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(56) Documents Cited:
JP 110230792 A **JP 110183448 A**
JP 100318994 A **JP 020024521 A**
DIXON, N. et al; "Acoustic emission monitoring of slope instability: development of an active wave guide system", Proc. Inst. of Civil Engineers Geotechnical Engineering, 2003, 156, 2, pp83-95
DIXON, N. et al; "Quantification of slope displacement rates using acoustic emission monitoring"; Canadian Geotechnical Journal, 2007, 44, 6, pp966-976

(58) Field of Search:
INT CL **E02D, G01N, G08B**
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(54) Title of the Invention: **Apparatus and method for monitoring soil slope displacement rate by detecting acoustic emissions**
Abstract Title: **Monitoring soil slope displacement rate by detecting acoustic emissions**

(57) An apparatus for monitoring soil slope (A) displacement rate comprises a sensor locatable on an active waveguide (E) partially buried in the soil to detect acoustic emissions transmitted through the waveguide as a result of soil displacement. The apparatus also includes a processor which analyses the detected acoustic emissions to determine a ring down count (RDC) rate, compares the RDC rate with a predetermined trigger value, and generates an alert when the RDC rate exceeds the predetermined trigger value. There is a predetermined relationship between RDC rate and soil slope displacement rate and the RDC rate thus provides a direct indication of the soil slope displacement rate. The processor may also determine the rate of change of the RDC rate and hence the soil slope displacement rate.

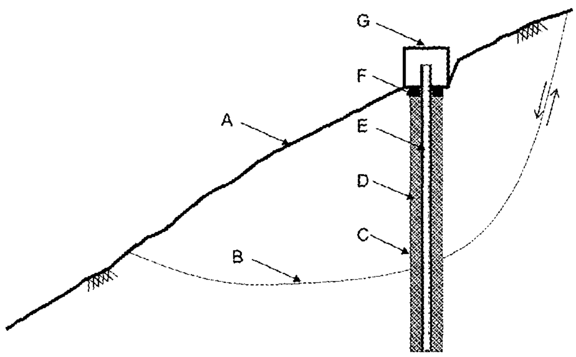

Figure 1

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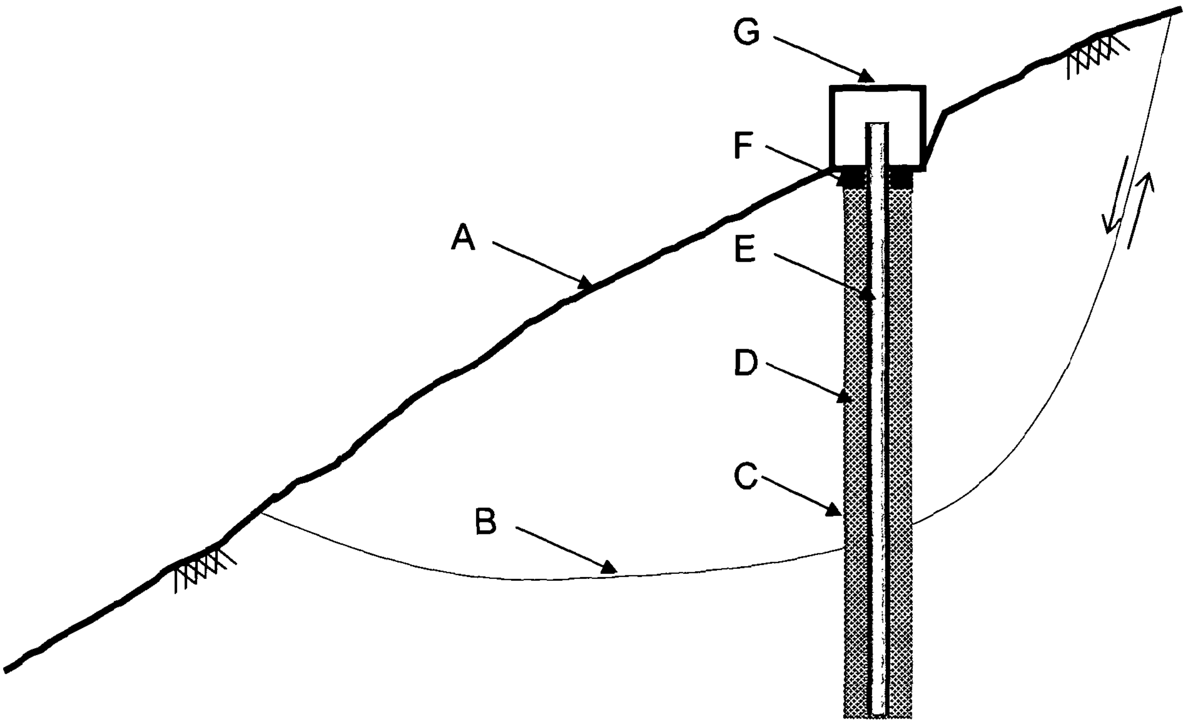

