Geotechnical Instrumentation News

John Dunnicliff

Introduction

This is the forty-fourth episode of GIN. Two articles this time, one full-length, and one mini-length.

Acoustic Emission (AE)

To quote from the following article by Matthew Spriggs and Neil Dixon:

> *"AE is a natural phenomenon that occurs when a solid is subjected to stress. This stress, from an external source, causes a sudden release of sound waves resulting in microseismic activity, which can be detected by transducers. Within a slope the stress induced by destabilizing forces causes a re-arrangement of particles along developing shear surfaces. This inter-particle friction results in the release of AE, and is an indication of straining within a soil body."*

AE has also been called *sub-audible rock noise*, and *microseismic activity*. I first learned about it from Walter Nold, who some of you will remember as the enthusiastic developer of the DeAerator™ . He put some earphones on my head, connected them to an amplifier and microphone, placed the microphone alongside a piece of coal, and squeezed the coal with a C-clamp. Click, click, click, with gradually increasing time intervals between clicks, and a look of glee on Walter's face. I've used it on a project only once – an attempt at a **qualitative** determination of deformation trends around a large excavation in rock. Plenty of clicks, but too much background noise for meaningful results.

The following article is based on a PhD thesis by Matthew Spriggs, written here in England. It focuses on monitoring the instability of slopes in soil, and concludes that the approach can provide a **quantified** output in terms of rate of deformation. The location of the zone of deformation can also be obtained, and therefore AE can be used to provide an early warning of slope failure.

Protecting Instruments from Damage

The brief article by Gord McKenna describes a simple and inexpensive method for protecting instruments at the ground surface. I remember one of my colleagues returning from an earth dam project and showing me a photograph of how vertical riser pipes were protected from damage by earth-moving equipment. A cage around each riser, with a person inside, who became an expert at waving!

FMGM-2007

The next international symposium, *Field Measurements in Geomechanics (FMGM),* will be held in Boston in September 2007. This will be the seventh in the series of once-every-four-years symposia, previous venues having been Switzerland (1983), Japan (1987), Norway (1991), Italy (1995), Singapore (1999) and again Norway (2003). The event will be sponsored by the Geo-Institute of ASCE. I've been told that details will be announced on *www.geoinstitute.org* in the near future.

For more information about these symposia, please visit *www.fmgm.no*. They provide an excellent forum for exchanging technical information and for meeting others with an interest in geotechnical instrumentation. Having lived in Boston for 30 years I can say with confidence that there will be no snow, the agonizing hot/humid weather should be over, and that September and October are the best times of year. So come and join us! Perhaps the Red Sox will be on top one more time – see later.

Lesson Learned from Others

Some of you may know of the collapse in April last year of Nicoll Highway cut-and-cover excavation in Singapore, which killed four construction workers. In May this year the Committee of Inquiry submitted its final report, which includes a recommendation for legal action against four engineers, who may face prison terms. The collapsed section had a depth of 33m (108 ft), with diaphragm (slurry) walls and ten levels of internal bracing. According to the Summer 2005 issue of *European Foundations* (published by Emap Construct in London), among the findings of the report were:

- *"Warnings of the approaching collapse were present from an early stage, but these were not taken seriously … A multiplicity of events led to the position where design, construction, instrumentation, management and organizational systems … failed."*
- *"The catastrophic collapse was the finale to mounting incidences and warnings … of excessive deflections, surging inclinometer readings … plunging strain gage readings …"*
- *"A stop work order is an essential and crucial element that must exist as a viable safety measure in the con-*

> *struction process. A stop work order must be an exercisable and realistic option."*

No stop work order was issued prior to the collapse. Further criticisms include:

- Inclinometers at key locations of the diaphragm wall were not monitored daily during critical periods. The opportunity to detect adverse events was lost.
- Interpretation of instrument data was perfunctory.

Let this be a lesson for us all!

Cricket Again

I say "again" because I explained what the game is all about in the March 2001 episode of GIN. For those of you who have forgotten:

- *You have two sides, one out in the field and one in.*
- *Each man that's in the side that's in goes out and when he's out he comes in and the next man goes out.*
- *When they are all out, the side that's out comes in and the side that's been in goes out and tries to get those coming in out.*
- *When both sides have been in and out, including the not outs, that's the end of the game.*

Okay so far?

