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Instrumentation for slope stability - experience from an urban area

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Abstract

This paper describes the monitoring of several existing landslides in an urban area near Wollongong in the state of New South Wales, Australia. A brief overview of topography and geology is given and reference is made to the types of slope movement, processes and causal factors. Often the slope movements are extremely slow and imperceptible to the eye, and catastrophic failures are quite infrequent. However, cumulative movements at these slower rates do, over time, cause considerable distress to structures and disrupt residential areas and transport routes. Inclinometers and piezometers have been installed at a number of locations and monitoring of these has been very useful. The performance of instrumentation at different sites is discussed in relation to the monitoring of slope movements and pore pressures. Interval rates of inclinometer shear displacement have been compared with various periods of cumulative rainfall to assess the relationships.

Keywords

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Instrumentation for Slope Stability - Experience from an Urban Area

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ABSTRACT: This paper describes the monitoring of several existing landslides in an urban area near Wollongong in the state of New South Wales, Australia. A brief overview of topography and geology is given and reference is made to the types of slope movement, processes and causal factors. Often the slope movements are extremely slow and imperceptible to the eye, and catastrophic failures are quite infrequent. However, cumulative movements at these slower rates do, over time, cause considerable distress to structures and disrupt residential areas and transport routes. Inclinometers and piezometers have been installed at a number of locations and monitoring of these has been very useful. The performance of instrumentation at different sites is discussed in relation to the monitoring of slope movements and pore pressures. Interval rates of inclinometer shear displacement have been compared with various periods of cumulative rainfall to assess the relationships.

KEYWORDS: landslides, subsurface shear movement, monitoring, inclinometer, piezometer, velocity of movement, pore water pressure

Introduction

Monitoring and observation of slopes is an essential part of the assessment of slope stability. Observational approaches facilitate the assessment of hazard and risk associated with slope movement and landsliding processes. The most important measurements associated with foundation investigations, natural slopes and earth dams concern pore water pressures, settlements, lateral movements and shear movements. Amongst these, the two most important for slope stability and landslide monitoring are subsurface shear movement and pore water pressures.

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In geotechnical engineering applications, instrumentation, observation and monitoring may serve several purposes. For some projects it is necessary to check important assumptions concerning the basic geotechnical/geological models used for analysis and interpretation. In slope stability problems it may be necessary to verify the shape and location of the slip surfaces and the character of the movement, e.g., rotational or translational. Furthermore, it may be necessary to check the assumptions made in analysis and design about the magnitude of subsurface pore water pressures and their spatial and temporal variability.

Apart from checking design assumptions, continued monitoring can be a useful tool for updating of assessments concerning stability, hazard and risk. In addition, continued monitoring is essential for assessing the effectiveness of remedial measures after their installation and/or construction.

This paper is concerned with monitoring of geotechnical instrumentation in sloping urban terrains. Subsurface shear movements were monitored at a number of existing inclinometer installations near the city of Wollongong, on the south coast of New South Wales, Australia. Subsurface shear movement was compared to antecedent rainfall patterns in a number of instances. Water levels in open standpipes were measured at several sites. In some instances subsurface pore pressures were also measured more accurately using vibrating wire piezometer installations. However, the emphasis during the research was on subsurface shear movements and their relationship to rainfall.

The Wollongong Area

The City of Wollongong, including the northern suburbs, is a major urban centre on the south coast of NSW with a population of approximately 200,000 people. A total of 328 past and present sites of land instability are known in an 87km^2 area within the Wollongong City Council local government area. At least 60 houses have been damaged and a further 29 houses have been destroyed since the turn of the century by land instability. As well as affecting suburban areas, landslides affect the major road and rail transport routes which link Wollongong to Sydney and other regional centres (Shellshear 1890, Hanlon 1958, Bowman 1972 and Pitsis 1992).

Wollongong is situated on the coast approximately 80km south of Sydney (Fig. 1). The local government area includes a highland plateau area to the west of the escarpment topped by a near vertical sandstone cliff line which grades down to the east into terraced lower slopes. The eastern and southern margins of the district comprise a narrow coastal plain which is flanked on the east by the Pacific Ocean.

Geological Setting

The Sydney Basin comprises a basin sequence of dominantly sedimentary rocks extending in age from approximately Middle Permian to at least Middle Triassic. The study area lies on the south eastern margin of the Sydney Basin (Fig. 1).

The geological bedrock sequence of the Illawarra district is essentially flat lying with a low angle dip, generally less than five degrees, towards the northwest. This gentle northwesterly dip is a result of the relative position of the district on the southeastern flanks of the Sydney Basin. The northwesterly dip is superimposed with relatively minor syn-depositional and post-depositional structuring (folding and faulting). Normal faulting within the Illawarra area is common, although the fault throws infrequently exceed 5 metres. The structural geology of Wollongong, Kiama and Robertson, mapped on 1:50000 sheets, has been discussed in detail in Bowman (1974).

