HYDROLOGICAL PROCESS, VOL. 4, 35–43 (1990)

# TRIALS OF AN ACOUSTIC METHOD OF MEASURING PIEZOMETRIC LEVELS IN STANDPIPES

W. HEATH
*Overseas Unit, Transport & Road Research Laboratory, Old Wokingham Road, Crowthorne, Berkshire, RG11 6AU, UK*
AND
DEDI S.
*Institute of Road Engineering, Bandung, Indonesia*

## ABSTRACT

The role of the open standpipe Casagrande piezometer for determining soil pore pressures is still important because of its simplicity and reliability in comparison with transducer type instruments. Such factors are especially relevant when instrumentation is used on remote and inaccessible sites. The limitations of Casagrande type systems relate to poor response times, particularly in soils of low permeability, and the complexity of the normal gas bubbling equipment used to monitor and record data from this type of piezometer.

The response can be improved, providing the design of the installation is taken into consideration in terms of the piezometer collection area and standpipe sizes. A simple acoustic technique has been developed by Geotechnical Monitoring Ltd, to monitor and record piezometric levels. This is based on measuring the period for the return echo of a high frequency signal; a technique widely used to focus cameras that has been found to be reliable and accurate. However, trials on landslide sites in Indonesia highlighted problems which related more to a lack of development rather than any fundamental problems in the method of monitoring standpipes. This paper describes such problems and how they might be overcome.

KEY WORDS Acoustic piezometer monitoring Pore pressure Piezometer response

## INTRODUCTION

Despite the development of a range of piezometer instruments in recent years, including hydraulic, vibrating wire, and pneumatic types, considerable reliance is still placed on the simpler open hydraulic Casagrande system. This reflects the self de-airing characteristics and general simplicity and reliability of such techniques, combined with the ease of installation. These advantages are most apparent when instrumentation is used on inaccessible sites where high levels of expert skill in installing and subsequently supervising their use are not generally available.

The main problems with such systems are reflected in the poor response, particularly in soils of low permeability, and the need either to monitor water levels manually or make use of the more complex Scanivalve and gas bubbling methods of determining water levels automatically. The latter generally requires a network of tubes to connect piezometers to a central control and recording unit.

The problems of response can be overcome to some extent by restricting the amount of groundwater flow required to achieve an equilization of the water level in the soil and the standpipe. This can be undertaken by extending the filter area of the open piezometer pipe and by restricting the volume of the standpipe within limits that allow self de-airing and the determination of the level in the pipe.

A new method of automatically reading and recording the pore pressure data using an acoustic signal has been developed. It is a low cost method and its flexibility allows it to be used for small groups (or possibly single) piezometers without the need for numerous fragile cables or pipes. The technique is based on a method of measurement which has been well tried and utilizes simple components. As a result it should provide a standard of reliability rarely achieved in other piezometer monitoring systems.

0885–6087/90/010035–09$05.00

*Received 7 June 1989*

However, trials with the prototype, in Indonesia, did highlight some operating problems which need to be overcome before this much needed technique is introduced into general use.

This paper describes the technique of measuring water levels with an acoustic system and how development of the present system could be extended to provide a simple and extremely reliable monitoring technique.

## PIEZOMETER INSTRUMENTATION

The determination of pore water pressures is an important requirement in terms of evaluating the effective shear strength properties of soil. The use of appropriate instrumentation for determining pore pressure changes is generally of considerable importance in landslide investigations. In other applications the need to monitor pore pressure, for example during and after the construction of dams, in order to monitor soil consolidation processes is of equal importance. Both applications may require pore pressures to be monitored over extended periods of time in conditions that are difficult and inaccessible so that instrumentation reliability is a prime requirement.

For such purposes there is a considerable range of instrumentation including open and closed hydraulic, pneumatic, and vibrating wire techniques. Hanna (1985) has described these devices and their relevance to different conditions, but emphasizes the need for experience and skill in installing and servicing such equipment if the results are to be at all meaningful. In many overseas countries such experience and skill are not to be found and even equipment servicing becomes a problem on the inaccessible and infrequently visited sites.

