Figure 5. Test results of buried pipe test hole in summer working condition of heat extraction

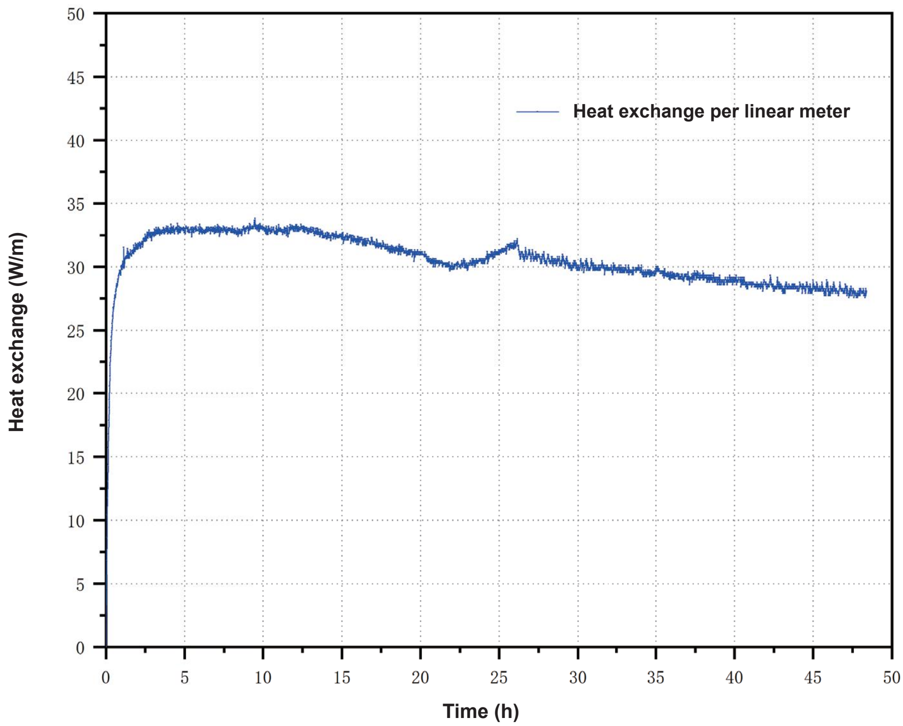

Figure 6. Heat exchange of buried pipe test hole in winter working condition of heat extraction

ously. The inlet and outlet water temperatures continue to drop, reaching a stable state after 26 hours, and the inlet water temperature is kept at 4°C. It takes 26 hours for the system to enter stabilization, which is caused by the small temperature difference between inlet and outlet water and the limited refrigeration capacity of the air conditioning unit. The fluctuation of inlet water temperature at 26h is caused by the operation fluctuation of the air conditioning unit.

As shown in Figure 6, the heat exchange trend per linear meter is generally in a stable state at 26h, compared to the summer working condition in Figure 4, and stability time is longer. The inlet/outlet water temperature difference is smaller in the winter working condition of heat extraction, which causes its heat exchange rate to be slower and the heat exchange with the surrounding geotechnical soil to be less, and it takes a longer time to reach the dynamic equilibrium of heat extraction. At the same time, the heat exchange power table per linear meter in winter is 30.45 W/ linear meter, which is lower compared to summer working conditions. One of the reasons for this is the smaller temperature difference between the inlet and outlet water, and the slower accumulation of coldness in the soil around the borehole makes the heat extraction in a variable process. Hence, after a certain amount of coldness accumulation, the heat extraction remains constant. Another reason is the relatively low initial ground temperature of the geotechnical soil, resulting in a slower rate of heat exchange between the inlet temperature and the surrounding geotechnical soil. This test also verifies the importance of the influence of the initial ground temperature of the geotechnical soil on the heat exchange capacity of the buried pipe heat exchanger. Under the present test conditions, it takes 26h to reach a steady state under simulated winter heat extraction conditions, which is a longer stabilization time compared to summer working conditions, and the thermostatic method of thermal response testing requires a longer period of time to ensure accurate geotechnical thermal response testing.

4. Test Results of Geotechnical Thermophysical Parameters

The heat exchange power of single hole and the reference value of heat exchange power per linear meter in summer and winter working conditions can be obtained intuitively and realistically through the geotechnical thermal response experiment by the constant temperature method. According to the test results, the thermal conductivity and thermal resistance of geotechnical thermophysical properties can be obtained by using the drilling linear model and simulating calculation according to the formula. The detailed test results of the experimental hole of PE pipe double U buried tube heat exchanger are as follows:

1) Under the test conditions of constant inlet temperature of 35 °C and flow rate of 1.5 m/h in simulated summer working conditions, the reference value of unit linear meter heat exchange power is 84.79 W/linear meter, and the single hole heat exchange power is 16.95kW.

2) The reference value of heat exchange power per unit linear meter is 30.45W/linear meter, and the single hole heat exchange power is 6.09kW under the condition of constant inlet water temperature of 4°C and flow rate of 1.5m/h.

Table 2. Main parameters of the model

Test hole	Hole depth (m)	Initial ground temperature (℃)	Working conditions for test	Thermal conductivity coefficient W/(m · k)	Thermal resistance (m · k)/W	Heat ex-change per linear meter (W/m)	Single hole heat exchange (kW/hole)
PE double U buried pipe	203	12.27	Summer working condition	1.68	0.08	84.79	16.95
			Winter working condition	1.01	0.09	30.45	6.09

5. Conclusions

The geotechnical thermal response test method can more accurately obtain geotechnical thermophysical parameters, which is an important basis for the design of buried pipe heat exchangers and display of heat exchange performance of buried pipe heat exchangers. In this paper, the thermal response test of the borehole is carried out by thermostatic geotechnical thermal response test method, and the main conclusions are as follows:

1) Compared with other thermophysical parameter tests, the thermostatic thermal response experiment can simulate heat removal in summer and heat extraction in winter, and obtain thermophysical parameters more accurately. It is more realistic for the design of buried pipe heat exchangers, and can intuitively obtain the heat exchange per linear meter.

2) The thermostatic thermal response experiment realistically simulates the heat removal and extraction working conditions of the buried pipe heat exchanger, and the test proves that the heat exchange capacity of the buried pipe heat exchanger is higher than that of the heat extraction working condition, and the heat exchange per unit hole is higher than 10.9kW/hole, which also indirectly verifies that initial geotechnical ground temperatures have a great impact on the heat exchange capacity of buried pipe heat exchangers.

3) During the thermophysical thermal response experiment, the stable time of heat removal in the working condition during summer is shorter than that of heat extraction during winter, so it is suggested to extend the stable time of heat extraction in winter when conducting constant temperature test. When calculating relevant parameters, it is recommended to discard the unstable data of long winter heat extraction working conditions, which can improve the accuracy of testing geotechnical thermophysical parameters.

The references are the same as the Chinese version

TO MAKE "ACCELERATING THE DUAL CARBON GOALS THROUGH GEOTHERMAL SERVICES" THE HIGHLIGHT OF CHINA IN WGC2023

Written by: Zheng Keyan

Director of Expert Committee of Geothermal Industry Working Committee of China Technical Supervision Information Association

China has been granted a rare opportunity to host the 2023World Geothermal Congress. I have been thinking: we should present a bright image and achievements to the 2023 World Geothermal Congress (WGC2023).

Highlights of Previous World Geothermal Congresses

The International Geothermal Association was founded in 1989, and the first World Geothermal Congress was held in Florence, Italy in 1995. As the world's birthplace of geothermal power generation, this was where the five-yearly World Geothermal Congresses was launched, and the five 20cm-thick collections created an unprecedented record of geothermal symposium proceedings.

In 2000, the World Geothermal Congress was held in Beppu and Morioka, Japan, with over 1,700 delegates from 61 countries showcasing the power of geothermal power generation in small land areas.

In 2005, the World Geothermal Congress was held in Antalya, Turkey, attended by more than 1,500 delegates from 83 countries. The promulgation of the Turkish Geothermal Law after the Congress turned geothermal power generation into a breakthrough.

In 2010, the World Geothermal Congress was held in Bali, Indonesia, with more than 2,500 delegates from 85 countries attending. After the Congress, Indonesia enacted its geothermal law that allowed geothermal power generation to grow rapidly without the restrictions of the mineral resources law.

In 2015, the World Geothermal Congress

was held in Melbourne, Australia, with over 1,600 delegates from 82 countries attending. Australia lacks hydrothermal geothermal resources and was late to geothermal development, but demonstrated remarkable EGS megawatt generation.

In 2020, the World Geothermal Congress was held in Reykjavik, Iceland, with only an online opening ceremony and several online conferences held from March to June 2021, postponed due to the global epidemic.

China's Geothermal Achievements and Tasks Ahead

Although China started early in geothermal power generation, we are now falling behind in development. During the 1995 World Geothermal Congress, China's direct geothermal ranked second in the world, just behind Iceland. But since the World Geothermal Congress in 2000, China has consistently ranked first, and is becoming increasingly stronger, far exceeding the second, third and fourth places combined. China's ground source heat pump development has grown even faster, climbing to the top in the world in just over 20 years, so far ahead of subsequent rankings that they are no longer able to catch up. That is how we won the right to host the 2023 World Geothermal Congress, and it seems we are going to add a fresh splash of color on the world's geothermal industry and put a new spin on the traditional lens of geothermal power generation: direct geothermal use can be so wonderfully exciting.

Geothermal Energy can make a Tangible Contribution to the Double Carbon Target

With national energy conservation and emission reduction policies supporting the development of renewable energy sources, the use of geothermal energy in China has made great strides over the years. However, compared to other renewable energy sources, geothermal energy in China has not yet become strong, even though it presents many advantages in terms of cost-effectiveness as determined by technical and economic feasibility in the context of promoting clean heating in northern areas in recent years. The contribution made by geothermal energy has not yet matched its advantages, and on many occasions geothermal energy is still being underused.

Geothermal energy can make a tangible contribution to carbon emission peak and carbon neutralization, and the magnitude its contributions are obvious.

(1) Carbon Dioxide Emission Rate

Natural gas prides itself on being a clean energy source, but its carbon emission rate is still half that of coal. natural gas also emits 31 times more CO_2 emissions than geothermal energy (wind power, hydropower and nuclear power) for the generation of one million kWh of electricity.

(2) Capability Coefficient

The CO_2 emission rates of geothermal energy, wind power, hydropower and nuclear power are all in the lowest bracket, but their capability coefficients still differ, with geothermal being energy the highest at 0.72, hydropower in the middle at 0.40, and wind power the lowest at 0.22. The CO_2 emission rate of solar photovoltaic power generation is higher than that of geothermal and wind power, and the capacity coefficient is still the lowest at 0.14.

(3) Comparison of the Overall Contribution to Carbon Emissions

In view of the above two constraints, we can introduce a "overall contribution to carbon emissions," which is set as the product of the number of tons of CO_2 for a million kWh of electricity and the number of megawatts of a million kWh of electricity produced annually. The result is that coal and oil are among the first and second highest respectively, with an overall contribution of 200,000 and 180,000 respectively. Natural gas is in third place with an overall contribution of over 90,000, followed by solar energy with over 30,000, biomass energy with over 10,000, wind power with over 7,000, hydropower with over 4,000, geothermal energy with over 2,000, and nuclear with less than 2,000 at the bottom of the list. Hence, to achieve carbon emission peak and carbon neutrality, natural gas should be less used, and nuclear power and geothermal energy are the top choices with the best capability.

