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An Automatic Geological Forward-prospecting Technique Safeguarding TBM Tunneling

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Stakeholders

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Dr. Zhengyu Liu

Lei Chen & Yuxiao Ren

SHANDONG UNIVERSITY

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2. Main achievements

3. Applications & Benefits

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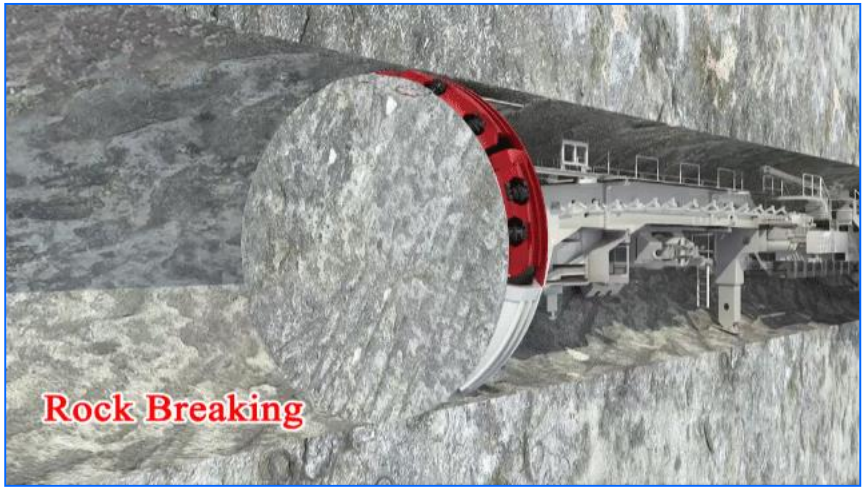
More and more hard-rock TBMs are applied in engineering projects

- 18 hard-rock TBMs were applied in a water diversion project in Xinjiang Province, China.
- The Sichuan-Tibet Railway in China intends to use about 30 hard-rock TBMs.

The TBM for the Xikang Qinling Tunnel, China



Illustrations of TBM tunnelling

Water and mud inrush

Parbati Hydroelectric Project in India

Water inrush

A TBM project in Switzerland

TBM tunneling has poor adaptability for adverse geology, which often causes serious disasters: water inrush and collapses……

TBM blockage

A water diversion tunnel in China

Serious Consequences

-- TBM blocked or damaged
-- heavy economic loss
-- casualties

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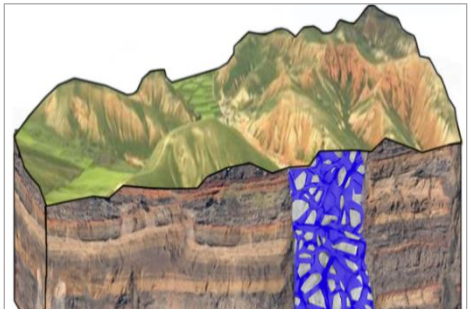
Two main adverse geology: water body and fault fractured zone

Water body-karst cave

Water body-karst cave



Fault

Fault

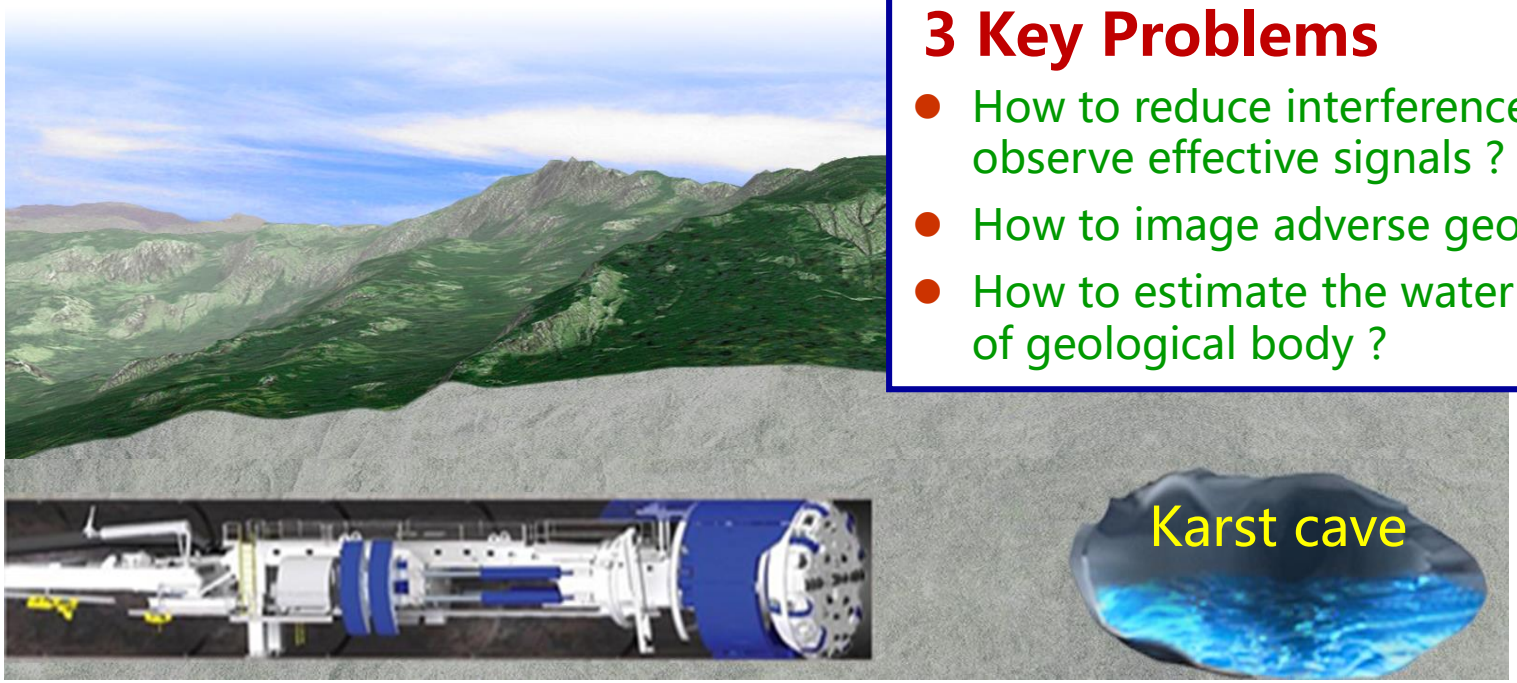
The location and water volume of adverse geology

Key factors determining the level of disaster

Prospecting the location and water volume of adverse geology ahead is of crucial importance for tunneling safety

Challenges of forward-prospecting in TBMs

- Severe electromagnetic interferences can overwhelm the effective signals.
- Few effective forward-prospecting techniques suitable for TBM.



