Observational approach for urban landslide management

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Abstract: The occurrence of landslides in urban hillside areas poses significant challenges for risk management within residential suburbs as well as along road and railway lines. The main focus of this paper is the development of an "observational approach" for landslide risk management and its application within an important landslide study area, the Wollongong Local Government Area, in the state of New South Wales, Australia. Monitoring of subsurface shear movement and pore water pressures at a number of places in the study area during the last decade has already proved very useful in combination with rainfall data from a number of existing rainfall stations. Analyses of observational data have led to the assessment of rainfall triggering thresholds for the occurrence of landslides. Four new real-time monitoring landslide field stations have now been established for obtaining continuous data on subsurface shear movements, pore water pressures and rainfall in real time. The data is transferred automatically to a web-server and displayed on the web. These recent developments have resulted in a vast improvement in research techniques for understanding the initiation and progression of landslide movement triggered by rainfall. The data will prove to be very useful in the management of risk during rainstorms in real time or near real time. Moreover, over the medium to long-term, such accurate data will facilitate improvements in the planning and management of assets and land-use.

Résumé : Les phénomènes de glissement de terrain dans les régions urbanisées entourées de collines posent des problèmes importants liés à la gestion des risques dans les zones résidentielles ainsi que le long des routes et chemins de fer. Le but principal de cette publication est de développer une "approche observatrice" dans le but de contrôler le risque de glissement de terrains et son application dans une importante zone d'étude, la Wollongong Local Governement Area, dans l'état du New South Wales en Australie. Des relevés de mouvements de cisaillement sous la surface et de pression d'eau dans les pores à différents endroits dans la zone étudiée a déjà prouvé être très utile en combinant en parallèle des données de pluviométrie collectées à différentes stations météorologique. L'analyse des données observées a mené à évaluer les chutes de pluies déclenchant les phénomènes de glissement de terrains. Quatre nouvelles stations relevant en temps réel les glissements ont été établies pour obtenir des données continues sur les phénomènes de cisaillement sous la surface, la pression d'eau dans les pores ainsi que la pluviosité, tout ceci en temps réel. Les données sont transférées automatiquement sur un serveur Internet et affichées sur l'Internet. Ces récents développements ont contribué à une vaste amélioration des techniques de recherche pour comprendre l'initiation et la progression des glissements de terrains provoqués par des chutes de pluies. Les données scientifiques vont prouver être très utiles pour gérer, en temps réel ou très proche du temps réel, les risques de glissement de terrains pendant des averses orageuses. De plus, à plus ou moins long terme, la précision de ces données va permettre d'améliorer la planification et la gestion des biens et de l'utilisation du terrain.

Keywords: landslides, risk assessment, geological hazards, geographic information systems, regional planning, inclinometer.

INTRODUCTION

Progress in understanding the causes and processes of slope instability and the mechanisms of landsliding has increasingly led to better methods of recognition, classification, prevention, remediation and control. However prevention of landslide occurrence in a region is not always feasible and even when preventative measures are implemented, they may be successful only partially. Similarly, remedial measures for landslides which have occurred may have only limited success or, in some cases, not work at all. The main reasons for lack of success in prevention and remediation are the significant uncertainties with regard to the factors which contribute to slope instability and the uncertainties and unknowns with regards to triggering events such as rainstorms and earthquakes. These uncertainties include the frequency, magnitude and timing of occurrence and spatial variability of a triggering event such as rainfall. Major landslide disasters continue to occur around the world with an increasing frequency and these include new landslides as well as reactivations of existing landslides.

In many urban areas, there often is a continuing adverse impact of slope instability during the intervals between major triggering events. Even relatively small magnitudes of landslide movement can cumulatively damage and destroy residential houses and lead to a reduction in the value of the surrounding properties. Progression and retrogression of significant landslides into highway and railway corridors can result in significant economic loss in addition to increased levels of risk to human safety and, in some cases, lead to injuries and even fatalities. Increasing urbanisation of many hillside areas, associated with the continued growth of populations within urban centres and along urban corridors, has contributed greatly to such problems. The effects of urbanisation are, of course, superimposed on and often exacerbate the consequences of natural slope forming processes.

Landslide management must include but also go well beyond the remediation of new and reactivated landslide sites. Long-term planning of land use, protection of sensitive areas including those of high landslide susceptibility, and the application of development control in areas of marginal slope stability are important. The installation of monitoring stations as part of 'an observational approach' to regional landslide management is highly desirable. For instance, in a region characterised by rainfall-triggered landslides, data from monitoring of a number of locations can facilitate studies of relationships between rainfall, pore water pressures and subsurface shear movement. Landslide management must also include the development and use of appropriate early warning systems. For all these aspects to be carried out on a systematic and rational basis within a region, comprehensive research studies are required. It is suggested here that a modern landslide management strategy should also include the capability for effective risk mitigation during and immediately after a significant landslide triggering event such as a major rainfall event or an earthquake. Consequently research is required concerning the application of continuous, real-time monitoring at a number of selected sited within a region.

In this paper significant aspects of a regional case study are presented to illustrate the concepts and applications of an 'observational approach'. The term is defined in the next section. Such an approach is currently being developed as part of a comprehensive project in an urban area of Australia, the Wollongong Local Government Area (WLGA) in the state of New South Wales, Australia. The main features of an effective urban landslide risk management strategy are outlined here. The paper also provides details of the continuous monitoring program and how it will enhance the research.

OBSERVATIONAL APPROACH

In this paper, the term 'observational approach' is used to signify the monitoring of a number of locations within a study area and using such observational data to assist with various aspects of landslide risk management such as the following:

- Estimating landslide triggering rainfall thresholds
- Estimating landslide triggering pore water pressure thresholds
- Assessing magnitudes and rates of landslide displacement with respect to triggering agents
- Assessing landslide susceptibility, frequency, hazard and risk
- Landslide risk management decision-making particularly during extreme rainfall events
- Land management decision-making for the medium to long term, and
- Development of policies for land-use planning

(Note that only some of these aspects will be covered in the rest of this paper.)