Creating Chinese Highlights at WGC2023

China's geothermal presence at the World Geothermal Congress over the past 20 years has enabled China to go global and take the crown for the world's direct geothermal use. This glorious achievement should not only be attributed to the efforts of the Chinese geothermal industry itself, but also to the support by a great number of favorable national policies. On this basis, we can expect to create other new highlights for China at the 2023 World Geothermal Congress.

(1) In the process of realizing carbon emission peak and carbon neutrality in China, making a greater contribution from geothermal energy should be a Chinese highlight of the 2023 World Geothermal Congress. According to the target for geothermal energy development in China proposed by the Comprehensive Department of the National Energy Administration in the "Several Opinions on Promoting the Development and Use of Geothermal Energy (Draft for Public Comments)", the areas heated (and cooled) by geothermal energy will increase by 50% by 2025 compared with that of 2020. This figure alone is still far from the carbon emission peak target, and we need to make greater efforts.

(2) After last year's Geothermal Power

Generation Prospect 100 Forum and media coverage, coupled with the proposals of many committee members and representatives at this year's two sessions, the industry estimates that the national subsidy policy for geothermal power generation feed-in tariff is expected to be implemented. If so, it will definitely usher in a big growth of geothermal power generation in China. At present, large state-owned enterprises such as China National Nuclear Corporation and Three Gorges Group have planned and implemented geothermal power generation projects, and this will effectively change the backward situation of geothermal power generation in China.

(3) We should follow the laws of geothermal science and rectify the order of geothermal management. We fervently hope that the Geothermal Law will be established, at least to sort out the chaos of geothermal management from the administrative order of shutting down geothermal wells across the board. The problem has not been identified and resolved at the source, and it has not been managed well, with new problems emerging even involving urban management authorities' regulations. This situation should be resolved and present a new appearance in the international community, through innovation and creativity for an appropriate transformation.

(4) We should start by actively hosting the 2023 World Geothermal Congress. The World Geothermal Congress 2020+1, which was affected by the epidemic, took positive measures to respond by holding a March-June online opening before the postponed physical meeting in Iceland in October, but the organizing committee were not satisfied with the Chinese response (due to mistakes and delays). We should learn from these lessons, make corrections, and redeem our image.

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OPENING REMARKS OF THE 2021 GEOTHERMAL INDUSTRY ENTREPRENEURS' FORUM AND ALLIANCE ANNUAL MEETING

Distinguished guests, ladies and gentlemen,

Greetings, everyone!

Today, the 2021 Geothermal Industry Entrepreneurs Forum and Annual Meeting of the Alliance, co-hosted by the China Geothermal and Hot Spring Industry Technology Innovation Strategic Alliance (hereinafter referred to as the Alliance), the Hydrogeology Bureau of China National Administration of Coal Geology, Shaanxi Coalfield Geology Group Co., Ltd. and XCMG Foundation Machinery Division, and sponsored and supported by China University of Mining and Technology will be held in Xuzhou, an ancient and beautiful historical and cultural city. The gathering will discuss and exchange new opportunities for the development of China’s geothermal industry, and jointly study national policies, industrial innovation, technological progress, and international cooperation in the context of peak carbon emissions and carbon neutrality in the industry.

In recent years, to promote the rapid development of the geothermal industry, relevant national authorities have issued a number of supportive and encouraging policies.

In March 2016, the Notice of the National Energy Administration on the Issuance of Guidance on Energy Work in 2016 mentioned that new energy sources such as geothermal energy and biomass energy should be actively developed and utilized.

In December 2017, the Notice on Accelerating the Development and Utilization of Shallow Geothermal Energy to Promote the Use Reduction and Replacement of Fire Coal in Northern Heating Areas” proposed that by 2020, shallow geothermal energy will be effectively applied in the field of heating (cooling) with a greatly enhanced application level and play a positive role in replacing civilian bulk coal for heating (and cooling). The energy use structure of regional heating (and cooling) will be optimized, relevant policy mechanisms and guarantee systems will be further improved, and the industrial system of shallow geothermal energy utilization such as technological development, consultation and evaluation, key equipment manufacturing, engineering construction and operation services have been further strengthened.

In January 2020, the Opinions and Suggestions on the Report on the Inspection of the Implementation of the Renewable Energy Law mentioned that it is necessary to strengthen the research and development of deep-sea, offshore wind power and deep-layer geothermal energy.

In February, 2021, the Notice of National Energy Administration on Actively Pursuing Renewable Energy Heating According to Local Conditions proposed to promote the development and utilization of geothermal energy, and focused on geothermal energy heating in the middle and deep layers. According to the principle of “ascertaining mining by irrigation, balancing mining and irrigation, and balancing water and heat,” based on geothermal formation mechanisms, geothermal resource grade and quantity, and groundwater ecological environment conditions, geothermal energy heating from the middle and deep layers should be promoted in centralized and decentralized manners by implementing total amount control, zoning and classified management.

In September 2021, eight ministries and commissions including the National Development and Reform Commission jointly set targets in Several Opinions on Promoting the Development and Utilization of Geothermal Energy: by 2025, all localities will aim to establish a sound and standardized geothermal energy development and utilization management process, and the national information statistics and monitoring system for geothermal energy development and utilization will be perfected. Geothermal energy heating areas will be increased by 50% compared with 2020, and a number of geothermal energy power generation demonstration projects will be built in areas with advantageous resource conditions; by 2035, the heating area of geothermal energy will double that of 2025.

The intensive introduction of relevant policies will surely usher in a wider potential of development and unprecedented historical opportunities for the industry. On this basis, the alliance will also play a leading role in the industry, promote the implementation of industry-related policies, promote cooperation in industry technologies and projects, and provide a multitude of services required by enterprises.

With the theme of “geothermal industry policy, opportunity, and future” and the purpose of “cooperation, development, co-creation, and win-win”, this conference interprets and analyzes the macroeconomic situation and technological innovation of geothermal industry; discusses the development and utilization of geothermal energy in shallow, middle and deep layers and dry hot rocks, geothermal energy exploration, design, drilling and construction, underground water exploitation and recharge, construction, commissioning, operation and management of geothermal heating systems, development trend of hot spring industry, design and operation of project engineering, among other topics. Acclaimed experts and scholars in geothermal industry, leaders of relevant government functional departments, outstanding representatives of geothermal industry demand and supply enterprises, financial institutions, etc. are invited to seek common development, exchange experiences and information, help geothermal industry-related entities break through the bottleneck of development, and build bridges for image-promotion platforms, brand promotion and business cooperation.

The successful convening of this conference has received strong support and trust from people from all walks of life and all those who are present today. I would like to express my sincere welcome and heartfelt gratitude for your attendance. I hope this conference can provide a service platform for friends in the field of geothermal industry development to obtain information, make friends and achieve results so that all guests at this conference will make gains, make contributions, and create brilliant achievements on the road of geothermal energy development and utilization industry.

Finally, I wish the “Geothermal Industry Entrepreneurs’ Forum and Annual Meeting of the Alliance” a complete success.

Thank you all!

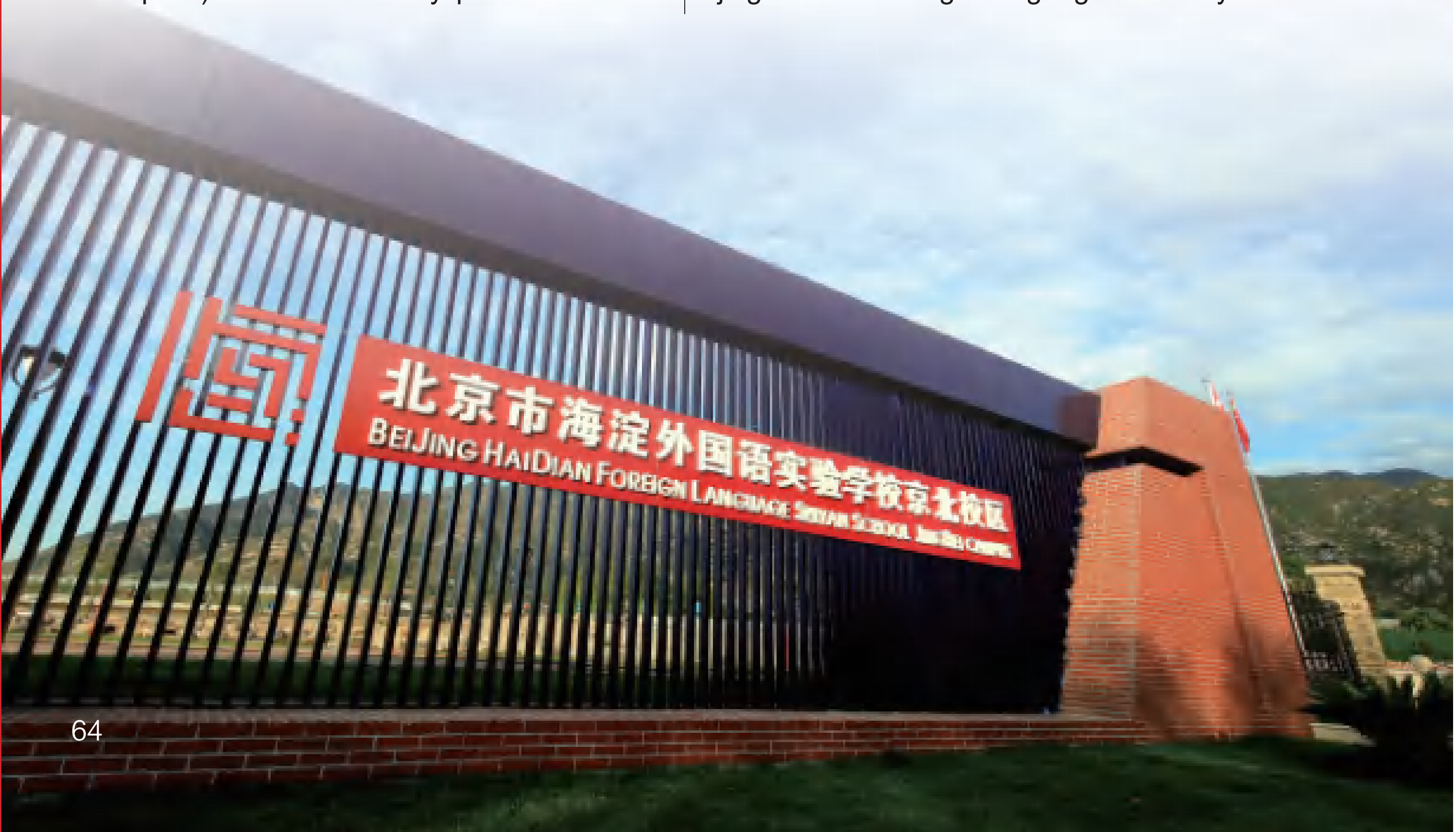
General Counsel of the Alliance,
Senior Counselor Representative of the State Council

Wang Bingchen

Haidian Foreign Language Academy and its Northern Beijing Campus:

20 YEARS OF PROTECTING OUR CHILDREN THROUGH SHALLOW GEOTHERMAL ENERGY TECHNOLOGY

With a zoo full of small creatures, pristine grass lands, a constant-heat swimming pool that operates in all four seasons, an excellently facilitated comprehensive sports center, a professional snow-and-ice sports center, and a ski driving-range, Haidian Foreign Language Academy's Northern Beijing Campus (hereinafter referred to as "Beijing North Campus") has been widely praised for its myriad of advantages in both hardware and software capabilities. By actively practicing the concept of "sports and education integration, art and education integration, science and education integration," it has garnered wide acclaim among primary and secondary schools in China. As a prestigious school in not only Beijing but also across China, Beijing Haidian Foreign Language Academy has



inherited the tradition of Beijing Campus in terms of its academic philosophy and principles in environmental protection.