3 Key Problems

- How to reduce interference and observe effective signals ?
- How to image adverse geology ?
- How to estimate the water volume of geological body ?

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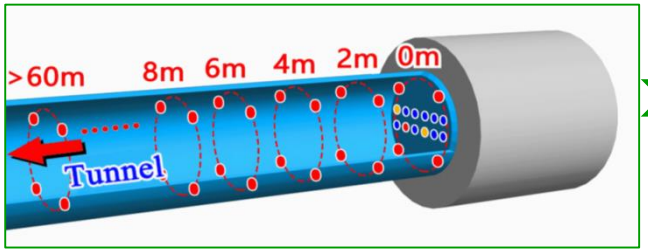
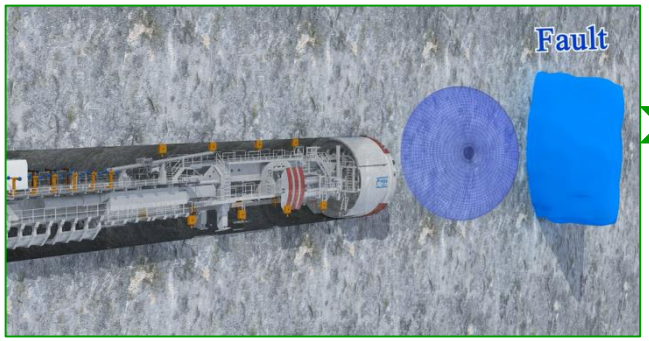
Solution: Automatic geological forward-prospecting technique



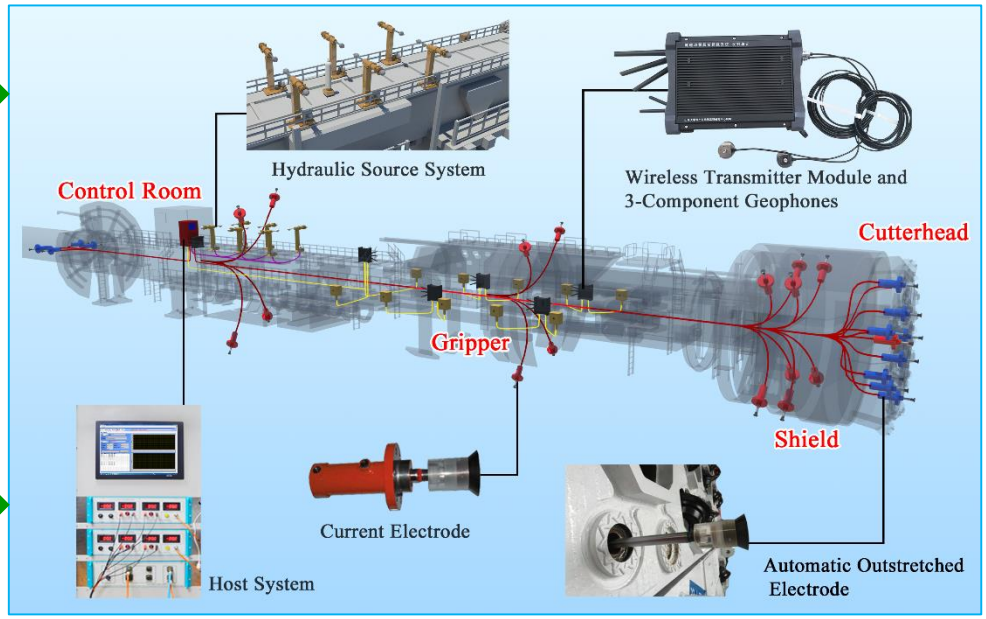
Water body → TIP

Tunnel Induced Polarization



Fault fractured zone → SFP

Seismic Forward-prospecting



Automatic forward-prospecting system

Three Safety Innovations

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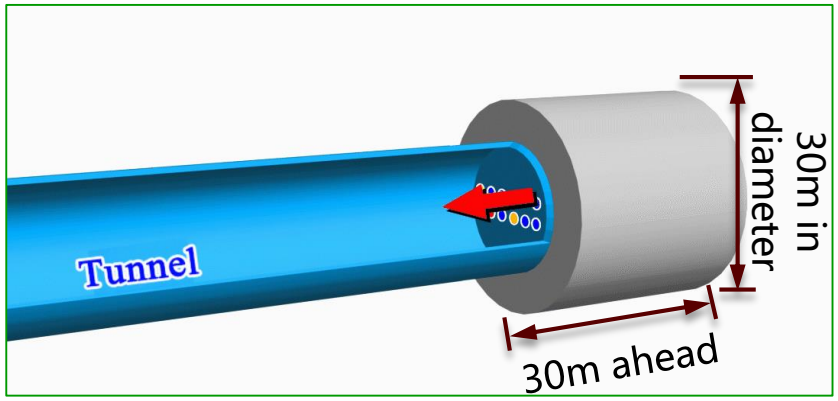
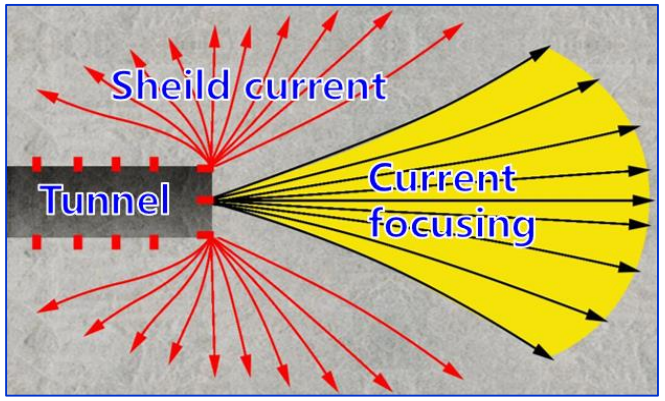
Innovation1: Tunnel Induced Polarization technique for water bodies

- New observation mode & interference removal method



By moving current electrodes, the detection range reaches **30m ahead**.



