

# Acoustic emission monitoring of coastal slopes in north-east England, United Kingdom

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**Abstract:** Acoustic emission (AE) monitoring of active waveguides (a steel tube with a granular backfill surround) installed through a slope can provide real-time warning of slope instability by quantifying increasing rates of movement (i.e. accelerations) in response to slope destabilising effects. The technique can also quantify decelerations in movement in response to stabilising effects (e.g. remediation or pore-water pressure dissipation). This paper details the AE monitoring approach and presents results from a field trial that compares AE measurements with continuous subsurface deformation measurements. The results demonstrate that AE monitoring provides continuous information on slope displacement rates with high temporal resolution. Case studies are presented where the AE technique is being used to monitor coastal slopes at Filey and Scarborough in North Yorkshire, UK, to inform on-going risk assessments for these slopes. The results demonstrate that the AE approach can successfully be used to monitor slopes with relatively deep shear surfaces (> 14 m); however, they also show that potentially contaminating AE can be generated by ground water flowing through the active waveguide from relatively high permeability strata in response to rainfall events.

## 1. Introduction

The paper details the use of acoustic emission (AE) generated by active waveguide subsurface instrumentation to monitor slope stability. The operation of the active waveguide and the unitary battery operated AE measurement sensor node are described. Results are presented from a field trial that compares AE measurements with continuous subsurface deformation measurements, and demonstrates that the approach can be used to detect changes in rates of movement (i.e. accelerations and decelerations) in response to destabilising (i.e. rainfall) and stabilising (i.e. remediation or pore-water dissipation) effects. Case studies are then presented where the AE technique is being used to monitor coastal slopes at Filey and Scarborough in North Yorkshire, UK, to inform on-going risk assessments for these slopes.

## 2. Acoustic emission monitoring of active waveguides

The AE monitoring approach employs an active waveguide (Figure 1), which is a subsurface instrument installed inside a borehole that intersects existing or potential shear surfaces beneath the slope (Smith *et al.*, 2014a; Dixon *et al.*, 2015a; Dixon *et al.*, 2015b; Smith & Dixon, 2015; Smith *et al.*, 2016a; Smith *et al.*, 2016b; Smethurst *et al.*, 2017). It can also be retrofitted inside existing inclinometer (e.g. Smith *et al.*, 2014b) or standpipe casings to convert these periodically-surveyed to continuously-monitoring instruments. It comprises a steel tube with a granular backfill surround. As the host slope deforms, the active waveguide also deforms, and particle-particle and particle-waveguide interactions generate AE that propagates along the waveguide, which is monitored at the ground surface using an AE measurement sensor node (e.g. Slope ALARMS; Dixon & Spriggs, 2011).

A transducer is coupled to the waveguide at the ground surface to convert the mechanical AE to an electrical signal, which is then processed. A band pass filter is used to attenuate signals outside of the 20 to 30 kHz range to eliminate low-frequency background noise (e.g. construction activity and traffic). Filtering is performed in the analogue part of the system to remove the need to digitally reconstruct the full waveform, reducing power, processing and storage capacity requirements and hence enabling the system to operate continuously for long durations in the field environment on battery power. The sensor then logs the number of times the detected waveform crosses a pre-programmed voltage threshold level within pre-set time intervals; ring-down counts (RDC) per unit time. RDC rates are the units of measured AE rates. Figure 2 shows an annotated photograph of the system taken from inside a surface cover. In this study, voltage threshold levels of 0.25V and measurement intervals of 30-minutes were used.

Figure 3a shows continuous cumulative RDC and deformation time series measurements from an active waveguide and ShapeAccelArray (SAA) in-place inclinometer installed through a reactivated natural soil slope (after Smith *et al.*, 2014a; Dixon *et al.*, 2015b) in response to a series of slide

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movements, which were preceded by periods of rainfall that induced transient elevations in pore-water pressures along the shallow shear surface. Figures 3b,c show the SAA measured velocity and the AE rate time series from this period of slide movements. The AE rate and velocity time series are proportional to one another and this demonstrates that AE monitoring provides continuous information on slope displacement rates with high temporal resolution.