It's all for the children. In order to create a low-carbon, environmentally friendly, and comfortable learning environment for students, the Beijing North Campus has adopted the single-well circulation heat exchange technology of Hengyouyuan Group, as used in the Haidian Campus since 2001, to provide heating in winter and cooling in summer for the whole school. Meanwhile, water for the natatorium and day-to-day use are ensured, a decision that achieves energy-saving, emission reduction, efficient, and clean goals. For over 20 years, Hengyouyuan Group's single-well circulation heat exchange ground energy acquisition technology has constantly innovated. Its achievements not only make teachers and students feel the comfort of environmental protection and low carbon, but also strengthen the determination of the school to build an environmentally friendly campus.

Building Warm Winter and Cool Summer Venues for Students in the Spirit of the Winter Olympics

Beijing Haidian Foreign Language Academy, founded in 1999, has developed into Haidian Foreign Language Education Group after more than 20 years, with various campuses domestic and abroad. It has developed based on the model of "Two Schools, One Campus and Multiple sites," with "Two schools" referring to Beijing Haidian Foreign Language Experimental School and Beijing Haidian International School, "One Campus" referring to the affiliated kindergarten of Beijing Haidian Foreign Language Experimental School (Haidian/Beijing North/Chaoyang Campus), and "multiple sites" referring to the two campuses in Haidian and Northern Beijing. The Haidian campus is located in Haidian District, Beijing, while the Northern Beijing Campus is located in the Ecological New Area in the north of the capital, in Huailai and Yanqing of Hebei Province, in close proximity to the venues of the Winter Olympics.

From looking at the infrastructure of the school, the comprehensive scale of the Northern Beijing campus and facilities include a campus zoo, a swimming pool, unique large indoor sports venues which include the snow-and-ice sports center, a ski-driving range, tennis courts, a badminton hall, a fencing hall, and large venues such as the school theatre. Beyond these, the cooperation agreement with Beijing Archery Sports Association helped to establish the Youth Archery Sports Center in the Northern Beijing Campus, to cultivate teenagers' interest in shooting sports from young and provide a reserve pool of athletes for the national youth professional sports teams and the state general administration of sports reserves for the Olympic Games. Likewise, the snow-and-ice and tennis facilities on campus are also meant for this similar purpose. What is more special is that students in the Northern Beijing campus can commute to school via a small train, which demonstrates the effort and care that the school takes in catering to its students' academic success.

From understanding, the Northern Beijing Campus's architectural design is very user-friendly with students' dormitories, classrooms, dining halls, indoor basketball courts, natatorium, and other places all interlinked to each other, which serves well to avoid students from experiencing temperature switches in different indoor-outdoor environments after sweating from sport activities. Not only that, the school also equipped each dormitory building with central air conditioning and air ventilation system, to keep the students warm in winter and cool in summer.

In addition to architectural design, another essential factor which ensures a constant indoor environment in the Northern Beijing Campus is the use of single-well circulation heat exchange technology. Since the Haidian Campus has been using this technology for nearly 20 years, it has fully felt the enormous advantages brought by constant source single well circulation heat exchange geothermal energy acquisition technology: heating in winter and cooling in summer, low carbon and environmental protection, and 24-hour hot water.

The first phase of the Northern Beijing Campus of Haidian Foreign Academy is located in Yuanxiang, Beixinbao Town, Huailai County, Zhangjiakou City. There are 6 buildings in the campus, including 1# primary school, 2# Middle school, 3# overseas Theater, 4# comprehensive sports center, 5# ice and snow center, ski hall, etc. The total construction area of heating and cooling is 59292.93m^2. These have been in use since September 2019.

"Everything for the children, for it is everything that matters to the child, for every child." These three "every" of Ms. Soong Ching Ling have not only become the motto of generations of teachers, but also the bounden responsibility of every responsible individual in society. As a leader in the shallow geothermal energy industry, Hengyouyuan

Group adheres to this three "every" concept in the construction of Beijing Haidian Foreign Languages Beijing North Campus, focusing on the combined efforts of the company to escort children in every spring, summer, autumn, and winter by utilizing the shallow geothermal energy.

Making the Indoors feel like Spring All-year-round: Creating a Comfortable Academic Environment

Skiing, skating, shooting, fencing, horseback riding… students at the Northern Beijing Campus can enjoy a full range of quality education. It is the common responsibility of the school and Hengyouyuan Group to create a comfortable learning environment. The project adopts to the function of buildings in the school area, using the constant source energy heat pump environment system, which comprises of 4 centralized cold and heat source machine rooms, 1 centralized heat exchange station, and 22 constant active single well circulation heat exchange ground energy acquisition wells to supply a centralized ground energy, with each machine room operating independently. This meets the building's heating needs in winter, cooling needs in summer, providing domestic hot water and swimming pool heating all year round.

No matter how the weather changes outdoors, the indoor remains like spring all-year-round. Through the constant source energy heat pump environment system, the indoor temperature of each building can be adjusted at will between 18°C and 26°C to meet the requirements of indoor environmental comfort in winter and summer. Domestic hot water system is set at 40-45°C, with 24 hours of uninterrupted water supply.

Energy conservation and Environmental Protection Replaces 1844 tons of Thermal Power provided by Coal Plants

In the Northern Beijing campus, surrounded by mountains and rivers, not only is there comprehensive academics, students can also experience living in an environment that champions low-carbon values and beliefs in environmental protection. The original intention of the project is to be more environmentally friendly and low-carbon on the basis of comfort. The total electricity consumption of the project in winter heating is 2,267,800 KWH per year. Compared with electric boiler heating, it saves 5.518 million KWH of electricity and 184 tons of coal. Compared with the direct heating boiler, it saves 90.4 tons of coal every year, reduces the smoke emission by 100,000 standard cubic meters, reduces 236.8 tons of carbon dioxide and 0.3 tons of sulfur dioxide.

The project consumes 508,900 KWH of electricity for refrigeration in summer every year, saving about 171,100 KWH of electricity compared with traditional central air-conditioning system. Because there is no cooling tower, there is no evaporation loss of water, saving 396 tons of water every year.

After analysis and calculation of the operation, the average power consumption of this project is estimated to be 38.2kW•h/ m^2 for heating and hot water in winter (including domestic hot water for 1400 people), 8.6 kW•h/ m^2 for summer (free hot water production and auxiliary cooling by waste heat recovery in summer), and 46.8kW•h/ m^2 for heating, cooling and domestic hot water supply in the whole year. According to the residential electricity price of 0.52 yuan/ kW•h, the annual operating cost is 24.4 yuan /m^2 (146 days of heating, 200 days of hot water, 365 days of swimming pool heating, 90 days of cooling).

Constant-source Ground Energy Heat Pump Technology Saves over 40% of Costs

The project uses the single well circulation heat exchange geothermal energy acquisition technology to collect the low temperature heat energy (>25°C) contained in the soil, sand and groundwater within 100 meters below the surface, and combines it with the mature heat pump technology to provide heating, refrigeration and domestic hot water for buildings. There is no water consumption, no pollution to groundwater and no potential geological disaster.

The heat generated by the system refrigeration can be recycled directly through the heat pump unit to prepare domestic hot water or to heat the water in the swimming pool to realize the recycling of system energy. At the same time, the project has realized the complete marketization of original technology. Through referencing previous similar operational projects and combining with the characteristics of this current project, the low-cost operation of the project can be realized without obtaining any project-related subsidies. The annual operating cost is 24.4 yuan /m^2, which is 44.7% lower than the heating price of 44.1 yuan /m^2 (building square meter) for non-residential areas (schools) in Zhangjiakou city, as released and implemented in 2018.

At present, the third phase of Beijing North Campus is under construction. In the future, it will carry out strategic cooperation with Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, and other major scientific research institutes in Beijing, so as to build a futuristic high-tech science city, so that children can not only look up at the stars, but also explore the world together. Hengyouyuan Single well circulation heat exchange ground energy acquisition technology will continue to work hand in hand with Haidian Foreign Language School to create a more environmentally friendly and comfortable teaching environment for children, and use shallow geothermal to guard and escort children on their way forward.

DISCUSSION AND PROGRESS-TRACKING OF THE FORMATION MODEL OF DRY HOT ROCK RESOURCES IN THE SOUTHEAST COASTAL AREA

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Abstract

Dry hot rock resources are an important component of geothermal resources, most of which are mainly extracted from heat contained in intermediate-acidic intrusive rock mass in the earth's crust that have developed since the Mesozoic times. China's southeast coastal area is the most important distribution area of highly radioactive granite, containing large areas of Mesozoic acidic granite bodies. It is a exemplar target area for searching dry hot rock resources. By studying the tectonic setting, regional heat flow distribution, crustal thickness, Curie surface burial depth, and neotectonics along the southeast coast, this paper analyzes the occurrence background of dry hot rock resources in southeast coast and explores the existence of dry-hot rocks in Fujian. Based on the analysis of heat-controlling thermal structures, this paper puts forward the formation model of dry hot rock resources in southeast coastal areas and preliminarily establishes the ternary heat accumulation model of dry hot rock reservoir formation in southeast coastal areas. This paper also summarizes the exploration progress in dry hot rock resource target areas in Zhangzhou and Huizhou. The relevant findings can provide a basis for future exploration and evaluation of dry hot rock resources in southeast coastal areas of China.

Keywords：Dry Heat Rocks; Southeast Coast; Formation Models; Progress-tracking

Introduction

Hot Dry Rock (HDR) is an important form of geothermal resources. It refers to the dense body of hot rock without the presence of water or steam which exists deep in the strata (generally 3~10km below ground). HDRs are widely distributed and are the main direction for future geothermal development. According to a 2006 report by the Massachusetts Institute of Technology (MIT), the mere development of 2% of the U.S. dry heat rock reserves at a depth of 3500~7500m would reach 260,000 EJ, which is 2600 times the U.S.'s total annual energy consumption in 2005. This indicates an enormous potential for the development of HDR. According to preliminary estimates, the total HDR resources in mainland China at a depth of 3~10km is 2.5×10^{25}J, equivalent to 860 trillion tons of standard coal. If 2% can be extracted, it is equivalent to 4000 times of China's total national single-time energy consumption in 2015.

Compared to nuclear energy, solar power, and other renewable energy sources, HDR geothermal power generation is an important potential energy source and consists commercial value, despite the fact that the technology has not yet matured. So far, the development of HDR resources and its technical research in China has been unsatisfactory, especially in the evaluation of HDR resources, target area selection, key technology research, and the establishment of demonstration projects. There is an urgent need to narrow the gap between China and developed countries, keep pace with the international community, discover and master the HDR resources suitable for China's geological conditions, and strive to hold a place in the world in the field of utilization research in the near future. At present, high quality HDR bodies have been discovered in Gonghe Basin of Qinghai Province, and HDR exploration and research are being carried out along the southeastern coast.