Mutually exclusive of the same polarity current → **P**roduce a focusing effect

Critical breakthrough

TBM interference is reduced from over 30% to 1%

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Innovation1: Tunnel Induced Polarization technique for water bodies

- Constrained inversion & imaging method

Innovation

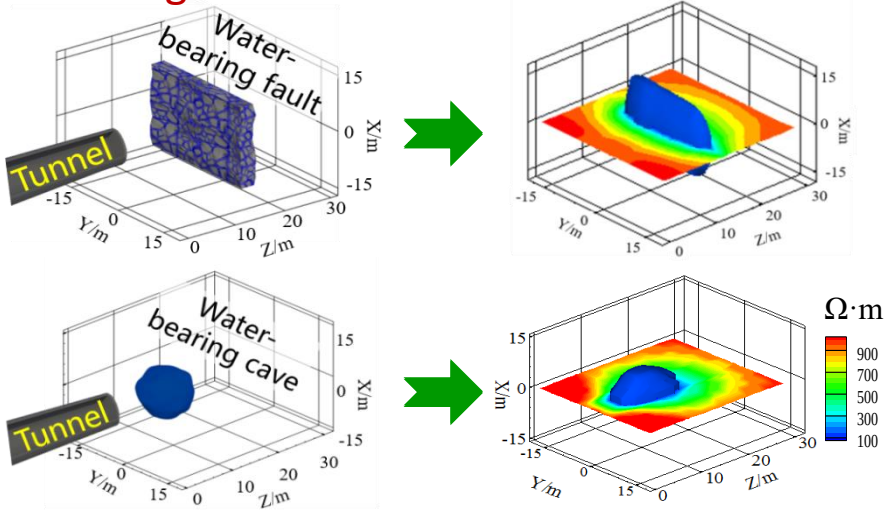
- Over **2000** data will be collected
- Incorporate the **known information** into inversion
- Water body could be **accurately imaged.**

$$\left[(W_d A)^T W_d A + \lambda C^T \Lambda C\right]\Delta m = (W_d A)^T W_d \Delta d$$

Constrained inversion equation

Imaging cases of typical water body

Geological models | Our method results



Low-resistivity area represents water body

Innovation1: Tunnel Induced Polarization technique for water bodies

- Water volume estimation method

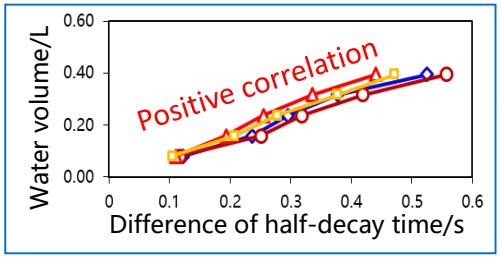
Innovation

- Conduct a large number of laboratory and field tests
- Reveal the **positive correlation relationship** between the water volume and the decay-time difference of TIP secondary field
- Solve the key problem of **on-site water volume estimation**.

$$V = k_a S + b$$

Empirical equation

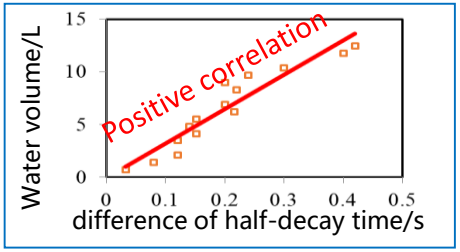
Physical test platform



Laboratory data

Field research

data come from Yinsong project



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Innvation2: Seismic Forward-Prospecting technique for faults

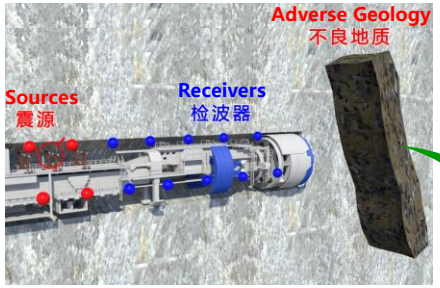
- Full waveform inversion(FWI) & imaging

Innovation

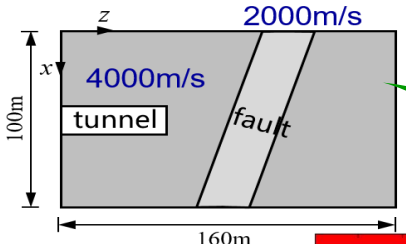
- Use **all information** including geological constraints, time, amplitude, phase.
- **Accurate** velocity distribution and imaging, positioning error <5%

$$S'(\lambda,\mu)=\left(\frac{1}{2}\sum_{s}\sum_{d}\sum_{\tau}\left[V(\lambda,\mu)\text{-}V_{obs}\right]_{d,\tau}^{T}\cdot\left[V(\lambda,\mu)\text{-}V_{obs}\right]_{d,\tau}\right)\cdot\left(\begin{array}{l}1+\alpha_1\sum_{x}\left[\max(\lambda-\lambda_{\max},0)-\min(\lambda-\lambda_{\min},0)\right]\\+\alpha_2\sum_{x}\left[\max(\mu-\mu_{\max},0)-\min(\mu-\mu_{\min},0)\right]\end{array}\right)$$

