Surface deployed Distributed Acoustic Sensing (DAS) for seismic monitoring: An example of the Stanford Array Data

Gang Fang*, Yunyue Elita Li, Yue Du, Joseph Ho Yin Ma, Eileen Martin and Diming Yu

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Near-surface geohazards in urban environments

➢ Urban sinkhole

A sinkhole appeared in the centre lane of Clementi Road of Singapore on 06 Mar 2013
Near-surface geohazards in urban environments

- Urban sinkhole

A sinkhole appeared in the centre lane of Clementi Road of Singapore on 06 Mar 2013
A giant sinkhole caused by the rains of tropical storm Agatha in Guatemala City, June 2010. At least 175 people are killed in this disaster.
Near-surface geohazards in urban environments

➢ Landslide

How to monitor the near surface changes efficiently?

Landslide in eastern China on Nov 16, 2015 that has killed at least 25 people.

Shenzhen landslide on 20 December 2015, 73 people was dead and 4 people reported missing.
Outlines

- Distributed Acoustic Sensing (DAS)
- Near-surface monitoring with Stanford DAS data
Distributed Acoustic Sensing (DAS)
Distributed Acoustic Sensing

It is a laser-based sensor system measuring vibration along the length of a fiber optic sensing cable.

DAS Advantages:

✓ Non-intrusive
✓ Permanent
✓ Low-cost
✓ High spatial resolution
Distributed Acoustic Sensing

➢ DAS VSP
  • Hydraulic fracturing characterization
  • Time-lapse monitoring of the reservoirs fluids
  • CO$_2$ injection monitoring

➢ Surface DAS
  • Earthquakes analysis
  • Near surface geophysical detection

(From OptaSense)

(Lindsey et al. 2017)
Near-surface monitoring with Stanford DAS data

- Stanford DAS Array
- Quarry blasts data
- Seismic interferometry
- Construction monitoring
Stanford DAS Array

Layout of Stanford DAS Array (Biondi et al., 2017)
Stanford DAS Array

Layout of Stanford DAS Array  (Biondi et al., 2017)
Stanford DAS Array

Layout of Stanford DAS Array  (Biondi et al., 2017)
Stanford DAS Array

DAS Array parameters

- 2 x 2.45 km fiber-optic cable
- 2 x 305 channels
- ~8 m sensor spacing
- 7 m gauge length
- Continuous recording
- 0-25 Hz digital recording
- OptaSense DAS (ODH 3.1)
- Single-mode fibre

Layout of Stanford DAS Array (Biondi et al., 2017)
Near-surface monitoring with Stanford DAS data

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Quarry blasts data

(a) Google Earth

(b) d=13.3 km

2nd NUPRI Workshop
Quarry blasts data — raw data

Construction A is begin at 2016/11/7. Compare blast data before and after the construction.

Challenges:
- High frequency noise
Quarry blasts data — BP filtering (0.25~2.5HZ)

Construction A is begin at 2016/11/7. Compare blast data before and after the construction.

Challenges:

• High frequency noise
Quarry blasts data — Surface wave

Construction A is begin at 2016/11/7. Compare blast data before and after the construction.

Challenges:

- High frequency noise
Quarry blasts data — Traffic noise

Construction A is begin at 2016/11/7. Compare blast data before and after the construction.

Challenges:

- High frequency noise
Construction A is begin at 2016/11/7. Compare blast data before and after the construction.

Challenges:

- High frequency noise
- Traffic noise
Quarry blasts data — Denoise

Challenges:

- High frequency noise ✓
- Traffic noise ✓
- Inconsistent source wavelets
Quarry blasts data — Denoise

Challenges:

- High frequency noise ✓
- Traffic noise ✓
- Inconsistent source wavelets

Solution:

- Seismic interferometry
Near-surface monitoring with Stanford DAS data

- Stanford DAS Array
- Quarry blasts data
- *Seismic interferometry*
- Construction monitoring
Seismic interferometry
Seismic interferometry

$R_S$ $R_A$ $R_B$
Seismic interferometry

Wavefield at $R_A$: $U(R_A, \omega) = S(R_s, \omega)e^{ik(R_A-R_s)}$

Wavefield at $R_B$: $U(R_B, \omega) = S(R_s, \omega)e^{ik(R_B-R_s)}$
Seismic interferometry

Wavefield at $R_A$: $U(R_A, \omega) = S(R_S, \omega) e^{i k (R_A - R_S)}$

Wavefield at $R_B$: $U(R_B, \omega) = S(R_S, \omega) e^{i k (R_B - R_S)}$

Source wavelet
Seismic interferometry

Wavefield at $\mathbf{R}_A$:
$$U(\mathbf{R}_A, \omega) = S(\mathbf{R}_S, \omega) e^{i k (\mathbf{R}_A - \mathbf{R}_S)}$$