At present, most HDR resources are extracted from heat contained in intermediate-acidic intrusive rocks in the earth's crust that have developed since the Mesozoic times. The southeastern coastal area is the main distribution area of highly radioactive granite in China, producing a large area of Mesozoic acidic granite bodies, which are rich in radioactive elements such as U, Th and K. The decay heat of radioactive elements generates important heat sources, and the geothermal heat flow value in granite distribution areas can exceed 100μW/m2 if both the crust and mantle source heat production are under ideal conditions. Where the cover layer is ideal, it is possible to obtain high quality dry heat rock resources. At the same time, as one of the major energy consumption areas in China, the southeastern coastal area has long been an area which experiences abnormal shortage of coal, electricity and oil, and the vast majority of energy has to rely on sources transferred in from outside regions. Rapid economic growth, especially due to the development of a large number of high energy-consuming industries, has led to an excessive growth in energy consumption in the region, causing tension in energy supply. The development and utilization of HDR resources can provide a back-up energy base for the local area, which is of great significance.

1 Geological Background of Dry Hot Rock Resources

The southeast coastal areas, particularly Jiangxi, Guangdong and Fujian provinces, contain large-scale granite distribution attained from different periods. These granite bodies have various rock types, different formation eras, complex characteristics of source rock and geological evolution, and are closely related to deep fault zones. In addition, there is an output of large-scale sedimentary basins from different periods in the region. These favorable geological conditions are ideal for the production and preservation of heat from HDR in the region.

1.1 Tectonic Background

The distribution of geothermal energy, volcanos and fractures is strictly controlled by geotectonic features. The southeastern coast is located in the southern part of the eastern margin of the Asian continent, and the entire region is covered by a large number of Late Mesozoic volcanic-intrusive mafic rocks, which are an important part of the tectonic-magmatic belt along the Pacific Ocean. The subduction of the Pacific plate and the collision of the Philippine plate since the Late Mesozoic were crucial in controlling the Paleocene and Quaternary magmatic-volcanic activity throughout the eastern part of the Asian continent, which is directly related to the availability of high-temperature geothermal resources similar to those in Taiwan along the southeastern coast.

The results of P-wave tomography in the present-day Taiwan Strait region show that the present-day southeast coastal region is dominated by the collisional compression between the Eurasian and Philippine continental plates. The NW-oriented extrusion of the Philippine plate played an important role in the formation of the geothermal system in the Zhangzhou area and the Southeastern Coast. According to 1964-1996 earthquake records and kinematic indications in the Taiwan Strait region, the collision caused by the subduction of the Eurasian plate beneath the Philippine plate and the subduction of the Philippine plate beneath the Taiwan region are the main cause of earthquakes in the region, and the main stress direction in the region is consistent with the direction of plate subduction and collision.

1.2 Deep Thermal Structure Revealed by Geophysics

1.2.1 Characteristics of Crustal Thickness

As can be seen from the crustal thickness distribution map along the southeastern coast (Figure 1), the characteristics of crustal thickness distribution along the southeastern coast are similar to that of the terrain. The crustal thickness gradually thins from the southwestern to the southeastern coast, reaching less than 30 km from the inland to the coast in the area

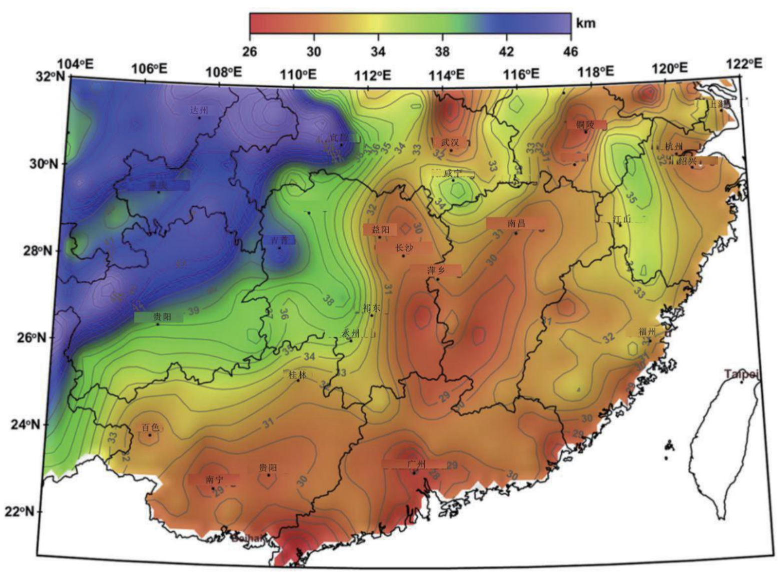


Figure 1. Crustal thickness in southeast coast

of Fuzhou-Guangzhou, except for Jinhua-Fuzhou area, where the overall crustal thickness is thickened in the north-east direction. This indicates an overall trend where the crustal thickness changes from thick to thin.

According to the earth's crustal thickness variation characteristics, taking the area of Beihai-Daiyunshan-Hangzhou as the boundary, the southeastern coastal area can be divided into two zones, west of which is the southeastern coastal crustal thickening zone, characterized by the north-east directional crustal thickening in Jinhua-Fuzhou, and east of which is the southeastern coastal crustal steep-sloping zone, characterized by sharply thinning of crustal thickness towards the coast.

1.2.2 Seismic Wave Velocity

There are various geological factors that can cause a decrease in P-wave velocity. For example, it may be a fracture zone, where the P-wave velocity decreases due to increased fractures and pore space. Changes in rock pore pressure, temperature, water-bearing properties, as well as the presence of partially molten material in the crust can also significantly reduce the P-wave velocity. The deep tectonics of the Zhangzhou Basin region revealed by seismic refraction profiles YCA and L3 in Fujian indicates that the region is a deep structural anomaly. Low velocity P-wave bodies with velocities less than 5.8 km/s exist in the middle and upper crust directly below Zhangzhou City at a depth of 10.2 km (Figure 2). It is also possible that because the Moho surface in this area is only about 29km deep and there is a deep NW-oriented tension deep fracture, the heat source in the crust may be constantly supplemented by the mantle heat source. This causes local geothermal anomalies in the area. Low velocity bodies at this depth

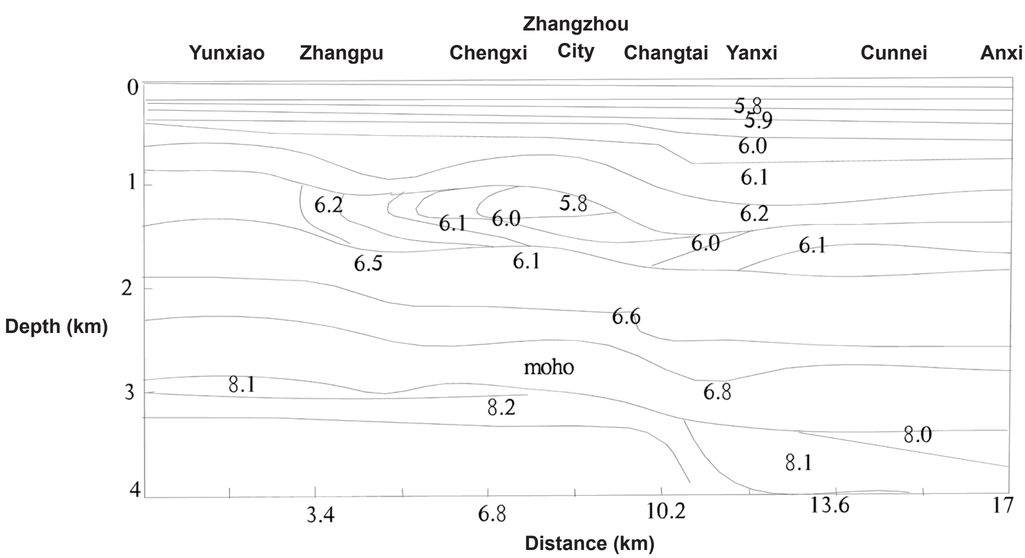


Figure 2. P–wave velocity contour profile of the YCA survey line

are found from southwest Jiangxi to coastal Fujian, indicating the unity and continuity of the regional geotectonic setting.

According to the difference in electrical structure, it can be interpreted that the lithosphere layer in the southeast coastal area is gradually thinning from west to east, and combined with the shallow deformation performance, it can be inferred that the lithosphere has experienced a certain degree of extension (Figure 3). The flow of asthenosphere promoted the extension of the lithosphere, and at the same time, a series of crust-mantle mixed zones were formed by local melting at the depth of the Moho plane, while a series of shovel-like extension and detachment faults were formed in the shallow crust. The upper part of the faults is brittle, and the lower part gradually transitions from brittle-ductile to ductile, which relates with the crust-mantle mixed

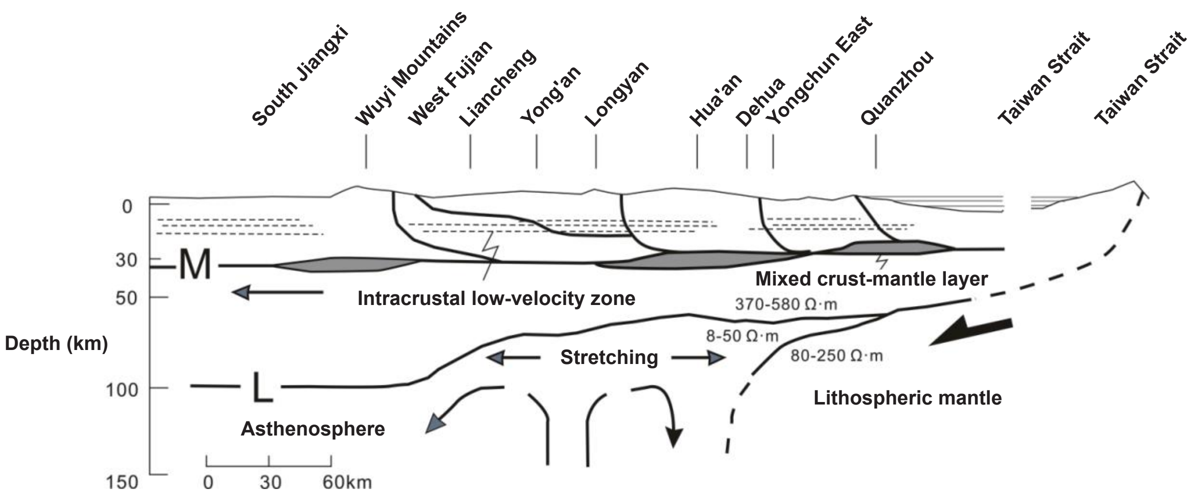


Figure 3. South Jiangxi–Fujian–Taiwan integrated geophysical profile

zone. Geophysics shows that there is a low velocity layer about 15km from the surface of the middle and upper crust, and the layer is distributed from the south of Jiangxi to the coast of Fujian Province, which may represent partially molten magma body in the middle crust or a ductile flow layer in the middle and lower crust.

1.2.3 Heat Flow Value

The geothermal heat flow value is a comprehensive parameter characterizing the thermal state of the earth's crust, and one of the important geothermal geological indicators of the distribution of HDR resources. The overall geothermal heat flow values in the southeast coastal region of China is clearly influenced by the geotectonic background (Figure 4): the basin area on the northwest side is more stable in terms of overall tectonic activity and shows lower geothermal heat flow values, while the southeast coastal area near the plate contact zone shows higher geothermal heat flow values. With the overall trend of gradually increasing heat flow values from west to east, local deep thermal structures control the geothermal heat flow values. The highest geothermal heat flow values can be seen in Figure 4, with heat flow values reaching over 95 μW/m^2 in Fuzhou and Zhangzhou, Fujian and Yangjiang-Maoming, Guangdong.

