Instrumentation Systems for Selborne Cutting Stability Experiment

E. N. BROMHEAD, M. R. COOPER, AND D. J. PETLEY

A full-scale cutting slope failure experiment has been carried out at Selborne, Hampshire, England. The experiment used an extensive instrumentation system comprising inclinometer tubes, string inclinometers, piezometers, and surface wire extensometers. A high proportion of the instruments were connected to an electronic data gathering system that incorporated alarm-level outputs. Slope failure was successfully induced by pore-pressure recharge. The rationale of instrument selection and the performance of all the instrumentation systems in capturing comprehensive data are described.

The Selborne slope study is a collaborative investigation that draws together particular expertise from Southampton University, Warwick University, and Kingston Polytechnic. One face of a brickworks' clay pit was steepened to an overall slope of 1:2. An intensive instrumentation system was installed to monitor the behavior of the 9-m-high slope as it was brought to failure using pore-pressure recharge.

The general nature of the project is described, and a detailed account of the instrument systems adopted and their performance is given. The wider aspects of the experiment and a full presentation of the instrument results and observations on the nature and development of the failure are in the preparation stage. Following publication of the comprehensive paper, the research team intends to make all appropriate site data and instrument results available in a standard spreadsheet format. Construction details of individual instruments have not been included because they are not significantly different from standard systems. The measures adopted to provide multiple options for instrument-reading methods along with the measures to establish automatic alarm systems that warn of approaching failure are emphasized.

It should be noted that the instrumentation in this study was designed to record a single failure event and was not intended for routine performance monitoring. Therefore, it was essential that, whatever conditions prevailed at failure, the required readings could still be obtained. Several aspects of the system's design were influenced by this requirement.

STUDY SITE AND GROUND CONDITIONS

The Selborne slope study site is 4 km east of Selborne, near Alton in Hampshire, England, as shown in Figure 1. Its National Grid reference is SU-768342. The actual study area occupies about a quarter of the west face of the clay pit at the Honey Lane Brickworks of the Selborne Brick and Tile Company.

A feasibility study conducted in 1984-1985 showed the ground profile of the slope to be composed of about 1.5 m of soliflucted slightly gravelly clay over 6 m of slightly weathered gault clay. Unweathered gault clay made up the lowest 1 to 2 m and extended at least another 5 m below the pit-base level, where a 1- to 2-m thick basal layer separated it from a thin transition layer to the lower greensand. This ground profile sequence has been confirmed by further exploratory borings, which were conducted as part of the present study.

GEOTECHNICAL DATA

Laboratory tests on 75-mm-dia. triaxial and 60-mm shearbox specimens gave the effective stress shear strength parameters samples obtained by HWF rotary coring, as shown in Table 1 (*1*).

The preexisting groundwater regime, established from prolonged standpipe observations during the feasibility study, can be characterized as being underdrained to the lower greensand with a downward hydraulic gradient of about 0.75 and a pore pressure of 0 at ground level.

GENERAL DESCRIPTION AND RATIONALE

The instrumentation design evolved in response to the three main objectives of the experiment:

1. It should provide a very detailed record of the condition of the slope at all stages of the experiment.
2. It should give useful information on prefailure strains and displacements as part of a study of progressive failure.
3. The system should contain sufficient redundancy and duplication to produce results up to, and if possible beyond, the final failure event, even with a high level of component failure.

The instrument layout plan shown in Figure 2 was developed in response to these requirements.

The study area is 25 m wide and the cut slope is 9 m high. The instrumented area extends for 18 m back from the crest of the slope and 6 m beyond the toe. The resulting 1,050 m^2 of plan area contains:

- 30 pneumatic piezometers,
- 30 vibrating wire piezometers,

E. N. Bromhead, School of Engineering, Kingston Polytechnic, Canbury Park Road, Kingston-on-Thames, Surrey, England. M. R. Cooper, Department of Civil Engineering, University of Southampton, Southampton, Hants, England SO9 5NH. D. J. Petley, Department of Engineering, University of Warwick, Coventry, England.