Equation of FWI

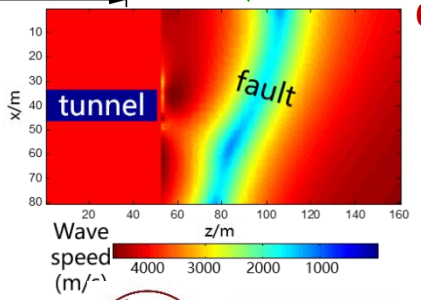


Observation mode



Geological model with a fault

FWI → Velocity distribution



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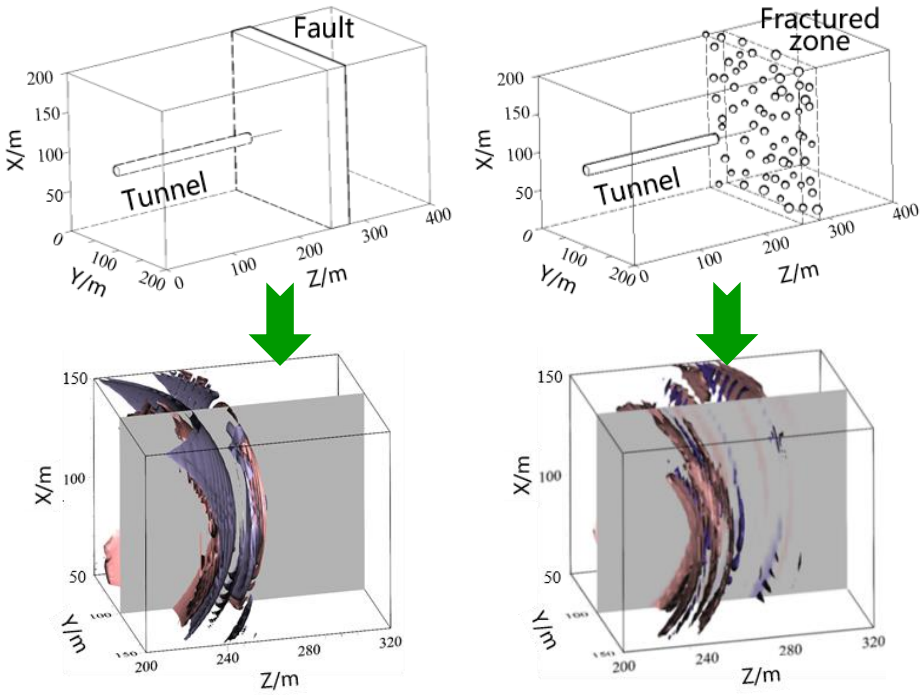
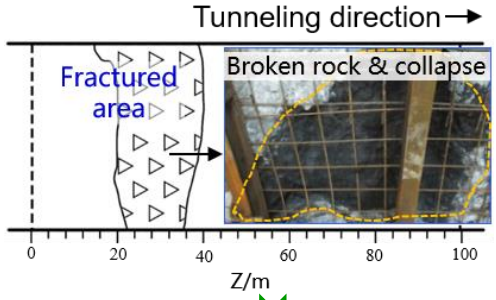
Innovation2: Seismic Forward-Prospecting technique for faults