In such circumstances the aims are generally to use the simplest equipment on such sites. Whilst the open hydraulic piezometers generally meet such requirements, in that they are relatively easy to install and need little maintenance, their limitations in terms of response and the complexity of monitoring such devices leads to difficulties. The response depends upon the way the piezometers are installed and in soils with permeabilities of less than $1 \times 10^{-6}$ mm $s^{-1}$ the installation requires careful planning. However, there are guidelines available and Hvorslev (1951) provided a solution to the basic time lag for piezometers when flow rate ($q$) into the system equals:

$$q = F.k.H \tag{1}$$

where $F$ is the shape factor of the piezometer tip, $k$ is the soil permeability, and $H$ the head of groundwater. Therefore when the total volume for pore pressure equilization is $V = A.H$ the time lag can be represented as:

$$T = V/q = A.H/F.k.H. \tag{2}$$

Anderson and Kneale (1987) have determined responses for a range of typical bore hole diameters and filter sizes based on such response criteria. Therefore the use of relevant tables and response curves, such as those shown in Figure 1 need to be considered prior to the installation of hydraulic piezometers.

Such piezometers are normally monitored using an electronic dip probe to determine the depth to water in the standpipe. However this may be a demanding task when frequent readings are required and slopes are in a dangerous condition. For such conditions Brand (1983) has described a simple automatic method of determining the maximum level that standpipe water has risen to, using 'Halcrow Buckets'. These simply retain water when it reaches their level so that the maximum level is recorded. A more comprehensive monitoring and recording technique consists of a gas bubbling system. A narrow pipe carries air, at a constant pressure, to the bottom of the standpipe where it is release. The back pressure of air equates approximately to the hydrostatic head of water in the standpipe. However there are many limitations, described by Insley and McNichol (1982), relating to how this system can be used and also the complicated installation and calibration procedure described by Pope *et al.* (1982).

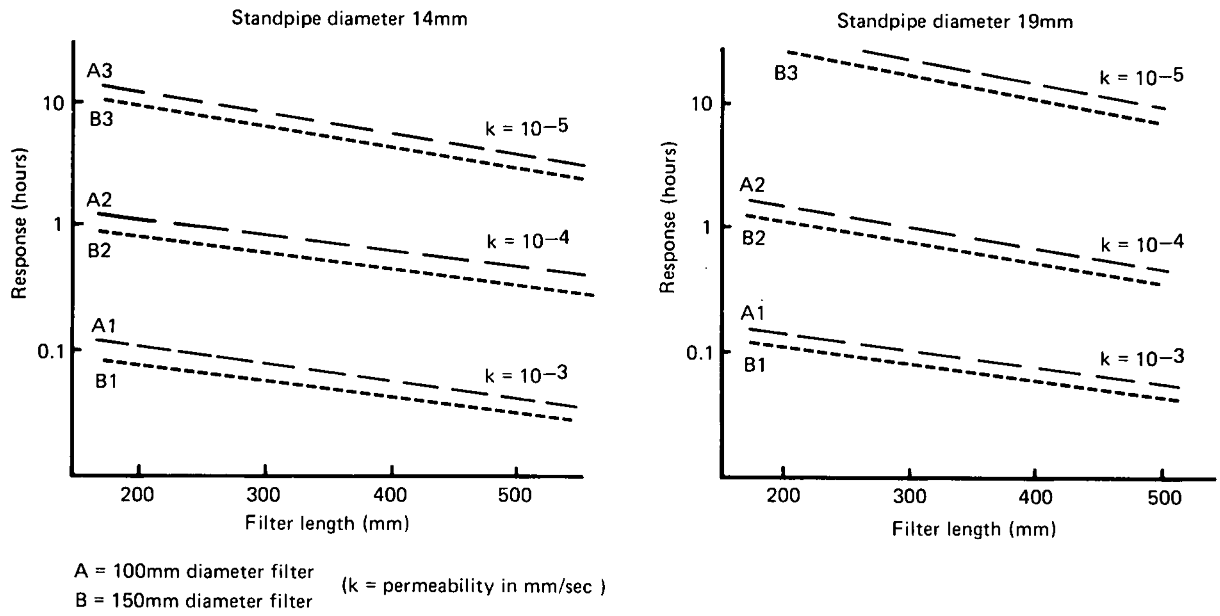


Figure 1. Time lag response curves for 90 per cent equalization calculated from the Hvorslev equation

## ACOUSTIC METHODS

The measurement of distance by the time taken for a pulse of high frequency sound to reach and return from a designated target has been in use for some time. Considerable development by the Polaroid Corporation has gone into the method for automatically focussing cameras. Similar transponders can be used to emit pulses of high frequency sound down an open standpipe and such signals are returned as echoes when they meet the water surface in the pipe. Electronics are capable of measuring the periods between the emitted signal and returned echo and equating it to accuracies of better than 5 mm over distances up to 10 m.