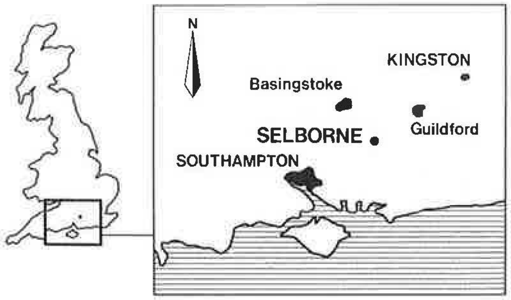

FIGURE 1 Site location.

TABLE 1 EFFECTIVE STRESS SHEAR STRENGTH PARAMETERS

Soil type	c'_{peak} kN/m²	ϕ'_{peak}	$\phi'_{residual}$ ($c'_r=0$)
Soliflucted Layer	5	20°	13°
Upper Weathered Gault	10	22-24°	13°
Lower Weathered Gault	15	22-25°	14°
Unweathered Gault	20-25	23-26°	15°

- 12 inclinometer access tubes,
- 2 in-place inclinometer strings (total 20 monitoring elements),
- 10 wire extensometers (on 2 cradles), and
- 20 recharge wells.

On the average, the system provides one monitoring instrument for each 8.6 m² of plan area.

This level of instrumentation is not common. The size of most natural slides subjected to detailed study generally leads to sparse coverage. Devin et al. (*2*) present a table of inclinometer usage at 13 landslide sites. The highest intensity of coverage noted was equivalent to 8 access tubes/hectare, or about 1/30 the intensity at Selborne (without considering the string inclinometers). Previous investigations have used special study sites to undertake prolonged monitoring but have rarely been able to instrument so intensively. The excellent study at Saxon Pit (*3*) used five piezometers, three magnet extensometers, five manually read extensometers, and three deep leveling points. Surface movement points and photogrammetry completed the coverage on a 200-m-long study face.

Perhaps the most intensive instrumentation use in Geotechnical Engineering is associated with earthfill dams. The instrumentation used to monitor displacement of the Kielder Dam is described by Millmore and McNicol (*4*). The 1140-m-long, 52-m-high embankment contained 11 inclinometers, 29 extensometers, 62 settlement devices, and used 185 piezometers of various types. On a surface area basis this represents about 1/100 the Selborne intensity.

The decision to install the large number of piezometers was a direct consequence of the proposed recharge method of inducing failure and would produce an entirely new pore-pressure regime requiring precise definition.

The inclinometer coverage was designed to give detailed displacement readings throughout the body of the slope and

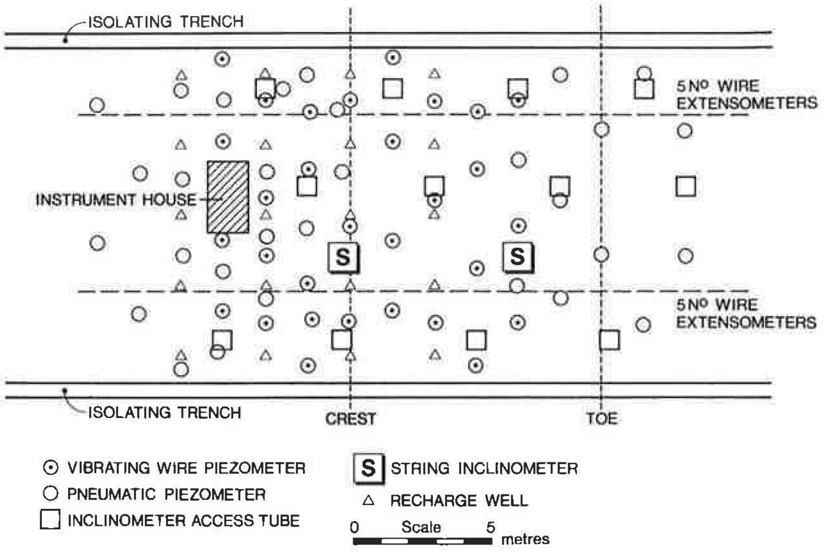

FIGURE 2 Instrument layout plan.

through the entire prefailure period. A standard manually read inclinometer probe was used to monitor displacements in 12 access tubes, which gave good spatial coverage. The string inclinometers were intended to give continuously logged movement-depth profiles at two key locations.