- Imaging cases of typical adverse geology

Geological models

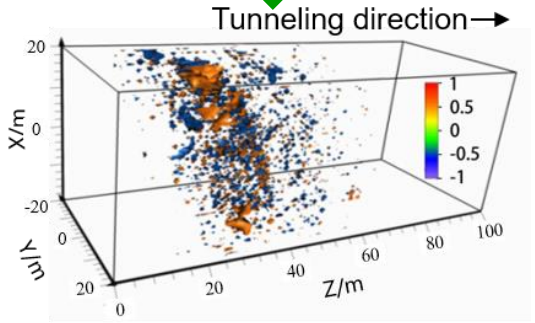


Field case



Imaging results

Imaging results



Strong reflection represents geological interface

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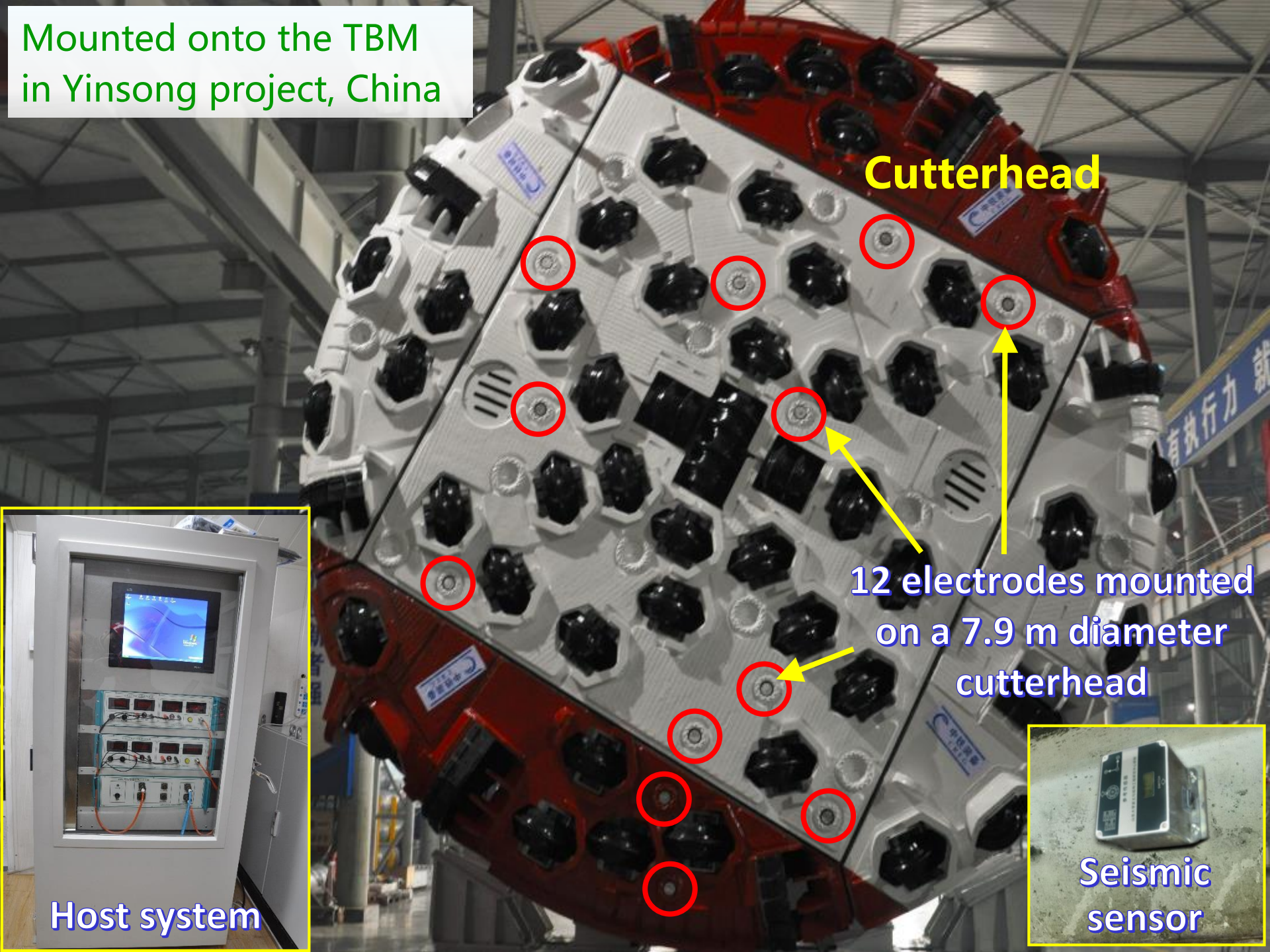
Based on the above theoretical achievements