Acoustic transducers: Polaroid supply transducers, which have the advantage of long-term development, to be used for any purpose but apparently the metal coatings on such devices may be subject to fungal attack in certain tropical environments. As a consequence the ultrasonic acoustic transducer used in the piezometer monitoring system, made by Geotechnical Monitoring, is ceramic but is otherwise similar to other acoustic systems in that it contains the emitting and detecting devices in the same unit.

The chosen frequency for the sound signal depends on the characteristics of the transducer and, from the published specifications, Geotechnical Monitoring appear to have selected an extremely low frequency of 5 kHz. Other acoustic transducers work at multifrequencies, typically 60 kHz, 56 kHz, 52·5 kHz, and 49·1 kHz. These multifrequency systems are slightly less efficient but overcome many of the problems of signal attenuation found in single signal units.

Low frequency systems operate at longer wavelengths, up to 60 mm, in the case of the Geotechnical transducer, and in theory these longer wavelength distances set the limit of resolution. Consequently the frequency does not relate to either the claimed accuracy of 5 mm or even the accuracy of 8 mm achieved during trials in Indonesia. The lack of any audible tone, which a 5 kHz signal would provide, was also puzzling and left some doubt about the claimed signal frequency.

Normally the echo signal is attenuated by a factor of up to one million times before it is too weak to be detected by the receiving transducer. This can occur over a distance of about 10 m in the open which determines the maximum operating distance. The closest distance is dictated by the length of the emitted pulse and is about 1·6 ms or 270 mm.

Physical constraints: The velocity of sound in air at 20°C is 343·2 m $s^{-1}$. Figure 2 indicates the dependence of the velocity of sound on temperature and shows a change of 5 per cent within temperature extremes of 5 to 30 degrees Centigrade. In terms of distance this would correspond to a maximum error in readings of about half a metre when standpipe water levels are at a maximum depth of 9·95 m. In their design of a water level recorder Geotechnical Monitoring originally used thermal sensors in the transducer housing to compensate for temperature differences. Other factors including humidity, pressure, and frequency have a negligible influence on the velocity of sound waves and can be ignored.

A feature of the circuits used in all acoustic measuring systems is that gain control for the echo signal operates as a function of time, so that for longer distances increased amplification of the returning signal is available. Typical gain curves are described in a publication relating to camera transducers (Polaroid, 1984). This feature is an essential requirement because of signal strength over long distances, but imposes certain limitations in terms of standpipe design, when spurious signals reflect off joints and other protusions within such pipes.

The Geotechnical Monitoring Unit: Reference to the theoretical design aspects of this system has been made by Hanna (1985), Anderson and Kneale (1987), and Brand (1987). Figure 3 shows the general principles of the technique. It consists of acoustic transducers encapsulated in metal instrument boxes which are attached to the top of the piezometer standpipes. A six core coaxial cable supplies current and feeds signals back to a control and processing unit which has input for six transduers; see Figure 4. An internal microprocessor-controlled clock selects each transducer in turn at a pre-determined period in the range of 15 to 99 × 15 minute intervals and the microprocessor memory will store the readings from 99 such events for the six piezometer channels. Data may be read on the systems display or printed on a small portable printer. System power comes from a 6 volt sealed battery which is rechargable and lasts for several months.