Now, here in England, we have something extraordinary going on. I'll begin this report by explaining cricket in a different way, in baseball terms, using substantial artistic license. Cricket has various formats – what follows applies to "limited over" games, which are the subject of this report. No, I'm not going to explain what an "over" is!

- *There are eleven players in each team.*
- *There is only one inning per team.*
- *Each team is allowed a maximum number of pitches, sometimes 120, sometimes 300.*
- *A pitcher can be rested – he then joins the fielders and another fielder pitches. Any pitcher can later pitch again, except that each pitcher is limited to a maximum number of pitches.*
- *The objective of the fielding side is to dismiss all players on the batting side. As in baseball, a batter can be caught, given out on the base paths because a fielder with the ball got to a base first, or struck out. But in this case, "struck out" means that the ball knocks down some sticks at home plate.*
- *No gloves, except for the catcher.*
- *A batter scores one run for each base that he touches. The ballpark has a boundary. A batter scores four runs if the ball crosses the boundary having touched the ground. A home run scores six.*
- *When a batter hits the ball he is not obligated to run. There are no such things as fair or foul balls, or balls and strikes. But we* **do** *have "no-balls"!*
- *One side bats, completes an inning by using up the maximum number of pitches or because all batters have been dismissed. The other side then bats and tries to score more runs.*

Now, of course, everything is much clearer to you – yes? Before getting to the current events here, I need to explain that cricket is a truly international sport, not like baseball, despite adopting the self-important designation "World Series" for a mere national final. [It's okay, I'm a Red Sox fan, and have just read every word of "Faithful", the game-by-game book by Stephen King and Stewart O'Nan about the Red Sox 2004 season. You have to be addicted to do that. Bye-bye curse!]. The primary World Champs of cricket over the years have been the Australians (in this case "World" truly means that!). The acknowledged bottom-of-the-heap team is from Bangladesh – think of them as the farm team for the hapless Devil Rays (adjective courtesy of King and O'Nan). England is in there, sometime good, sometimes not so good, but very rarely do they beat the Aussies. So now to the current events.

Let's refer to the Australians as the Yankees, England as the Red Sox, and Bangladesh as the hapless Devil Rays. The Yankees and hDRs are "on tour" here, meaning that they play games against English clubs, and international games among themselves and the English national team. Four games for the Yankees so far, one against a club team and three against an international team:

1. A lowly club side beat the Yankees.
2. The Red Sox thrashed the Yankees by a huge margin.
3. The hapless farm team beat the Yankees. Wild cheering!
4. A repeat of the second – a dramatic come-from-behind game, by a lesser margin, but nevertheless worth getting hoarse about – my wife and I were there.

So – for all you Yankee and Australia fans – times they are a changin'[1].

Closure

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to *johndunnicliff@attglobal.net, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. and fax +44-1626-832919.*

Inu Ho'omaikai (Hawaii). (EENUU HO OH MY KY). "To drink – good health". Thanks to Bobbi Daugherty for this.

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[1] Just before going to press – I have to be open about this and regrettably admit that things are beginning to get back to normal. Since writing the above words, the Yankees have won more than the Red Sox. There was an extraordinary 196-196 tie in the final of one series. For those of you who know about these things, we now wait for the ashes series. Perhaps I'd better focus on the **real** teams, with the Sox 2½ games ahead of the Yankees at the all-star break. Can they repeat?

The Instrumentation of Landslides Using Acoustic Emission

Matthew Spriggs
Neil Dixon

Figure 1. View of slope failure at Cowden, located through centre of instrument array (Dixon et al. 2003)

What is Acoustic Emission?

For many countries around the world landslides can be the most severe of all natural disasters, with large humanitarian and economic consequences. Italy is one such country, where it is estimated that the cost of landslide remediation since 1944 totalled 500 million euros (approx 620 million US$), with an average of 1000 million euros (approx 1250 million US$) being spent each year in damages to individuals affected by landslides (Barla *et al.* 2003). The ongoing need to discover and develop new techniques to lessen both the humanitarian and economic disasters is self-evident. This article is concerned with the use of acoustic emission (AE) as a non-destructive technique for providing an early warning of failures in soil slopes.