Innovation3: TBM-mounted prospecting system

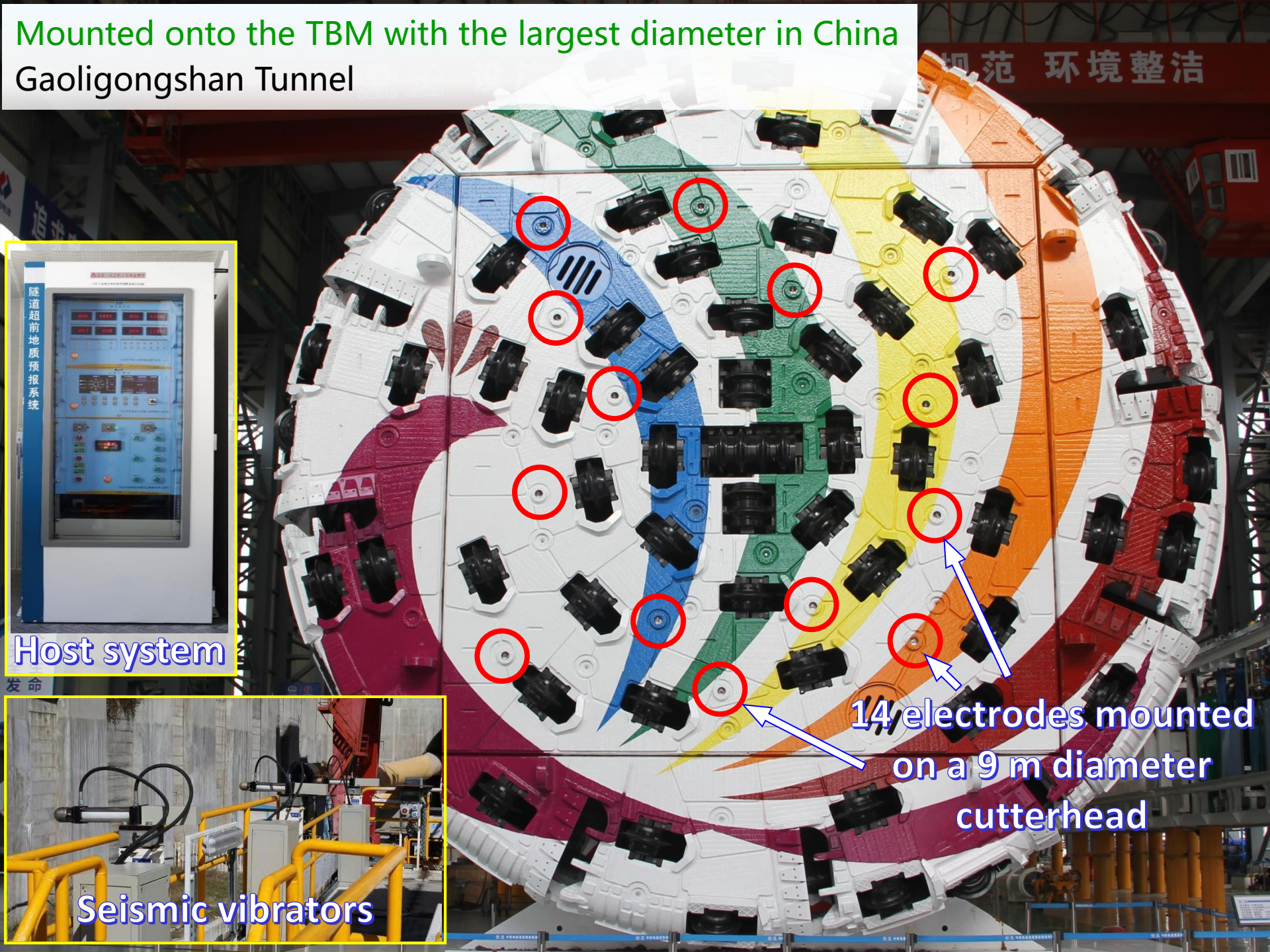
Video

Mounted onto the TBM
in Yinsong project, China



Mounted onto the TBM with the largest diameter in China

Gaoligongshan Tunnel



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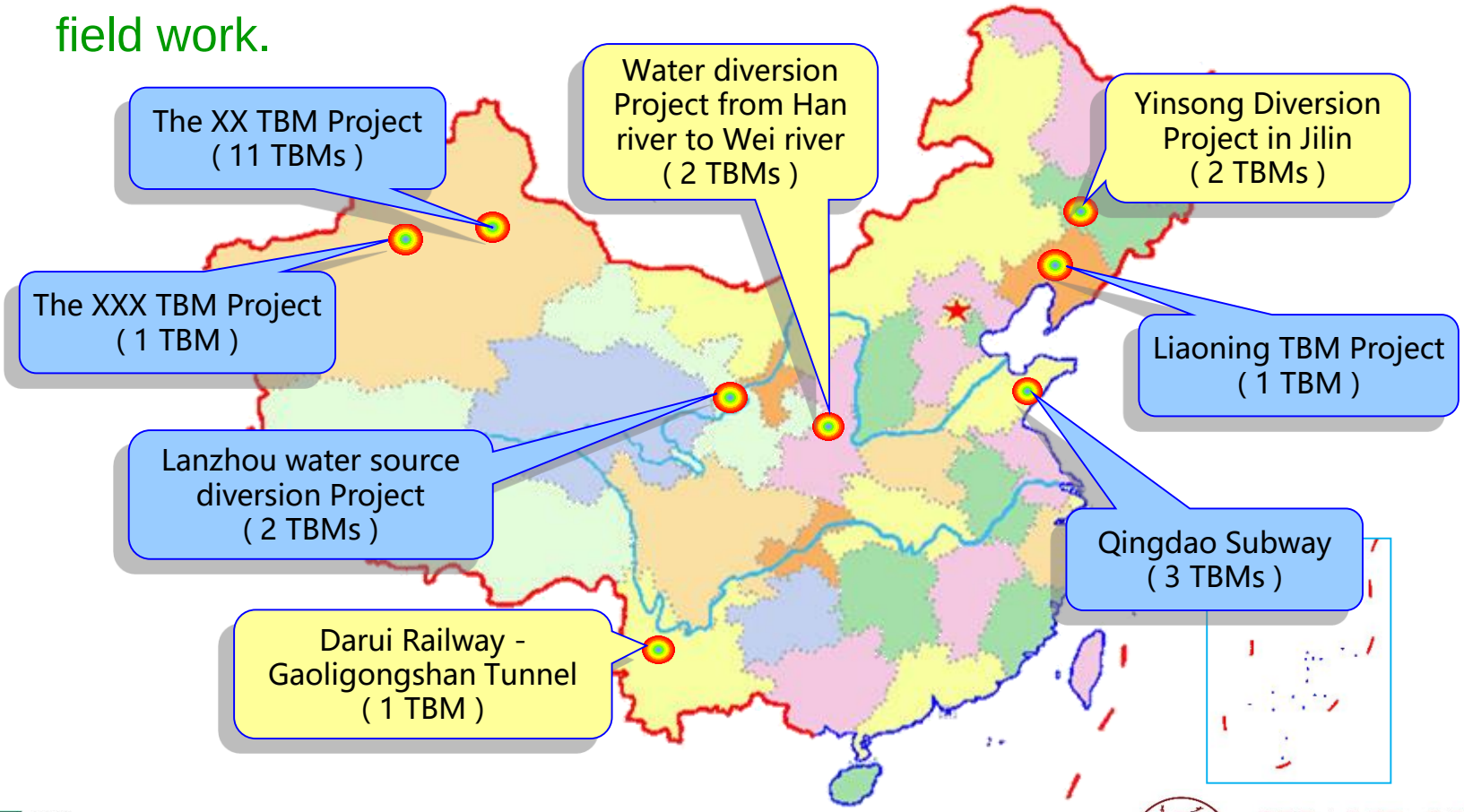
20 tunnels, 794 times

No significant geo-hazard-causing geological bodies were missed in our field work.



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Case1: 4th section of Yinsong water supply project in Jilin Province

- **TBM tunneling through a 7 km limestone stratum**
- **High risk of water inrush**

- **139 detections**
- **61 major water inrush sources were detected**

Application certification

中国中铁隧道股份有限公司
CHINA RAILWAY TUNNEL STOCK CO., LTD.

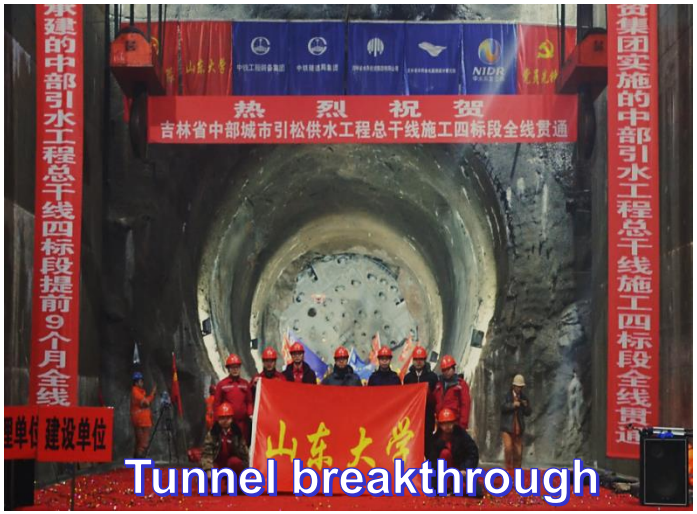
Technology Application Certificate

The 4th section of the Yinsong water supply project is in Changchun City, Jilin Province, China. Its overall length is 23 km with biggest buried depth of 260 m, and it is excavated by a Tunnel Boring Machine (TBM). There is a 7 km limestone stratum with developed karst geology and 39 faults along the designed tunnel route. This complex geological condition makes the tunnel construction even harder and may cause geo-hazards like water/mud inrush and collapse.