### 3. Coastal slope case studies

#### 3.1. Introduction

Cliff instability along the Filey and Scarborough coastlines (Figure 4) has necessitated Scarborough Borough Council to commission ground investigations, which have been interpreted by Halcrow (now CH2M) to facilitate stability assessments and inform on-going risk assessments and site management. As part of a monitoring programme an array of instruments were installed across the cliffs, and active waveguides were installed at both Filey (in September 2011) and Scarborough (in November 2012). Their locations are shown in Figure 5.

The slope at Flat Cliffs, Filey, is a reactivated landslide that threatens a settlement of houses, access roads and utilities, and moves along a relatively deep shear surface (14 m) in response to excess pore-water pressures, and due to toe erosion by the sea. Instability is indicated at the ground surface by repeat deformation of an access road.

A section of cliff behind the Scarborough Spa, South Bay, Scarborough, was identified to have marginal stability, and could potentially develop reactivated and first-time failures. This slope threatens a road and a historical building.

Deformation monitoring instruments (conventional inclinometers) were also installed at each of the slopes, adjacent to the active waveguides, to allow comparisons of the deformation and AE measurements.

#### 3.2. Flat Cliffs, Filey

The geology at Flat Cliffs has been confirmed by ground investigations. All boreholes terminated within glacial sediments at depths between 22.5 and 35 m below ground level. Despite fragmentary core recovery, the data revealed that the site is underlain by glacial sediments comprising diamicts with localised and discontinuous stratified sands and gravel (meltwater deposits). The glacial sediments have a maximum recorded thickness of 35 m, but could exceed this given that none of the boreholes encountered the underlying Kimmeridge Clay. The contact between the glacial sediment and Kimmeridge Clay at Flat Cliffs is therefore indicated to be an unknown depth beneath the base of the cliffs and beach.

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An active waveguide (location in Figure 5) was installed in a 130 mm diameter borehole to a depth of 25 m below ground level, with the annulus around the steel tubing backfilled with compacted angular 5 to 10 mm gravel. The steel tube (50 mm diameter 3 mm thick) extends 0.3 m above ground level and is encased in a secure protective chamber (Figure 6). The adjacent inclinometer casing was installed to a depth of 24.5 m below ground level. The battery powered AE sensor is located inside the protective cover with the piezoelectric transducer coupled to the waveguide, and monitoring is continuous at 30-minute intervals.

### 3.3. Scarborough Spa

The published geological maps for the Scarborough site show Glacial Till overlying mudstone and limestone of the Scarborough Formation of Jurassic age. Logs from the borehole in which the active waveguide was installed show the predominant material down to the bottom of the hole was glacial sediment (boulder clay), with bands of sand and gravel from 15 to 18 m below ground level. Figure 7 shows a photograph of the slope.

The AE instrument installation and monitoring protocol at Scarborough was the same as that at Filey (described in Section 3.2). In this slope, the active waveguide was installed to a depth of 40 m below ground level, and the adjacent inclinometer casing was installed to a depth of 43 m. Figure 8 shows a photograph of the instrument location.

### 3.4. Sample time series measurements

#### 3.4.1. Filey

Shear surface deformation was first recorded at Filey at the beginning of 2013. This was due to the unusually dry weather in 2010/2011 combined with a relatively deep shear surface depth. High winter rainfall intensity and duration are required to increase groundwater (and therefore pore-water pressures along the deep shear surface) to critical levels, reduce the shear strength and hence induce movement (e.g. Moore *et al.*, 2010). A prolonged period of above average precipitation occurred throughout the summer months of 2012 and this was followed by a wet winter in 2012/2013, and this rainfall pattern triggered deformations in early 2013. The inclinometer monitoring interval 17 January 2013 to 22 March 2013 shows approximately 13 mm of resultant incremental shear surface deformation.

Figure 9 shows AE rate measurements, hourly rainfall, inclinometer measured shear surface displacement and AE derived displacement for the period January to March 2013. Measured AE rates were converted to cumulative displacement using the method developed in Dixon *et al.*, (2015a) (i.e. through determination of the rate of change with respect to time and equating the area under the curve

to the magnitude of displacement measured by the inclinometer), which increases the temporal resolution of the inclinometer deformation information. The period of increased AE rates at the end of January 2013 is interpreted to define the initiation of landslide movement. The increased AE rates at the end of February and in the middle of March 2013 (peaks of 3000+ RDC/hour) are in response to periods of accelerated slope movement. The AE rate vs. time curve exhibits periodic surges of movement; such movement patterns cannot be detected using conventional manually read inclinometers. Antecedent rainfall over the weeks and months prior to the period presented in Figure 9 caused the build-up of pore-water pressures, which triggered the movement (Dixon *et al.*, 2015c).