AE is a natural phenomenon that occurs when a solid is subjected to stress. This stress, from an external source, causes a sudden release of sound waves resulting in microseismic activity, which can be detected by transducers. Within a slope the stress induced by destabilizing forces causes a re-arrangement of particles along developing shear surfaces. This inter-particle friction results in the release of AE, and is an indication of straining within a soil body.

Of particular concern are slopes formed in strain-softening materials, (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 millimetres may be sufficient to reduce their shear strength to post-peak values, and lead to failure. The earlier that decreasing stability can be detected, the earlier a warning can be given to those likely to be affected by any failure, thereby creating the possibility for remedial measures to be carried out to arrest the movements.

The Use of Acoustic Emission to Date

Traditional methods of monitoring slope movements have included surface surveying and sub-surface instrumentation techniques. However, many of these methods can lack the sensitivity to detect deformation at very low pre-failure strain rates. Over 40 years of research has been conducted into the use of AE to monitor soil movements. The most notable contributions in terms of field monitoring were provided by Koerner *et al.* (1981) and Dixon *et al.* (2003). Dam embankments, stockpiles of soil, trench walls and sea cliffs were all monitored, and demonstrated that the use of AE and its associated instrumentation was both sensitive and robust enough to be used outside of the laboratory.

Figure 1 shows extensive monitoring on the Northeast coast of England in 20m (65ft) high cliffs. Dixon *et al.* (1996) successfully detected measurable AE from pre-failure strains in a stiff cohesive (high sand content) glacial till. AE monitoring was demonstrated to be particularly sensitive to pre-failure deformations, where traditional techniques were unable to detect or locate movement. As deformation progressed towards failure, AE monitoring was validated by the presence of other sub-surface instrumentation (inclinometers).

Table 1. A qualitative approach to assessing slope instability using acoustic emission (After Koerner *et al.* 1981)

Level of AE	Conclusion
Generate very high levels of AE	Undergoing large deformations and are probably in a state of failure
Generate high levels of AE	Substantial deformations considered unstable, immediate remedial measures required
Generate moderate levels of AE	Deforming slightly but marginally stable, continued monitoring is necessary
Generate little or no AE	Probably not deforming and are therefore stable

However, to date only a qualitative AE method (shown in Table 1) exists for the assessment of slope movements (After Koerner *et al.* 1981).

As with all qualitative scales, this assessment is open to human error in interpretation and implementation. Only a quantitative approach would achieve the necessary accuracy and reliability needed to produce a rigorous early warning of slope instability. This article describes advances in the development of an early warning system for landslides, based on the quantification of AE.

Detecting AE from Soil Deformation

Detecting AE generated by a developing shear surface within a slope is not an easy task. As AE propagates through soil, it suffers from a loss of signal amplitude (attenuation). Attenuation is high in soils because it is a particulate medium, and energy is lost as AE travels across boundaries from one particle to another. The use of a waveguide to provide a path of low attenuation from the source of the AE (within a soil slope) to the sensor (usually situated above ground surface) has become standard practice in AE research. The presence of a waveguide, typically a metal pipe inserted within an unstable slope, also greatly increases the monitoring range of the sensor.

Dixon *et al.* (1996) outlined two generic types of waveguide; passive and active. A passive waveguide does not introduce additional sources of AE, and thus all detected AE is assumed to originate from the surrounding soil slope. In comparison, the active waveguide uses an annulus of high AE-responsive backfill material around the waveguide. As the slope deforms the waveguide, AE is assumed to originate from the backfill only. If the acoustic properties of the backfill are known, then a calibrated waveguide monitoring system can be used within an unstable soil slope without prior knowledge of the geological acoustic characteristics of the slope.

Kousteni (2002) showed that gravel emitted higher levels of AE than sand. Tests showed that whilst sand produced a greater number of events, gravel produced events of greater amplitude. Because of its increased size and angularity, larger forces were required to rearrange the interlocked gravel particles, and thus the deformation mechanism is more sudden and severe. The result is the generation of 'noisy' AE events (high amplitude events).