Rates of movement and strains within the slip mass were also of interest, and it was decided that useful information could be obtained using continuously logged surface-mounted wire extensometers.

The vibrating wire piezometers, string inclinometers, and wire extensometers were all continuously logged. Great care was taken in designing a system that had considerable flexibility in reading procedures. It was essential that readings could be taken even if some component of the data logging system were to fail during a critical period. Alarm systems were required to warn on- and off-site researchers of the possibility of impending failure.

The whole instrumentation system was designed with strict cost constraints. The overall study had a maximum possible funding limit of £200,000, and after all other costs were determined the amount available for instrumentation was less than £80,000. Both the total number of instruments and the balance of the complete installation were primarily determined by the stringent requirement that this overall figure (in 1987 prices) could not be exceeded.

PIEZOMETERS

Two types of piezometer were used to give the maximum coverage of pore-pressure measurement and recharge control within the established cost limits. A cross section showing the arrangement of the piezometer installations is shown in Figure 3*a*.

The 30 vibrating wire piezometers were concentrated in the zone below the slope face and the front part of the crest. This distribution was designed to cover the range of expected positions of the eventual failure surface. Vibrating wire piezometers can be continuously monitored electronically. In this case they were intended to provide frequent pore-pressure readings in the critical zone up to and during the failure event. It was also hoped that the piezometers above the eventual failure surface would continue to monitor postfailure pore-pressures.

The 30 pneumatic piezometers were installed in the areas at the toe. They were farther back from the crest and at depth,

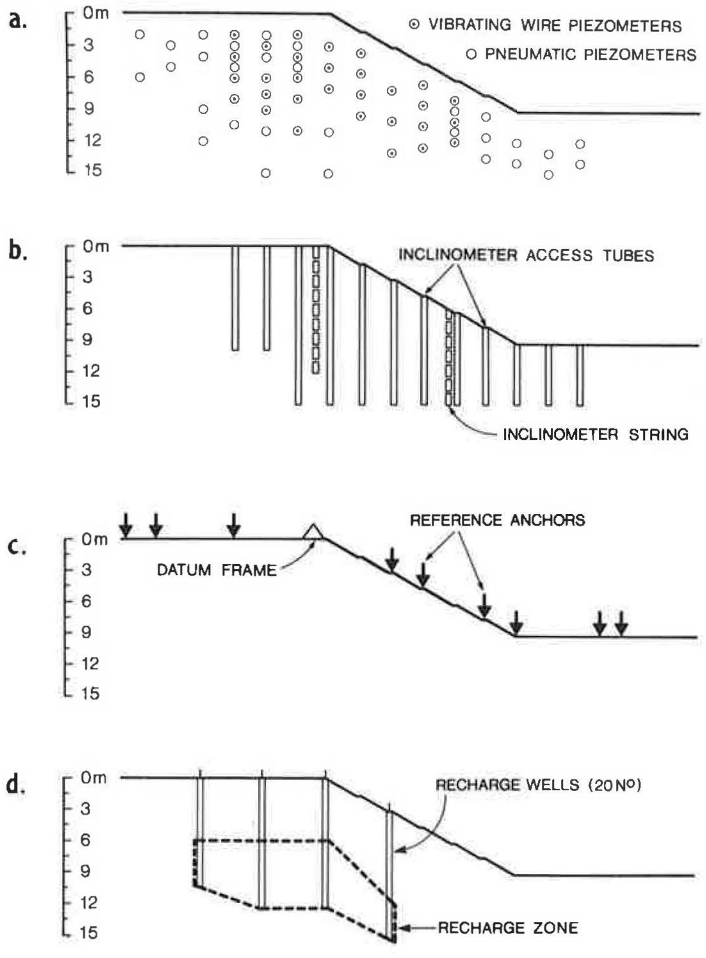

FIGURE 3 Instrument layout sections: *a*, piezometers; *b*, inclinometers; *c*, extensometers; *d*, recharge system.

areas where it was thought the failure would be less critical. Their main purposes were to extend the area over which pore pressure information would be available and to set the detail from the vibrating wire instruments in a wider framework. Although this type of piezometer cannot be read electronically, it does have a considerable cost advantage over the vibrating wire type (in this case approximately a fifth the cost). By using this cheaper system in areas thought to be less important, a considerable cost saving was produced, and money could then be diverted to ensure that critical areas were well served with continuously logged instruments.