Figure 1 – *Study Area Location Plan showing the extent of Triassic and Permian sediments in the Southern half of the Sydney Basin*

The geological units encountered within the district, in ascending order, include the Illawarra Coal Measures (locally including intrusive/extrusive bodies collectively known as the Gerringong Volcanic facies), the Narrabeen Group and the Hawkesbury Sandstone. The geology of these units has been discussed at length in several publications such as Bowman (1974) and Herbert and Helby (1980).

Extending down from the base of the upper cliff line, the ground surface is often covered by debris of colluvial origin. This material comprises variably weathered bedrock fragments supported in a matrix of finer material dominantly weathered to sand, sandy clay and clay and brought downslope under the influence of gravity.

Instrumented Sites

Inclinometer monitoring records of forty two boreholes from 19 landslide sites have been examined and analysed. Records of movements prior to 1993 have been acquired from government authorities and from consulting engineers who were responsible for the initial drilling of boreholes and installation of the inclinometers. Monitoring at several sites was continued during the period 1993-1997 as part of a

Landslide Hazard Assessment project. The inclinometer monitoring records comprise the recorded profiles of the borehole inclinometers and the date of each monitoring visit.

A sample of 10 boreholes each with a brief summary of monitoring coverage and movement data are listed in Table 1. This table also shows the borehole identification number and the site reference code of each landslide.

Table 1 – *A Sample of 10 Boreholes out of a total of 42 in the borehole inclinometer dataset with site reference code (SRC), monitoring coverage and rates of movement.*

Borehole Name	**SRC**	**1st reading**	**last reading**	**number readings**	**depth to shear (m)**	**peak rate mm/day**	**average rate mm/day**
2	026	28/03/93	9/12/96	12	15-16	0.03	0.02
4	026	28/03/93	9/12/96	12	8.5-9.5	0.03	0.02
6	026	28/03/93	9/12/96	12	11.5-12.5	0.04	0.02
3	064	9/03/89	8/08/96	30*	7.0-8.0	1.93	0.07
7	064	19/10/89	8/08/96	27*	1.5-2.5	2.09	0.06
WH2	134	14/12/90	16/05/96	16*	11.0-12.0	1.1	0.01
WH10	134	12/11/91	15/05/96	11*	13-13.5	0.03	0.004
WH13	134	12/11/91	16/05/96	11*	16.5-17.5	0.11	0.01
WH14	134	12/11/91	16/05/96	10*	3.4-3.9	0.08	0.01
WH15	134	18/02/92	16/05/96	9*	creep	0.03	0.002

* denotes that some readings were collected as part of this research project

It was considered necessary to adopt a standard numbering system for the 328 sites of instability incorporated into a landslide inventory of this area (Chowdhury and Flentje, 1997, 1998a). This landslide inventory was compiled during the research project mentioned above. Each site is identified with a 3 character Site Reference Code (SRC). This site reference code is unique to each location, is plotted for each site on a map record and constitutes the “primary” or “key” field in a land instability database.

In general, landslides in the Wollongong area can be summarised as follows:

- predominantly rainfall triggered but often a consequence of urbanisation
- 80 % of the total number of landslides have volumes in the range 500 m^3 to 50,000 m^3, but the maximum landslide volume is 600,000 m^3
- velocities are typically very slow to extremely slow according to the international scale (WP/WLI, 1993)
- depths to the slip surfaces range from 0.5 m to 20 m
- movements are rotational and/or translational
- landslide material generally comprises of clay and sandy-clay colluvium
- more than 50 % of the landslides can be classified as complex debris slump - debris flows (Varnes 1978)

In addition to inclinometer monitoring, open standpipe piezometers have been used to record standing water levels at some sites. Two vibrating wire piezometers (VWP) are installed in the head area of one landslide. These VWP have been monitored as part of this research project.

Inclinometer Profiles

Before giving details of three significant landslide sites in subsequent sections, some general comments on the installation of inclinometers and generated inclinometer profiles are provided here.

The inclinometers have been installed by various government organisations and engineering consulting firms as part of geotechnical investigations of landslide sites. These installations generally comprise 70 mm outside diameter plastic probe inclinometer casing installed within the full length of the borehole. The space between the casing and the wall of the borehole is backfilled with sand.

Inclinometer records used during this research project include the displacement at 0.5 m intervals along the length of the borehole, relative to the position of the bottom of the borehole. Cumulative displacements are summed from the base of the borehole to the top. Recording displacement at 0.5 m intervals provides optimum accuracy, such that probe inclinometers can measure changes in inclination of the order of 1.3 mm to 2.5 mm over 33 m lengths of inclinometer casing (Mikkelsen 1996), although one manufacturer claims a system accuracy of ± 6 mm per 25 m.