Figure 1

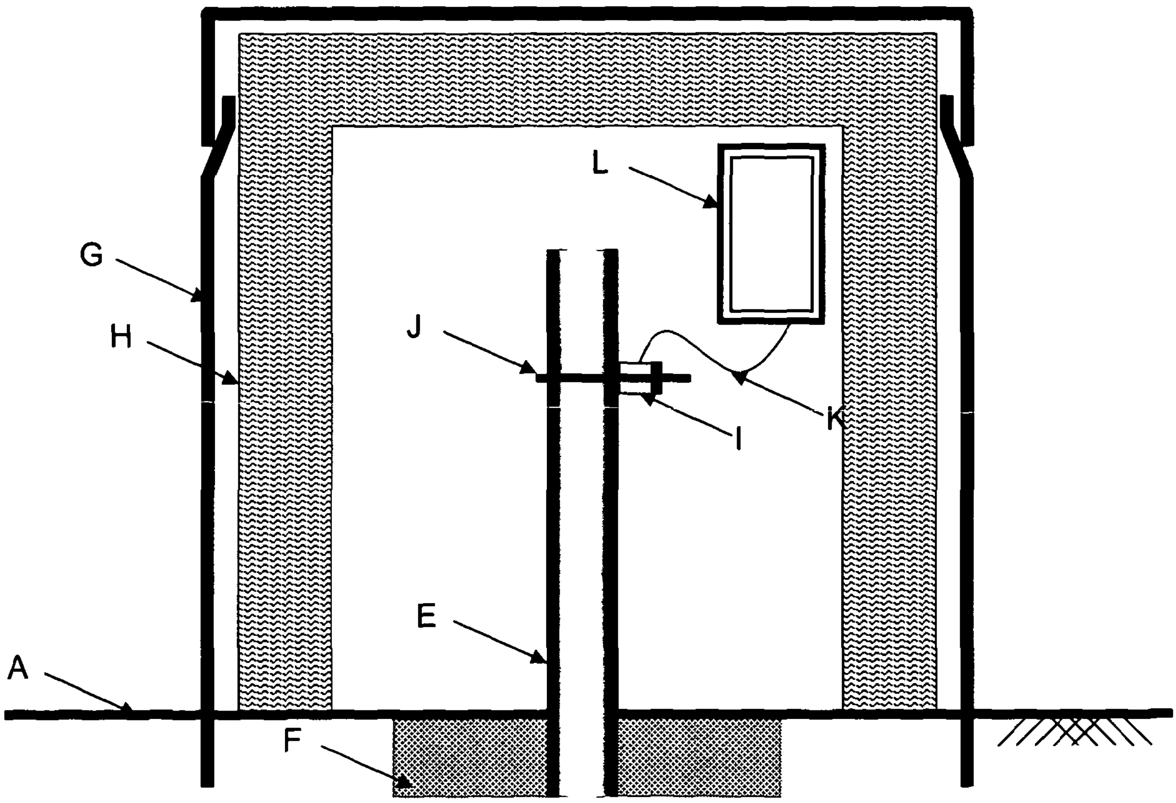

Figure 2

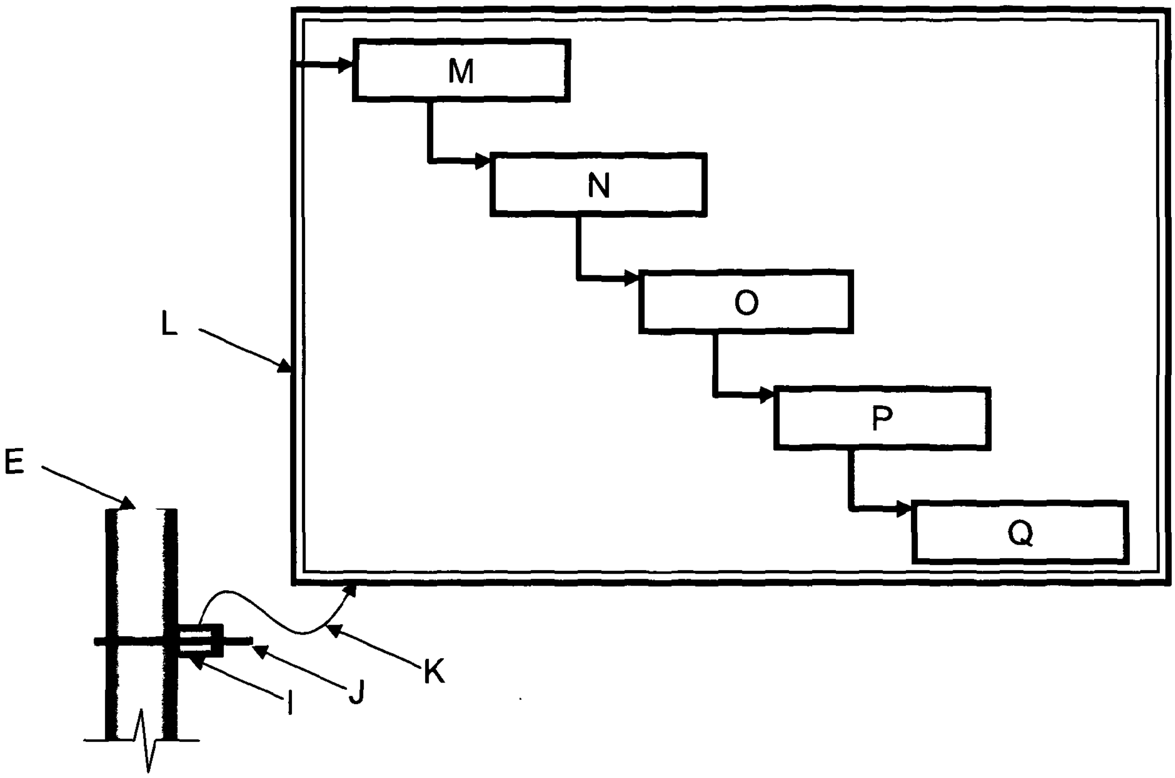

Figure 3

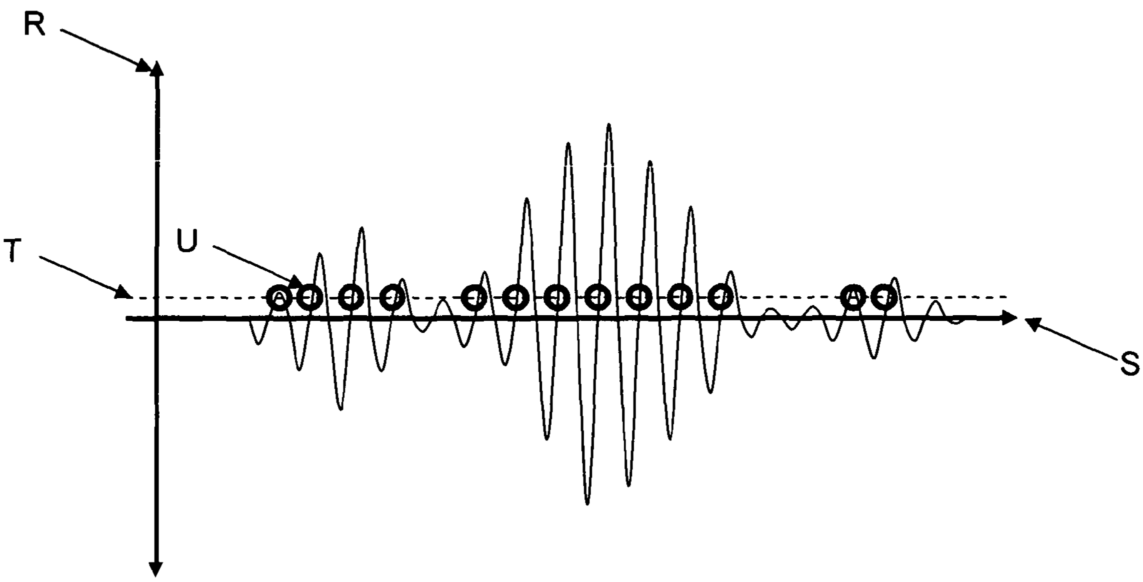

Figure 4

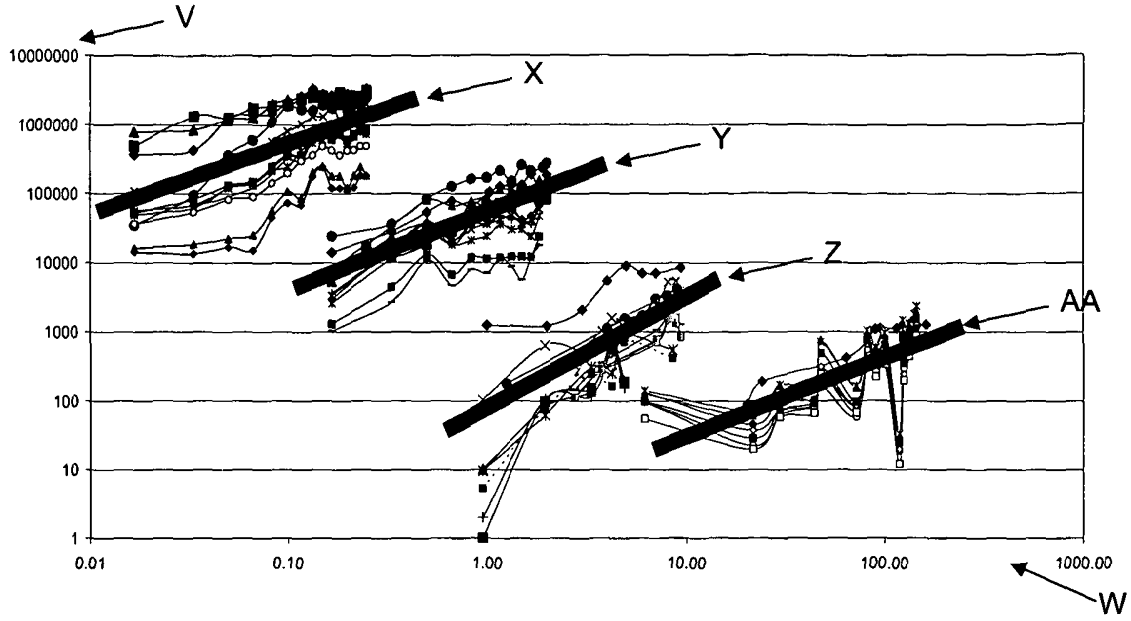

Figure 5

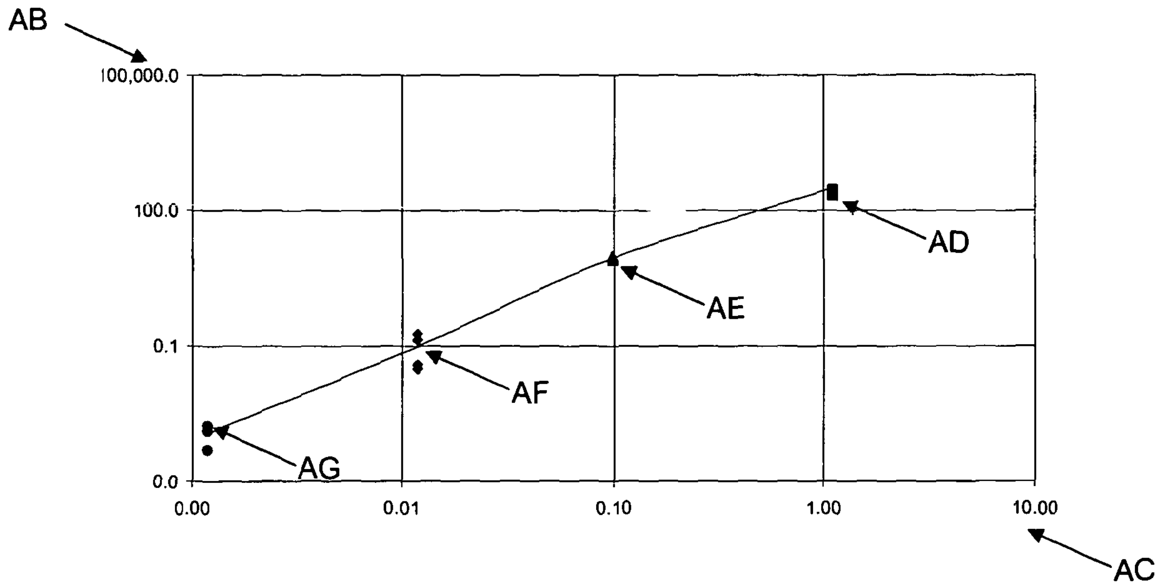

Figure 6

Step No.	RDC Rate (counts per hour)	RDC Rate Calculated Every...	Take Average RDC rate every...	Condition	Rate Designation	Action
1	>300,000	1 Minute	1 Minute	>300,000	**RAPID RATE**	**Emergency Protocol**
				<300,000	Poss. Moderate Rate	Move to step 2
2	>15,000	10 Minutes	10 Minutes	> 300,000	Poss. Rapid rate	Move to step 1
				>15,000	**MODERATE RATE**	**Urgent Assessment Protocol**
				<15,000	Poss. Slow Rate	Move to step 3
3	>1,000	10 Minutes	1 Hour	>15,000	Poss. Moderate rate	Move to step 2
				>1,000	**SLOW RATE**	**Site Investigation Protocol**
				<1,000	Poss. Very Slow Rate	Move to step 4
4	>100	10 Minutes	1 Day	> 1,000	Poss. slow rate	Move to step 3
				>100	**VERY SLOW RATE**	**Continue Monitoring**
				<100	NO MOVEMENT	No Action

Figure 7

TITLE

Apparatus and method for monitoring soil slope displacement rate by detecting acoustic emissions

FIELD OF THE INVENTION

Embodiments of the present invention relate to an apparatus for monitoring soil slope displacement rate and/or to a method for monitoring soil slope displacement rate by detecting acoustic emissions arising as a result of soil displacement.

BACKGROUND OF THE INVENTION

For many countries world-wide landslides can be the most severe of all natural disasters, with large humanitarian and economic consequences. The ongoing need to develop new techniques that can be used to lessen damage and loss of life caused by slope instability is self-evident. Of particular concern are slopes formed in strain-softening materials (e.g. plastic clays and shales) and those which incorporate discontinuities with strain softening behaviour (e.g. joint/bedding surfaces and fault zones), which can experience progressive failure and hence undergo deformation prior to collapse. In these types of materials, shear deformations of the order of a few tens of millimetres may be sufficient to reduce shear strength to post-peak values leading to rapid and potentially catastrophic slope failure. The earlier that decreasing stability can be detected, the earlier a warning can be given to those likely to be affected by any event, thus allowing evacuation or remedial measures to arrest the movements.

Monitoring of potentially unstable slopes has three primary objectives: to detect displacements as early as possible, to measure the rate of displacements and to detect and quantify changes in the rate of displacement. To provide timely (i.e. early) information on slope instability, including the timing and likely significance of the potential failure event, requires all three objectives to be met. It is common and established practice to classify slope deformations using descriptive terms related to magnitude of displacement rate (e.g. Transport Research Board (1978). Landslides, Analysis and Control. National Academy of Sciences). The descriptors of displacement rate (i.e. rapid, moderate, slow and very slow) are related to, and hence separated by, orders of rate magnitude. Magnitude and rate of displacements are typically measured directly using instruments such as inclinometers, extensometers and using surface surveying techniques (e.g. see Dunnicliff, J. (1988). Geotechnical instrumentation for monitoring field performance: John Wiley & Sons, pp 577). Many of the techniques commonly in use require measurements made at time intervals to indicate slope movements and rates of change of slope deformation rates, and the resolution of displacements that can be detected is often in the order of a few millimetres. In some cases this will not provide sufficient time to allow a response to the monitoring output. However, in-place inclinometer strings and Time Domain Reflectometry (TDR) systems are capable of providing real-time measurements of displacements. A major consideration when using these costly in-place instruments is that they are damaged by large displacements and thus become inoperable. This can be a significant problem in slopes with regular reactivated movements.

Materials undergoing deformation generate acoustic emission. Studies of acoustic emission (AE) have sought to use capture and measurement of the signal to determine the extent of material deformation. In soil, acoustic emission is generated from inter-particle friction and in rock by fracture propagation and displacement along discontinuities. The presence of AE is an indication of microscopic defect growth or localised inter-particle displacements within the soil or rock body. Within a soil slope the shear stresses induced by destabilising forces cause re-arrangement of particles along developing shear surfaces and this generates AE. Fine grained soils (i.e. silt and clay dominated) generate low levels of AE when sheared. Even if the host soil is considered to be relatively noisy (i.e. a coarse grained soil), attenuation of generated AE is very high due to energy loss as AE is transferred from one particle to another. Use of acoustic emission to asses the stability of soil slopes has been investigated by researchers for many years (e.g. McCauley, M.L. (1977). Monitoring slope stability with acoustic emission: Proceedings First Conference of Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University, June 1975, Trans Tech Publications, 257-269; Koerner, R.M., McCabe, W.M. and Lord, A.E. (1981). Acoustic emission behaviour and monitoring of soils: Acoustic Emission in Geotechnical Practice, ASTM STP 750, 93-141). However until the work of Dixon and his co-workers (Dixon, N., Hill, R. and Kavanagh, J. (2003). Acoustic emission monitoring of slope instability: Development of an active wave guide system. Institution of Civil Engineers Geotechnical Engineering Journal, 156, 2, 83-95; Dixon, N. and Spriggs, M. (2007). Quantification of slope displacement rates using acoustic emission monitoring. Canadian Geotechnical Journal, 44,6, 966-976) it has not been possible to reliably measure AE from a deforming soil slope and to interpret the measured AE to quantify slope displacement rates.