### **3.4.2. Scarborough**

Surveys of the adjacent inclinometer casing have not revealed the occurrence of any subsurface deformations thus far during the period of monitoring. However, AE measurements show a distinctive and rapid response to periods of rainfall. It is believed that the AE detected at Scarborough is in response to rainfall-induced ground water flow interacting with the active waveguide backfill column; particularly from rainfall-induced ground water flowing through the relatively high permeability bands of sand and gravel. Figure 10 shows sample AE and rainfall time series measurements, which demonstrate the AE response to rainfall events. The AE response typically occurs between 2 and 4 hours after the rainfall events.

## **4. Conclusions**

AE rates generated by active waveguides are proportional to the velocity of slope movement, and can therefore be used to detect changes in rates of movement (i.e. accelerations and decelerations) in response to destabilising (i.e. rainfall) and stabilising (i.e. pore-water dissipation and remediation) effects. This paper has detailed the AE monitoring approach and has presented case studies where it is being used to monitor coastal slopes at Filey and Scarborough in North Yorkshire, UK, to inform on-going risk assessments and management for these slopes. The results demonstrate that the AE approach can successfully be used to monitor slopes with relatively deep shear surfaces (> 14 m); however, they also show that potentially contaminating AE can be generated by ground water flowing through the active waveguide from relatively high permeability strata in response to rainfall events.

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**Figures**

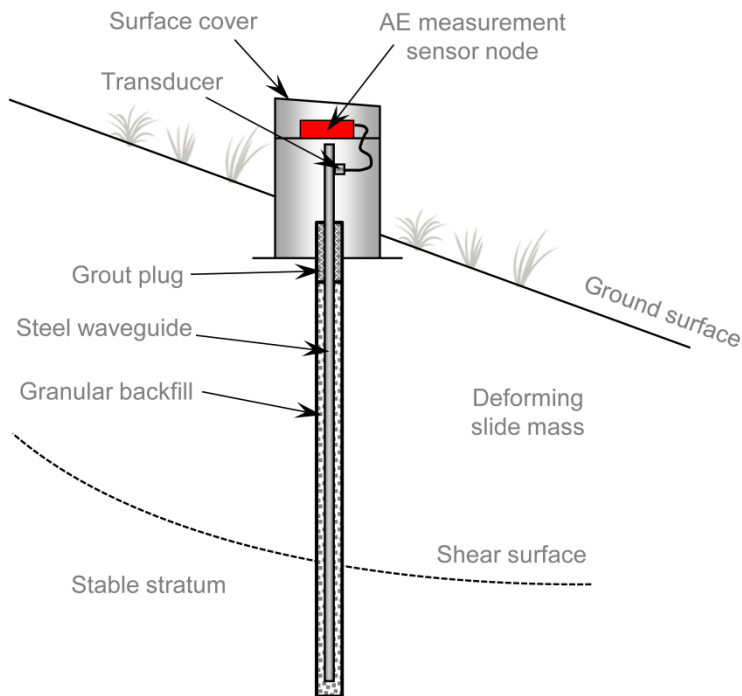


Figure 1. Schematic illustration of an active waveguide installed through a slope with an ALARMS sensor connected at the ground surface