Analysis of each record enables the identification of time intervals between each subsequent monitoring visit and the magnitude of the movement during each such time interval. This enables the cumulative displacement in subsurface shear movement to be compared over time and, therefore, allows the interval rates of shear to be determined.

There are numerous different methods of reporting and discussing inclinometer profiles. For example, the New South Wales Government Railway Services Authority Geotechnical Services (RSA) employs an A^+/A^- and B^+/B^- axis nomenclature system with the A^+ axis orientated perpendicular to the railway line and pointing downslope, with the B^+ axis clockwise 90° from the A^+ axis. The RSA typically reports the A axis data only. The New South Wales Government Roads and Traffic Authority (RTA) employs an A/B and C/D axis nomenclature system with the A axis orientated along the direction of maximum slope and the C axis orientated 90° in a clockwise direction from the A axis. The RTA typically reports the profiles of both axis. Coffey Partners International (CPI) uses the same axis labelling system as that employed by the RSA, except the A^+ axis is usually orientated along the steepest inclination downslope. CPI reports both axes profiles, and then calculates and reports the maximum resultant displacement vector (magnitude and azimuth).

Composite 20 Year Rainfall Histogram and Antecedent Rainfall Curves

Rainfall is recognised as an important causal and triggering factor for slope instability. To assess the relationship between slope instability and rainfall within the study area daily rainfall totals have been used to determine daily rolling antecedent rainfall curves, for which Antecedent Rainfall Percentage Exceedance Time (ARPET) values have been determined (Chowdhury and Flentje 1998b). These antecedent rainfall curves and percentage exceedance values have been compared with monitored landslide shear displacement curves to examine upper and lower bound antecedent rainfall thresholds associated with landslide movement.

Daily rainfall totals have been collected from several rainfall stations to compile an unbroken 20 year composite record, which is currently being extended to cover a 100 year period. The existing 20 year record extends from 1 January 1977 to 31 December 1996. This period is significant not only for its duration, but also for some exceptional rains that have fallen during this period and several periods of significant land instability which it encompasses. The data were entered into a computer spreadsheet whereby antecedent rainfall for daily rolling periods of 7 days, 30 days, 60 days, 90 days and 120 days have been computed.

In the following sections three significant landslide sites are discussed in some detail.

The Coalcliff Terrace Landslide, Site 026

This landslide site covers an area of approximately 66,000 m^2, and has a volume of approximately 600,000 m^3 making it the largest volume landslide in the Wollongong study area. According to Cruden and Varnes (1996) this landslide can be described as an active, advancing, composite, extremely slow, moist to wet debris slump in the head area and a debris slide-debris flow lower down. The landslide is rotational in the head area of the site, but predominantly translational for most of the site below the head area. The depth of the colluvium material at this site is up to 16 m. Shear displacement is typically occurring along the bedrock/ colluvium interface.

This site is traversed by the South Coast Railway Line (a dual electric freight and passenger railway line) and a two lane main road. Ground movements have been reported at least every decade at this site since 1942. The site has been the subject of several detailed geotechnical investigations. During the most recent of these, 13 boreholes were drilled, 6 of which had inclinometers installed, and another 6 had a total of eleven pneumatic piezometers installed.

In late 1997 and early 1998 this site has had an elaborate series of remedial measures installed, and as a result may have been stabilised. These remedial engineering construction works include a 200 m long row of vertical drainage wells with an interconnecting series of subhorizontal, gravity-fed, drainage relief drives.

Inclinometer profiles (A axis only) recorded by the Railway Services Authority, from three borehole inclinometers at this site have been examined for rates of movement. One of these inclinometer profiles is shown in Figure 2. This profile displays a block style of movement with a depth to the slip surface of 9.25 m. Progressive movement at a depth of 4.5 m in borehole 4 is shown in Table 2.