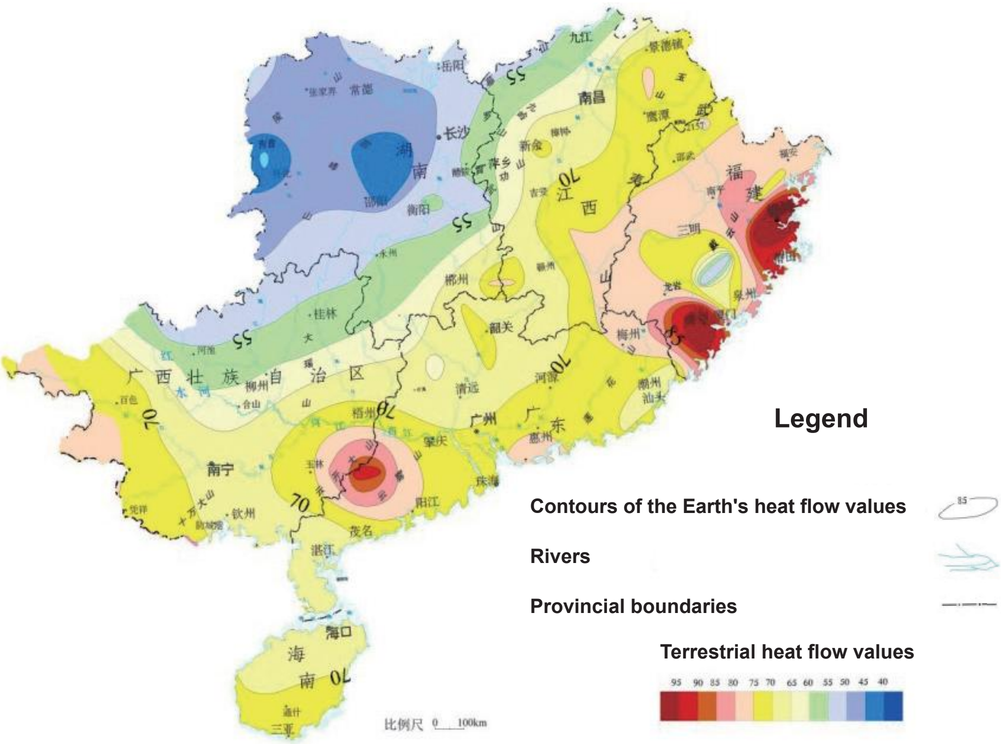


Figure 4. Contour map of geothermal heat flow values in the southeast coastal region of China

2 Exploration of the Formation Model of Dry Heat Rocks in the Southeastern Coast

2.1 Debate on the Existence of Dry Hot Rock Resources in Fujian

2.1.1 Belief in the Existence of Dry Hot Rock Resources

The east-west geothermal anomaly corridor from the Zhangzhou Basin to the estuary of the Jiulong River, formed by the near-north-south Jiulong River's deep-active fault and the near-east-west deep-cut Xixi active fault, covers an area of about 2000km^2, with concentrated geological stress, thin crust, high-temperature thermal storage distribution in the middle crust, and the possible existence of huge magma reservoirs in the lower crust. Dry and high-temperature thermal storage conditions make it the most promising area for development in Fujian Province.

Teng Jiwen, et al. believe that the Fuzhou and Zhangzhou Basins are located in the aggregation zone where the Pacific plate collides, compresses, and subducts with the Eurasian plate. The crust-mantle structure there is unique, and there are low-velocity layers in the upper crust, especially in Zhangzhou basin, where lenticular low-velocity bodies are present in some areas, so it is reasonable to infer the existence of underground heat reservoirs. The deep and large fault zone between Zhangzhou-Changtai, which runs through the crust and reaches the top of the upper mantle, may constitute the upward migration channel of deep materials, that is, the replenishment path of heat energy.

2.1.2 Belief in the Non-existence of Dry Hot Rock Resources

Wan Tianfeng et al. studied the thermal state of the Fujian lithosphere and concluded that Fujian does not possess the conditions for the development of HDR that can be used for power generation. According to calculations, even in the deeper Zhangzhou region, where temperatures are high, a temperature of 194.6°C can be reached only at a depth of 5km, with 187.6°C in Dehua, while other regions consist less than 180°C. Based on the above temperatures, to develop artificial thermal storage within Fujian's dry hot rocks, a significant increase in technical conditions would be required to make it possible for a reduction in construction costs.

Liao Zhijie argues from the plate tectonic context in which Fujian is located in that temperature conditions for magmatic heat sources are unlikely to occur in the upper part of the Fujian crust [17]. The low-velocity layers found by artificial blast earthquakes are relatively stable in distribution and cannot be caused by molten or semi-molten layers, but rather by rock fragmentation, i.e. by the Fujian-Taiwan shovel-like activate faults or slip surfaces, and the Fujian-Taiwan low-angle active fault system is buried at a depth of just over 10 km in the coastal area. Liao Zhijie et al. attribute the large-scale hydrothermal activity anomaly in Fujian to the strong compression from the southeast by the Philippine oceanic plate since the Neoproterozoic, which results in a shovel-like fault system in the relatively brittle and consolidated land crust of the Fujian-Taiwan region. The developed fracture grid allows abundant atmospheric water to seep deep into the subsurface and absorb heat from the rocks. Due to the difference in waterhead pressure and density, underground water can be discharged along faults, especially north-west tension-shear faults, to the surface or storage near the surface, constituting a large number of deep circulation hydrothermal convection systems. They are mainly low and medium temperature warm water storage, but can also form high-temperature hot water systems when the circulation depth is large enough. In such geothermal geological conditions, it is more difficult to form exploitable dry-heat rock systems, and to obtain high-temperature rock masses above 150°C, granite bodies with thick overlying caprocks need to be sought.

2.2 Analysis of Regional Heat Control Systems

2.2.1 Heat Source Mechanism

The results of surface heat flow values

show that the southeast coastal area contains higher values than the inland South Ridges area. There is a direct response of various heat sources (including mantle heat, magma heat, tectonic heat, radioactive element decay heat, etc.) at the surface, and the magnitude of the value reflects a large extent of deep heat sources. A great deal of previous research has been carried out on granites in the southeast coastal region, and the results are shown in Table 1 where the heat generation rate statistics per unit volume for granites shows the region does not contain uranium ore. The statistical results show that granite has the widest range of heat generation rates per unit volume (0.9-10.9μW/m^3) and the highest average heat generation rate per unit volume (4.11μW/m^3) of all crystalline rock types in the southeast coast. The values in the table show that granite has a significantly higher heat generation rate per unit volume compared to other rock types. In particular, Yanshanian granites, especially late Yanshanian granites, have the highest mean heat generation rate per unit volume (6.4μW/m^3), which is significantly higher than the mean heat generation rate per unit volume for Jinninian, Caledonian and Indochinese granites, and the data also show that the more recent the granite formation, the higher the mean heat generation rate per unit volume. Therefore, granites in the southeast coastal region, especially Yanshanian granites, have significantly higher heat production rates per unit volume, which provides good conditions for the formation of dry hot rock resources. Based on geothermal and hydrogeochemical modelling results, Pang Zhonghe shows that the contribution rate of mantle source heat in Zhangzhou area is about 60%, while the contribution rate of radioactive element decay heat is about 40%. Based on the simulation of elemental and isotopic geochemical characteristics of the Zhangzhou rock mass, Zhou Xunruo et al. also find that the material contribution rate of the mantle in the granite body exceeds 60%, which is basically consistent with the results of Lin Leifu et al. The above studies show that there is both contribution from mantle heat and crustal materials in the granite bodies of Zhangzhou area, but the contribution from mantle heat is dominant.

Table 1. Heat generation rates per unit volume of basement rocks from different periods in the southeast coastal region

Age of granite body formation	Average heat generation rate per unit volume (μW/m^3)
Granite from Jinningian period	3.1
Granite from Caledonian period	3.3
Granite from Indochinese period	3.9
Granite from early Yanshanian period	5.2
Granite from late Yanshanian period	6.4

2.2.2 Thermal Conductivity Channels

Granite exposed in southeast coastal areas is closely related to several major fault zones in the region, such as the Pingxiang-Guilin fault zone, Longyan-Dapu-Haifeng fault zone, Gan River fault zone, Chaling-Guangchang fault zone, Wuzhou-Sihui concealed fault zone, and Changle-Nan'ao fault zone, etc. Granite usually occurs in the intersection areas of fault zones. Granites, especially Yanshanian granites, have specific distribution directions. Early Yanshanian and Indosinian granites mainly distribute in the east-west direction, while late Yanshanian granites contain obvious north-east distribution characteristics. In addition, the age trend of granite is younger from west to east from inland (Nanling area) to coastal areas. At the same time, granite exist close to various types of sedimentary basins. Additionally, the granites related to orogeny in each stage contains two age peaks. The older granites are generally formed in the syn-collision orogenic period in compressional environments, while younger granites are generally formed in the post-orogenic period in extensional environments. This change in the forming environment may be accompanied by the transfer of energy and matter.

Generally speaking, the zoning boundary of hot springs is equivalent to the large-scale tectonic line. The outcrop of the hot springs is not directly related to trunk fracture, but it is more closely related to the secondary fracture structures, such as Fujian Zhangzhou Basin, Pinghe Gongzaiqian – Xiangcheng Pangu, Jiuhu Xintang – Zhangzhou Geothermal Field – Guokeng Huangkeng – Changtai Xuemei, Dongsi Songling – Jiaomei Tianli – Jimei Houxi, Xiamen Guiguan Lake – Xiangan Dongshan and other hot springs. Two to four hot springs are outcropped in succession along the NE direction, with Gongzaiqian - Pangu, Xintang - Zhangzhou - Huangkeng - Xuemei, Dongshi - Tianli - Houxi, and Kuiguan Lake – Wuyuan Bay – Dongshan and other lakes aligned in a north-east direction, reflecting that the heat source of underground hot water is mainly controlled by the NE direction tectonics. However, analysis of individual hot spring outcrops shows that they are mainly outcropped at the intersection of the NE and NW direction tectonics, and the NW direction tectonics in the working area shows the latest regional tectonics, displaying relatively good underground water connectivity and water-richness, providing the main source of recharge and runoff channels for underground hot water to indicate the good thermal conductivity of the fractures.

Therefore, due to the presence of deep fractures in the southeast coastal area, the heat energy from local melting or deep heat flow can be transferred more directly to the shallow parts through deep fractures. This thus creates an upward rise in the geothermal contour, where hot springs are often outcropped around the intersections of deep and shallow-tension fractures.

2.2.3 Thermal Storage Caprock

To preserve base heat and prevent atmospheric precipitation from infiltrating cooling rocks, a low thermal conductivity caprock is required as an overlying basement. These materials are usually made of mainly sedimentary (deposits) or volcanic rocks, or sometimes a suitably thick layer of weathered crust. Standard one-dimensional steady-state equation simulations show that a granite basement covered by a sedimentary caprock is 30-40°C warmer than one without a sedimentary caprock at a depth of about 5km, with all other physical parameters being equal. This thus demonstrates the importance of the caprock for heat retention in HDR.