In particular, such a strategy (as outlined in Figure 1) would involve a combination of both manual periodic and automated continuous, real-time monitoring (Figure 2) of landslide displacement, pore water pressure and rainfall. The monitoring may be used for emergency risk management in near-real-time during and in the immediate follow up response period following a significant rainstorm event, or simply during more general day to day land management operations. This definition of the term 'observational approach' is different from that widely adopted in geotechnical engineering practice for the last 4 decades. That definition refers primarily to performance-based geotechnical design and construction in order to minimise over-conservatism and optimise safety. Moreover, that definition covers a wide range of geotechnical applications. Here the term is used exclusively for slopes and landslides but in a more flexible way, to include a better understanding of slope performance based on observation under varying conditions coupled with the use of observed data in decision-making for risk management.

For landslide management, one may also extend the definition of the 'observational approach' even more broadly to include the whole process of landslide susceptibility, hazard and risk assessment, including the development of a landslide inventory and the subsequent analyses and mapping of landslide susceptibility.

This broad definition has been applied over the last decade by the landslide research team at the University of Wollongong. It is important to note that even the proper selection of sites for continuous monitoring can not be done without knowledge concerning the location of existing landslides, their frequency of occurrence and their severity. All of these aspects are greatly facilitated by observation and monitoring. The definition adopted here implies the establishment of a systematic monitoring regime within a region. Therefore, the term should not be applied to the monitoring of a single landslide with the limited aim of designing remedial measures or validating a stability model.

Having emphasised the particular role of continuous monitoring in real-time, it must be pointed out that the traditional, periodic monitoring is also important. For example data from periodic monitoring stations are important for designing continuous monitoring stations and, in particular, for selecting the depths at which shear movement and pore water pressure may be monitored continuously. In Wollongong, periodic inclinometer monitoring has been used extensively for over a decade. Among other benefits of such monitoring it is important to mention the estimation of preliminary landslide triggering rainfall thresholds, as discussed in a separate section of this paper.

WHY AN OBSERVATIONAL APPROACH?

To answer this question, it is appropriate to consider how the role of observation and monitoring in slope stability is generally perceived by geotechnical engineers, engineering geologists and other professionals. One important role is as a tool for a detailed understanding of (a) slope performance at individual sites and (b) failure mechanisms in specific circumstances, so that assumed geotechnical models can be validated. In addition, a monitoring program at a site may have the specific purpose to help design the most appropriate remedial measures, and post construction, determine the success of the works program. Another important role is as a research tool so that the relevance of important concepts can be verified such as the relationships between cumulative displacement, rate of displacement, pore water pressures and rainfall.

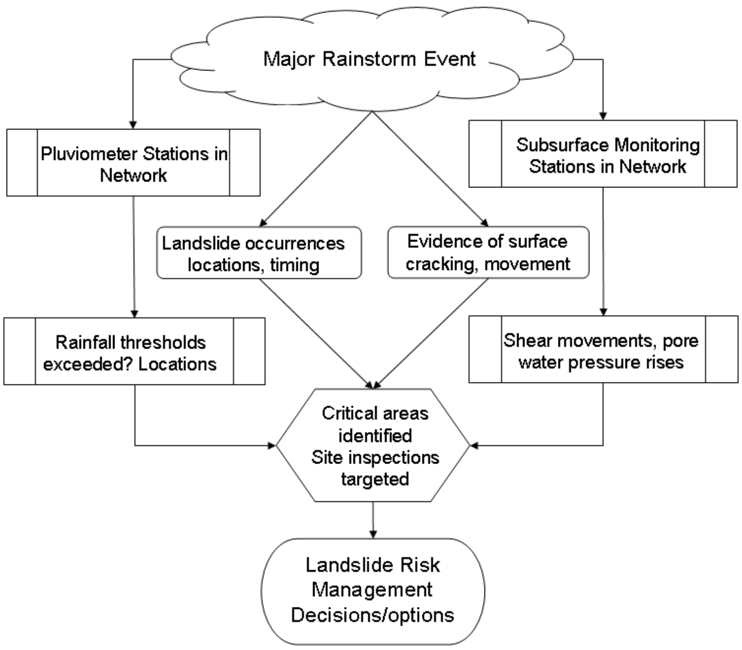


Figure 1. Overview of the 'Observational Approach' as applied during a major rainstorm event incorporating real-time information from a network of field stations.

For landslide management in a regional context and, in particular, for urban landslide management, the widely accepted approach is to develop and use landslide susceptibility maps. In some instances, maps of landslide hazard or even landslide risk may be used. The enormous usefulness of each of these types of maps is, of course, well known. The difficulty in preparing them is also well known. However it must be appreciated that such maps, however elaborate, are not predictive tools. During a significant landslide triggering event such as a major rainstorm event, significant landslides and minor slope failures may occur at different locations. In addition, there will be subsurface shear movements which have not yet developed to the extent of being part of a recognizable landslide. The locations and timings of these effects are difficult, if not impossible to predict on the basis of susceptibility maps alone. Thus, there is considerable justification in advocating the use of observation and monitoring as key aspects of a more comprehensive approach for landslide management.

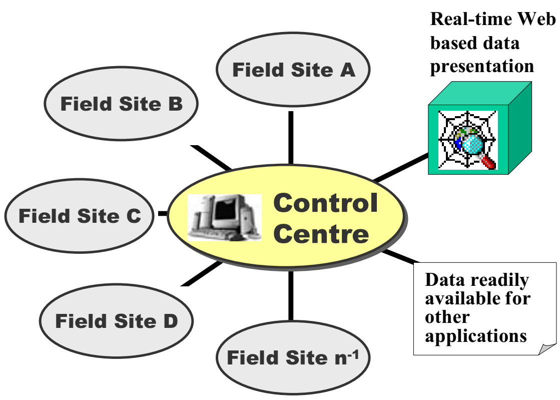


Figure 2. Continuous Real-Time Monitoring landslide field stations, their automated linkage to a control centre and associated web-based data display.