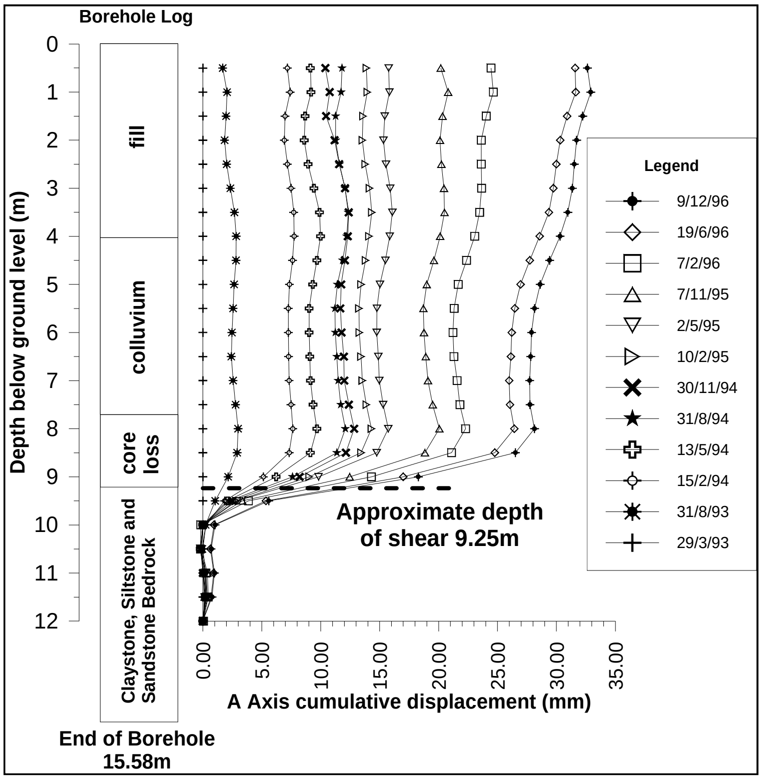

Figure 2 – *Summary Borehole Log and Inclinometer Profiles for Borehole 4, Site 26 at Coalcliff, near Wollongong in New South Wales, Australia*

Table 2 – *Borehole 4, Site 026, monitoring period and displacement (A axis data only) recorded at 4.5m depth*

Date of reading	Days (since start)	Interval (days)	Displacement (mm)		Rate of shear (mm/day)	
			Resultant	Interval	Interval	mean
28/03/93	0	0	0	0.00	0.000	0.000
31/08/93	156	156	2.81	2.81	0.018	0.018
15/02/94	324	168	7.61	4.80	0.029	0.023
13/05/94	411	87	9.67	2.06	0.024	0.024
30/08/94	520	109	11.86	2.19	0.020	0.023
10/11/94	592	72	12.04	0.18	0.003	0.020
10/02/95	684	92	13.8	1.76	0.019	0.020
2/05/95	765	81	15.49	1.69	0.021	0.020
7/11/95	954	189	19.61	4.12	0.022	0.021
7/02/96	1046	92	22.37	2.76	0.030	0.021
19/09/96	1271	225	27.74	5.37	0.024	0.022
9/12/96	1352	81	29.42	1.68	0.021	0.022

Total displacements indicated for boreholes 2, 4 and 6 over the period 28th March 1993 to 9th December 1996, are 27.6 mm, 29.4 mm and 29.0 mm respectively, all at average rates of approximately 0.02 mm per day, or, if extrapolated, 8 mm per year. On the WP/WLI (1993) velocity scale, such a rate of displacement is classified as extremely slow. Yet, RSA engineers maintaining the dual electric railway line that traverses this site have reported an annual maintenance cost exceeding tens of thousands of dollars.

Cumulative displacement and rate of shear for three boreholes at this site, including borehole 4, are shown in Figure 3 together with the 90 day antecedent rainfall curve. The cumulative displacement curves for the three boreholes show the continual movement at the site over the period of monitoring, 28th March 1993 to 9th December 1996. Periods where movement is lower than 0.015 mm per day (the average rate of movement is approximately 0.02 mm per day) correspond to periods of low antecedent rainfall, except Borehole 2 for the period November 95 to February 1996. Movement has continued at this site for the duration of the whole monitoring period.