The two systems were overlapped at the toe and at the crest to enable their outputs to be cross-checked and if necessary cross-calibrated. The filter dimensions and grouting up arrangements were the same for both systems. In all cases a 200-mm filter length was formed at the base of the installation borehole. The filter was sealed above with bentonite pellets and the hole filled to ground level with bentonite-cement grout. The short filter length was chosen to give a precise location for the measured pore pressure.

The pneumatic piezometer layout in the toe area was also intended to model a typical low-cost monitoring arrangement. It was suggested in preplanning discussions that the onset of instability in this passive zone might be preceded by noticeable changes in pore pressure. Pneumatic piezometers represented a low-cost means of monitoring these changes.

INCLINOMETERS

As with the piezometers, two different types of instruments were chosen to give a balance between detail and cost. The positions of the inclinometer installations are shown in cross section in Figure 3*b*. Twelve standard plastic inclinometer access tubes were installed to give broad, manually obtained coverage of lateral displacements. The main functions of this part of the system were to give an indication of the way in which the early stages of the failure developed and, by virtue of their greater sensitivity, to give an early indication of possible failure.

Continuous electronic monitoring of displacements within the slope was achieved by means of two in-place inclinometer string installations, one at the crest of the slope and the other at the lower-third position. Both installations were on the same near-central cross section of the slope. The string at the crest was made up of 12 independent inclinometer sensors on 1-m gauge lengths between 1 and 13 m deep, with each sensor being separately and continuously monitored. The lower string comprised 8 similarly arranged sensors between ground level and 8-m deep. The string inclinometers were the most expensive single items in the system but fulfilled three important functions:

1. Continuous monitoring of displacements within the slope. The shortest possible reading cycle for the manually read inclinometers could yield only two or three complete sets of readings per week, if other systems were not to be neglected. This would be insufficient to yield useful information on actual variations in rates of movement.
2. Taking of continued readings through the failure event. Manually read inclinometers require access at ground level and it was not intended to allow personnel on the slope if rapid failure was indicated. Conventional access tubes, at quite modest distortions, do not allow free passage of the reading torpedo. The string inclinometers overcome both of these shortcomings because they are remotely monitored and because they continue to function at much greater distortions.
3. Automatic alarm triggering. By providing continuous monitoring of displacements the string inclinometers allowed the provision of an automatic alarm system, which warned of any sudden increase in the rate of displacement on the slope.

WIRE EXTENSOMETERS

Surface strains on the slipping mass and larger relative movements between the slip mass and the adjacent ground were monitored by 10 wire extensometers, arranged in two groups of 5. Each group was based on a datum frame, anchored at the crest of the slope with four minipiles. Each datum frame carried five gearboxes, and each gearbox was driven by a sprocket carrying a chain connected to the free end of the invar extensometer wire. The positions of the datum frames and wire anchorage points are shown in Figure 3*c*. Relative movements of the anchor points and the datum frame are thus converted into rotations that are detected and measured within the gearboxes, which also contain the signal conditioning circuitry. By selecting the gearing at the datum frame, it was possible to fix the required range and sensitivity of each extensometer. In the event all the extensometers, irrespective of range, were found to give output to a precision of 1 mm, which was thought to be the maximum achievable stability of the cradle/wire/anchor system.

The wire extensometers were continuously monitored electronically and were incorporated into the automatic alarm system. It was intended that they would provide a continuous record of the amounts and rates of slip-mass movement throughout the final failure event and yield peak velocity components of the slip mass.

RECHARGE WELLS

The recharge wells comprise simple standpipes in long filter zones. The extent of the zones for each row of wells is shown in Figure 3*d*.