In order to in advance verify the geological condition accurately before TBM tunnelling and provide a guidance for construction plan, a TBM-mounted geological forward-prospecting technique and instrument was applied in this section. During the period of June 10th, 2015 to the final breakthrough of this section, there were 139 geological detections conducted on 4.8 km of tunnel route and 61 water-bearing structures or fractured zones were detected with their 3D spatial shape and water content. In other words, all the geological structures that may cause geo-hazards were recognized in advance within the detection range of 100m and the positioning error was less than 5%. Usually it takes about 10 minutes for data acquisition, and geological prospecting report can be issued within 30 min. Based on the forward-prospecting results, excavating and supporting schemes could be adjusted accordingly. The actual excavation speed in this section is about 628m per month on average, which is higher than the previous excavation speed (about 400 m per month) by 57%. With the help of this prospecting technique, we realized a safe and efficient TBM tunnelling and successfully passed through the 7 km limestone stratum. In fact, we set a national record in China for tunnelling 1318.7 m within one month by an open-type TBM in November 2017.

In addition, the accurate detection of geo-hazard sources like water-bearing structure could provide reference for preventing geological disasters. Based on the quantitative prospecting of water volume inside of water-bearing body, a reasonable water plugging or drainage plan could be designed. Thus, the prospecting technique can prevent ground subsidence and water level degradation due to the loss of groundwater resources, and protect the local ecological environment.

Yang Bin
General Project Manager of
the 4th Section of Yinsong Water Supply Project,
China Rail Way Tunnel Stock Co., Ltd



Safeguarded this project to be completed 9 months ahead of schedule.

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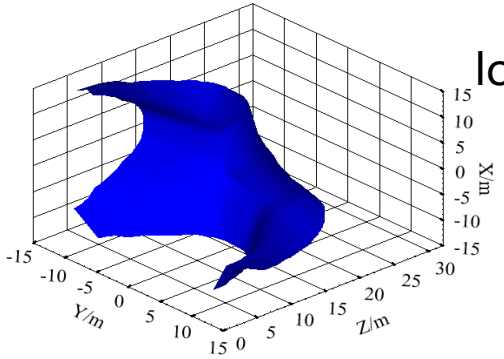
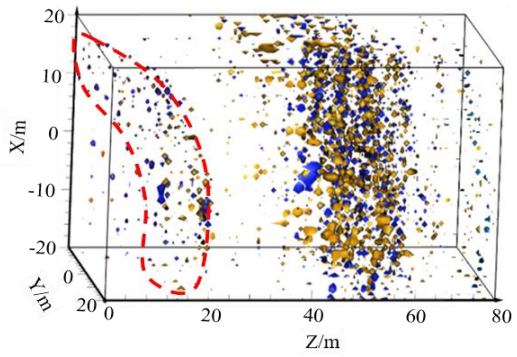
Case1: 4th section of Yinsong water supply project in Jilin Province

Typical case



TIP result

low resistivity area



Seismic result

Strong reflection

a large-scale water body with a 2500m³/h water inrush was accurately detected

A fatal TBM accident was avoided

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Case2: 3rd section of Yinsong water supply project in Jilin Province

In the beginning, the TBM was blocked for 135 days.

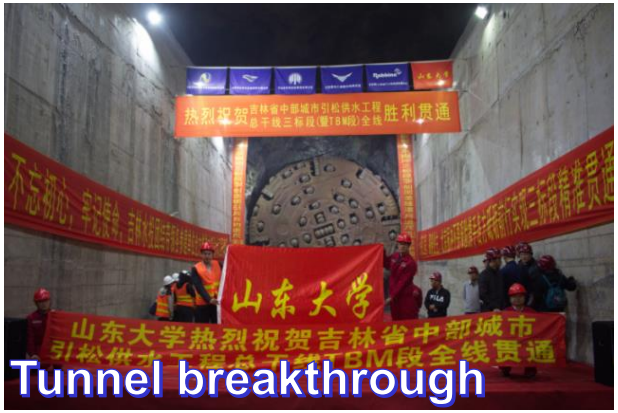
↓

Since then, we have been entrusted to perform prospecting (151 detections).

↓

16.7 km tunnel safely broke through without any accident.

This formed a sharp contrast !



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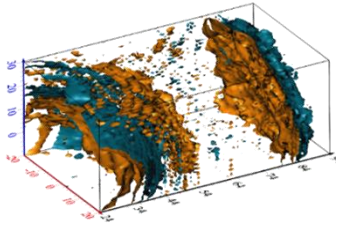
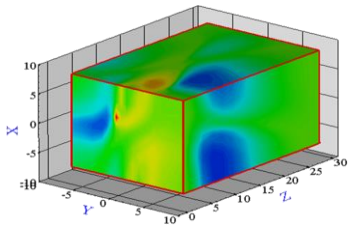
Case3: the Yinhanjiwei project in Shaanxi Province, China

- **The longest tunnel in Asian** (98.3km)
- **Accurately detected 19 major water inrush sources & fault fracture zones**

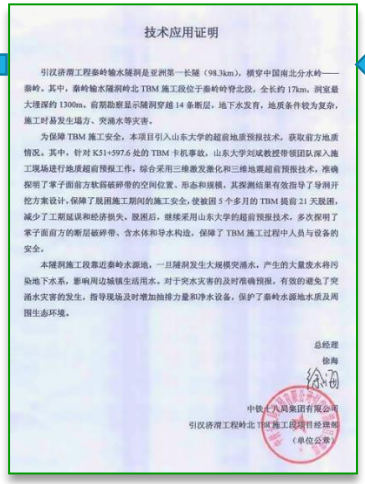


Seismic result



TIP result

Application certification



技术应用证明

引汉济渭工程秦岭输水隧洞是亚洲第一长隧（98.3km），横穿中国南北分水岭——秦岭。其中，秦岭输水隧洞岭北TBM施工段位于秦岭岭脊北段，全长约17km，洞室最大埋深约1300m，前期勘察显示隧洞穿越14条断层，地下水发育，地质条件较为复杂，施工时易发生塌方、突涌水等灾害。