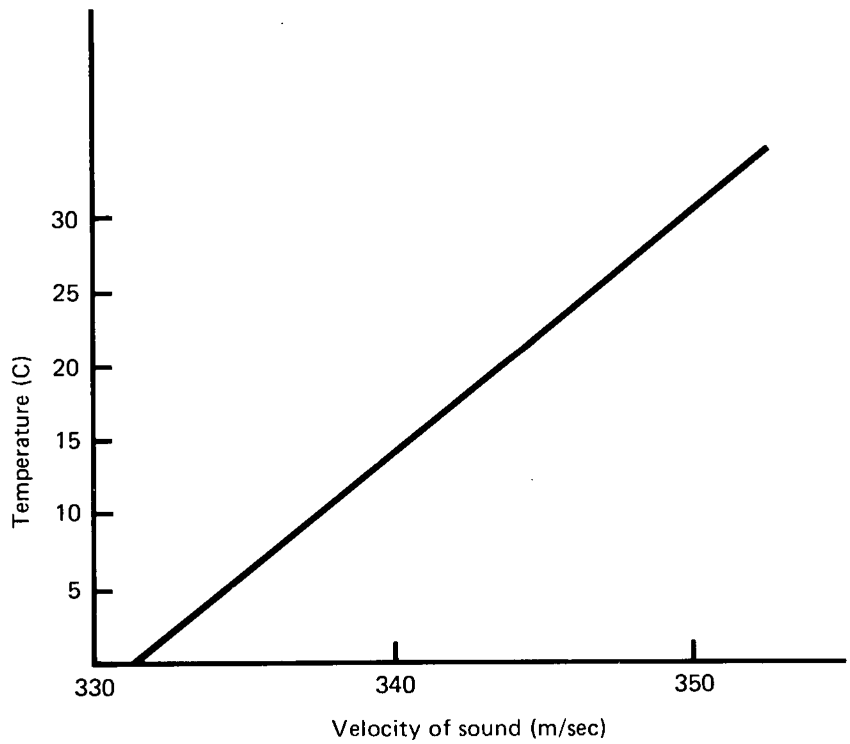


Figure 2. Variations in the velocity of sound with temperature

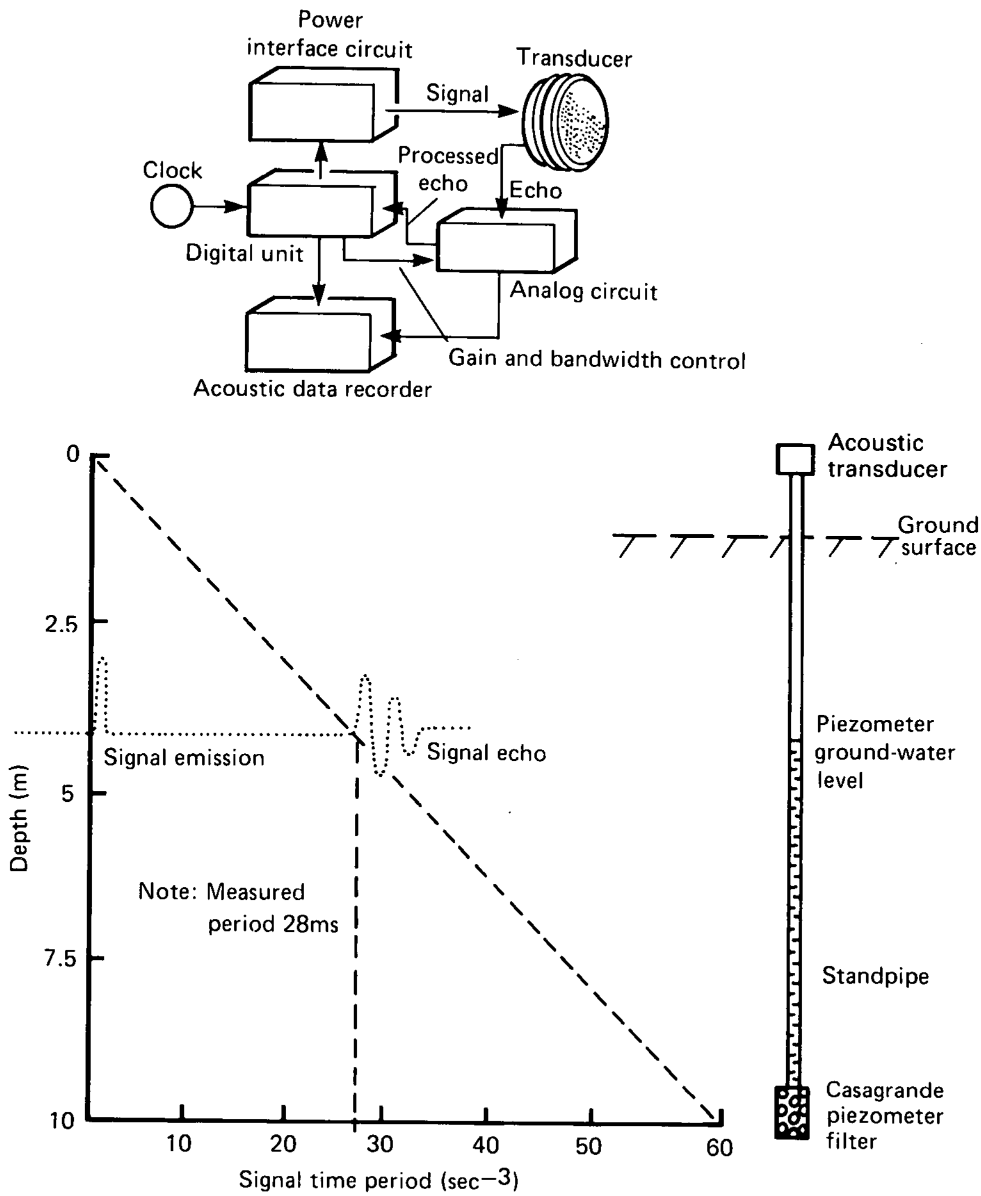


Figure 3. General details of the acoustic method of piezometer monitoring

## INSTALLATION AND RESULTS

In Indonesia the system was used, by the author, on an extensive landslide site on the Bandung to Cirebon road in West Java (Heath and Saroso, 1988): see Figure 5. Fifteen hydraulic piezometers were connected to 19 mm diameter plastic standpipes installed on the site and readings were made manually at three-day intervals using a dip probe. The acoustic technique was used to monitor six of the piezometers.

Installation: Generally any transducer system that relies on long lengths of cable or tubing to connect it to a processing and recording unit is liable to outside electrical or other interference distorting the data. The acoustic system would