DESCRIPTION OF THE PRIOR ART

Research of applicant(s)

Dixon *et al.* (2003) proposed the use of an active waveguide for monitoring soil slopes. This system comprises installation of a steel tube in a pre-formed borehole with coarse grained soil backfill (e.g. sand or gravel) placed in the annulus around the tube. The tube and soil surround composite is termed the active waveguide. Deformation of the host soil body generates deformation, and hence AE, in the active waveguide, which is transmitted to a sensor at the ground surface. Through a series of field trials, Dixon *et al.* (2003) demonstrated that the active waveguide produced detectable AE in response to periods of slope instability. AE rates were shown to be linked to slope deformation rates and AE monitoring indicated the onset of instability before traditional deformation monitoring techniques. This study showed that AE monitoring could be used to provide an early warning of slope instability. Dixon & Spriggs (2007) extended the work of Dixon *et al.* (2003) by detailing a method for quantifying slope movement rates, and changes in these displacement rates with time, using detected AE events from an active waveguide. They demonstrated that event rates are directly related to displacement rates over a range that is consistent with standard landslide movement classification (i.e. 1 to 0.001 mm per minute), and hence using AE event rates it is possible to differentiate deformation rates by an order of magnitude. This research employed field measurement of AE for discrete time periods and/or post processing of AE to obtain displacement rates. It also used generic high cost, bulky, mains operated signal capture hardware and standard processing software. The need for a low cost AE slope displacement rate unitary sensor with an independent power supply based on a simple signal processing strategy is self evident.

Existing patents

Existing patents related to the use of AE to monitor the state of soil slopes have focussed on the design and operation of waveguides to both generate AE from a deforming slope, transmit AE from the sub-surface to a sensor located above ground level and to locate the source of generated AE. In addition, some patents relate to the use of artificial sound sources generated to assess propagation of AE through the soil material forming the slope. A number of the patents relate to rock slopes and not soil slopes. The existing patents do not provide a generic approach for obtaining information on rates of soil slope displacement and how these change with time. A summary of relevant patents is provided below:

- *JP58187852 (1983) – Measuring method for acoustic emission in cohesive soil ground.* **Purpose:** To perform an assessment of the stability of cohesive soil ground by a method of using a flexible tubular body packed with acoustic emission generating material (e.g. placed within a borehole).

AE generated by deformation of the tube of emitting materials by movement of the cohesive soil is measured. Transducers are buried at intervals within the tube of AE emitting material. The approach detailed can be used to provide information on whether deformations are occurring. **Relevance:** The patent describes formation of an active AE element that is placed in an unstable material. However, it does not use a waveguide to transmit generated signals to the ground surface and most importantly it does not define an approach for obtaining soil displacement rates from the measured AE.

- *DE3419548 (A1) (1985) – Method and device for monitoring ground movements and locating their depth.* **Purpose:** A U-shaped waveguide is used to locate the position of AE source generated by deforming soil beneath the ground surface. **Relevance:** It does not define an approach for obtaining soil displacement rates from the measured AE.
- *JP62083685 (A) (1987) – Method for measuring AE in ground.* **Purpose:** A water filled borehole in a rock slope is used to transmit AE generated by crack formation in the rock body to sensors located at either end of the water filled borehole. **Relevance:** This patent is related to crack propagation in rock slopes and is not relevant to soil slopes. Also, it does not define an approach for obtaining slope displacement rates from the measured AE.
- *JP63075554 (A) (1988) – Method and device for measurement utilizing acoustic wave.* **Purpose:** To efficiently inspect the state of a tube installed in a borehole and to locate the position of deformation of the tube. **Relevance:** This patent is focused on surveying the condition of a tube located in a borehole, and hence it provides information on the state of the borehole. This is achieved by transmitting acoustic signals down the tube and locating zones of past deformation by analysing the reflection of the acoustic waves. Importantly, it does not provide information on rates of ground deformation.
- *JP02024521 (A) (1988) – Apparatus for predicting collapse of natural ground.* **Purpose:** An approach is described to detect the collapse of natural

ground using analysis of acoustic emission signal waveform to obtain characteristics including frequency. **Relevance:** Importantly this apparatus does not provide a measure of the rate of slope displacement or changes in the rate with time.

- *JP1039580 (A) (1989) – Measuring method for in-ground displacement by acoustic emission method.* **Purpose:** An approach is given to locate the source of acoustic emission generated by deforming ground using a wave measurement rod. Acoustic counts and events are obtained. **Relevance:** The generated AE rates are related to the in situ ground materials and therefore interpretation of ground movements using these measurements is not unique and is hence site specific, requiring individual calibration to be undertaken.
- *JP2024521 (A) (1990) – Apparatus for predicting collapse of natural ground.* **Purpose:** Acoustic emission monitoring of material forming a slope is used to detect the onset of instability. The characteristics of the AE waveform are used in conjunction with AE counts to predict the collapse of the natural ground. **Relevance:** Importantly this apparatus does not provide a measure of the rate of slope displacement or changes in the rate with time.
- *JP2190520 (A) (1990) – Setting of degradation position of ground.* **Purpose:** An approach is defined to locate the source of acoustic emission generated by deforming soil using a waveguide with sensors located at each end. **Relevance:** It does not define an approach for obtaining soil displacement rates from the measured AE.
- *JP5112958 (A) (1993) – Detection sensor of sound generated in ground.* **Purpose:** A sensor encased in a water filled container and buried in the ground is used to improve the detection of sound generated by ground movements. **Relevance:** The approach does not consider the sources of the sound or the quantification of the detected sound to provide information on ground displacement rates.
- *JP5112923 (A) (1993) (A) – Evaluating method for natural ground with AE measurement.* **Purpose:** The approach uses real-time monitoring of AE and analyses the signals into groups with similar properties. The number

of signals generated in each group over time is used to provide information on changes in destructive behaviour in the natural ground. **Relevance:** Importantly the method does not provide a measure of the rate of ground displacement or changes in the rate with time.

- *JP11183448 (A) (1997) – Method and system for monitoring of collapse of slope.* **Purpose:** To monitor acoustic emission using a sensor installed in a slope and detect waveforms in order to judge the collapse of a slope. A continuity degree parameter is computed from the waveform and the trend of this with time is used to detect collapse. **Relevance:** Importantly this apparatus does not provide a measure of the rate of slope displacement or changes in the rate with time.

- *JP10318994 (A) (1997) – Detection signal processing method for predicting breaking of base rock.* **Purpose:** To simplify the circuit for detecting an event in a detected acoustic emission wave by using ring down counts. This is applied to prediction of base rock collapse. **Relevance:** The method applies to rock and not soil collapse and importantly this apparatus does not provide a measure of the rate of slope displacement or changes in the rate with time.

- *JP10307128 (1998) – Method for predicting slope disaster by acoustic emission technology.* **Purpose:** An artificial sound source is generated and propagates through the slope across a developing shear surface. The AE signal is detected by a sensor located on a waveguide. The signal decays as it propagates across the forming shear surface and the degree of decay can be used to provide information on the process of shear surface development and hence reduction in slope stability. **Relevance:** The approach uses an artificial generated AE source and stability is interpreted using the decay of the signal as it propagates across a developing shear surface. The method does not use AE generated directly by the deforming slope and importantly it does not provide a measure of the rate of slope displacement or changes in the rate with time.