Landslide management during and after the August 1998 rainstorm event which affected the WLGA (Figure 3) is a useful example of the role of an observational approach as defined in this paper. Previous research in the study area, which included observation and monitoring over many years, enabled predictions of widespread landsliding to be made and warnings to be issued. There was good information concerning preliminary rainfall thresholds, known pre-existing landslide locations and on subsurface shear movements at a number of locations. In fact, on this occasion, the rainfall was so intense (up to 750mm in 5 days) that there was widespread professional and community recognition of the imminent danger of landsliding. Thus landslide management after the event was greatly facilitated. However, real-time management during and in the few days immediately following the rainstorm event was less successful, being more retro-active as there were no continuous monitoring stations and because ‘an observational approach’ had not been fully developed. All the monitoring that was carried out as a result of this event was manually undertaken and results were not available for days and weeks after the event.

An emergency geotechnical team of 3 experienced practitioners, including the first author, was assembled and carried out inspections at locations based on reports of damage and also at other sites of known previous instability within the urban area. This approach was successful and a range of geotechnical issues relating to approximately 150 landslides triggered during the rainfall event were addressed and expedited efficiently. However, the need for a fully developed ‘observational approach’ employing an automated network of Continuous Real-Time Monitoring (CRTM) Stations at selected representative landslide sites across the city (as conceptualised in Figure 2) was identified by the authors as a key requirement for enhancing the tools and capacity for landslide management within the region. Such a network of CRTM stations would be particularly useful during major rainstorm events.

GIS BASED INVENTORY

The GIS-based Landslide Inventory for the study area shown in Figure 3 comprises digital landslide datasets (shapefiles in an ESRI ArcGIS Personal Geodatabase), from which maps are generated of all the known landslide sites. The Landslide Inventory has existed now for 10 years and has grown substantially in capacity every year since it was first developed (Chowdhury and Flentje 1998). The Inventory currently includes 569 landslide sites with a total of 958 landslide ‘events’ (including all known occurrences and recurrences). For example, Site 113 in the suburb of Thirroul (shown in Figure 3) has 17 documented recurrences following its first recorded movement in March-April 1950. Amongst the total of 569 landslide sites, there are 20 rock fall category landslides, 24 debris flow category landslides whilst the remaining 525 sites are slide category landslides (Cruden and Varnes, 1996).

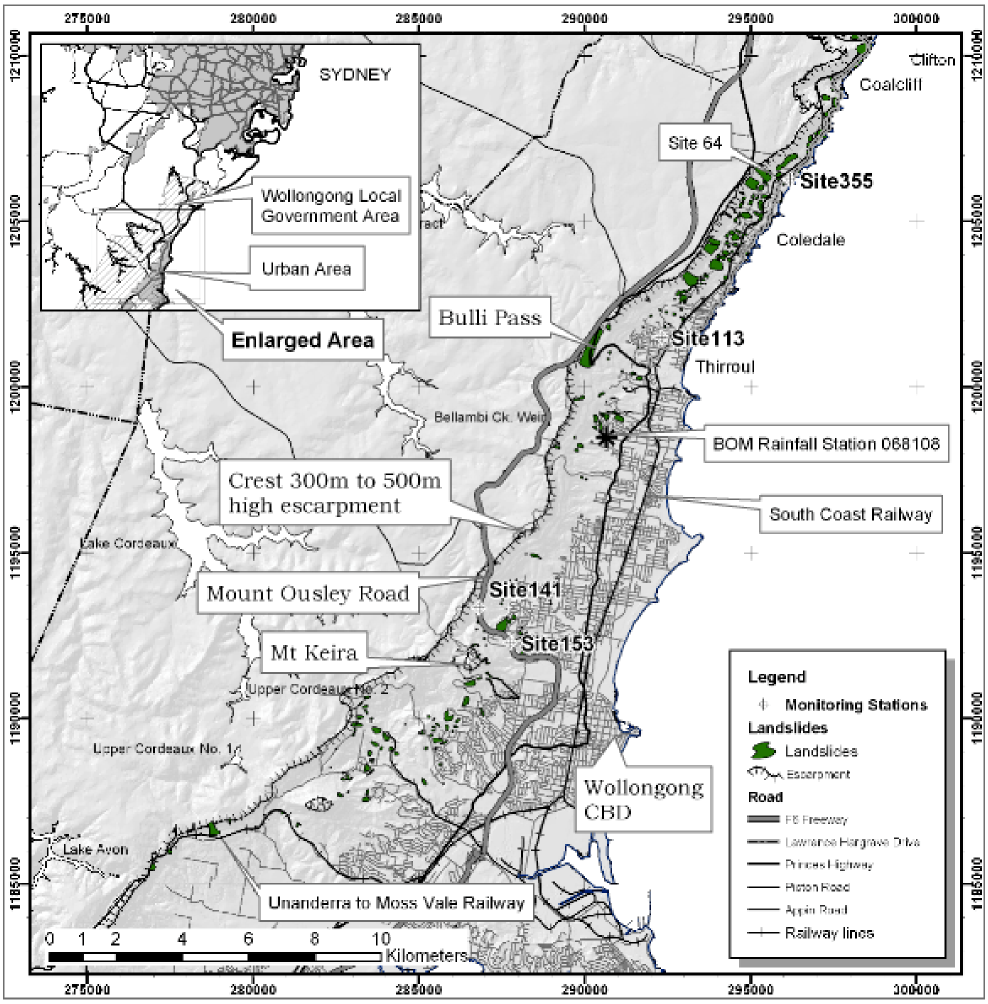


Figure 3. The central region of the WLGA study area showing the landslides, escarpment, CBD and northern suburbs. Several specific site locations referred to in this paper are shown.

The key identifier for each record in the Landslide Inventory is the unique Site Reference Code. An abbreviated data dictionary for the 22 standard fields required for each landslide site is shown in Table 1. The database has a total of 75 fields available for each site and a comprehensive data dictionary is available for the complete database.