Figure 2 shows a schematic representation of a typical AE instrumentation system. AE originating from the deformation of backfill within the active waveguide propagates along a steel waveguide to a piezoelectric sensor secured to the top of the metal waveguide. The AE is then strengthened by a preamplifier and an amplifier to enable the signal to travel down lengths of ca-

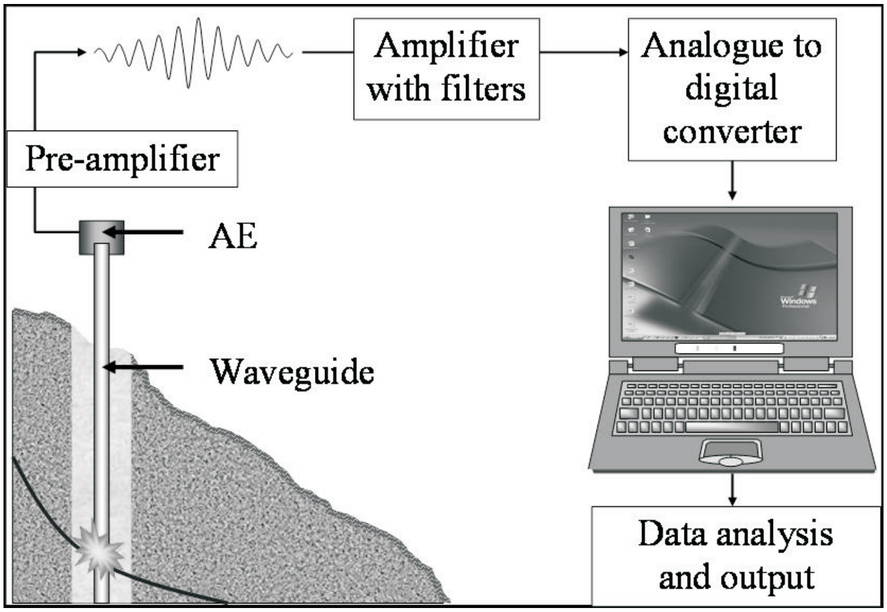

Figure 2. Components of an AE monitoring system

ble without being subsequently affected by background or electrical noise. Finally the AE is converted to a digital signal for subsequent analysis and manipulation using real time data acquisition software.

Establishing criteria for measuring AE recorded in the above system is the first step towards a quantified output. Figure 3 (Dixon *et al.* 1996) shows a simplified AE pulse waveform from a transient event. An event is identified as beginning when an amplitude threshold is first crossed and ending when a waveform falls below that same threshold for a pre-determined length of time. The example in Figure 3 shows one such event.

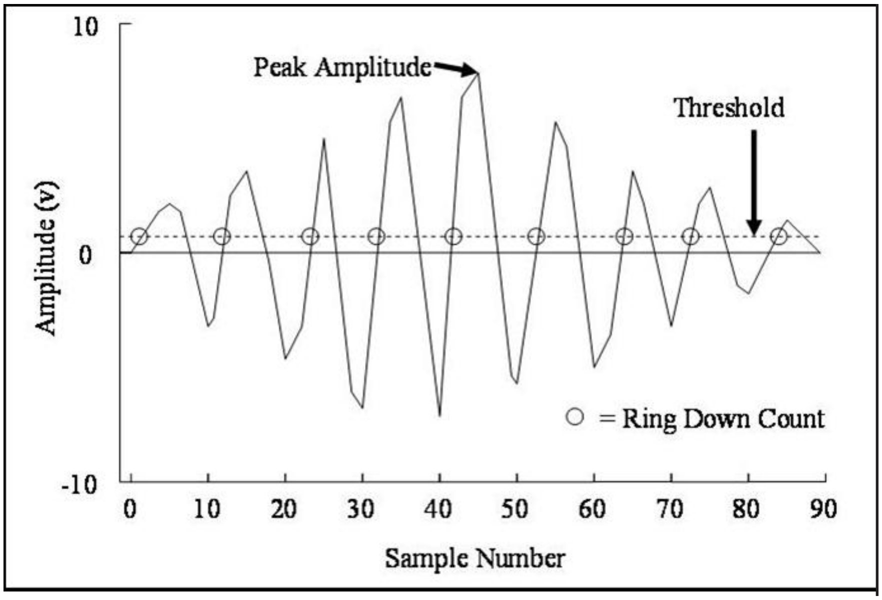

Figure 3. A Typical AE event waveform (After Dixon et al. 1996)

Determining Deformation Rates

Current standards for characterising slope deformations separate rates by orders of magnitude of movement, and are shown in Table 2.