- *JP11230792 (A) (1999) – Detection system for avalanche of sand and stone.* **Purpose:** The system is designed to provide an early warning of failure by monitoring the sonic waves generated as an avalanche of sand and stone enters a body of water at the toe of the slope. **Relevance:** The approach does not provide information on the rates of slope displacements

- *NL1010459 (C1) (2000) – Acoustic probe for investigating soil parameters, includes a receiver combining with the probe tube to form a chamber filled with a fluid and containing acoustic sensors.* **Purpose:** This patent is a design for a waveguide that can be inserted in a soil body to provide information about soil physical parameters. AE signals propagate through the water filled tube to the acoustic sensor. **Relevance:** This patent is not applied to deforming soil slopes and importantly it does not provide a measurement of slope displacement rates.
- *JP20042119075 (A) (2004) – AE measurement body, function testing method for AE measurement body, AE measurement method, and active natural ground stabilization evaluating method.* **Purpose:** The method is to detect deformation or a precursor of a large scale collapse phenomenon of a steep rock slope using AE monitoring. **Relevance:** This patent is not applied to deforming soil slopes and importantly it does not provide a measurement of slope displacement rates.

BRIEF DESCRIPTION OF THE INVENTION

According to a first aspect of the present invention, there is provided apparatus for monitoring soil slope displacement rate, the monitoring apparatus comprising:

a sensor locatable on an active waveguide partially buried in the soil to detect acoustic emissions transmitted through the active waveguide as a result of soil displacement; and

a processor arrangement operable to:-

analyse the detected acoustic emissions to determine a ring down count rate, wherein there is a predetermined relationship between ring down count rate and soil slope displacement rate;

compare the determined ring down count rate with a predetermined trigger value; and

generate an alert when the determined ring down count rate exceeds the predetermined trigger value.

According to a second aspect of the present invention, there is provided a method for monitoring soil slope displacement rate using an active waveguide partially buried in the soil, the method comprising:

(i) detecting acoustic emissions transmitted through the active waveguide as a result of soil displacement;

(ii) analysing the detected acoustic emissions to determine a ring down count rate, wherein there is a predetermined relationship between ring down count rate and soil slope displacement rate;

(iii) comparing the determined ring down count rate with a predetermined trigger value; and

(iv) generating an alert when the determined ring down count rate exceeds the predetermined trigger value.

The predetermined relationship between ring down count rate and soil slope displacement rate enables the soil slope displacement rate to be determined in a simple and effective manner by directly determining the ring down count rate.

The alert may be a visual alert and/or an audible alert. Alternatively or in addition, the alert may be generated by transmitting the determined ring down count rate(s) and/or corresponding soil slope displacement rate(s) to a remote location, for example using a suitable wireless communication device.

Optional, but sometimes preferred, features of the invention are defined in the dependent claims.

One embodiment of the invention provides an integrated unitary sensor for quantifying soil slope displacement rates using measured acoustic emission, said sensor comprising:

a single piezoelectric transducer for detecting acoustic emission signals generated by deformation of an active waveguide (steel tube with granular backfill surround) through interaction with a deforming slope;

a pre-amplifier and filters to condition the said signal for processing and to remove low frequency background noise;

processing of said signal to obtain ring down count rates for determined time periods;

use of said ring down count rates to calculate said soil slope displacement rates;

storage of said obtained ring down count and displacement rates data;

transmission of said ring down count and displacement rates data using a wireless communication system;

power supply for said integrated unitary sensor; and

a housing for the said sensor to provide a secure and acoustically insulated chamber.

The real-time acoustic emission soil slope displacement rate sensor is comprised of the following elements: piezoelectric transducer, pre-amplifier, filters, an integrated signal processing, data storage and communication device, power supply and a secure, acoustically insulated chamber. The integrated signal processing, data storage and communication device performs the following functions: measurement and quantification of detected AE as Ring Down Count (RDC) rates; conversion of RDC rates into displacement rates; comparison of these with trigger values and generation of alert communication. The acoustic emission soil slope displacement rate sensor is located on an active waveguide. This comprises a steel tube installed within a granular material filled borehole constructed into a potentially unstable soil slope, and the whole is enclosed in a secure and acoustically insulated housing. The waveguide length can be many tens of metres long, with the length dictated by the need to intersect potential shear surfaces that may form beneath the slope. Acoustic emissions are generated as the straining soil slope deforms the granular backfill in the borehole and are transmitted to the ground surface by the steel waveguide. In real-time, generated AE ring down count rates are recorded at pre-defined time intervals and using a relationship between AE ring down count rates and displacement rates, derived through a laboratory calibration process, the RDC rates provide quantitative information on slope displacement rates. The RDC rates are recorded. The RDC rates are compared to pre-determined trigger/action values based on both magnitude and changes in rate. If the trigger values are exceeded, an alert message that includes the measured displacement rates is communicated to a nominated person(s) to enable relevant action to be taken.

ADVANTAGES OF THE INVENTION

1. The acoustic emission soil slope displacement rate sensor is highly sensitive and can detect displacement rates as low as 0.001 mm per minute. This is more sensitive than traditional direct deformation measurement devices.

2. The acoustic emission soil slope displacement rate sensor can detect changes in soil slope displacement rate of orders of magnitude (0.001, 0.01, 0.1 and 1 mm per minute), which is consistent with established slope displacement rate classification and monitoring procedures.

3. The acoustic emission soil slope displacement rate sensor can detect changes in soil slope displacement rate within one minute of the change occurring.

4. The acoustic emission soil slope displacement rate sensor design can be configured for any length of the waveguide (i.e. including backfill type, sensor specification and cover system).

5. Measurements can be made at continuing large magnitude displacements (>>100mm), as the interaction between granular backfill and waveguide will continue to generate AE proportional to displacement rates at the shear surface. Traditional down-hole displacement measurement devices are destroyed at such large displacements.

6. The acoustic emission soil slope displacement rate sensor can be re-used on other waveguides of the same design without the need for re-calibration or modification.

7. The acoustic emission soil slope displacement rate sensor design is independent of the soil materials that form the slope being monitored and the slope geometry (i.e. slope height, length and slope angle).

8. Monitoring is of subsurface soil slope deformations for an extended depth below the slope surface (i.e. the depth of the waveguide) using one acoustic emission slope displacement rate sensor located at the surface. This is a low cost approach compared to currently used down hole measurement sensors.

9. Alerts obtained from continuous measurements are real-time enabling timely responses to reduce consequences of slope failures and hence reduce risk.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows an active waveguide located in a borehole and penetrating a shear surface in an unstable soil slope.

Figure 2 shows details of the acoustic emission soil slope displacement rate sensor, attached to the top of the waveguide, and the housing arrangement.

Figure 3 shows a schematic of the acoustic emission soil slope displacement rate sensor elements and functions.

Figure 4 shows example simulated acoustic emission generated by deformation of waveguide backfill and definition of ring down counts and threshold.

Figure 5 shows a relationship between AE ring down count rates and displacement rates obtained from laboratory calibration tests.

Figure 6 shows the correlation between ring down count (RDC) rates and displacement rates obtained from Figure 5.

Figure 7 is a table showing the decision logic for a communication protocol based on comparison of measured RDC rates with pre-determined trigger values.

Legend for figures

A	Slope Profile	R	Amplitude Axis
B	Shear Surface	S	Time Axis
C	Borehole	T	Threshold
D	Active Waveguide Granular Backfill	U	RDC Symbol
E	Waveguide	V	Rate of RDC Axis (Counts per hour)
F	Low Permeability Material	W	Time Axis (hours)
G	Waveguide Sensor Housing	X	Rapid Rate Trend Line
H	Acoustic Insulation	Y	Moderate Rate Trend Line
I	Transducer	Z	Slow Rate Trend Line
J	Transducer Clamp	AA	Very Slow Rate Trend Line
K	Transducer Cable	AB	Gradient of Count Rate Axis (Counts/minutes^2)
L	Acoustic Emission Slope Displacement Rate Sensor	AC	Deformation Rate Axis (mm/hour)
M	Pre-amplifier and Filters	AD	Rapid Rate
N	Power Supply	AE	Moderate Rate
O	Signal and Data Processor	AF	Slow Rate
P	Data Storage	AG	Very Slow Rate
Q	Wireless Communication Unit		

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Embodiments of the present invention will now be described by way of example only and with reference to the accompanying drawings.