Statistically, the average values of thermal conductivity of rocks in the southeast China, especially in sedimentary rocks, are higher than the average values of crustal rocks [24]. Analysis of the mineral composition of rocks shows that the content of calcareous, siliceous, and muddy minerals is the main factor determining the high or low thermal conductivity values of sandstones and mudstones. For example, the average thermal conductivity value of quartz sandstones is up to 6.46 W/m.K and calcareous sandstones up to 4.58±0.28 W/m.K. This type of sedimentary caprock has a relatively limited role in preventing heat loss, making it less effective in retaining heat.

2.2.4 Thermal Reservoir

Highly radioactive granite bodies are the main thermal reservoirs in dry hot rocks in southeast coastal areas. Radioactive heat generation is one of the main sources of heat in lithosphere, and U, Th and natural radioisotope 40K are the main heat generation elements. Most areas in the southeast coastal areas are in the range of high heat generation rate. Especially, a large area of granite is outcropped in Guangdong Province, southwest Jiangxi Province and south Fujian Province, and the background of heat generation rate exceeds 2.8 μW/m3. Such a large area with a high heat generation rate is rare among the world's continents. According to existing borehole temperature measurements in the southeast coastal area, the geothermal gradient in the southeast coastal area is 20-40°C/km. Taking 180°C as the starting temperature of dry hot rock resources, it can be preliminarily concluded that the buried depth of thermal reservoirs in the southeast coastal area is generally greater than 5km, while the buried depth of thermal reservoirs in areas with high geothermal gradient such as Huangshadong in Huizhou, Guangdong, Zhangzhou in Fujian, and North Hainan is about 4-5km.

According to the above analysis on the heat control system in the southeast coastal area, the author believes that the possible dry hot rock resources in the southeast coastal area should contain the following ternary heat accumulation mode, that is, the reservoir formation mode of radioactive heat generation by acidic rock mass, heat conduction by fracture, and heat preservation by caprock, as shown in Figure 5.

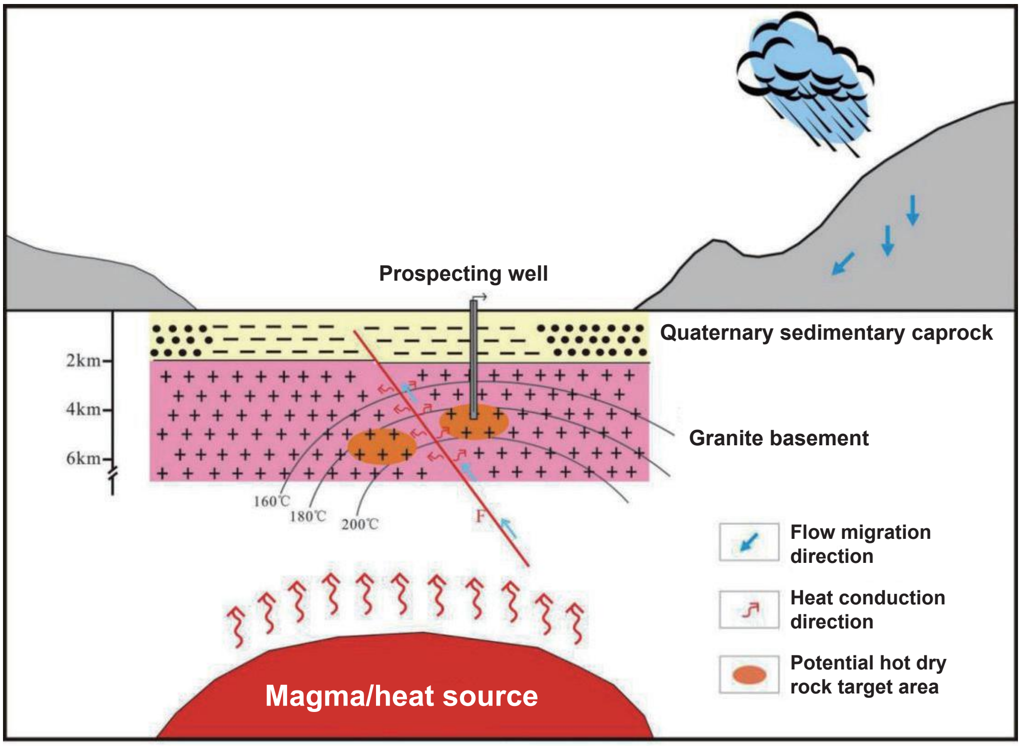


Figure 5. Ternary polythermal model of dry hot rock resource formation in the southeast coast

4. Tracking the Progress of Key Target Areas of Dry Hot Rock Resources along the Southeast Coast

4.1 Zhangzhou

Zhangzhou is a typical geothermal anomaly area along the southeast coast of China. Most of the outcropped hot springs in Zhangzhou are 40-80°C in temperature, and there are 13 hot springs with a water temperature higher than 60°C, which are the highest among the medium and low temperature hot springs in China. Under the background of hydrothermal anomaly, the occurrence characteristics of deep dry hot rocks in Longhai area of Zhangzhou are studied by geothermal investigations, geophysical exploration, and geothermal drilling. The results show that the strata from the Jurassic to Quaternary times are generally missing in the area, the lower part is invaded by Yanshanian granite, and the surface is covered by Quaternary Pleistocene diluvium strata with a thickness ofgreater than 20m (Figure 6).

From the comprehensive interpretation results of geophysical prospecting (Figure 7), it can be seen that there is a large-scale granite intrusion in the area, and it is speculated that the 4th, 9th and 19th rock masses are the third stage $\gamma5^{2(3)c}$ rock masses, and other granite bodies are

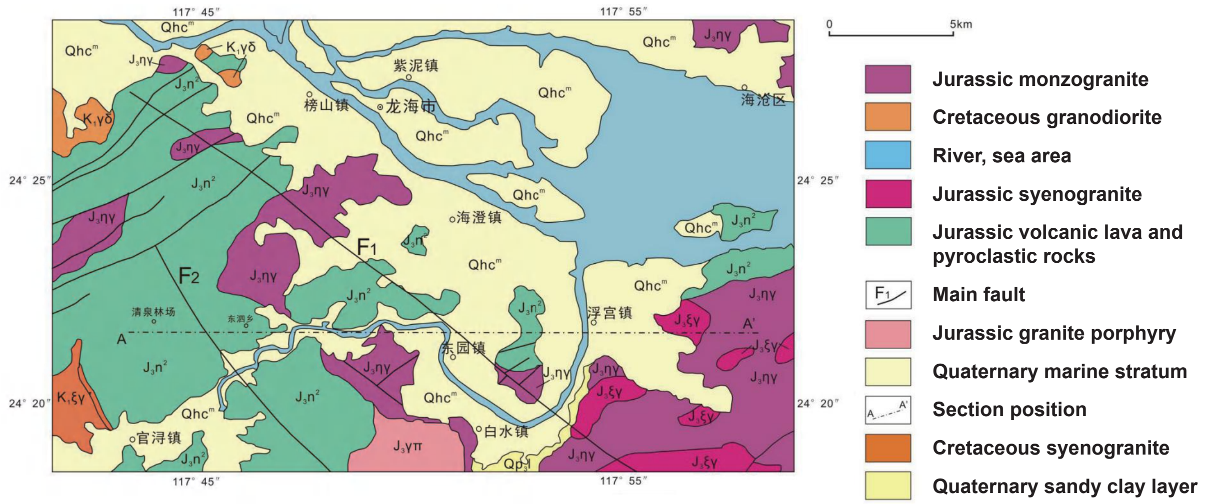
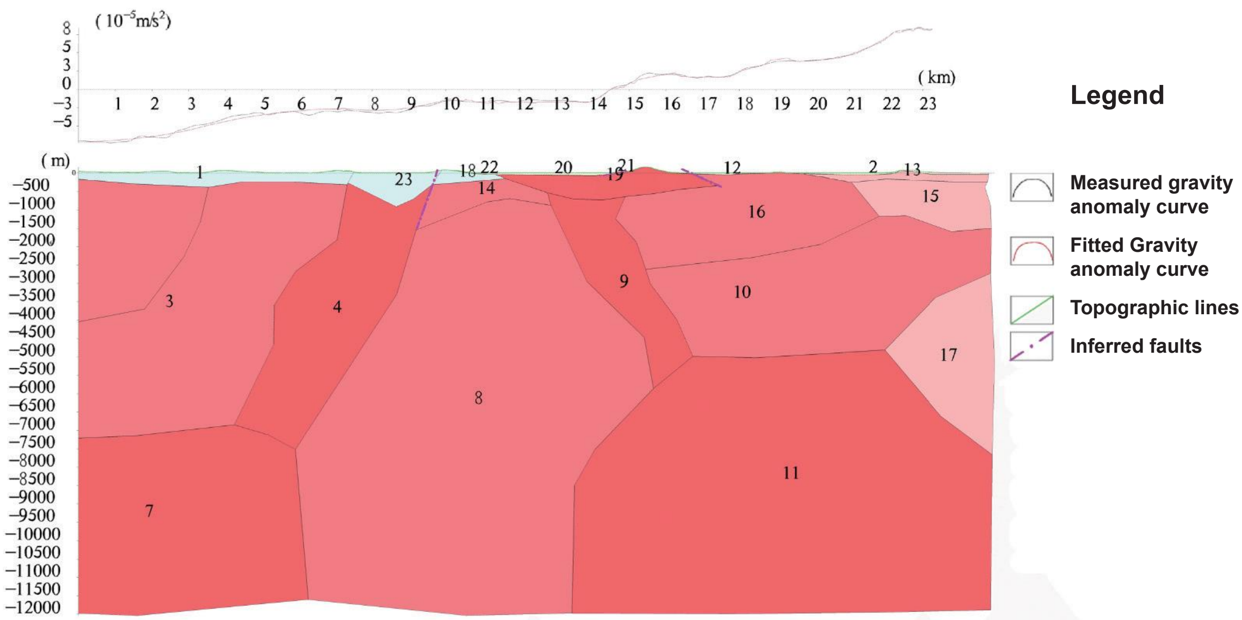


Figure 6. Geological diagram of Zhangzhou (A–A' is geophysical comprehensive section)



1.2.59Jurassic tuff	7.2.62Granite	13.2.68Granitic diorite	19.2.61Granite
2.1.81Quaternary	8.2.62Granite	14.2.61Granite	20.1.81Quaternary
3.2.62Granite	9.2.61Granite	15.2.68Granitic diorite	21.1.81Quaternary
4.2.62Granite	10.2.62Granite	16.2.61Granite	22.1.81Quaternary
5.2.62Granite	11.2.62Granite	17.2.68Granitic diorite	23.2.56Jurassic tuff
6.2.58Granite	12.1.81Quaternary	18.2.6Jurassic tuff	

Figure 7. Joint gravity and geomagnetic–inferred interpretation profiles in the Longhai area

earlier; the 13th, 15th and 17th are granodiorite masses. There is a large range of low resistivity masses (7th and 11th rock masses) in the east and west of the section below 7 km, which is inferred to be semi-melted lava masses.