The recharge-well tubes were also to serve a secondary function as simple slip surface position indicators. However, as it became necessary to provide a closed, surcharged recharge system the slip indicator function had to be abandoned.

INSTALLATION

The instruments were installed in August–September 1987. Each subsurface instrument was placed in its own 150-mm-diameter hole, which was drilled by means of a continuous-flight auger technique that gave precise control over drilling depth. Instruments under the slope face were installed from temporary benches cut as part of the formation of the eventual slope. Drilling was therefore synchronous with the major earthworks.

READING SYSTEM

The reading system used at Selborne was of particular interest in two respects. First, a comparatively high proportion of instruments were connected to the continuous monitoring system and the inclusion of inclinometer and wire extensometer output in the data logging system is unusual. Second, the failsafes incorporated into the system are considered to be unusually thorough. It must be appreciated that in this application the function of the instrumentation was not just to warn of possible failure, nor simply to monitor the compliance of an as-built structure with design assumptions. The system had to record all of the details of a major one-off event, which could not be predicted in time or position to an accuracy that would permit reliable preprogramming.

The electronic reading system comprised two parallel subsystems. Each subsystem carried half of the vibrating wire output and half of the analog output from the string inclinometers and wire extensometers. Each subsystem was made up of the following:

- All the instruments were connected to a switch card–multiplexor, which handled all of the electronic switching during scanning and also incorporated EEPROMs to refine input signals and to give fully reduced and corrected output in engineering units directly.
- The switch cards–multiplexors were controlled by programmable data loggers, with each containing approximately 170 kb of internal memory (enough for about 86,000 readings). In normal operation either the data loggers could output continuously to printers and personal computers, or the readings could be extracted and transferred using independent interrogators. The latter was the preferred mode of operation onsite.

The data loggers could be programmed to a variety of logging strategies. Scan rates and intervals, for instance, could be varied according to the rate of change being recorded in any reading. More routinely, a threshold mode could be used where readings are taken at a scan rate of 1 set/min. but only recorded if different from the previously stored value by a preset threshold amount. The program also allowed the use of alarm levels as described in the next section.

Considerable attention was given to designing in alternative reading paths to cover any component failure. The first safeguard was the cross division between the two data loggers. The failure of one data logger would still leave half of the instruments of each type on-line. The following reading hierarchy was established:

1. Normal operation with automatic output to printers and automatic or interrogator transfer to floppy disk storage.
2. In the event of a computer failure, output would still be recorded on the printers and held in the internal memory to be accessed later.
3. In the event of failure of the data logger, the switch cards–multiplexors could still be accessed directly by manual readout units, each with internal memory sufficient to store 500 readings. This system required that a plug-in connection be made in the instrument house. As circumstances might have led to this house being positioned within the failure zone, special long fly leads were ordered to enable the manual readout units to be operated at a safe distance. They did not prove to be necessary.
4. In the extremely unlikely event of a switch card–multiplexor failing at a critical moment, the manual readout units could be connected directly to signal cable ends, but this would depend on the rate and position of failure and the degree of risk involved. Fortunately this option did not have to be attempted.

ALARM SYSTEMS

Special facilities incorporated within the programmable data loggers allowed different levels of alarm event to be recognized and acted on. Alarm levels were to be set at absolute values, fixed and modified for each instrument.

Approximately half of the instruments were programmed to trigger a first-level alarm in the instrument house and the remainder were set at a much higher level (selected as a possible indicator of incipient failure). If this level were reached, a set of contacts would close to activate an auto-dialer, which in turn would send a prerecorded message to key telephone numbers. On-site audible alarms and floodlighting were also to be triggered at this higher level.