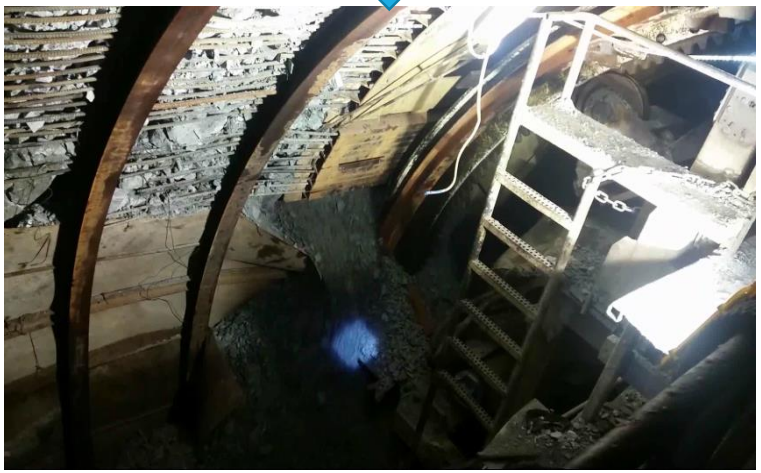
为保障TBM施工安全，本项目引入山东大学的超前地质预报技术，获取前方地质情况。其中，针对K51+597.6处的TBM卡机事故，山东大学刘斌教授带领团队深入施工现场进行地质超前预报工作。综合采用三维激发激化和三维地震超前预报技术，准确探明了掌子面前方软弱破碎带的空间位置、形态和规模，其探测结果有效指导了导洞开挖方案设计，保障了脱困施工期间的施工安全，使被困5个多月的TBM提前21天脱困，减少了工期延误和经济损失。脱困后，继续采用山东大学的超前预报技术，多次探明了掌子面前方的断层破碎带、含水体和导水构造，保障了TBM施工过程中人员与设备的安全。

本隧洞施工段靠近秦岭水源地，一旦隧洞发生大规模突涌水，产生的大量废水将污染地下水系，影响周边城镇生活用水。对于突水灾害的及时准确预报，有效的避免了突涌水灾害的发生，指导现场及时增加抽排力量和净水设备，保护了秦岭水源地水质及周围生态环境。

总经理
徐海

中铁十八局集团有限公司
引汉济渭工程岭北TBM施工段项目经理部
（单位公章）

- **TBM blocked for over five months**
- **Safeguarded the TBM getting out 21 days ahead of schedule**



Fault fractured zone at K51+597

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Benefits and Promotions

More than 15 application certifications suggest that:

Safe

- **Ensure** safe TBM tunneling
- **Avoid** potential casualties and economic losses
- **Protect** occupational health

Benefits

Sustainable

- Our technique has **become a common process** in TBM tunneling in China.
- **Improve** the tunnel health of full life circle
- **Protect** the eco-systems

Application certifications

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Benefits and Promotions

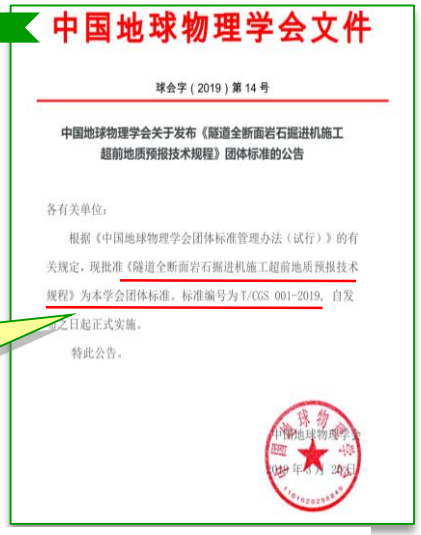
- **Patents and standards**

  - **Four U.S. patents**
  - **Ten Chinese patents**

Four U.S. patents

- **Published the first forward-prospecting standard for TBM tunneling in the world as chief editors**
- **Our techniques have been included**

Association standard of CGS



中国地球物理学会文件

球会字（2019）第14号

中国地球物理学会关于发布《隧道全断面岩石掘进机施工超前地质预报技术规程》团体标准的公告

各有关单位：

根据《中国地球物理学会团体标准管理办法（试行）》的有关规定，现批准《隧道全断面岩石掘进机施工超前地质预报技术规程》为本学会团体标准。标准编号为T/CGS 001-2019，自发布之日起正式实施。

特此公告。

"Technical specification for geological forward-prospecting in tunnels using full face hard rock tunnel boring machine " has been published as the association standard of Chinese Geophysical Society. (No. T/CGS 001-2019).

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Benefits and Promotions

Our technique not only realizes the imaging of water bodies and faults, but also achieves water volume estimation and automatic detection by TBM-mounted instruments.

Functions	Traditional techniques	Our technique
Water body detection	➢ Not reduce the TBM interference ➢ Estimate the existence of water ➢ Can not estimate water volume	➢ **3D imaging** the water body ➢ Solve the key problem of **water volume estimation**
Fault fractured zone detection	➢ Calculate velocity by travel time ➢ Inaccurate velocity estimation and positioning	➢ Using full wave information ➢ **Accurate velocity** estimation ➢ **Positioning error <5%**
Automaticity	➢ No instrument mounted on TBM ➢ Manual operation	➢ TBM-mounted instrument ➢ **Automatic detection** ➢ **Data acquisition <10 min**

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Summary

- Has been proved to be an effective technique of ensuring TBM safety by accurately detecting water bodies and faults.
- No significant geo-hazard-causing geological bodies were missed.
- We hope it can be employed worldwide to safeguard TBM tunneling in the future.

Thank You!