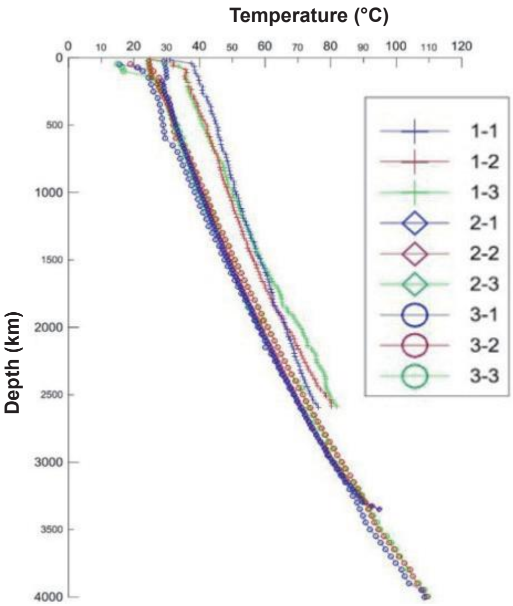


Figure 8. Logging temperature profile of 4,000m well depth in Longhai area, Zhangzhou

Using geophysical interpretation, the scientific drilling of dry hot rock was carried out in Dongsi Town, Longhai, with a drilling depth of 4000m. After drilling, a total of three tests were carried out, each time with three groups. The first time was 0-2500m, the second time was 0-3350m, and the third time was 0-4000m. The results are shown in Figure 8. It can be seen from the figure that the first logging temperature was about 3°C lower than the other two temperatures, and the coincidence degree of the second and third logging temperature curves is higher, which indicates that the first logging temperature has not yet reached the equilibrium state, showing a large deviation in the test results. The second and third logging's well temperatures have reached the equilibrium, and the logging temperature reflects the actual formation temperature, making results more credible. The results of this logging are close to those of 3350m logging, and the highest temperature at 4000m is about 109°C, which is within the predicted temperature range.

Utilizing TOUGH2 software to simulate the evolution of the geothermal field, to reduce the error caused by numerical calculation, Thiessen polygon is used to subdivide the plane, and the maximum area of a single grid is limited to 10000m^2. Vertically, the method of equidistant subdivision is adopted, with 40 layers every 200m and 39,680 grids in total. Some related parameters in the model are shown in Table 2. The thermal reservoir is mainly granite. According to logging data and core thermal conductivity tests, combined with empirical values, it is determined that the thermal conductivity is 3.4 W/(m•K), porosity is 0.01, and permeability is 1×10^{-17} m^2. Silicification exists in the fracture, and its thermal conductivity is higher than that of ordinary thermal reservoir, which is 5.5 W/(m•K).

Table 2. Main parameters of the model

Model	Porosity	Permeability m^2	Thermal conductivity W/(m · K)
Thermal storage	0.01	1×10^{-17}	3.4
Superficial fractures	0.05	1×10^{-12}	5.5
Deep fractures	0.02	1×10^{-17}	5.5

The initial pressure of the model is calculated by hydrostatic pressure P=P0 + ρ water • g • h, where P is the target grid pressure, Pa; P0 is atmospheric pressure, Pa; G is gravitational acceleration, N/kg; H is the depth of the center point of the grid. Taking 2,500m to conduct linear fitting with shallow temperature measurement data, the results are as follows: T=23. 403 +0.0186 Z, where T represents temperature, °C, and Z depth, m. This is taken as the initial temperature condition of the model.

The simulation results of deep ground temperature distribution in the research area are shown in Figure 9. It can be seen from the figure that heat in the deeper part is mainly transmitted to the shallow part along the fault, and the obvious phenomenon of geothermal isoline bulging can be seen. The model predicts that the temperature of 5,100m formation can reach 140°C.

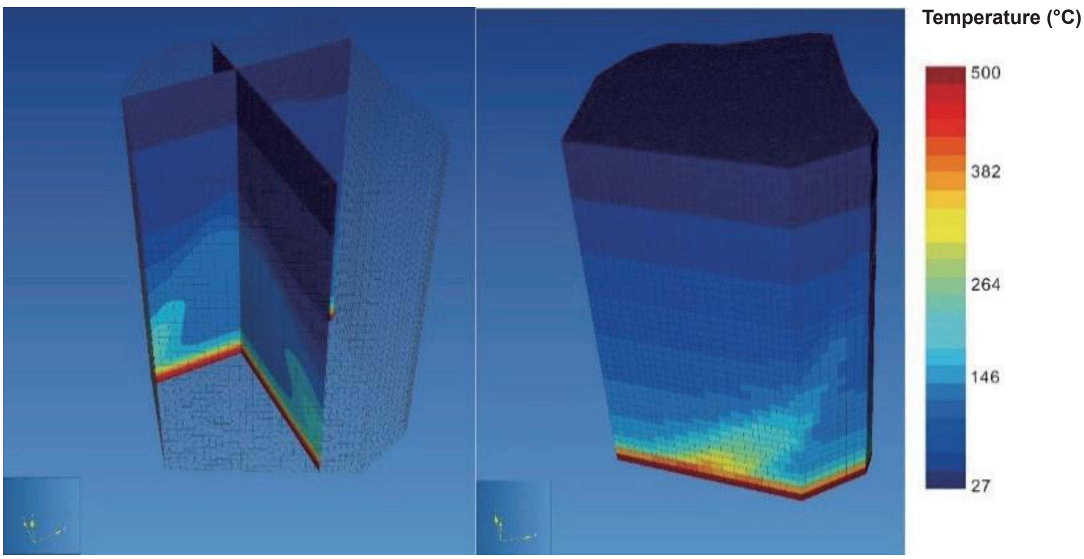
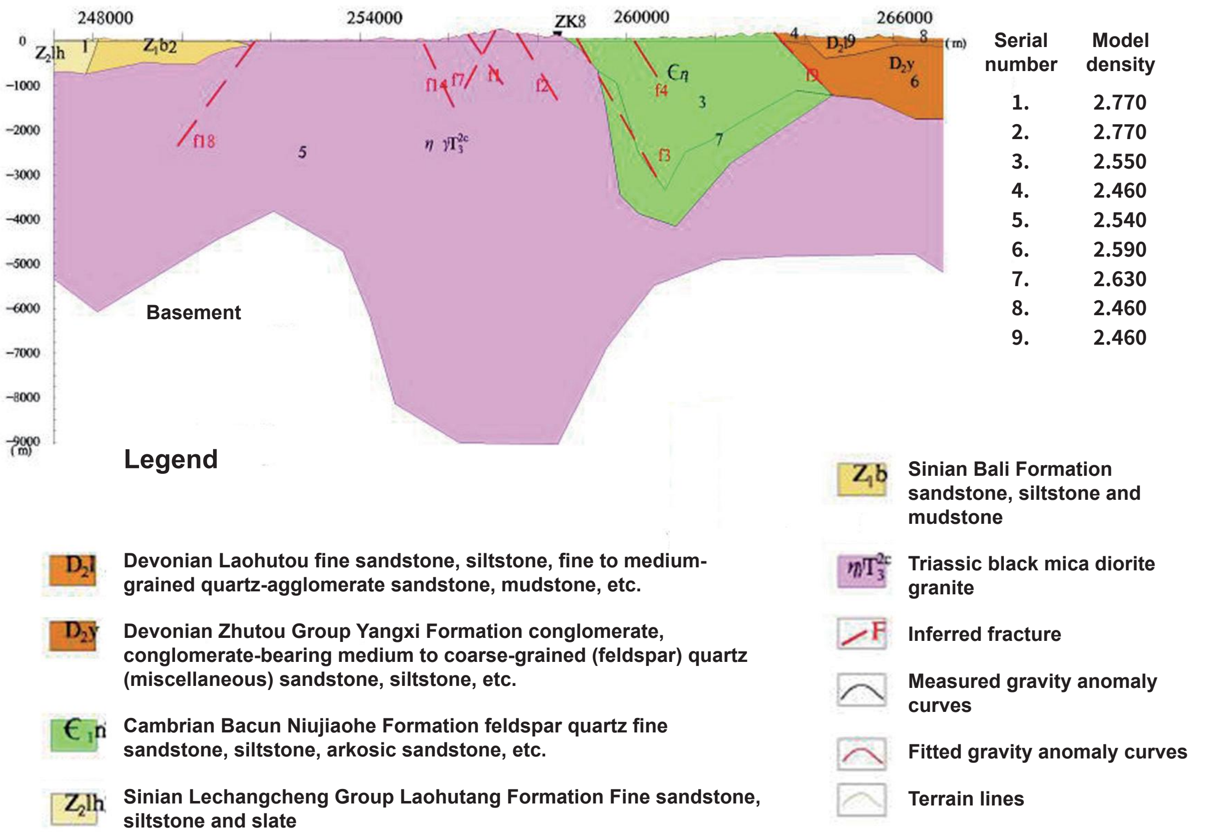


Figure 9. Distribution of deep geothermal temperature in the study area

4.2 Huangsha, Huizhou

The Huangshadong, Huizhou region is part of the South China Plate, south of the Huaxia Land Mass, about 30 km south-east of the Heyuan Deep Fault Zone, 12 km south-east of the Zijin-Boluo Deep Fault Zone, and 40km north-west of Lianhua Mountain Deep Fault Zone. The exposed strata in this study area includes the Sinian Laohutang Formation (Z2lh), the Cambrian Niujiaohe Formation (Єn), Devonian Laohutou Formation (D1-2l), Maozifeng Formation (D3C1m), Carboniferous Ceshui Formation (C1c), and Quaternary Huanggang Formation (Qp3hg), with Dadianding rock mass (J1D) to the north-west which contains fine to medium-grained black cloudy monzonitic granite.

According to the gravity-inferred section (Figure 10), it can be seen that the basement depth of burial fluctuates from 4 to 9 km, and basement tectonics in the study area are very developed, showing mainly mutual cutting in the north-east and north-west directions. These large fractures control the intrusion and deposition of the rock masses, and Aipi rock masses are intruded along the intersection of the fractures. The basement of the study area is composed of crystalline bedrocks of Early Palaeozoic Sinian metamorphic rocks.



Serial number	Model density
1.	2.770
2.	2.770
3.	2.550
4.	2.460
5.	2.540
6.	2.590
7.	2.630
8.	2.460
9.	2.460

Figure 10. Gravity inferred section of the study area

The CSAMT method is used for shallow fracture detection and a total of four survey lines are laid out, numbered L1, L2, L3 and L4, with L1 and L3 lines in the NW direction and L2 and L4 lines in the NE direction. The joint interpretation of the audio geomagnetic lines L2 and L4 shows that a corresponding low-resistance body channel exists, located east of the L3 line (Figure 11). Projected onto Fig. 12, the channel is NW oriented and the L2 line reflects a smaller range of low resistance body channels than the L4 line, so it can be inferred that this low resistance body channel decreases from south to north and is defined as T1.

The joint interpretation of the audio geomagnetic L1 and L3 lines shows that there is a corresponding low resistance and high resistance body demarcation line (T2) in a position that roughly coincides with the L4 line (Figure 12). Projected in Figure 12, the channel is NE-oriented, consistent with the direction of the surface NE-oriented fracture zone (F2-F4) located between Maerzhai fracture F3 and Chuanlongao fracture F4. It can be inferred that the F3 fracture and the F4 fracture are reflections of the demarcation line between low resistance and high resistance at the surface.