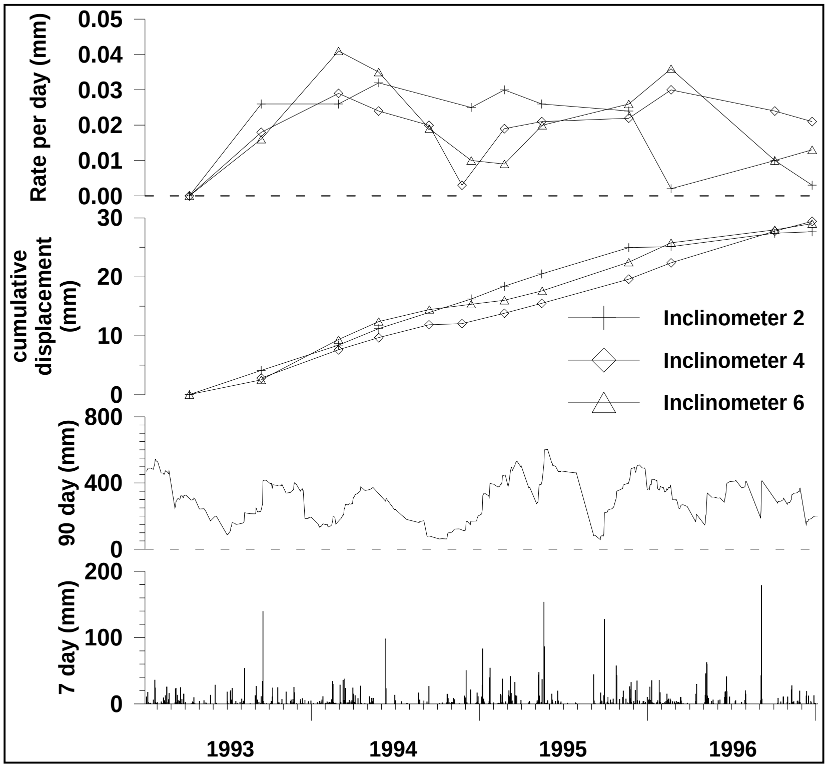

Figure 3 – *Site 026, daily and antecedent rainfall and shear displacement for 3 boreholes.*

Periods of accelerated movement, leading either to peaks or steep positive slopes on the rate per day curves, generally correspond to high values in the antecedent rainfall curves over the monitoring period.

The effects of the recently completed remedial stabilisation works on shear displacement at depth and ground movement at this site is yet to be assessed. This assessment will be largely based on data obtained from the instrumentation installed at this site, and on other ground surface survey data. The results of this assessment will be reported elsewhere.

A Landslide in Goodrich Street, Scarborough, Site 064

Site 064 covers an area of approximately 5000 m^2 and a volume of almost 18,000 m^3, making it the 77th largest landslide in the study area. The head area of this landslide is also traversed by the South Coast Railway Line. The area below and downslope of the railway side-fill embankment is residential land.

The most recent geotechnical investigation of this site was carried out by the then State Rail Authority of New South Wales, now a subsidiary of that organisation known as the Railway Services Authority Geotechnical Services, and by their consultants in the period from 1989 to 1991. These investigations followed various land instability "events" during the preceding 40 years. These events include scour wash outs, general track "subsidence", development of tension cracks between the two tracks, a train derailment and inundation of the site with debris resulting from ground movements upslope.

These investigations included the excavation of test pits, the drilling of numerous boreholes with installation of two inclinometers and two vibrating wire piezometers. Three additional open standpipes were also installed.

The monitoring results from all the instrumentation installed at this site, combined with daily rainfall and a daily rolling 90 day antecedent rainfall curve (rainfall station 7km away from the site) are shown in Figure 4. The inclinometer profiles (not included here) clearly define the depth to and style of movement at this site, which, combined with surface surveys of ground movement, allowed the approximate plan area and volume of this landslide to be calculated. The cumulative shear displacement and rates of shear displacement curves in Figure 4 clearly show the response to rainfall, and, in particular, the 90 day antecedent rainfall in the periods March - June 1989 and February - April 1990. A series of longitudinal subsurface drainage trenches were designed and installed at this site, at a cost of almost $400,000.

Monitoring of the site following the installation of these remedial works has been continued. This "post construction" monitoring has revealed a significant decrease in slope movement but the site has not been stabilised fully.

Interval rates of displacement following the first monitoring visit since completion of the remedial works have ranged from a maximum of 0.03 mm/day down to less than 0.01 mm/day. However, in the head area of the landslide, as indicated by inclinometer 3, 21 mm of displacement has occurred since the remedial works, whereas only 2.5 mm of displacement has been indicated in the toe area of the landslide, as indicated by the monitoring data from inclinometer 7. Monitoring data from the shallow vibrating wire piezometer, installed at a depth of 4.2 m in the head area of the landslide, in the vicinity of borehole inclinometer 3, has shown a significant increase in pore water pressure during 1994 and 1995. This build up of pore pressure may be part of the reason for continued movement in this area of the landslide.