One aspect of the Landslide Inventory that has been extremely useful is the listing per site of the first occurrence and any subsequent recurrences of each landslide site (Flentje and Chowdhury, 2002). This information is important for the assessment of landslide frequency, and provides significant evidence of landslide reactivation hazard at individual sites. For example Site 113 was first reported in April to March 1950, and was most recently active in October 2004, a period spanning 55 years. With the 18 landslide events known at this site, the average annual frequency of landsliding is 0.33. If additional information regarding magnitudes or rates of displacement are available for each event, the frequency of landsliding could be defined even more precisely. Such calculations may be used in the quantitative assessment of landslide risk.

Table 1. Data dictionary for the basic fields of the Landslide Inventory

Field Name	Data Type	Description
SRC	Number	Decimal number with one significant figure, ie 222.2 (decimal displayed only if required)
WCC Map Sheet	Text	Wollongong City Council Map Index Reference
Suburb	Text	Suburb as per Gregory's Street Directory1991
ISG Position Easting	Number	ISG Easting grid position to centre of back scarp
ISG Position Northing	Number	ISG Northing grid position to centre of back scarp
Dimension	Text	Width across the slope in metres, Length up/down slope in metres
Area	Number	Area in square metres covered by the instability (from WCC GIS)
Depth used for volume	Number	Depth used for volume calculations, an average, known or guessed, in metres
Location	Text	Location to aid geographic positioning for other workers
Site Description	Text	Physical description of site to aid detail positioning for other workers
Site Status	Number	What is the current status of the site? Select from options list.
Ground slope	Number	Local area average ground slope. Select from options list.
Author of original entry	Text	Name of original author of this entry
Record entry date	Date/Time	Date of entry of this record (dd/mm/yy)
Varnes classification	Text	Varnes 1978 Types of Slope Movement classification
Nature of Instability	Number	Natural or man made. Select option, 1 or 2 recorded
Primary Instability Type	Text	Select from list or enter own
Secondary Instability Type	Text	Select from list or enter own
What is the relationship to ra	Text	What is the relationship between movement and rainfall
Comments	Memo	Addendum to any of the above
Current Site	Yes/No	Is this site still a current site or has it been superseded, see comments

SUSCEPTIBILITY, FREQUENCY AND LANDSLIDE HAZARD

The sloping escarpment terrain of the WLGA is prone to slope instability. The susceptibility to landsliding varies significantly across the region and even within each suburb. The Landslide Inventory highlights 569 sites of instability with a total of 958 'events', including first time and subsequent re-activations at many sites. In addition to these known sites of instability a Borehole Database comprising 748 boreholes has been developed from available records of drilling by different companies. The record of this Borehole Database, combined with wide local experience, confirms the almost ubiquitous presence of a colluvium layer blanketing the escarpment slopes. The estimated average colluvium thickness on the basis of available information is 3.5m. However, the colluvium thickness varies significantly across the WLGA and within each suburb.

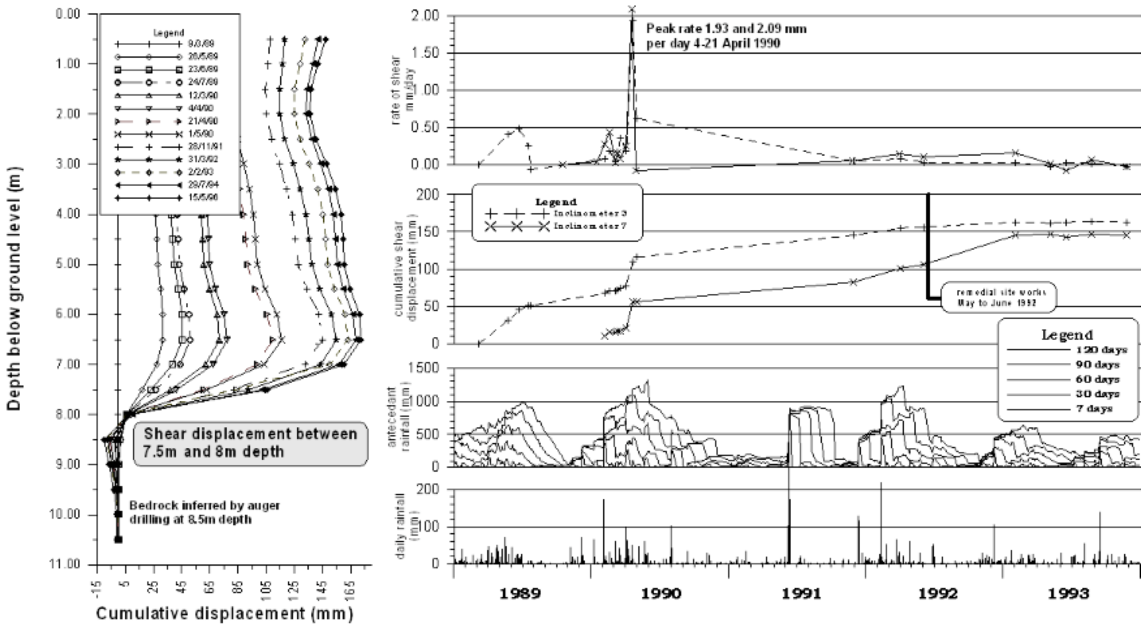
The Landslide Inventory has been used to determine site-specific landslide frequencies using the recorded dates of each landslide occurrence and of any recurrences. The frequencies were determined by dividing the number of yearly recurrences of each landslide, by the total period covered by the land instability database, which is 118 years, extending from 1887 (for the first recorded site in the database), to the present 2005. The range of frequencies determined using this methodology ranges from 0.0085 to 0.15.

Three main categories of landslides have been recorded in the local area, namely slides, flows and falls. The volume of the slides range from several m^3 up to $600,000m^3$ and recorded slide velocities range from 'extremely slow' or 'creep' rates up to 'moderate' rates (Cruden and Varnes 1996). The maximum recorded depth to a slide plane is 17.5m, and the average depth is 7m. Individual debris flows range in volume from $20m^3$ up to approximately $8,000m^3$. Whilst no velocities have been recorded for the debris flow events, it can be assumed that they would travel at 'very rapid' velocities up to 5 m per second. Rockfalls range in volume from 10 m^3 up to 80,000 m^3 and, again although not documented, would travel at 'extremely rapid' velocities in excess of 5 metres per second.