PERFORMANCE

The performance of the complete instrumentation system was most satisfactory in that the failure event was recorded in the full level of detail hoped for and expected. In some respects, such as durability and displacement compliance, the performance was generally well above expectations. Many points of interest concerning the performance are still coming to light as the data produced are analysed. Among the observations to date, the following are highlighted:

1. Of the 89 independent instruments employed, 86 were still operative at the onset of failure, a reliability for the 2-year on-site period of 98.9 percent a year. One of the three lost instruments was damaged by site operations and the other two were either transducer or connection failures. Although still operative, the pneumatic piezometers recording negative pressures had become very difficult to keep on-line and were disrupted very early in the development of the failure. This very high retention rate was mainly due to two factors. First, this dedicated research site could be carefully managed and suffered none of the damaging interference often experienced when instrumenting working construction sites. The nature of the site, with fewer commercial pressures, also permitted very careful and high-quality initial installation. Second, the site itself was on remote private land and well protected from vandalism by the reputation of the site owner.
2. Three piezometers recovered during postfailure excavations were returned to the manufacturers (Geotechnical Instruments, Ltd.) for recalibration. The calibration results are presented in Table 2; they show remarkable stability over a 22-month period of burial. The units of pressure reported by the manufacturers are also retained for clarity.

TABLE 2 POSTFAILURE PIEZOMETER CALIBRATIONS AFTER 22 MONTHS OF BURIAL

Instrument Type, Number	Applied Pressure psi	Readout psi
Pneumatic, PP1.3	0.0	0.0
	0.3	0.3
	1.0	1.0
	15.1	15.2
	35.0	35.3
	50.0	50.0
Vibrating Wire, S/N 034	0.0	0.0
	10.0	10.0
	20.0	20.02
	30.0	30.10
	40.0	40.26
	50.0	50.34
Vibrating Wire, S/N 010	0.0	0.0
	10.0	10.01
	20.0	20.06
	30.0	30.14
	40.0	40.19
	50.0	50.25

3. Initial piezometer equalization times were between 1 and 3 months. This order of magnitude is longer than would be predicted by using the simple theory for pore-pressure equalization following stress disturbance around a driven pile (*5*). Soderberg's analysis, admitted to becoming inaccurate at high degrees of equalization, would predict 95 percent pore-pressure equalization of between $30.r^2/C_h$ and $60.r^2/C_h$. Falling-head permeability tests carried out in standpipes during the feasibility study had given (horizontal?) permeabilities near 10^{-9} m/sec, suggesting a C_h value of about 0.04 m²/day. The predicted 95 percent equalization time would therefore be 8 days. The true equalization rates are clearly shown in Figure 4, where the stabilization of a newly installed piezometer is compared with readings of an adjacent instrument that had been in place for 1 year. The slow equalization, though of wider interest, was not of significance for the project because all the piezometers were in place well before the final critical phase.

4. System response times were not considered to be a problem. Both types of piezometer contained a small-volume closed cavity that gave very low system compressibility, typically less than 10^{-3} cm³/F.S.D. for the vibrating wire instruments. It has long been accepted that such installations will have response times on the order of a few seconds (*6,7*). The response behavior, related to known driving events, is shown in Figure 5.

5. Groups of piezometers were consistent within themselves in the pattern of their response. Figure 6 shows the response records of three piezometers at the same level, but at different distances from the recharge wells.

6. Negative pore pressures were recorded at the toe of the slope. These were probably the result of the stress reduction caused by substantial excavations in this area. This effect