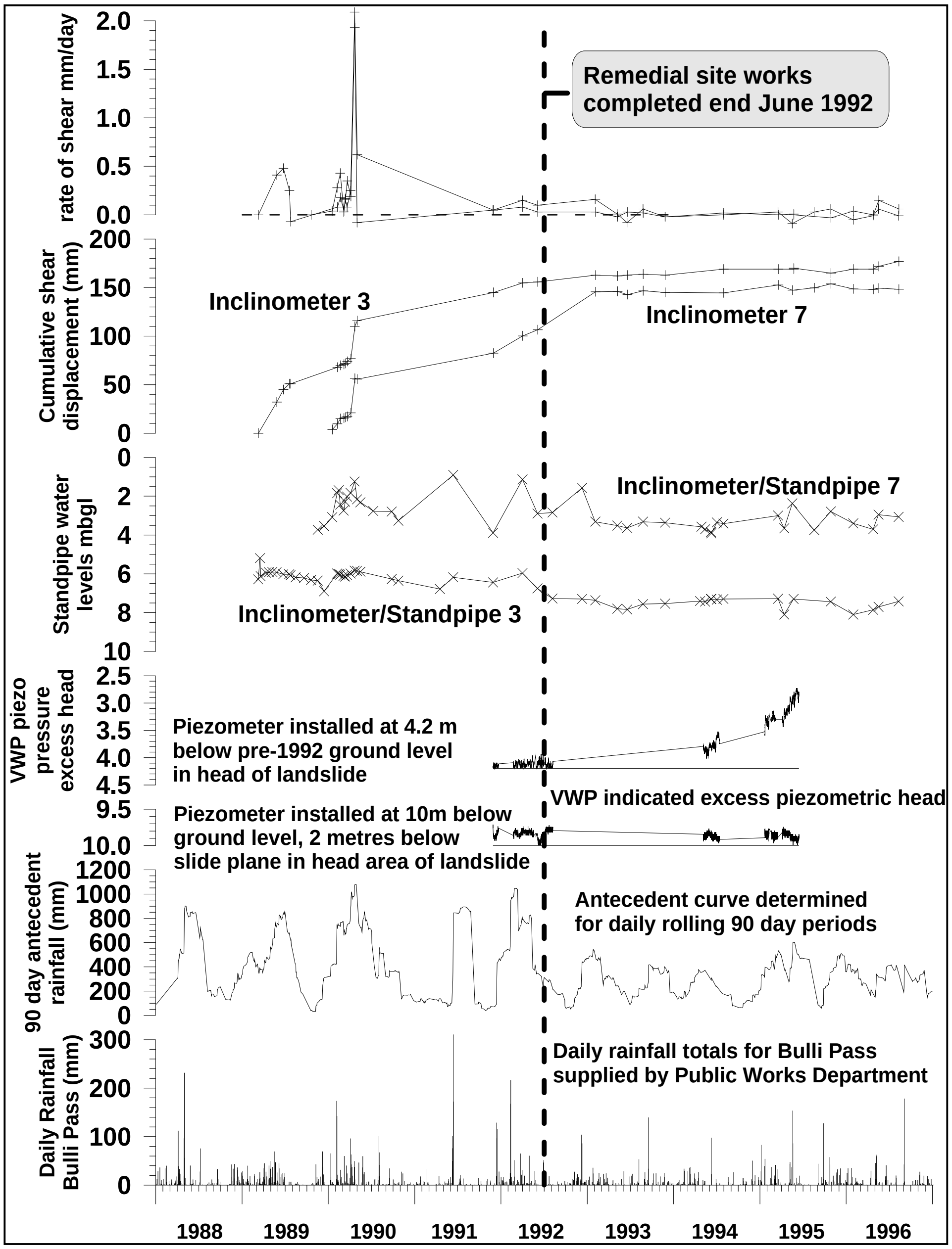

Figure 4 – *Site 064, MonitoringData for all of the Instrumentation Installed at this site plotted with Daily Rainfall Totals and 90 day Antecedent Rainfall Curve.*

It must also be noted that in other research work carried out by the writers and reported elsewhere (Flentje 1998, and Chowdhury and Flentje 1998b), the 90 day antecedent rainfall curve has been considered to show a close relationship to landslide movement at this site. Since the remedial works were completed in June 1992 the landslide site has not experienced 90 day antecedent rainfall magnitudes of similar scale to those which have been correlated with “failures” in 1989 and 1990. Hence, there is concern about the effectiveness of the remedial measures and monitoring of this site is continuing.

The Woonona Heights Landslide, Site 134

The Wonoona Heights Landslide has a plan area of approximately 20,500 m², a volume of approximately 225,000 m³ and is ranked in the land instability database as the 9th largest landslide within the subject area. The landslide site is located within a densely developed urban area, which contains up to 100 residential houses, 29 of which are situated within the landslide. Another 10 houses are located immediately adjacent to the margins of the landslide. One house has been destroyed by ground movement, whilst at least 19 have required major repairs.