MONITORING – PERIODIC

A total of 50 inclinometer casings have been installed and monitored during the last decade across the WLGA. The University of Wollongong currently monitors nineteen of these inclinometers at ten different landslide sites. The manual monitoring has been carried out by the University since 1993 and by others since the early 1980s. As an example, landslide site 64 is a slide category landslide with an area of approximately $5,000m^2$, a maximum depth of sliding of 7.5m and an approximate volume of $18,000m^3$. The crown of this landslide extends into the active track area of the dual electric railway line in the northern Wollongong suburb of Scarborough, and is located to the west of Site 355 (Figure 3). Subsurface remedial drainage slot drains, slope re-contouring and surface retaining structures were constructed during June 2002 by the State Rail Authority in a successful remediation strategy for the site. The manually monitored inclinometer profiles from borehole 3 near the crown of the landslide, for the period March 1989 to May 1996 are shown in Figure 4 (a). The cumulative magnitude and rate of displacement indicated by this record is shown as the dashed curve, together with daily rainfall and various antecedent rainfall curves in Figure 4 (b). The remedial works appear to have substantially slowed subsurface shear movement at this site.

The daily rainfall station nearest to this site with data for this period is 650m away at the Bureau of Meteorology Station 68223 at Reef Road Wombarra. A review of daily and cumulative rainfall data from this station, specifically for the period including 4th to the 21st April 1990, but also for the early April 1990 event and the April-May 1989 period together with the rate of landslide displacement data has enabled the estimation of landslide triggering rainfall thresholds for this site. Geotechnical consultants for the railways have suggested that landslide movement at this site could be triggered by one month rainfall totals exceeding 350mm and that movement would be maintained by subsequent monthly rainfall of 230mm.



(a) (b)

Figure 4. Manual monitoring record for Site 64 (a) Manual Inclinometer Profiles and (b) Cumulative and rate of displacement graph for displacement at 6.5m depth with daily and cumulative rainfall.

CONTINUOUS REAL-TIME MONITORING (CRTM) LANDSLIDE FIELD STATIONS

CRTM Station Summary

Currently five CRTM landslide field stations have been installed, four within the Wollongong Region, and one at a landslide site within the Geelong LGA, in south-western part of the state of Victoria, Australia. The stations are all powered by small solar panels which charge 12 Volt 7.0 Ah sealed lead-acid batteries housed in Campbell Scientific PS/12 Power Supply/regulator units. Tele-communications are performed by digital cellular mobile phones. Data logging and on-site data management is carried out with Campbell Scientific Inc CR10X data loggers. Slope Indicator has bundled these systems together and supplied them to the University of Wollongong including the programming for the CR10X data loggers. Slope Indicator staff have completed the CR10X programming incorporating our research-based landslide triggering rainfall thresholds.

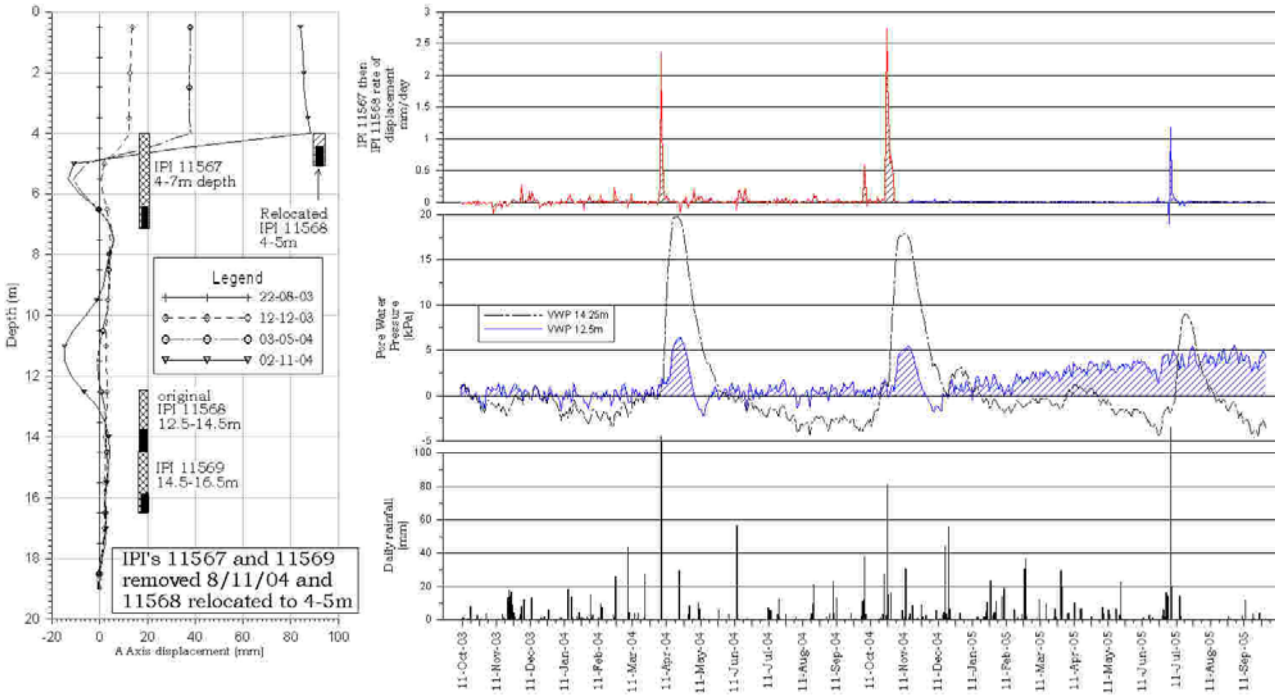
The instruments used so far in the Wollongong applications include In-Place-Inclinometers (IPIs) and vibrating wire piezometers (vwp) installed at depth in boreholes. Convergence monitors acting as Extensometers across ground surface landslide tension cracks have also been used in the Geelong application. Rainfall Pluviometers have been installed at all the field stations to record rainfall as it occurs (0.2mm or 0.5mm bucket tips). A discussion concerning the installation of inclinometer casing and vibrating wire piezometers is beyond the scope of this paper. However, it is worth noting that the IPI instrument itself is approximately 44cm from wheel to wheel centre and approximately 38.2mm in diameter. These dimensions highlight two important points. Firstly, the 38.2mm diameter of the IPI within the 58.5mm ID of the standard 70mm OD inclinometer casing allows for 20mm of casing deflection before the IPI starts to get tight in the casing. Secondly, the length of the instrument can be extended by the addition of a length of stainless steel tubing to achieve whatever gauge length is required. Experience has shown that the gauge tubing easily bends thereby masking actual shear displacement of the inclinometer casing. Therefore, ideally, the monitored IPI instrument length (instrument itself being 44cm plus any additional gauge tubing) should be kept to a minimum. In Figure 5 (a) IPI instrument and gauge lengths are indicated by black rectangles and hatched rectangles respectively.