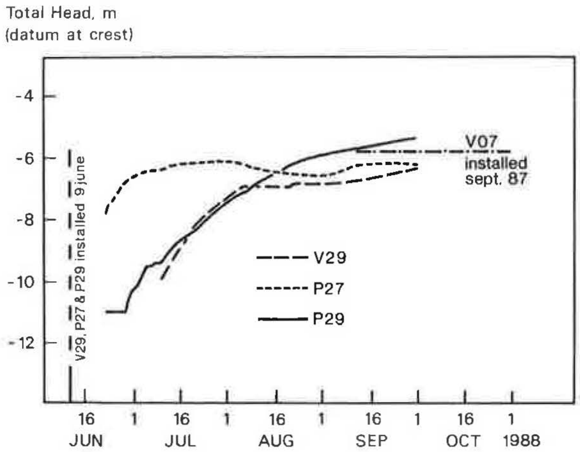

FIGURE 4 **Typical piezometer equalization curves.**

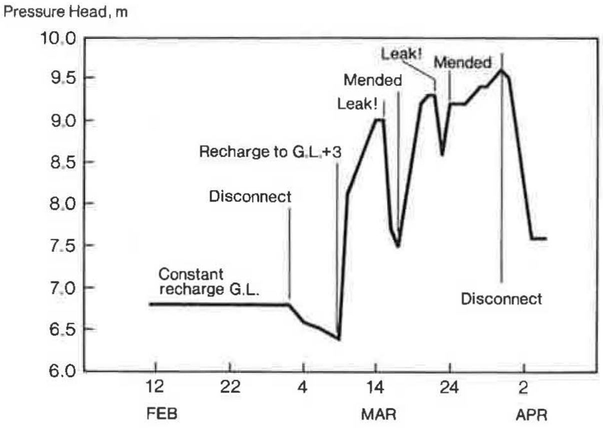

FIGURE 5 **Typical piezometer responses to driving events (Piezometer P24, GL = 8 m).**

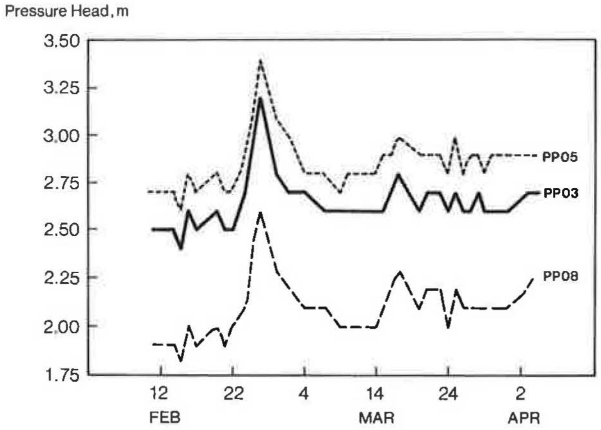

FIGURE 6 **Adjacent piezometer responses (GL = 5 m).**

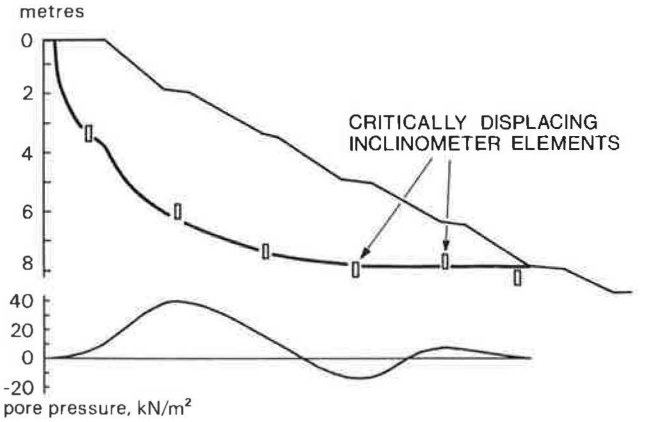

FIGURE 7 **Interpolated slip-surface section on centerline.**

is described by Bishop and Bjerrum, (*8*) and has subsequently been confirmed by a number of field studies (*9*). The pneumatic piezometers are not well suited to measuring negative pore pressures in low-permeability soils, and special procedures were devised that will be described in detail elsewhere.

7. The inclinometer records faithfully recorded the position of the slip surface as it was eventually exposed during the postfailure excavations. The interpolated shape of this surface at the center of the study area is shown on Figure 7.

8. The inclinometer torpedo calibration remained constant, although some maintenance of wheel bearings was necessary. Had a longer monitoring period been required, replacement of the running wheels would have been essential. By the end of the project, the torpedo had been used for readings equivalent to 17 km of travel.

The stability of the calibration was confirmed by observations of deflections over the very long fixed lengths below the movement zone, as well as the usual wall-mounted calibration frame. In all access tube inclinometers, the recorded cumulative deflection over the fixed length (up to 8-m long) was less than 2 mm over a period of more than 500 days, as shown in Figure 8.

9. Three inclinometer access tubes were carefully exposed during postfailure excavations. In each case, the deformed profile of the tube was aligned very closely along the exposed failure surface and had been pulled down out of its grout surround within the moving mass and laid flat along the failure surface. Figure 9 shows the relative positions of the distorted tube, slip plane, and empty grout column for an access tube that underwent about 4 m of relative displacement.