Wavefield at $\mathbf{R}_B$:
$$U(\mathbf{R}_B, \omega) = S(\mathbf{R}_S, \omega) e^{i k (\mathbf{R}_B - \mathbf{R}_S)}$$

Green function

Source wavelet
Seismic interferometry

Wavefield at $R_A$:
\[ U(R_A, \omega) = S(R_A, \omega) e^{ik(R_A - R_A)} \]

Wavefield at $R_B$:
\[ U(R_B, \omega) = S(R_B, \omega) e^{ik(R_B - R_A)} \]

Cross-correlation:
\[ C(R_B, R_A, \omega) = U(R_B, \omega) U^*(R_A, \omega) = S^2(R_A, \omega) e^{ik(R_B - R_A)} \]
Seismic interferometry

\[ U(R_A, \omega) = S(R_S, \omega) e^{ik(R_A-R_S)} \]

\[ U(R_B, \omega) = S(R_S, \omega) e^{ik(R_B-R_S)} \]

Cross-correlation:

\[ C(R_B, R_A, \omega) = U(R_B, \omega)U^*(R_A, \omega) \]

\[ = S^2(R_S, \omega)e^{ik(R_B-R_A)} \]

Redatum the source position from \( R_S \) to \( R_A \).
Seismic interferometry

Wavefield at $\mathbf{R}_A$: 
$$U(\mathbf{R}_A, \omega) = S(\mathbf{R}_S, \omega)e^{ik(\mathbf{R}_A-\mathbf{R}_S)}$$

Wavefield at $\mathbf{R}_B$: 
$$U(\mathbf{R}_B, \omega) = S(\mathbf{R}_S, \omega)e^{ik(\mathbf{R}_B-\mathbf{R}_S)}$$

Cross-correlation:
$$C(\mathbf{R}_B, \mathbf{R}_A, \omega) = U(\mathbf{R}_B, \omega)U^*(\mathbf{R}_A, \omega) = S^2(\mathbf{R}_S, \omega)e^{ik(\mathbf{R}_B-\mathbf{R}_A)}$$

Normalized Cross-correlation:
$$C_{norm}(\mathbf{R}_B, \mathbf{R}_A, \omega) = e^{ik(\mathbf{R}_B-\mathbf{R}_A)}$$

Redatum the source position from $\mathbf{R}_S$ to $\mathbf{R}_A$. 
Seismic interferometry

Wavefield at $R_A$:  
$$U(R_A, \omega) = S(R_s, \omega)e^{ik(R_A-R_s)}$$

Wavefield at $R_B$:  
$$U(R_B, \omega) = S(R_s, \omega)e^{ik(R_B-R_s)}$$

Cross-correlation:  
$$C(R_B, R_A, \omega) = U(R_B, \omega)U^*(R_A, \omega) = S^2(R_s, \omega)e^{ik(R_B-R_A)}$$

Redatum the source position from $R_s$ to $R_A$.

Normalized Cross-correlation:  
$$C_{norm}(R_B, R_A, \omega) = e^{ik(R_B-R_A)}$$

Remove the influences from amplitudes.
Near-surface monitoring with Stanford DAS data

- Stanford DAS Array
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Applied normalized cross-correlation

Wavelets of virtual source
Applied normalized cross-correlation

Wavelets of virtual source

Normalized Cross-correlation:

\[ C_{norm}(R_B, R_A, \omega) = e^{ik(R_B - R_A)} \]
Applied normalized cross-correlation

Normalized Cross-correlation:

\[ C_{\text{norm}}(R_B, R_A, \omega) = e^{ik(R_B - R_A)} \]

Wavelets of virtual source

Spectra of the normalized cross-correlation
Velocity changes

Normalized cross-correlation

- Calculated time-delays according to the reference velocity, 816 m/s
- Picked time-delays of the normalized cross-correlation

2016/10/12

Front

Back

2016/11/15

Front

Back
Conclusions

• Surface DAS
  An efficient geophysical tool to monitor near-surface changes;

• Normalized cross-correlation interferometry method
  Detect subsurface velocity changes caused by the basement construction;

• Passive seismic monitoring
  Uneven coupling, strong traffic noise …
  Kinematic information is more reliable than amplitude information.
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Thanks!
Continuous seismic data acquisition system

- **Geophone** seismic array
  - long-term costs: expansive
  - spatially sparse dataset

- **Surface DAS** seismic array
  - long-term costs: low
  - spatially dense dataset
Repeatability of the blasts data

Earthquakes analysis

Distributed Acoustic Sensing

The strain rate is proportional to extension (compression) of fiber between two points a gauge length apart.