An additional group of stations are now being developed along a major transport corridor within the WLGA study area.

CRTM Field Station Example

Site 355 is a deep-seated slow moving 'slide' category landslide with a volume of approximately 35,000m^3. A limited geotechnical investigation of this landslide, carried out by the University of Wollongong, has shown that this landslide has the potential to move rapidly. Thus it could possibly adversely affect some of the houses that lie immediately upslope of and/or within the crown area of the landslide. The consequences of such landsliding at this site represent, as a worst case scenario, a high risk of loss of life for several specific adjacent residential dwellings. This assessment was an important factor that resulted in the construction of this continuous monitoring station in mid 2003. Three IPIs, two vibrating wire piezometers and one rainfall pluviometer were installed at the site. Following a review of past movement at this site, prior to continuous monitoring, it was determined that rainfall totalling 130mm in 24 hours in combination with a 330mm 60 day cumulative total would trigger landslide movement at this site. The manual and recent continuous monitoring at this site is facilitating more accurate estimation of landslide triggering rainfall thresholds.

Manual inclinometer profiles recorded from Borehole 2 at the site, as shown in Figure 5 (a), have confirmed that the depth of sliding in borehole 2 is between 4 and 5m depth. The continuous monitoring record of Site 355 is shown as Figure 5 (b).



(a) (b)

Figure 5. Site 355 Monitoring History. (a) Manual inclinometer profiles, Borehole 2 showing location of IPI instruments with gauge lengths, and (b) Continuous data – 11th October 2003 to 30th September 2005. Rainfall, pore water pressure and landslide rate of shear.

The three original IPIs have been reduced to one and this instrument is now providing excellent data. The IPI 11567 rate of shear displacement curve in Figure 5 clearly displays two prominent spikes of accelerated displacement commencing on the 4th April and the 21st October 2004. The movement event, which commenced on the 4th April, continued for 5 days and peaked at 2.4mm per day. This was triggered by rainfall of 110mm and 106mm on consecutive days.

The movement event, which commenced on the 21st October 2004, lasted for 7 days and peaked at 2.5mm per day on the second day. A maximum daily rainfall of 81.5mm and several other days of 15mm to 30mm triggered this short duration of movement. This event is discussed again in a following section and is shown in Figure 8 where it is plotted with hourly logged data.

ESTABLISHING PRELIMINARY LANDSLIDE TRIGGERING RAINFALL THRESHOLDS

The historical rainfall record and Intensity Frequency Duration (IFD) plots

The historical frequency and duration of rainfall intensity determined from the rainfall record at any rainfall station can be graphically presented as an Intensity Frequency Duration (IFD) plot, as shown in Figure 6. The average, or expected, value of the periods between exceedances of a given rainfall total accumulated over a given duration, is known as the Average Recurrence Interval (ARI discussed fully in Pilgrim 1998 and Pilgrim and Doran 1998). The

ARI for 14 cumulative periods, ranging from 3 hours to up to 30 days, has been determined for selected locations in Wollongong. For example, Figure 6 represents such a plot for the data from the Bureau of Meteorology Rainfall Station 68108 in the northern Wollongong suburb of Woonona (location shown in Figure 3). ARI curves have been prepared for 1, 2, 5, 10, 20, 50 and 100 years. This rainfall analysis was completed for the University of Wollongong by the Bureau of Meteorology (BOM) Hydrometeorological Advisory Service (HAS) one year after the August 1998 rainfall event.

Brief review concerning rainfall thresholds for landsliding

For rainfall-triggered landslides, landslide triggering rainfall can also be presented as a relationship between rainfall intensity and duration. For example, in a benchmark paper, Caine (1980) reported on the relationship between threshold rainfall intensity and duration on the one hand and the occurrence of shallow landslides and debris flows on the other. Caine summarised the data from a selection of 73 international reports of shallow landsliding and proposed a landslide triggering threshold rainfall curve in the form:

$$I = 14.82 \times D^{-0.39}$$

where I is the rainfall Intensity in mm per hour and D is the duration of rainfall in hours. This curve is also shown in Figure 6 as a dotted line. Any combination of I and D that plots below this curve will not trigger landsliding. Plotting this type of curve with the IFD curves in the background allows the ARI to be determined for any combination of rainfall intensity and duration.

Two types of landslide triggering rainfall thresholds may be considered, regional thresholds and site-specific thresholds. Thresholds of both types have been developed for the Wollongong area, and an example of each is summarised below.