Introduction to acoustic soil slope monitoring system

A schematic representation of the soil slope AE monitoring system is shown in Figure 1. An active waveguide is installed in a pre-bored borehole through the slope, penetrating any potential shear zones. The active waveguide is formed from a steel tube (E) with granular backfill surround (D). A plug of low permeability material is placed at the top of the borehole (F) to stop ingress of surface water and to damp near surface generated acoustic emission. The deforming soil slope strains the waveguide backfill (D), generating AE that propagates along the steel waveguide (E) to the acoustic emission soil slope displacement rate sensor (I and L) that is secured to the top of the waveguide (E). In real-time, generated AE ring down counts (Figure 4, U) are recorded at pre-defined time intervals. AE ring down count rates are then calculated and related to displacement rates using a laboratory derived relationship (Figure 5). The RDC rates are recorded and are compared to pre-determined trigger/action values based on both magnitude and changes in rates (Figure 7). If the trigger values are exceeded, an alert message that includes the measured RDC rates is communicated to a nominated person(s) to enable relevant action to be taken.

The said sensor (I and L) is contained within a secure housing (G) lined with acoustic insulating material (H) (Figure 2). The sensor comprises (Figure 2) a piezoelectric transducer (I) clamped (J) to the top of the steel waveguide (E) and connected by a cable (K) to an integrated signal processing, data storage and communication device (L). This device (L) comprises (Figure 3) a signal pre-amplifier with filters (M), a power supply (N), signal and data processing (O), data storage (P) and wireless communication (Q). The signal and data processing (O) performs the following functions: measurement and quantification of detected AE as Ring Down Count (RDC) rates (Figure 4, U); and comparison of these with trigger values (e.g. Figure 7).

Description of components

Active waveguide

An active waveguide is required to generate detectable acoustic emission in response to straining of a soil slope and to transmit generated AE to the sensor located at the ground surface. The active waveguide is located in a pre-formed borehole made using established drilling techniques. The depth of the borehole should be sufficient to penetrate any existing and/or potential shear surfaces (Figure 1, B) within the soil slope (Figure 1, A). The borehole (C) could be located at the crest of the slope, beneath the slope (as in Figure 1) or at the toe of the slope. This is consistent with standard practice for the location of subsurface slope monitoring instrumentation such as inclinometer casings and TDR installations. The diameter of the pre-formed borehole should be sufficient to enable installation of the waveguide (E) and granular backfill (D) to the full depth of the borehole. There is no maximum diameter for the borehole. Permanent casing should not be used in the borehole over the length that contains the granular backfill.

The installed waveguide (E) is a length of steel tubing. The minimum diameter of the tubing is 50 mm. This is to allow connection of the transducer (I) so as to minimise losses of AE (i.e. smaller diameter tubing has a greater wall curvature giving a reduced contact area between the transducer and tubing). The maximum diameter is not specified, however practicalities of lifting the waveguide (E) to install it in the borehole (i.e. weight issues) and minimising drilling costs (i.e. a larger diameter borehole will be required for larger diameter tubing) dictate that the diameter would generally not exceed (100mm). Lengths of steel tubing are connected together to form the continuous installed waveguide (E). Connections should provide intimate contact between the ends of adjacent lengths, which is required to minimise attenuation of AE as they propagate from one section to the next. This can be achieved through the use of screwed or welded connections. The waveguide (E) is placed in the borehole so that the bottom of the waveguide is located beneath any existing or potential shear surfaces.

The top of the waveguide (E) will protrude above ground level to a height that allows connection of the transducer (I) and enclosure of the waveguide (E) and sensor (I and L) by the housing (G).

The wall thickness of the steel tubing is selected by considering the monitoring frequency used by the sensor. It is necessary to design the waveguide wall thickness/monitoring frequency relationship to optimise the propagation of detectable AE along the steel tube waveguide (E) in the form of Lamb waves. Lamb waves propagate within the wall of the tubing and this reduces attenuation of the AE as they travel along the waveguide (E). Lamb wave generated AE propagate many 10's metres along the waveguide (E). The monitoring frequency is matched to the waveguide wall thickness in order to provide detectable lamb wave modes at the sensor location that have been generated at depth by the deforming backfill (D).

Granular material (D) is placed in the pre-formed borehole to backfill the annulus between the waveguide (E) and borehole wall. The backfill is placed so as to surround the waveguide (E) from its bottom end to within 0.5 to 1.0 metres of the ground surface. The granular backfill (D) is placed to ensure that it is continuous (i.e. no voids are present) and in a dense state. Typically the granular backfill (D) will be coarse grained soil (i.e. sand or gravel). Each backfill type produces a unique relationship between generated AE RDC rates and slope deformation rates. Sand sized particles (0.1 to 2 mm) produce a larger number of AE events for a given deformation than gravel, however fine to medium gravel sized particles (2 to 20 mm) produce AE events of greater amplitude due to their increased particle size and hence larger forces required to re-arrange interlocked particles. Events of larger amplitude propagate further along a waveguide and are more easily detected by the sensor. Single sized (nominally 10mm) angular gravel has been demonstrated to produce detectable AE, with AE RDC (U) generation rates related to slope deformation rates (Figure 5).

Low permeability material (F) is used to backfill the annulus between the waveguide (E) and borehole wall along the borehole length from the top of the granular material (D) to the ground surface (i.e. a borehole length of 0.5 to 1.0 metres). The damping material is required to stop the ingress of surface water into the granular backfill (D) and to isolate the section of waveguide (E) in the top 0.5 to 1.0 metre of the borehole from sources that can generate AE (e.g. localised surface ground deformations and burrowing animals). The damping material (F) is typically a high plasticity, high moisture content clay such as Bentonite grout, but it could also be formed from alternative materials that exhibit low AE generation properties when they deform.

Housing

A housing (Figure 1, G) is located at the top of the active waveguide assembly. The housing (G) covers and encloses the waveguide (E), the transducer (I) and the sensor (L) (Figure 2). Its function is to provide a secure and acoustically insulated chamber. The housing is secure against the ingress of surface water and precipitation, access by animals and it isolates the waveguide from wind blown debris. It is also lockable to protect the sensor (I and L) and waveguide (E) from unauthorised access. An acoustic barrier is provided by a lining of insulating material (Figure 2, H) such as fibre glass loft insulation material.

Transducer clamp

A clamp (Figure 2, I) is used to position the transducer (I) on the waveguide (E). Its role is to locate the transducer in a fixed position for the entire period of monitoring with uniform contact stress between the transducer (I) base and waveguide (E) outer wall surface. A constant contact stress is required as this controls the acoustic coupling and hence transmission of AE from the waveguide (E) to the transducer (I). Constant contact stress provides uniform AE attenuation conditions for the connection. Silicon grease is applied to the base of the transducer to improve propagation of AE between the waveguide (E) and transducer (I). Clamp (J) types can include magnetic devices and those that use a 'U' shaped rod with threaded arms and nuts tightened against a reaction plate acting on the transducer through springs.

Acoustic emission soil slope displacement rate sensor

Transducer

The transducer (I) is positioned on the waveguide (E) > 0.1 metres from the top of the waveguide using the clamp (J). A piezoelectric type transducer is used to convert AE (stress waves), that propagate up the waveguide (E) to the measuring location, from mechanical waves to voltage output (the signal). The transducer has a frequency range 10kHz - 50kHz, a dynamic range 5g – 10g and sensitivity 1 -100mV/g. Output from the transducer is analogue voltage values that represent the wave form of AE at the measuring point on the waveguide. Figure 4 shows example simulated AE voltage output in the form of a plot of voltage amplitude (R) vs. time (S). A cable (K) connects the transducer (I) to the other elements of the sensor (L).