appear to be most vulnerable because of the low voltage signals involved. This concern was shared by the manufacturers who recommended that the transducers should be buried below

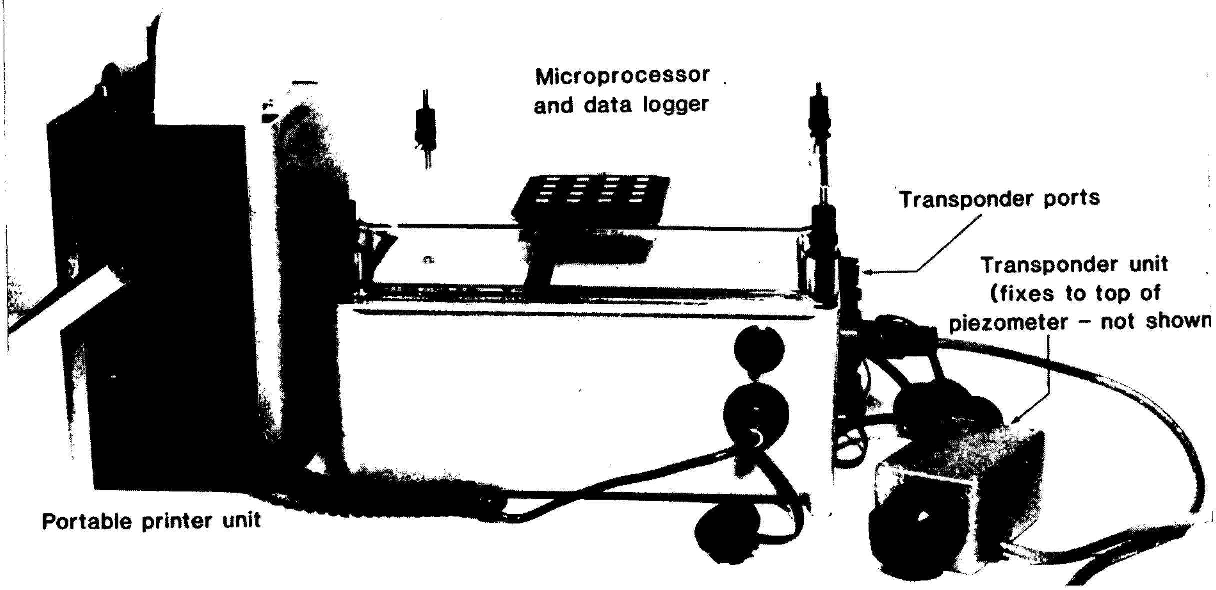


Figure 4. Acoustic monitoring unit manufactured by Geotechnical Monitoring Ltd.

the ground surface to reduce the effects of interference. This proved difficult as groundwater in the standpipes reached the ground surface after heavy rain. Nevertheless a trial was carried out with the transducers burried a few millimetres below the ground surface. This showed that not only was there a risk of the transducers flooding but when buried the metal transducer box collected rather than dissipated heat and reached temperatures of 60°C. The transducers were subsequently mounted 300 mm above the surface with no problems of interference. For the same reasons it was recommended that cable runs