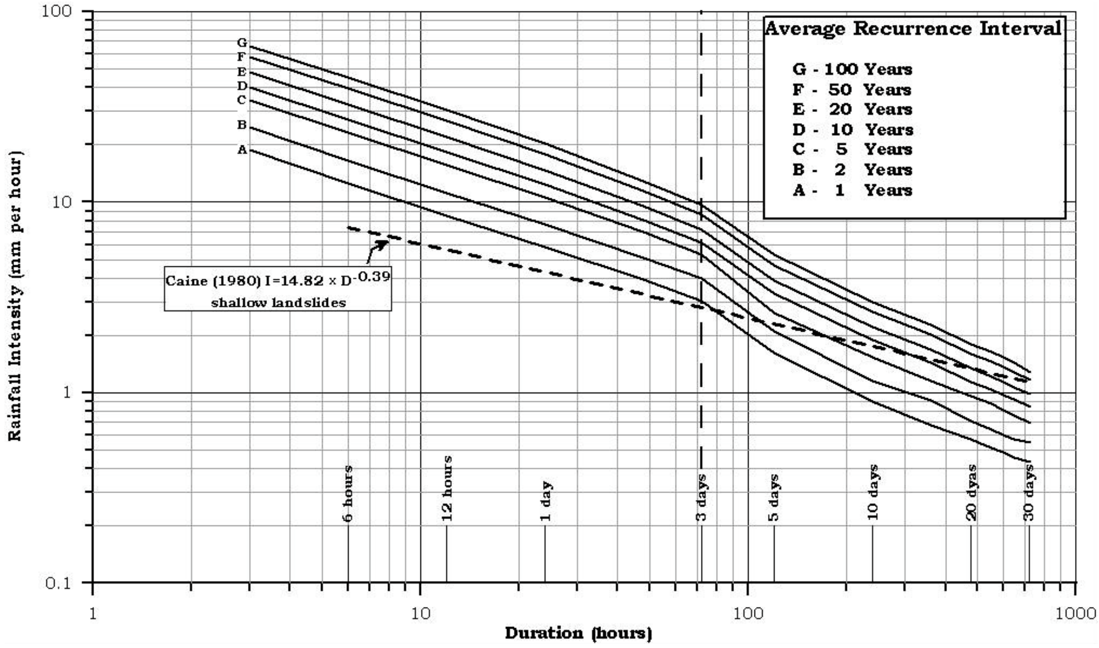


Figure 6. Rainfall Intensity Frequency Duration Analysis of the historical record for a rainfall station Woonona Rainfall Station 68108. The standard analysis up to 3 days is shown representative of a single contributing rainfall event with duration up to 3 days. Multiple contributing rainfall events may be involved for the periods of 5 days up to 30 days. Caine's 1980 threshold for shallow landsliding also shown.

Overview of the extreme 5 day rainfall event 15th – 19th August 1998 which affected the WLGA

The rainfall event extended from 6 p.m. Australian Eastern Standard Time (AEST) on Saturday 15 August to 6 p.m. AEST on Wednesday 19 August 1998. The highest rainfall total was 745mm recorded at Mt Ousley. Extremely heavy rainfall occurred on 17 August 1998 between 5 p.m. and 8 p.m. causing flash flooding with extensive damage to property and the loss of one life. Up to *5* p.m. on 17 August the rainfall total was 375mm over 47 hours. From 9 am Monday 17 August to 9 am Tuesday, 18 August the rainfall total was 445mm. Average recurrence intervals exceeding 1 in 100 years were determined for durations between 30 minutes and 24 hours along the top of the escarpment between Mount Ousley and Bulli Pass (Evans and Bewick, 1999). Post 5pm on the 17th August and in the weeks following the event, 142 landslide locations were recorded and each site was inspected and mapped (GTR, 1998). Of these 142 landslides, 72 were previously known and therefore reactivated landslides, whilst 70 were new first time failures. Research carried out in the years following this August 1998 storm event confirmed that rainfall intensity had significant spatial variability for a wide variety of durations.

A regional intensity frequency landslide triggering rainfall threshold for Wollongong based on the August 1998 event.

The spatial and temporal distribution of the rainfall that occurred during and prior to this extreme August 1998 event has been analysed extensively with the aid of GIS whereby a series of interpolated 10m × 10m grids based on the recorded rainfall at each of the 147 rainfall stations (including 36 pluviometers) within the region. Therefore, the interpolated cumulative rainfall at the centre of each landslide has been determined. The spatial distributions of cumulative rainfall over different antecedent time periods have been analysed with the aid of the GIS. The antecedent time periods of 6 and 12 hours prior to 7pm on the 17th August and 1, 3, 5, 7, 30, 60, 90 and 120 days prior to 9.00am on the 17th, 18th and 19th August have been considered in the various analyses (Grootemaat 2000, Murray 2001). Figure 7 shows the rainfall magnitudes for each antecedent rainfall period (one bar for each period) as a series of 142 crosses (one cross for each landslide site per vertical bar) making up each vertical bar. The curve extending across the graph near the base of each vertical bar is, therefore the lower bound 'regional threshold' for the city of Wollongong for the extreme August 1998 event.

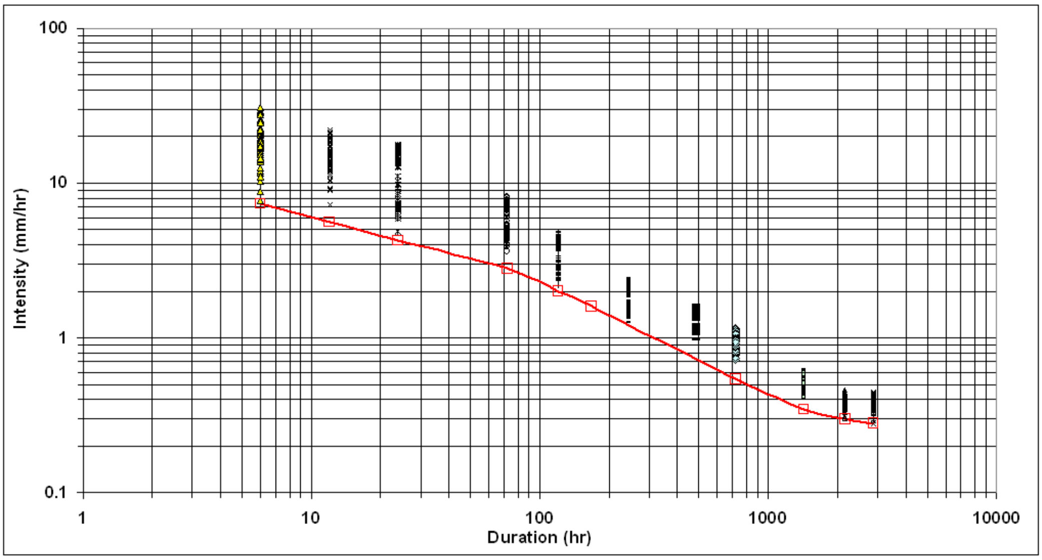


Figure 7. The lower bound 'regional landslide triggering rainfall threshold' for the city of Wollongong during the extreme August 1998 event.