10. The string inclinometers and wire extensometers performed their special functions very well. Both types of instrument provided continuous displacement-time plots of a type that could not have been obtained with manually read instruments, and both continued to function at very large displacements. Wire extensometers continuously recorded relative movements up to 150 mm at 1-min intervals over 3 hr, and the string inclinometers were still functioning with angular distortions between successive 1-m gauge lengths of up to 42 degrees. A 0.5-m torpedo passed through a maximum angular distortion of 35 degrees, but it did so at great risk to the instrument. At greater distortion, the lower part of the access tube became inaccessible, whereas the lower parts of the inclinometer strings remained operative even after large distortions had developed higher up.

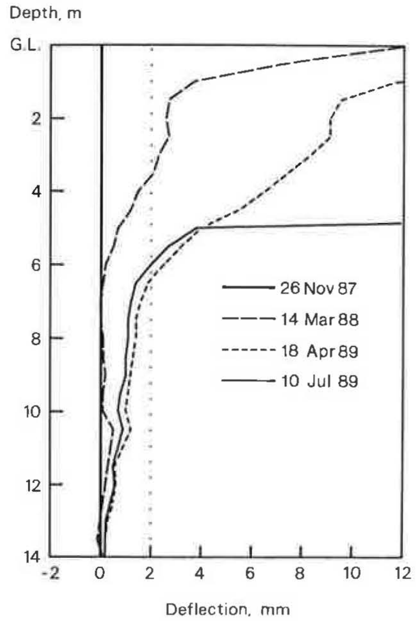

FIGURE 8 **Typical inclinometer fixed-length behavior (Inclinometer 06).**

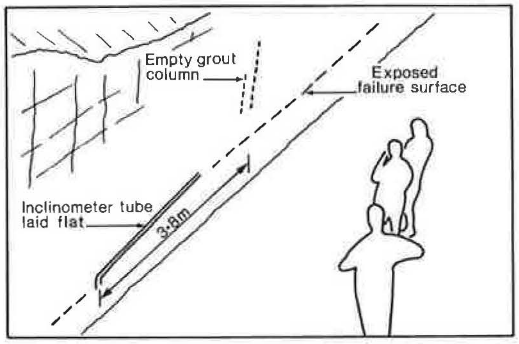

FIGURE 9 **Inclinometer tubing compliance.**

11. During the slope failure, the behavior of the connections to the pneumatic piezometers was very different from that of the vibrating wire connections. The very extensible tubing of the pneumatic instruments deformed and easily stretched to accommodate some very large movements. The vibrating wire signal leads were much less compliant, and many snapped very early in the failure event.

12. The full hierarchy of reading options was not required, although it was proved in practice routines.

13. The reading strategy adopted was the threshold change approach, which scans at 1-min intervals; values are only recorded if one of the readings is significantly altered. Instrument flutter frequently exceeded the very tight threshold limits that were set and about 60 percent of the scans resulted in recorded readings. By excluding the less-stable instruments or setting wider threshold tolerances, this percentage could have been greatly reduced.

14. The first alarm level triggered very quickly as the failure developed, and the majority of failure data was obtained from the simple 1-min interval reading strategy on all channels. The enormous quantity of data generated has caused some problems in subsequent data processing. This is acceptable in a research application for which detail and duplication are paramount in the design philosophy, but it would cause problems in the more usual monitoring applications for which delay in accessing data cannot be countenanced.

CONCLUSION

The instrumentation systems used for the Selborne cutting stability experiment performed well and have provided a detailed record of a unique experiment. The few shortcomings identified during the data processing are associated more with site pressures and manpower shortages (giving less than planned for reading frequencies on some instruments at some times) and financial constraints (a third string inclinometer would have been extremely useful) than with inadequate instrument performance. There is little doubt that instrument systems exist to cover all site-monitoring requirements for an exercise such as the Selborne experiment. The main difficulties to be overcome are in planning a successful layout for the instruments, in planning an efficient and workable reading schedule in which manual reading is employed, and in planning a data access system that allows rapid, user-friendly access to electronically logged data.

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