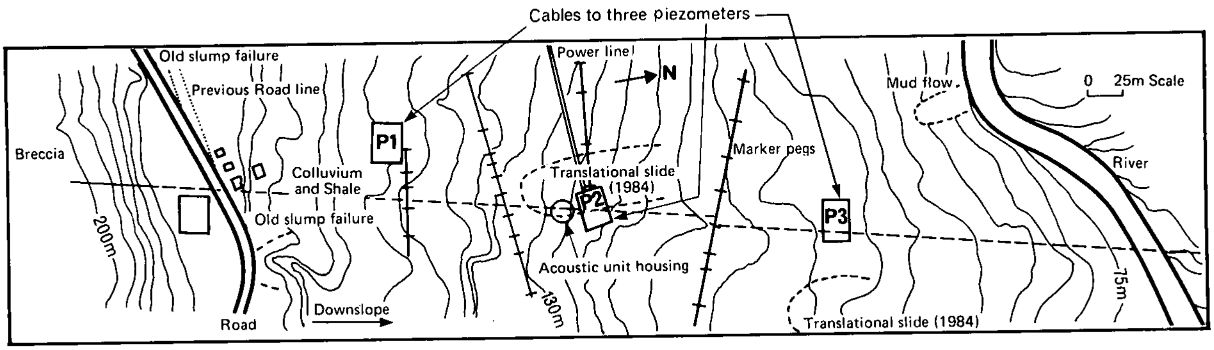


Figure 5. Map of Tomo site, Indonesia, where the acoustic monitoring unit (Figure 4) was installed

should not exceed 200 m and the cable should be screened coaxial. In fact the piezometers were in excess of 200 m apart and only non-coaxial cable could be obtained locally. Despite this and the presence of high voltage power lines directly over the instrumentation there was no indication of interference causing problems. However on the extensive slope damage to the cables connecting the piezometers to the recording unit was a constant problem and installations of overhead rather than buried cables were found to provide some solution.

Tests: Trials and development of the system continued for a period of one year during which time general reliability was a continuous problem. This was eventually traced to the standpipe profile and the requirements being more severe in terms of the materials used and its shape than had previously been assumed. The effects of temperature on the transducer units was an additional factor.

Standpipe design: The standpipes have been referred to as waveguides to the acoustic signal, but with a wavelength of 60 mm and a standpipe diameter of 19 mm this is impractical. Consequently there is a high loss of signal down the standpipes. It is also found that the consistency of the cross-sectional area of the standpipe was critical in terms of conducting the acoustic signal. When water in the form of condensation collects on joints or bends within the standpipe it reflects a proportion of the acoustic signal to the transducer. This is ignored unless the time-dependent gain control in the electronics reaches a high level prior to the return of the main echo signal. When this occurs spurious levels are recorded. Having dependence on both the amount of condensation and degree of gain control therefore made such events occur randomly. The solution was to line the open standpipes with a thin-walled close-jointed aluminium tube preventing the build up of condensation at any particular point. Aluminium also reflects rather than absorbs acoustic signals, as is the case with plastics, and therefore offers a better enclosure for such signals. Trials indicated that with aluminium the diameter of the standpipe tube could be reduced to 14 mm without affecting the performance of the acoustic transducer. Also because it reduces the amount of piezometer water needed to reach equalization, this would result in a two-fold gain in terms of piezometer response.

Transducer temperature: Measurements of the diurnal temperatures of the transducers mounted on the standpipes and soil temperatures at a depth of 300 mm provided the following results. Minimum and maximum operating temperatures encountered for the transducers were 10 to 60°C throughout the year. This range was reduced significantly by encapsulating the transducer boxes in expanded polystyrene. Prior to this a loss of data was attributed to the electronics cutting out completely at temperatures in excess of 60°C.

Temperature compensation: The need to compensate the signal for air temperature has been mentioned. However if outside air rather than standpipe temperatures are measured even greater errors can occur. The soil in Indonesia, at a depth of 300 mm, showed a temperature variation of only 2°C throughout the year although above this depth the temperature variations were considerable. The remarkable temperature consistency of many tropical soils, at depths below 300 mm, has been noted by numerous workers including Mohr (1944). Therefore temperature compensation appears to be unnecessary for tropical soils. The manufacturers had reached a similar conclusion after trials in Hong Kong, and temperature compensation was apparently fitted but not operating in the system used in Indonesia.