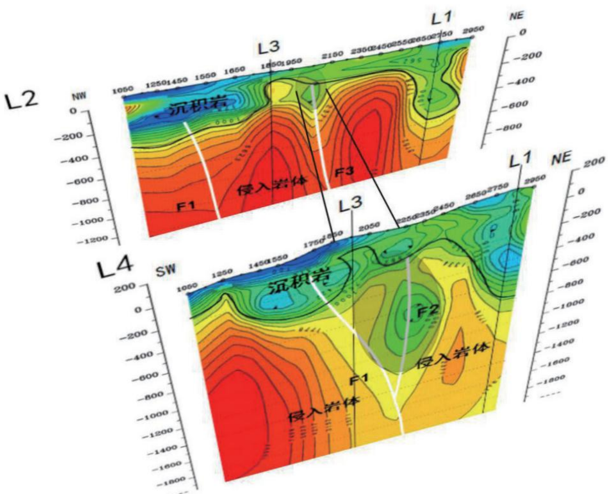


Figure 11. Joint interpretation of L1 and L3

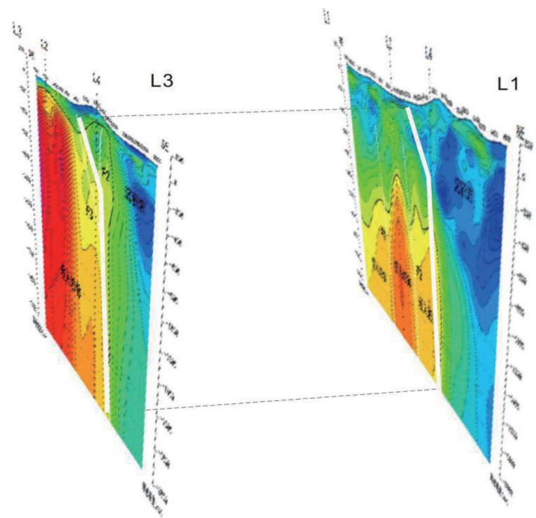


Figure 12. Joint interpretation of L1 and L3

According to the geophysical interpretations of T1 and T2 in Figure 14, it can be seen that the hot springs/geothermal wells outcropped in the NW direction are generally located on the low resistance channel T1, so T1 is presumed to be the heat-controlling and water-conducting structure of the hot springs/geothermal wells. In addition, according to the tectonic geological survey, NW-direction faults are developed in the strata in T1 range, with a high dip angle, which can be used as evidence of the existence of faults. In terms of regional stresses, the regional principal stress б1 direction is NW-SE direction extrusion (245° back-sloping folds towards the axial surface are visible in the hot spring area) and the NW direction, as the minimum stress б3 direction should be tensional in nature. This is also consistent with the role of the T1 water-conducting channel.

From the above arguments, it is concluded that the thermal formation model of Huangshadong geothermal field is a deep heat source which conducts to the shallow part along the NE-direction compressive-torsional fault zone T2 (F2-F4), and meets the NW-direction tensile low-resistivity channel T1, which transfers the heat to the surface with fluid as the medium, forming hot springs. According to this thermo-formation model, the selection principle of drilling hole position is located in the footwall of the north-west side of the compressive-torsional fault zone T2 and in the tensile low-resistivity channel T1 (Figure 13). Considering that T1 gradually decreases from SE to NW, the possible fracture (heat) transfer gradually weakens, so the position relatively close to T2 thermal conductivity fault zone is selected.

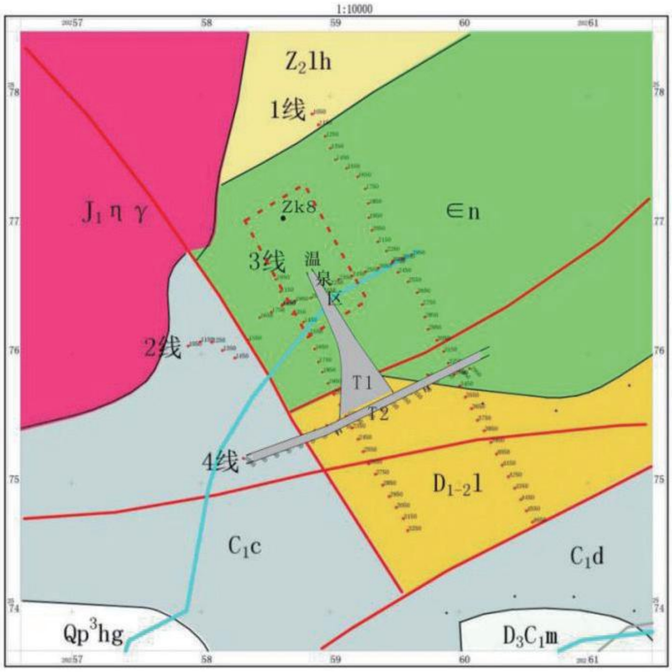


Figure. 13 Geological sketch and geophysical interpretation results of the study area

The drilling footage depth is 3,009m, and the construction started on November 29, 2017. At a depth of 1,560m, the drilling hole successfully exposed the sedimentary caprock and entered the buried granite body in the lower part. The lithology of the overlying sedimentary caprock is sandstone, Phyllitic shale, carbonaceous slate, tectonic breccia, and silicified quartz sandstone from shallow to deep, and a set of typical metamorphic sequences with drilling conducted in a metamorphic degree from shallow to deep. According to the drilling temperature measurement curve, the temperature at 2,900m reaches 127.5°C (Figure 14), and the temperature in the 2,400-2,500m section and 2,750-2,800m section abruptly changes. Combined with the analysis of drilling water leakage, these two changes should be caused by the temperature rise as a result of high temperatures of hot water produced by the two aquifers. Judging from the geothermal characteristics at 0-3,000m, it can be predicted that drilling at high temperature and waterless depths will present good exploration and development potential of dry hot rock resources.

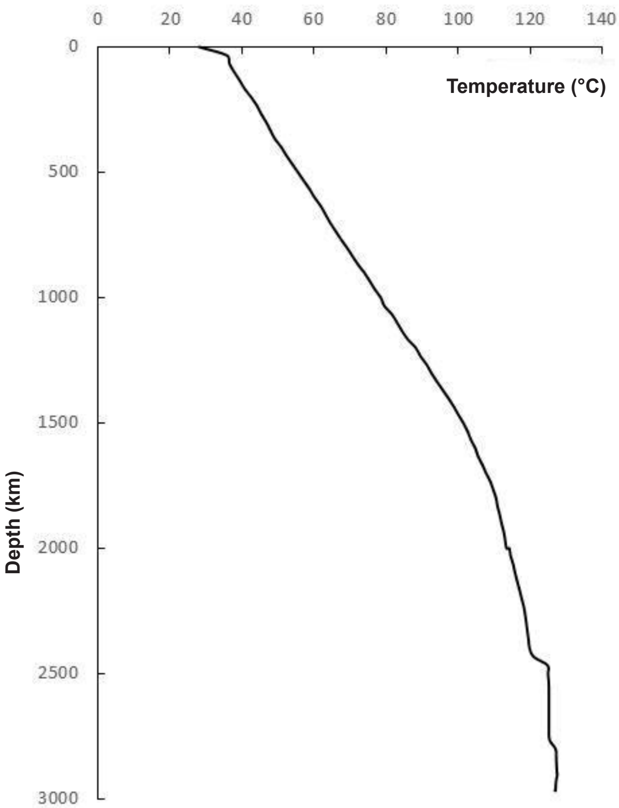


Figure 14. Geothermal temperature measurement curve of the #1 Huire well in Huizhou

5 Conclusions and Recommendations

(1) The dry hot rocks in the southeast coastal area have a ternary heat accumulation model of radioactive heat generation by acidic rock mass, heat conduction by fracture, and heat preservation by caprock. The heat generation rate of granite in the late Yanshanian period can reach 6.4μW/m3, and it is a main component of crust source heat source; regional fault structure acts as a heat conduction channel to communicate deep heat source with shallow surface, and conducts deep heat to shallow surface; sedimentary caprock plays a role of caprock insulation for radioactive heat generation and fracture heat conduction of acidic rock mass, which hinders heat dissipation to a certain extent.

(2) The key target areas of dry hot rocks in the southeast coast include Zhangzhou, Fujian and Huangshadong, Huizhou. Because of the lack of necessary caprocks, the temperature in Zhangzhou is 109°C at a depth of 4,000m. There is a sedimentary caprock at a depth of approximately 1,500m in Huangshadong area of Huizhou, and the NE-direction deep fault is its heat conduction channel. The drilling depth at 2,900m reaches 127.5°C, which is the highest temperature at the same present depth in the Huizhou area.

(3) At present, it is not clear how much radiation heat generation and fracture heat conduction of acid rock mass contributes to the heat of dry hot rocks. In addition, the heat preservation effect of sedimentary caprocks in the southeast coast is relatively poor. Therefore, it is suggested to study the heat contribution of each heat accumulation factor in the ternary heat accumulation model in the next step, and establish a more detailed index value model in consideration alongside the regional geological structure background.

References are not provided.

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敬告读者

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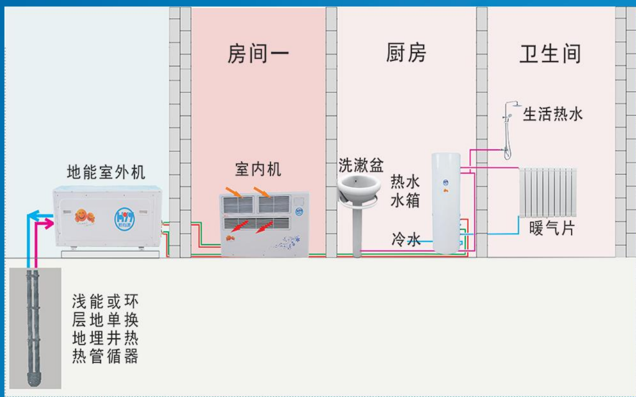

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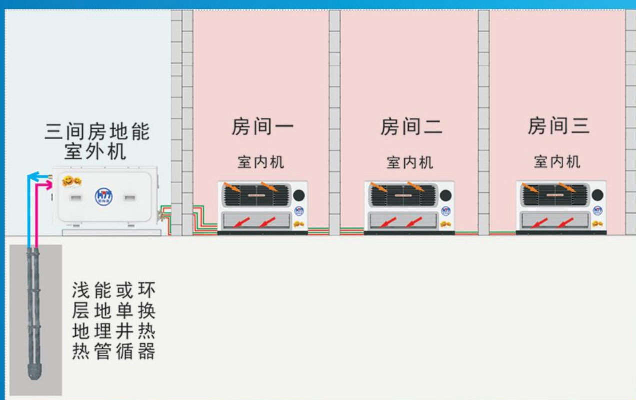

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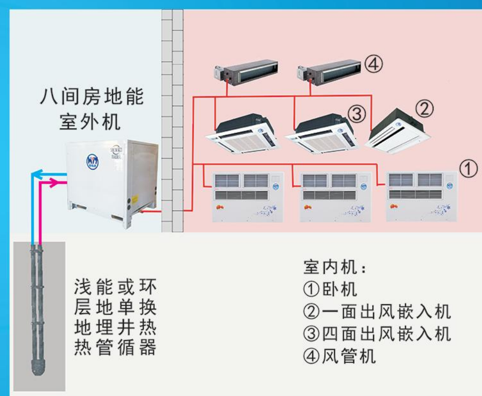

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