An early warning detection system based on AE must be able to detect the onset of failure at potentially very low deformation rates, and have the potential to differentiate between ‘rapid’, ‘moderate’, ‘slow’ and ‘very slow’ rates of movement.

A series of strain-controlled compression tests was carried out within the laboratory to determine a relationship between the rate of deformation and the generated AE events. A metal pipe waveguide 3m (9.8ft) in length (55mm (2.17in.) diameter and 3mm (0.12in.) wall thickness) was surrounded by an annulus of crushed river gravel (nominal size 5mm (0.197in.)). This gravel was confined around the waveguide by a lightweight flexible geomembrane sleeve and compacted to a density of 1506kg/m^3 (94lb/ft^3). This enabled the gravel surrounding the waveguide to be confined under similar conditions as it would be placed within the field, where the granular backfill would be surrounded by the in situ soil. Compression tests were used for ease of testing, and were later validated by large scale experiments in which the same waveguide and backfill arrangement underwent a shear deformation.

A sensor was placed 1.8m (5.9ft) from the loading position, and AE recorded within the frequency range of 25-28 kHz was analysed. The deformation rates used are shown in Table 3 along with their corresponding description as laid down by the Transport Research Board (1978).

Figure 4 shows the results of the compression tests by displaying the rate of events against time; both axes use a logarithmic scale. Figure 4 demonstrates that a clear correlation exists between the rate of events recorded and the time over which the events were recorded. These clear groupings of data demonstrate the ability of the AE monitoring system to differentiate between orders of magnitude of deformation. Large scale experiments were also carried out in which the backfill underwent shear deformation. These experiments gave similar results to those in Figure 4, and are discussed in full by Spriggs (2005).

The gradients of each experiment in Figure 4 were calculated and presented on a graph against the actual rate of deformation used during each experiment (Figure 5). A best-fit trend line was drawn through the average of each gradient to produce a relationship between the gradient of the event rate and the rate of deformation. This enables Figure 5 to be used to convert recorded AE, in terms of event, into a quantified rate of deformation.

In order to assess the use of the relationship shown in Figure 5, a blind test was conducted using the same experimental set-up. A total of nine separate deformation rates were identified within the blind test. The AE data from each identified deformation rate was plotted on a graph of event rate versus

Table 2. Standard for classifying slope deformation rates (After Transport Research Board, 1978)

Description	Deformation Rate			
	mm per minute		feet per hour	
	from	to	from	to
Rapid	300	1.044	59	0.2
Moderate	1.044	0.0336	0.2	0.0066
Slow	0.0336	0.00336	0.0066	0.00066
Very Slow	0.00336	0.000108	0.00066	0.000021

Table 3. Deformation rates used in compression tests

Description	Deformation Rate	
	mm per minute	feet per hour
Rapid	1	0.2
Moderate	0.1	0.02
Slow	0.01	0.002
Very Slow	0.001	0.0002

time (similar to Figure 4) and the gradient of each line was calculated and then converted to an estimated rate of deformation using Figure 5.

Each change in deformation rate was identified, and the system responded to a change within one minute of that change taking place. Such accuracy is necessary to provide sufficient warning of any unexpected increases in deformation rate, which might be brought about for example by a sudden increase in rainfall. The blind test showed that recorded AE data in response to unknown deformation rates can be quantified, and a calculated deformation rate, based on the event rate, can be obtained with an accuracy of one order of magnitude.