Landslide pore pressures: Certain data collected during the instrumentation trials are shown in Figure 6. This shows an increase in pore pressure associated with a period of rainfall during a stage when the slope started to fail. Whilst lengthy records of pore pressure were difficult to collect, due to the unreliability of the acoustic system for the reasons outlined, the versatility of the monitoring technique was of considerable value. The transducers could be transferred to different piezometer standpipes very quickly and the monitoring period adjusted to very short periods in order to evaluate the response of separate piezometer groups to peak rainfall on different parts of the slope. Finally the 'Acoustic' data unit was connected to a Cassela tipping bucket raingauge and programmed to respond only to high bucket pulses from the rainguage to the acoustic unit. These pulses are summed by the microprocessor of the acoustic unit, in terms of increments of rainfall, and at a preselected level the piezometers are monitored for a selected period of time. Such a procedure ensures that all data collected is related to periods when pore water pressure changes are likely.

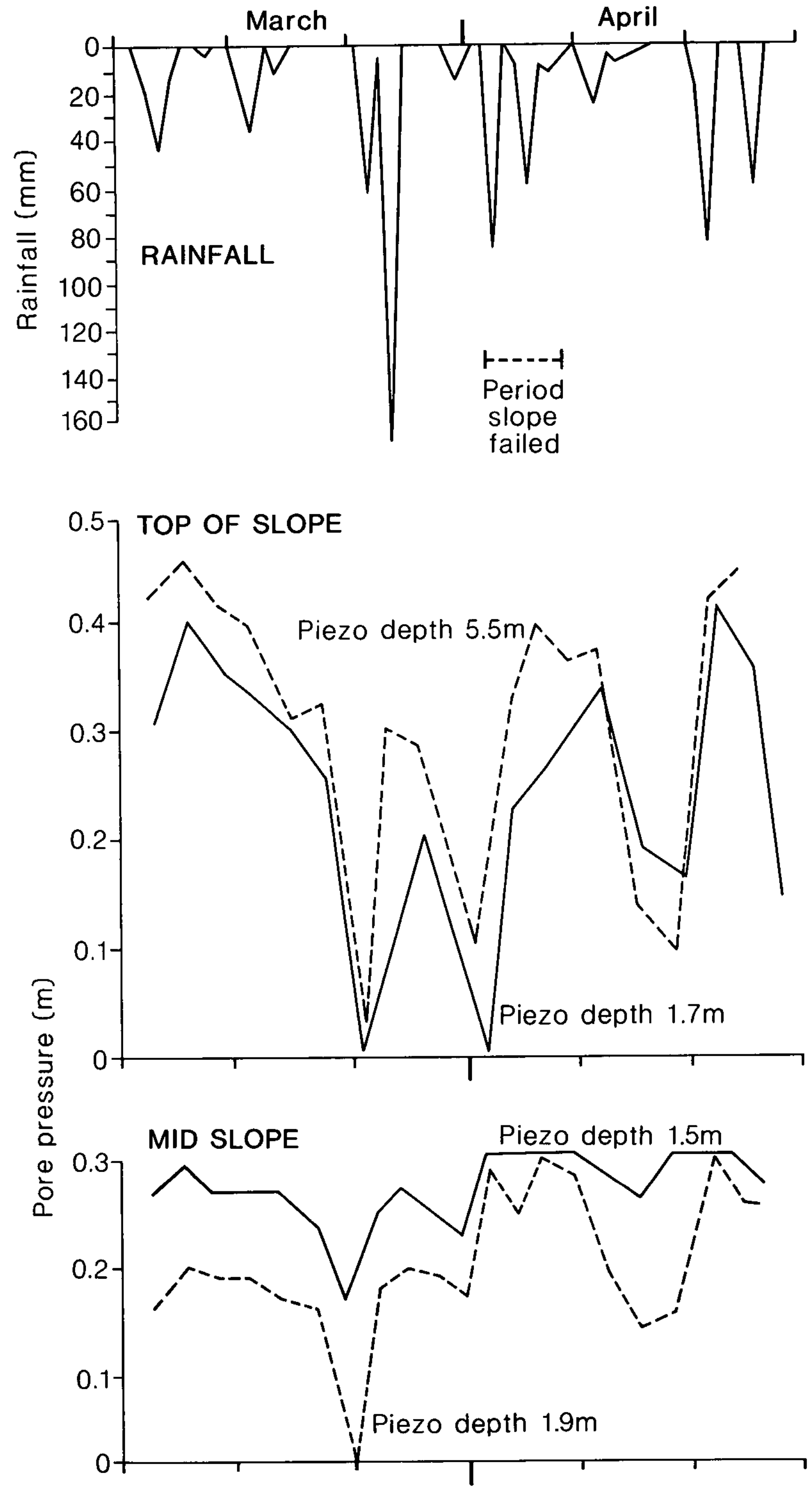


Figure 6. Pore pressure data recorded by the acoustic system for the tope of slope (location P1 figure 5) and mid slope (P2) sites in relation to site rainfall

## CONCLUSIONS

The acoustic method of measuring piezometer levels is simpler than existing methods, such as the gas bubbling technique, and it has proved easy to install on existing standpipe piezometers. There are also some advantages in cost and adaptability to large sites.

However, there has been relatively little use of the technique so far and almost no development in terms of its application in tropical countries. In this paper we sought to discuss improvements in the technique in the light of trials carried out in Indonesia.

The main modifications to the system need to be as follows:

1. The transducers should be enclosed in containers that insulate the components and prevent the build up of heat. In this respect the use of resins which encapsulate the electronic components needs to be avoided as these hold heat.
2. Only when there are temperature changes within the standpipe of more than 5°C, is there a need for temperature compensation and then measurements of temperature should be from within the standpipe and not the transducer housing.