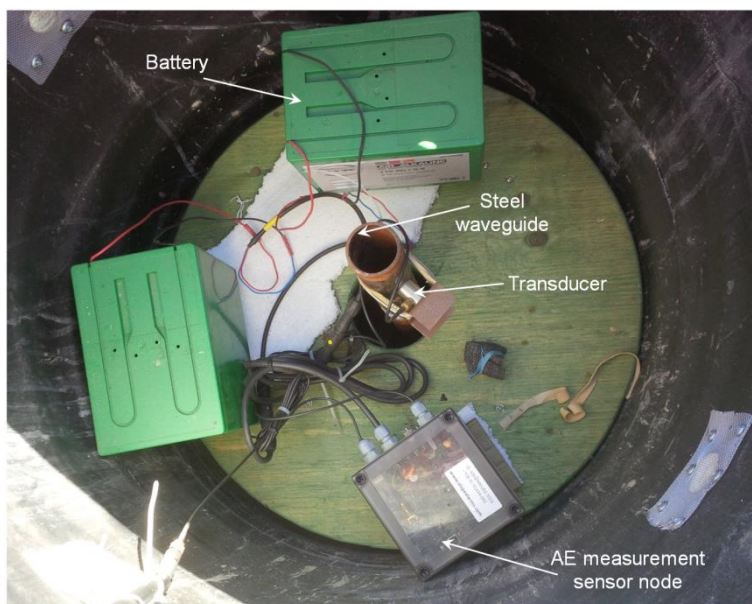


Figure 2. Annotated photograph of the AE instrumentation from inside the surface cover



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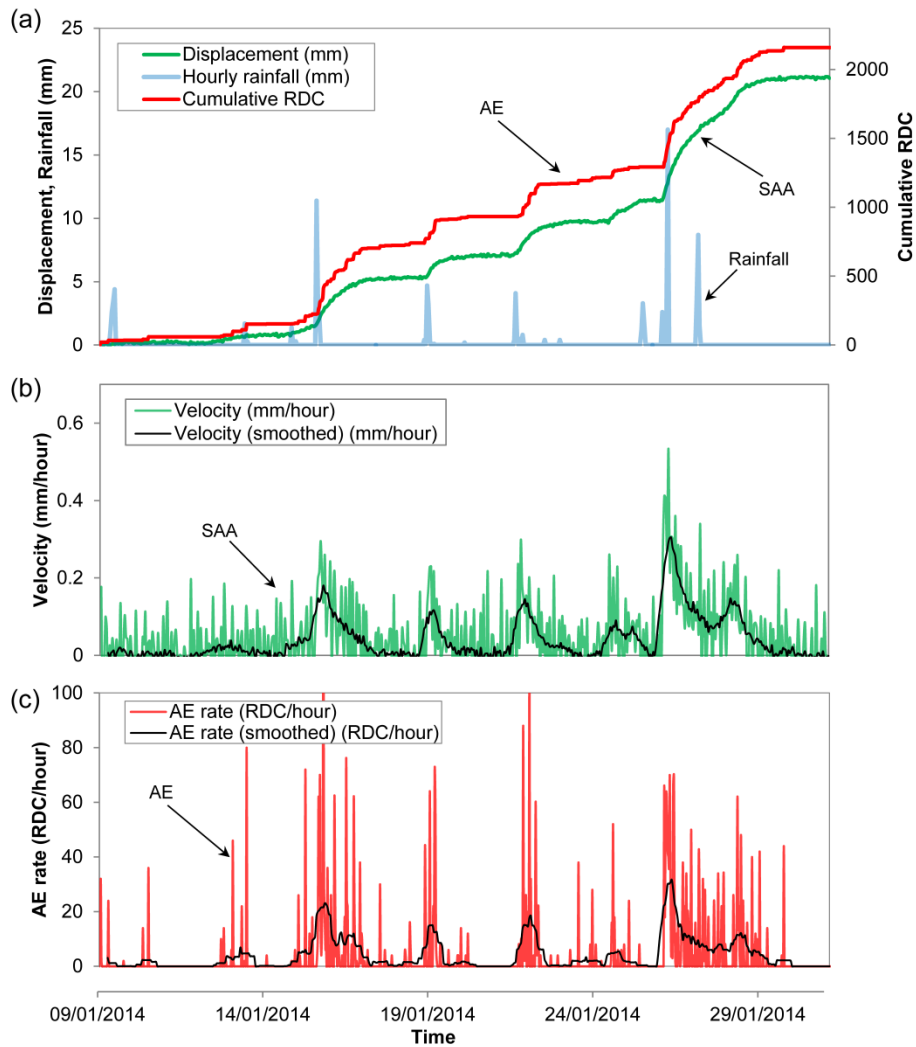