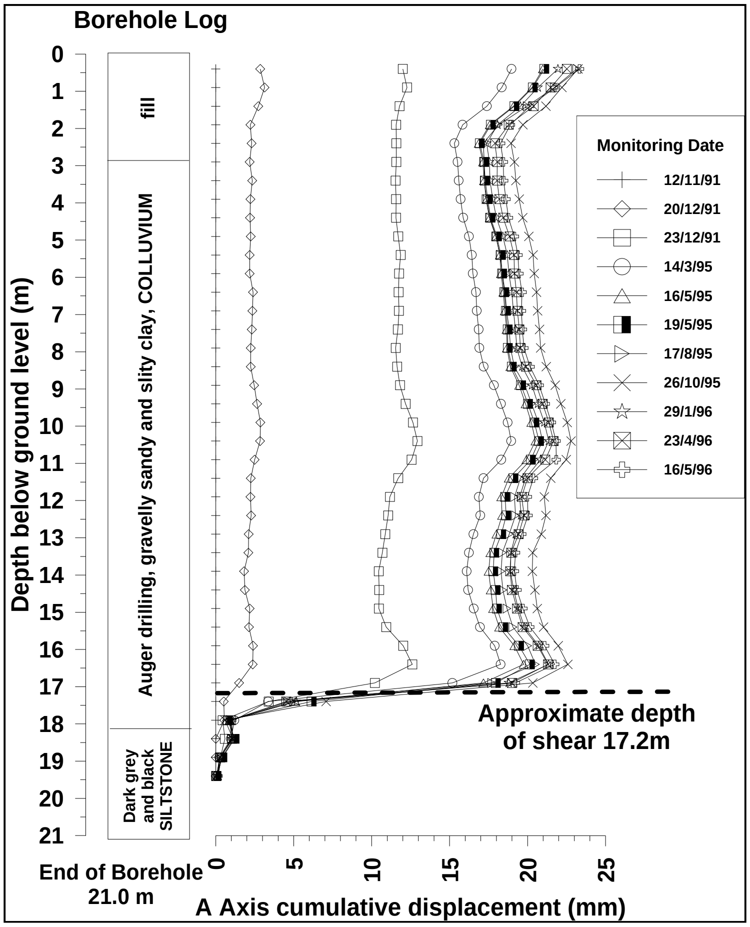

Figure 5 – *Summary borehole log and inclinometer profiles for borehole 13, Site 134 at Woonona Heights, near Wollongong in New South Wales, Australia.*

This landslide has a long history but is a subtle feature, very little damage being visible from the streets. According to a previous geotechnical report, disturbed ground can be observed in a 1948 black and white aerial photograph. Accelerated movement phases have been documented at this site in 1977, April 1990, March - June 1991 and November 1991 - March 1992, all of which have resulted in road and residential damage.

The site has recently been investigated on behalf of the local council by an international geotechnical consulting firm. The comprehensive investigation included the drilling of 22 boreholes, and included the installation and periodic monitoring of 7 inclinometers and numerous open standpipe piezometers. Following this investigation remedial works have been proposed. These works have not yet been implemented. Consequently, the site remains episodically active as an extremely to very slow moving landslide (WP/WLI, 1993).

This landslide is located within the area of subcrop of the Illawarra Coal Measures. The slide material comprises of a sequence of some fill and a gravelly and sandy-clay colluvium sliding over residual bedrock, which includes several coal seams. Monitoring of three inclinometers and piezometers has been carried out at this site. All the inclinometer profiles within the landslide show similar block styles of movement, with an approximate average depth of 11 m to the slip surface, the maximum depth being almost 18 m, as shown in Figure 5.

This monitoring has confirmed that movement at this site, under residual strength conditions, continues to occur when the piezometric levels associated with seepage reach about 1m below the ground surface (Fig. 6). The results of laboratory shear strength testing and stability analyses are outside the scope of this paper.

Further instrumentation and monitoring is required to investigate the lower half of the area of this landslide. In this area, the basal slip surface of this landslide is essentially horizontal and immediately overlies a highly fractured coal seam with numerous low strength claystone bands of tuffaceous origin. Additional inclinometers and piezometers would provide extremely useful information for the geotechnical model of this landslide and may facilitate the design of more economical remedial measures than those which have already been proposed.

Discussion

With the types of landslides common in this study area, an acceptable minimum inclinometer monitoring interval is 30 days. Additional monitoring visits are required in response to rainfall “events”, with additional follow up visits one day to several weeks later, dependent upon the rainfall and the associated movement response. During periods of dry weather, the period between monitoring visits can be extended. The preferred 30 day period allows accurate interval rates of displacement to be calculated. More frequent monitoring does incur significant costs, and it is accepted that monitoring schedules will often be controlled by available financial resources.

Use of instrumentation for subsurface monitoring of slopes along the Illawarra escarpment has been very useful for establishing the character, range and velocity of slope movements. The episodic nature of landslide movements has been established and more research is required to determine the conditions under which catastrophic failures may take place. This is likely to be a very difficult area of research because catastrophic failures are rare and because instrumentation may not be installed at the particular site which undergoes catastrophic failure. Furthermore, if instrumentation existed at the site, it may not survive the large movements which occur during a catastrophic landslide.