Pre-amplifier and filters

The signal is passed through a pre-amplifier (M) to strengthen the measured signal for data processing. Amplification of 40 to 60dB gain is achieved with a linear response from 15kHz – 45kHz and output +/- volts. The pre-amplifier incorporates a high pass filter of 10kHz and a low pass filter of 100kHz to improve the signal to noise ratio. Filtering out frequencies less than 10kHz removes much of the potential background noise found in a site environment.

Signal processing

Three options are available for real-time signal processing (O): Option A – analogue; Option B – combined analogue and digital; and Option C – digital. In all three cases the input signal is analogue voltages and this is used to quantify ring down count rates. Ring down counts (Figure 4) are defined as the number of times the signal exceeds a pre-set threshold voltage value

(T). RDC rates are obtained from the cumulative number of RDCs in a defined period of time. The threshold voltage is set at a level to exclude noise. This is AE generated by sources other than slope deformation and can include electronic noise from the measurement system and that generated by site activities.

Option A: The analogue signal output from the pre-amplifier and filters passes to a comparator. This has a pre-set threshold voltage value (T). Each time the threshold voltage is exceeded, a voltage pulse is generated. This pulse is an indication of one RDC (U). Data storage (P) is triggered and records the number of pulses/contact closures that occur within adjacent “time bin” periods. The bin period is selectable from 1 second to over 24 hours. At the end of each bin period, the total number of pulses/counts within the bin period is recorded (i.e. equivalent to RDC). Data storage then commences another bin period and continues until either the memory is full or the test period has ended. The internal real-time clock in the data storage device ensures that all data is time and date stamped. The data periods contain the cumulative RDC in the given time period. This number is then divided by the time period to calculate the RDC rate. If the RDC rate exceeds a pre-determined value (e.g. Figure 7), this number is transmitted to a nominated person(s). They can use the received RDC rates, including time series of these values, to obtain soil slope displacement rates (Figure 7) and make decisions on actions to be taken.

Option B: The analogue signal output from the pre-amplifier and filters passes to a comparator. This has a pre-set threshold voltage value (T). Each time the threshold voltage is exceeded, a voltage pulse is generated and detected by a Personal Digital Organiser (PDA) and read using the sound card (i.e. using a similar process to that outlined in Option A). The number of RDC occurring within a pre-defined time period (i.e. the RDC rate) is calculated and recorded using data acquisition software on the PDA. The time series of recorded RDC rates is used to calculate soil slope displacement rates and the values compared to pre-determined trigger levels (Figure 7). This information is then transmitted to a nominated person(s) who can review it and take action as required.

Option C: The analogue signal output from the pre-amplifier and filters passes to an analogue to digital converter and the signal is digitised (16/24 bit, sampling rate 100kHz, output serial). The digital signal is processed on a Printed circuit board using standard signal processing software. The number of RDC in pre-determined time periods are calculated and logged. The time series of recorded RDC rates is used to calculate soil slope displacement rates and the values compared to pre-determined trigger levels (Figure 7). This information is then transmitted to a nominated person(s) who can review it and take action as required.

Data storage

A data storage device (P) is used to record the RDCs measured in pre-determined periods of time (i.e. time bins) that can be from 1 second to over 24 hours in length, and which form the output of the signal processing (O) in Option A. A function to specify the bin length is required and the device must have sufficient storage space to be able to record RDC for each of the time bins over the duration of the monitoring period. The device must also be able to trigger output of measured values if pre-determined RDC rate thresholds are exceeded, for transmission to a nominated person(s).

Wireless communication

Output from the data storage device (P) in Option A, PDA in Option B and computer processor in Option C, is transmitted to the nominated person(s) using a wireless communication component (Q). This must have the capacity to transmit RDC rate values calculated for bin times at a rate of once every 1 minute or less (see Figure 7). A system based on standard wireless communication protocols is preferable (e.g. using a mobile phone SMS system).

Power supply

A power supply (N) (+/- 5V to +/- 30V) is required for operation of the sensor (I) components: pre-amplifier (M), signal processing (N) (Options 1, 2 and 3), data storage and wireless communication (Q). The power supply must be able to operate the sensor for the required monitoring period, which could be from 1 week to several months in length. Options for on site battery charging can be employed, such as the use of a small wind turbine and/or a panel of photo electric cells.

Relationship between ring down counts and displacement rates

Derivation of slope displacement rates from RDC rates is based on laboratory calibration of the active waveguide system. Site specific waveguide (E) and backfill (D) are deformed in a laboratory controlled test at a range of rates and generated AE is recorded. Figure 5 shows a relationship between AE ring down count rates and displacement rates obtained from laboratory calibration tests using a 50mm diameter steel waveguide with a wall thickness of 3mm and 10mm nominal single sized crushed rock backfill material. Figure 5 plots log rate of RDC (counts per hour) vs. log time (hours) for series of tests conducted at a range of waveguide system deformation rates. A best fit line can be drawn through sets of data obtained for each displacement rate. Line X is for tests at 1mm per minute deformation rate (equivalent to rapid slope displacement rate), line Y for tests at 0.1 mm per minute deformation rate (equivalent to moderate slope displacement rate), line Z is for tests at 0.01mm per minute deformation rate (equivalent to slow slope displacement rate) and line AA is for tests at 0.001mm per minute deformation rate (equivalent to very slow slope displacement rate). The calibration test provides a direct correlation between RDC rates and displacement rates (Figure 6). The relationship is used to define trigger levels for signal processing and to assess the significance of the measured soil slope behaviour both through signal processing and review by a nominated person(s).

The relationship between RDC rates generated by the deforming active waveguide and the soil slope displacement rates is of primary importance to obtaining quantitative outputs from the acoustic emission slope displacement rate sensor. Previous attempts to quantify generated AE has used event rates (Dixon & Spriggs 2007), however at high AE generation rates it is possible for events to overlap and be counted as one event, thus underestimating the event rates. This limitation led to the development of the present system using RDC rates for quantification of slope displacement rates.

Decision logic, trigger levels and actions

During monitoring, the measured RDC rates can be used to optimise the recording interval for processing and data storage (i.e. bin times) for signal processing Options B and C. Figure 7 shows an example decision logic used for the communication protocol. It is based on comparison of measured RDC rates with pre-determined trigger values and is specifically for the RDC information shown in Figure 5 (i.e. it is for the active waveguide design used to generate the data in Figure 5). Figure 7 uses RDC rates calculated for 10 minute intervals. When the calculated RDC rate is above 300,000 RDC per hour, the rate of monitoring increases to 1 minute intervals. For any RDC rate that is below 300,000 per hour, the recording period for data storage remains at a 10 minute interval, but average RDC are then sent to a nominated person(s) at 10 minute, 1 hour or 1 day intervals depending on classification of the current RDC rate. Time series of these rates can be used to identify trends in slope movement rates. Resulting action protocols can then be initiated based on this information as demonstrated in Figure 7.

Although embodiments of the invention have been described in the preceding paragraphs, it should be understood that various modifications may be made to those embodiments without departing from the scope of the present invention, as claimed.

CLAIMS

1. Apparatus for monitoring soil slope displacement rate, the monitoring apparatus comprising:

a sensor locatable on an active waveguide partially buried in the soil to detect acoustic emissions transmitted through the active waveguide as a result of soil displacement; and

a processor arrangement operable to:-

analyse the detected acoustic emissions to determine a ring down count rate, wherein there is a predetermined relationship between ring down count rate and soil slope displacement rate;

compare the determined ring down count rate with a predetermined trigger value; and

generate an alert when the determined ring down count rate exceeds the predetermined trigger value.