3. Finally the standpipes should be made from a non-sound absorbing material or lined with a thin metal tube that has close fitting joints.

With these modifications the acoustic method appears to provide a reliable and accurate alternative to the more complex gas bubbling techniques for measuring piezometric levels.

ACKNOWLEDGEMENTS

The paper describes work that has been carried out as part of the research of the Overseas Unit (Head Mr. J. S. Yerrell) of the Transport and Road Research Laboratory and is published by permission of the Director. The author appreciates the assistance of the engineers of the Geotechnical Unit of the Indonesian Institute of Road Engineering in conducting this study.



## REFERENCES

Anderson, M.G. and Kneale, P.E. 1987. 'Instrumentation of pore water and soil suction', in Anderson, M.G. and Richards, K. S. (Eds), *Slope Stability, Geotechnical Engineering and Geomorphology.* John Wiley, Chichester, 77–112.

Brand, E.W. 1983. 'Field measurements in Hong Kong residual soils', *Int. Symp. on Field Measurements in Geomechanics*, Zurich, 1983, 639–648.

Brand, E.W. (1987). 'Some aspects of field measurements for slopes in residual soils', *Second Int. Symp. on Field Measurements in Geomechanics*, Kobe, Japan, 1–14.

Gibson, R.G. 1963. 'An analysis of system flexibility and its effect on time lags in pore pressure measurements', *Geotechnique*, **13**, 1–19.

Hanna, T.H. 1985. *Field Instrumentation in geotechnical Engineering*, Trans Tech Publications, Germany, 843 pp.

Heath, W. and Saroso, B.S. 1988. Natural slope problems related to roads in Java, Indonesia, *The 2nd Int. Conf. on Geomechanics in Tropical Soils*, Int. Soc. for Soil Mech. and Foundation Eng. Singapore, 259–266.

Hvorslev, M.J. 1951. 'Time lag and soil permeability in groundwater observations', *Bull. Waterways Experimental Station*, Vicksberg, No. 36.

Insley, H. and McNicholl, D. 1982. 'Groundwater monitoring of a soil slope in Hong Kong', *Proc. 7th SE Asian Geotech. Conf.*, McFeat-Smith, I. and Lumb, P. (Eds), Hong Kong Institute of Engineers. 63–75.

Mohr, E.C.J. 1944. *Soils of Equatorial Regions, with Special Reference to the Netherlands East Indies.* J. W. Edwards, Ann Arbor, U.S.A., 766, pp.

Polaroid 1984. *Ultrasonic Ranging System. P1834C*, Polaroid Corporation, Cambridge, Massachusetts, 24 pp.

Pope, R. G., Weeks, R. C., and Chipp, P. N. 1982. 'Automatic recording of Standpipe Piezometers, *Proc. 7th SE Asian Geotech. Conf.*, McFeat-Smith I. and Lumb, P. (Eds), Hong Kong Institute of Engineers, 77–89.