An Automatic Geological Forward-prospecting Technique Safeguarding TBM Tunneling

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1. Background & Challenges

2. Main achievements

3. Applications & Benefits
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
TBM tunneling has poor adaptability for adverse geology, which often causes serious disasters: water inrush and collapses......

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**Serious Consequences**

-- TBM blocked or damaged
-- heavy economic loss
-- casualties
Two main adverse geology: water body and fault fractured zone

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 $\rightarrow$ TIP
Tunnel Induced Polarization

Fault fractured zone $\rightarrow$ SFP
Seismic Forward-prospecting

Automatic forward-prospecting system

Three Safety Innovations
Innovation 1: 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 → Produce a focusing effect**

**Critical breakthrough**

TBM interference is reduced from over 30% to 1%
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.

\[
\begin{align*}
\left[(W_d A)^T W_d A + \lambda C^T A C\right] \Delta m \\
= (W_d A)^T W_d \Delta d
\end{align*}
\]

Constrained inversion equation

Imaging cases of typical water body
- Geological models
- Our method results
- Low-resistivity area represents water body

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

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**Innovation 1:** 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*

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**Physical test platform**

**Laboratory data**

**Field research**

*Data come from Yinsong project*
Innovation 2: 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%

  \[
  S'(\lambda, \mu) = \left\{ \frac{1}{2} \sum_{d} \sum_{r} \sum_{t} \left[ V(\lambda, \mu) - V_{obs} \right]^{T}_{d,r,t} \cdot \left[ V(\lambda, \mu) - V_{obs} \right]_{d,r,t} \right\} \\
  + \frac{1}{\mu_{max} - \mu_{min}} \sum_{t} \left[ \max(\mu - \mu_{min}, 0) - \min(\mu - \mu_{min}, 0) \right] \\
  + \frac{1}{\lambda_{max} - \lambda_{min}} \sum_{t} \left[ \max(\lambda - \lambda_{min}, 0) - \min(\lambda - \lambda_{min}, 0) \right]
  \]

  Equation of FWI
Innovation2: Seismic Forward-Prospecting technique for faults

- Imaging cases of typical adverse geology

Strong reflection represents geological interface
Innovation 3: TBM-mounted prospecting system

Based on the above theoretical achievements

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Mounted onto the TBM in Yinsong project, China

Cutterhead

12 electrodes mounted on a 7.9 m diameter cutterhead

Host system

Seismic sensor
Mounted onto the TBM with the largest diameter in China
Gaoligongshan Tunnel

14 electrodes mounted on a 9 m diameter cutterhead

Host system
Seismic vibrators
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20 tunnels, 794 times

No significant geo-hazard-causing geological bodies were missed in our field work.
Case 1: 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

Safeguarded this project to be completed 9 months ahead of schedule.
Case 1: 4th section of Yinsong water supply project in Jilin Province

Typical case

TIP result

Seismic result

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

A fatal TBM accident was avoided
Case 2: 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!
Case 3: the Yinhanjiwei project in Shaanxi Province, China

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

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

Seismic result
TIP result
Fault fractured zone at K51+597
Benefits and Promotions

More than 15 application certifications suggest that:

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

**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

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

"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).
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.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Traditional techniques</th>
<th>Our technique</th>
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</table>
| 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 |
|                            | ➢ Calculate velocity by travel time  
➢ Inaccurate velocity estimation and positioning | ➢ Using full wave information  
➢ **Accurate velocity** estimation  
➢ **Positioning error <5%** |
| Fault fractured zone detection | ➢ No instrument mounted on TBM  
➢ Manual operation                  | ➢ TBM-mounted instrument  
➢ **Automatic detection**  
➢ **Data acquisition <10 min** |

Dr. Yong Li
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!