2. Monitoring apparatus according to claim 1, wherein the processor arrangement is operable to:

analyse the detected acoustic emissions during a series of predetermined time periods to determine a series of ring down count rates;

analyse the series of ring down count rates to determine the rate of change of the ring down count rate;

compare the determined rate of change of the ring down count rate with a predetermined trigger value; and

generate an alert when the determined rate of change of the ring down count rate exceeds the predetermined trigger value.

3. Monitoring apparatus according to claim 1 or claim 2, wherein the alert generated by the processor arrangement comprises one or more of a visual alert and an audible alert.

4. Monitoring apparatus according to any preceding claim, wherein the processor arrangement is operable to generate the alert by transmitting the determined ring down count rate(s) to a remote location.

5. Monitoring apparatus according to any preceding claim, wherein the processor arrangement is operable to determine soil slope displacement rate(s) from the related ring down count rate(s).

6. Monitoring apparatus according to claim 5, wherein the processor arrangement is operable to generate the alert by transmitting the determined soil slope displacement rate(s) to a remote location.

7. Monitoring apparatus according to any preceding claim, wherein the processor arrangement is operable to determine the ring down count rate(s) by recording the number of ring down counts during one or more predetermined time periods.

8. Monitoring apparatus according to claim 7, wherein the processor arrangement is operable to vary the predetermined time period depending upon the magnitude of one or more previously determined ring down count rates.

9. Monitoring apparatus according to any preceding claim, wherein the sensor is operable to generate a voltage signal having a magnitude corresponding to the magnitude of the detected acoustic emissions and the processor arrangement includes a signal and data processing device which is operable to analyse the generated voltage signal to determine the ring down count rate.

10. Monitoring apparatus according to claim 9, wherein the processor arrangement includes a pre-amplifier and filters to condition the voltage signal generated by the sensor.

11. Monitoring apparatus according to claim 9 or claim 10, wherein the signal and data processing device is operable to analyse the generated voltage signal and thereby determine the ring down count rate(s) by determining the number of times that the generated voltage signal exceeds a predetermined threshold voltage value during one or more predetermined time periods.

12. Monitoring apparatus according to any preceding claim, wherein the processor arrangement includes data storage means for storing the determined ring down count rate(s).

13. Monitoring apparatus according to claim 12, wherein the data storage means is also operable to store the determined soil slope displacement rate(s).

14. Monitoring apparatus according to any of claims 4 to 13, wherein the processor arrangement includes transmission means for transmitting the determined ring down count rate(s) to a remote location.

15. Monitoring apparatus according to claim 14, wherein the transmission means is also operable to transmit the determined soil slope displacement rate(s) to a remote location.

16. Monitoring apparatus according to claim 14 or claim 15, wherein the transmission means is a wireless communication device.

17. Monitoring apparatus according to any preceding claim, wherein the processor arrangement includes a power supply.

18. Monitoring apparatus according to any preceding claim, wherein the sensor is secured in use to the active waveguide at an upper end region of the active waveguide.

19. Monitoring apparatus according to any preceding claim, wherein the sensor is a piezoelectric transducer.

20. Monitoring apparatus according to any preceding claim, further including an acoustically insulating housing containing the sensor and processor arrangement and enclosing in use the upper end of the active waveguide.

21. A method for monitoring soil slope displacement rate using an active waveguide partially buried in the soil, the method comprising:

(i) detecting acoustic emissions transmitted through the active waveguide as a result of soil displacement;

(ii) analysing the detected acoustic emissions to determine a ring down count rate, wherein there is a predetermined relationship between ring down count rate and soil slope displacement rate;

(iii) comparing the determined ring down count rate with a predetermined trigger value; and

(iv) generating an alert when the determined ring down count rate exceeds the predetermined trigger value.

22. A method according to claim 21, wherein:

step (ii) includes analysing the detected acoustic emissions during a series of predetermined time periods to determine a series of ring down count rates and analysing the series of ring down count rates to determine the rate of change of the ring down count rate;

step (iii) includes comparing the determined rate of change of the ring down count rate with a predetermined trigger value; and step (iv) includes generating an alert when the determined rate of change of the ring down count rate exceeds the predetermined trigger value.

23. A method according to claim 21 or claim 22, wherein a sensor is located at an upper end region of the active waveguide to detect acoustic emissions transmitted through the active waveguide.

24. A method according to claim 23, wherein the sensor generates a voltage signal having a magnitude corresponding to the magnitude of the detected acoustic emissions.

25. A method according to claim 24, wherein step (ii) comprises analysing the generated voltage signal to determine the number of ring down counts during one or more predetermined time periods to thereby provide one or more ring down count rates.

26. A method according to claim 25, wherein the method comprises varying the predetermined time period based on the magnitude of one or more previously determined ring down count rates.

27. A method according to claim 25 or claim 26, wherein step (ii) comprises comparing the generated voltage signal with a predetermined threshold voltage value and determining the number of times that the generated voltage signal exceeds the predetermined threshold voltage value during said one or more predetermined time periods to thereby determine the ring down count rate(s).

28. A method according to any of claims 21 to 27, wherein step (ii) further comprises determining soil slope displacement rate(s) from the related ring down count rate(s).

29. A method according to any of claims 21 to 28, further comprising storing the determined ring down count rate(s) and/or the determined soil slope displacement rate(s) in a data storage means.

30. A method according to any of claims 21 to 29, wherein step (iv) comprises generating one or more of a visual alert and an audible alert.

31. A method according to any of claims 21 to 30, wherein step (iv) comprises transmitting the determined ring down count rate(s) to a remote location.

32. A method according to any of claims 28 to 31, wherein step (iv) comprises transmitting the determined soil slope displacement rate(s) to a remote location.

33. A method according to claim 31 or claim 32, wherein a wireless communication device is used to transmit the determined ring down count rate(s) and/or the determined displacement rate(s) to a remote location.

34. Apparatus for monitoring soil slope displacement rate substantially as hereinbefore described and/or as shown in the accompanying drawings.

35. A method for monitoring soil slope displacement rate substantially as hereinbefore described with reference to the accompanying drawings.

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Claims searched:	1-33	**Date of search:**	18 March 2010

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X,Y	X: 1-3, 5, 7-13, 17-30; Y: 4, 6, 14-16, 31-33	DIXON, N. et al; "Quantification of slope displacement rates using acoustic emission monitoring"; Canadian Geotechnical Journal, 2007, 44, 6, pp966-976 Abstract; Figs 1, 3, 4 & 7 and related description; in particular
X,Y	X: 1, 3, 5, 7-13, 17-21, 23-30; Y: 4, 6, 14-16, 31-33	JP11183448 A (FUJITA CORP) EPO & WPI abstracts; Figs 9, 10; translation paragraphs 1, 12, 27-34, 44-59; in particular
Y	Y: 4, 6, 14-16, 31-33	JP11230792 A (MITSUBISHI) EPO & WPI abstracts and Fig 1; in particular
A	-	DIXON, N. et al; "Acoustic emission monitoring of slope instability: development of an active wave guide system", Proc. Inst. of Civil Engineers Geotechnical Engineering, 2003, 156, 2, pp83-95
A	-	JP10318994 A (TAKENAKA KOMUTEN)
A	-	JP02024521 A (FUJITA)

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

E02D; G01N; G08B

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC

International Classification:

Subclass	Subgroup	Valid From
G01N	0029/14	01/01/2006
G01N	0029/24	01/01/2006
G01N	0029/44	01/01/2006
G08B	0021/10	01/01/2006