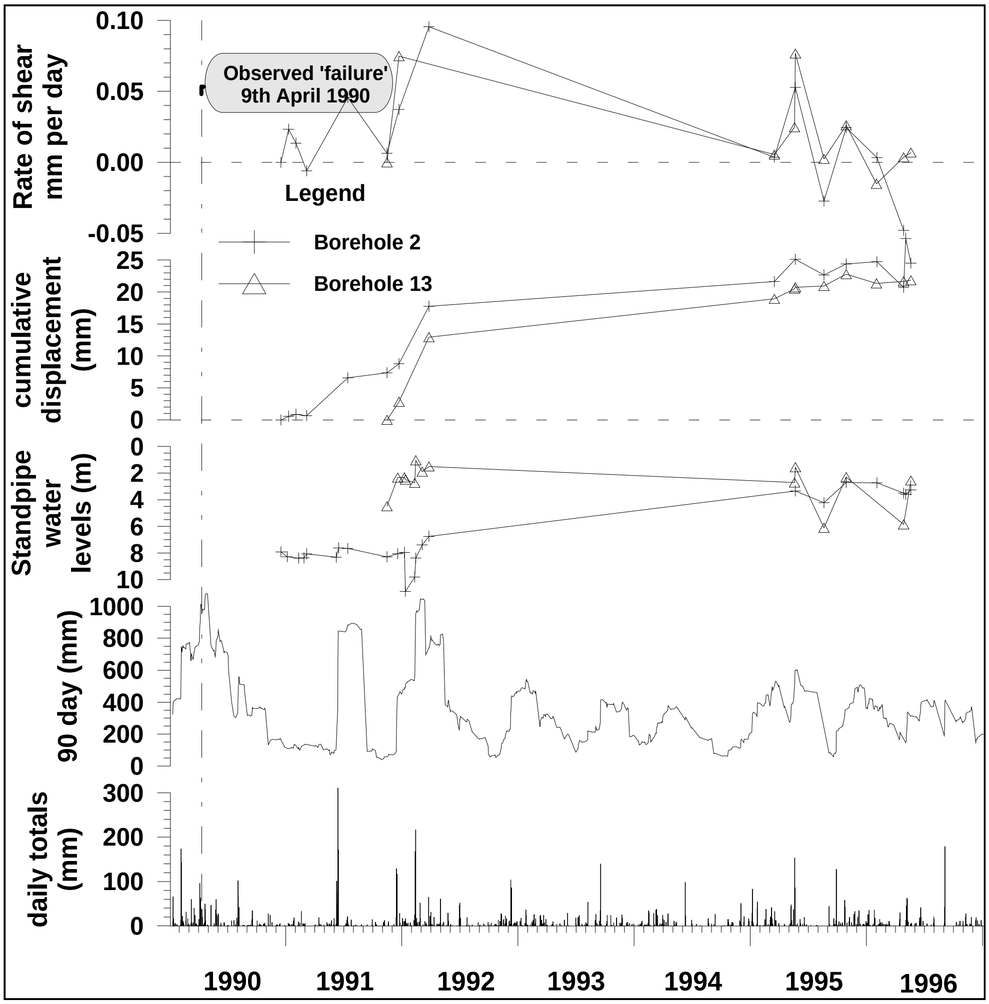

Figure 6 – *Site 134, daily and 90 day Antecedent Rainfall, Cumulative and Rate of Shear and Standpipe Water Levels.*

Some success has been achieved in correlating landslide movements to cumulative rainfall magnitudes and different levels of antecedent rainfall have been considered in this research. These relationships have been quantified on a site by site basis, as well as for the landslide "population" as a whole. It appears from this research that 90 day and 120 day antecedent periods correlate fairly well to peak or accelerating movement phases at many of the sites.

Open standpipes (slotted pipes, with the annulus back filled with sand over the entire borehole depth) have been widely used in the Illawarra region because of their low cost. Yet, it is recognised that the associated pore pressure data may not be reliable or accurate. Vibrating wire or pneumatic piezometers, whilst more expensive on a per unit basis, provide more reliable and accurate data.

Concluding Remarks

The use of inclinometers has proved to be immensely valuable for monitoring the performance of slow moving landslides in the Northern Illawarra Region of New South Wales, Australia. In fact this monitoring is considered to be the single most important factor in detailed site assessments of all such landslides regardless of their size and previous history. Experience has shown that simple and robust instrumentation is the best in these situations.

The inclinometers used at all sites have performed well and have proved to be reliable. Based on the experience gained during this research, movement rates of up to 17.6 mm per day and cumulative movements of up to 200 mm at slower rates of displacement can be measured with confidence. Rates of displacement as slow as 0.002 mm per day have been recorded over 90 day monitoring intervals. This level of accuracy is only relevant when considering the longer monitoring periods, e.g, more than a month. Measurements concerning extremely slow movements are not expected to be accurate or reproducible over very short monitoring periods, e.g, a few days. Of course, the use of inclinometers in faster moving landslides will require shorter intervals bewtween monitoring visits. In such cases, weekly or daily monitoring may be necessary.

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