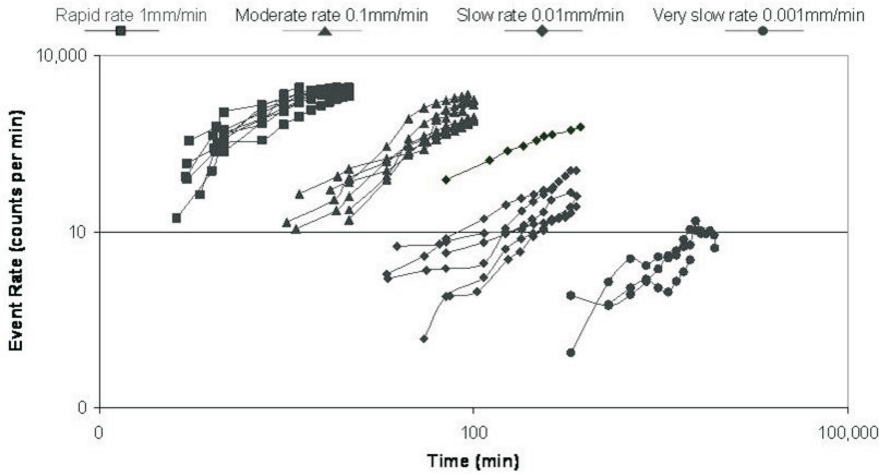

Figure 4. Rate AE (events per hour) verses time

A zero rate of deformation was also recognised within the blind test. Being able to indicate a zero deformation rate as well as increases and decreases in the deformation rate, demonstrates the capability of the system to monitor the effectiveness of remediation works.

Locating the Zone of Deformation

Identifying the location of a developing shear surface is necessary in order to gain information relating to the nature of the deformation mechanism. Characteristics of the waveform can be utilised to determine the distance of propagation of the AE.

Where two parallel surfaces exist, as is the case in a plate or a pipe, then Lamb waves become the predominant mode of propagation (Maji *et al.* 1997). Within any one AE event there exists an infinite number of AE modes which propagate at different velocities. By detecting the first two Lamb wave modes to arrive from the same event, it was possible to calculate the distant to source if the velocities of each mode were known.

Simple AEs were generated by breaking pencil lead on the waveguide at distances from the sensor up to 23m (75.5ft). Based on the arrival times of the first two Lamb wave modes, manual and automatic source location techniques were used to calculate the distance from source to sensor to within 1m (3.2 ft) of the actual distance. This was repeated with AE generated by the deformation of gravel around the waveguide, with similar accuracy.

The design of an automatic source location monitoring system has been produced. This enabled the analysis of thousands of AE events. Although many spurious events were analysed, resulting in incorrectly calculated distances, the credibility of the technique increased with every added event analysed, until a histogram of distance to source clearly identified the location of deformations. The technique was, however, never run in real time, but the capability of real time analysis does exist within the designed system. Full details of the approach for locating the zone of deformation in the slope are given by Spriggs (2005).

Providing an Early Warning

This article has outlined the potential of AE for use in pre-failure deformation monitoring, by considering the use of 'event rate' to provide quantified data pertaining to the rate of deformation.

The following can be concluded:

- By using an active waveguide it is possible to differentiate deformation rates by an order of magnitude when monitoring the rate of AE events. A relationship between the gradient of the event rate against time and the deformation rate can be produced.
- The use of a blind test demonstrated the ability of the system to detect increases and decreases in deformation rate, within an order of magnitude, and identify the time (within one minute) when that change took place.

In Table 1 the current use of AE for slope monitoring was summarised within a qualitative guide produced by Koerner *et al.* (1981). That same guide can now be updated to produce a quantified method for assessing soil slope instability based on deformation rates. This shown in Table 4.

This article describes a unique approach for monitoring the instability of soil slopes using AE. The approach can provide a quantified output in terms of rate of deformation that is accurate, reproducible and sensitive to changes within orders of magnitude of movement. The location of the zone of deformation can also be obtained. AE can therefore be used to provide an early warning of failures of slopes in soil.

References

Barla, G. (2003) Lessons learned related to risk mitigation. *ICFSM 2003, Fast slope movements prediction and prevention for risk mitigation*, Naples, Vol. 1.

Dixon, N. Kavanagh, J. & Hill, R (1996) Monitoring landslide activity and hazard by acoustic emission. *Journal of the Geological Society of China*, Vol.39, No. 4, P.437-464.