Figure 3. Time series for reactivated slope movements at Hollin Hill landslide: a) Rainfall, cumulative AE and cumulative SAA displacement; b) SAA velocity; and c) AE rate (after Smith *et al.*, 2014b; Dixon *et al.*, 2015b)

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Figure 4. Map showing the locations of the two coastal slopes in North Yorkshire at Scarborough and Filey (© 2015 Infoterra Ltd & Bluesky)



Figure 5. Instrumentation locations: a) Flat Cliffs, Filey; b) Scarborough Spa (© 2015 Infoterra Ltd & Bluesky)



Figure 6. Photograph of the coastal slope at Flat Cliffs, Filey, showing the instrumentation location



Figure 7. Photograph of the coastal slope at Scarborough



Figure 8. Downloading data from the AE instrumentation at the Scarborough coastal slope

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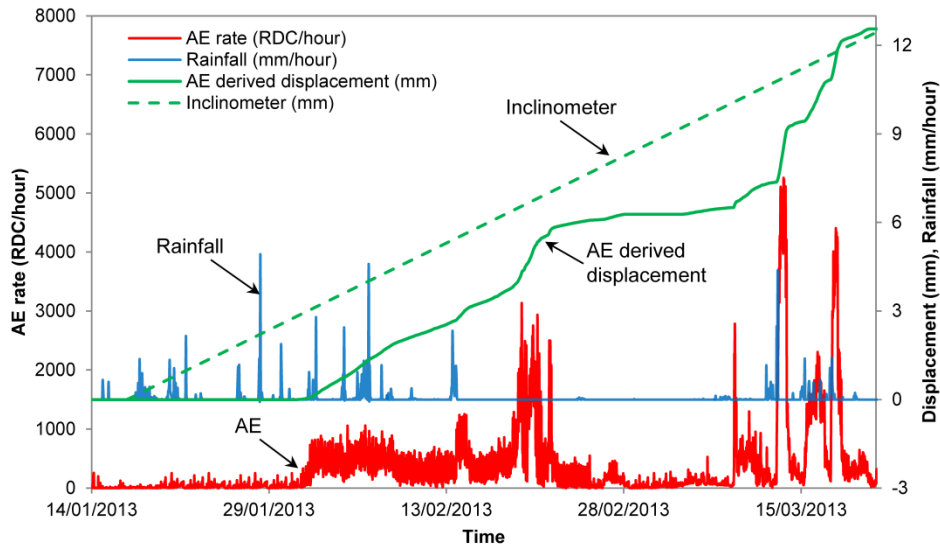


Figure 9. Example time series of measurements from Flat Cliffs, Filey: AE rate, rainfall, inclinometer measured displacement and AE derived displacement (after Dixon *et al.*, 2015c)

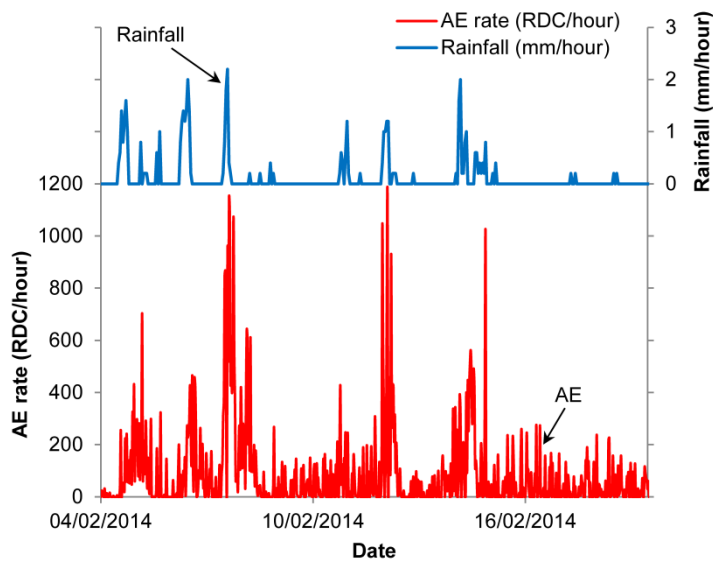


Figure 10. Example time series of measurements from Scarborough: AE rate and rainfall