Dixon, N., Hill, R. & 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.*

Koerner, R. M. McCabe, W. M. & Lord, A. E. (1981) Acoustic emission behaviour and monitoring of soils. *Proceedings of the First Synopsis on Acoustic Emission in Soils,* P93-141.

Kousteni, A. (2002) *Investigation of Acoustic Emission Waveguide Systems for Detecting Slope Instability.* PhD Thesis, The Nottingham Trent University.

Maji, A. K. Satpathi, D. & Kratochvil, T. (1997) Acoustic emission source location using lamb wave modes. *Journal of Engineering Mechanics*, Vol. 123, No. 2, P.154-161.

Spriggs, M. P. (2005) *Quantification of acoustic emission from soils for predicting landslide failure*. PhD Thesis, Loughborough University.

Transport Research Board (1978) *Landslides, Analysis and Control.* National Academy of Sciences.

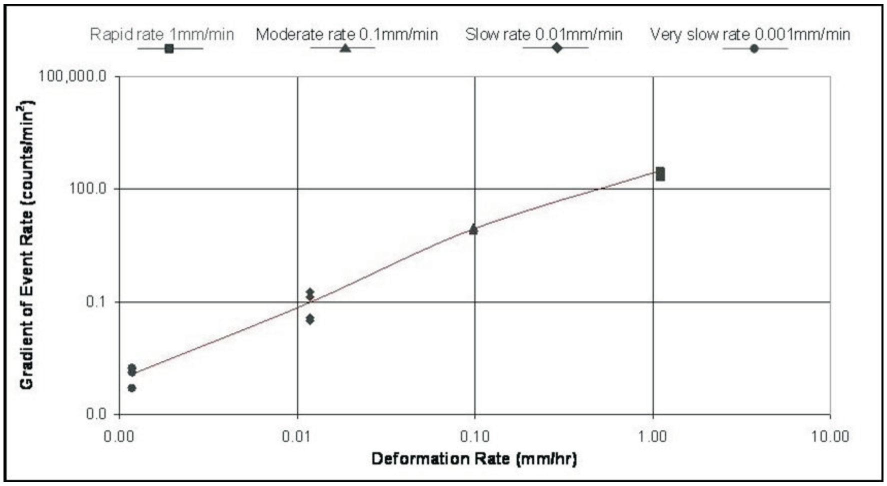

Figure 5. Relationship between gradient of AE event rate and rate of displacement

Table 4. A quantified approach to assessing slope instability with acoustic emission

Description	Deformation Rate		Conclusion
	mm per minute	feet per hour	
Rapid	1 or greater	0.2 or greater	Slope is undergoing large deformations and is likely to be in a state of failure. Urgent need to implement public safety measures
Moderate	0.1	0.02	Substantial deformations considered unstable, immediate remedial and public safety measures required
Slow	0.01	0.002	Deforming slightly but marginally stable, continued monitoring is necessary
Very Slow	0.001 or less	0.0002 or less	Slope is probably not deforming and is therefore stable

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Protecting Instruments from Damage

Gord McKenna

I'm seeing mines spending $20,000 on a piezometer hole and then leaving the wires in the mud, when there is an easy and inexpensive alternative.

Called instrument quadrupeds (or simply "quads"), these protective enclosures have been used for decades in the oil sands region of northeastern Alberta to mark the locations of geotechnical instruments, and to provide a place to hang the instrument cables neatly.

Begin construction by cutting two-by-four and four-by-four pieces of lumber to make four footers, and two diagonal braces as shown in Figure 1. Next apply a coat of paint to any surfaces desired. Using 3¼ in. galvanized Ardox/spiral nails, hammer the quad together. If you have the space, you can set up an assembly line, constructing a dozen or more quads at once! A nail gun and mitre saw can be used to speed up production and cut labour costs.

You can add some finishing touches depending upon your needs – a flasher, flag, instrument number placard, contact information sticker or placard, or even nail a plank of wood to make a field table.

do NOT print key lines

Original line drawing attached to hard copies for Friesens to drop into position

Figure 1. Instrument Quad

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