Continuous Monitoring record for Site 355 during October 2004 movement event

As discussed in the CRTM section above, the continuous monitoring of Site 355 has recorded three episodes of accelerated movement. Careful and detailed examination of the October 2004 data (Figure 8) confirm that the landslide commenced movement at 3am on the 21st October, accelerated to a peak daily displacement of 2.53mm per day at 7am on the 22nd October 2004 and continued to move for a period of at least 7 days. The associated 6 hourly, daily and cumulative rainfall has also been tabulated for this event together with the other two accelerated movement events recorded at this site. This data is helping to refine the site specific landslide triggering rainfall threshold for this site and providing highly accurate data such that magnitudes of displacement can be considered along with triggering rainfall.

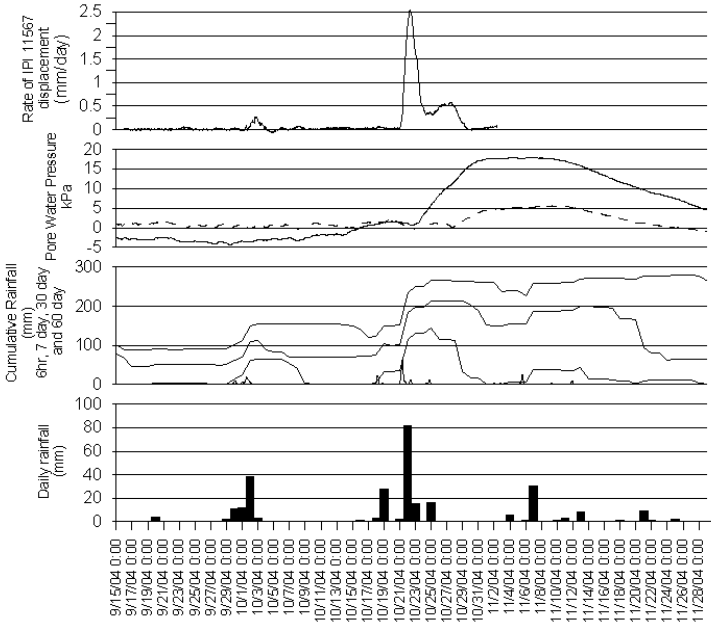


Figure 8. Continuous Monitoring record of Site 355 15th September to 29th November 2004.

REGIONAL LANDSLIDE TRIGGERING RAINFALL THRESHOLDS

Regional rainfall triggering landslide thresholds are presented in Figure 9 as a summary based on all the research carried out by the Landslide Research Team at the University of Wollongong over the last decade. Some of this research has been summarised in this paper. It is important to note that the thresholds proposed here encompass the wide variety of flow and slide category landslides within the WLGA. Furthermore, it is also important to reiterate that site specific thresholds for individual landslides may be significantly different in magnitude to this regional threshold.

The University of Wollongong research, supported by others internationally (Caine, 1980, Wieczorek 1987), confirms that the shorter duration thresholds (6 hours to 3 days for this study area) are most relevant for shallow debris flows and shallow slides whilst the longer duration thresholds (up to 90 days for this study area) are most relevant for deeper seated slide and slide-flow category landslides.

The upper dotted curve, the UOW 2005 Trigger, represents the rainfall intensity which would trigger landsliding. This curve 2005 is primarily based on the August 1998 threshold discussed previously and shown in Figure 7 but also supported by previous periodic inclinometer monitoring assessments and also by correlations between reported disruptive landslide occurrences and rainfall records from nearby rainfall stations.

There are two Warning thresholds and these have been developed to aid the management of the CRTM field stations, as discussed in the following section. In general, as the rainfall intensity increases the reporting frequency of the CRTM stations should also increase.

The UOW 2005 Warning curve is based on previous pre-1998 research work but has been modified on the basis of early results from the CRTM field stations. The UOW 2005 2nd level Warning has been set approximately half way between the UOW 2005 Warning and Trigger level to bring the CRTM stations to a maximum reporting frequency to provide regular 4 hourly updates of site performance. This has been set as an optimum reporting frequency at the current stage of research. The increase in frequency has to be offset against the cost of mobile phone calls.

CRTM FIELD STATION AUTOMATION

The two warning curves have been programmed into the CRTM field stations. With pluviometric logging of rainfall on site, the rainfall thresholds are used to control the reporting frequency of the CRTM field stations. In low rainfall conditions, with intensities below the UOW 2005 Warning threshold, the CRTM field stations record data hourly and call in weekly to download the data logger record of monitoring data, as the default schedule. With rainfall intensities below this level, no landslide activity is expected. When rainfall intensities exceed the UOW 2005 Warning threshold at two points (6 hour, 24 hour, 3 days, 7 days, 30 days, 60 days or 90 days) the CRTM field stations recording interval is decreased to 5 minutes and the call in frequency to download the data logger record of monitoring data is increased to 24 hours. When rainfall intensities exceed the UOW 2005 2nd level Warning threshold at any two points on the curve as set out previously, the CRTM field stations call-in frequency to download the data logger record of monitoring data is increased to 4 hourly, currently the most advanced status of the stations.

Additional reporting frequency controls governed by magnitudes of displacement per period are also being implemented.

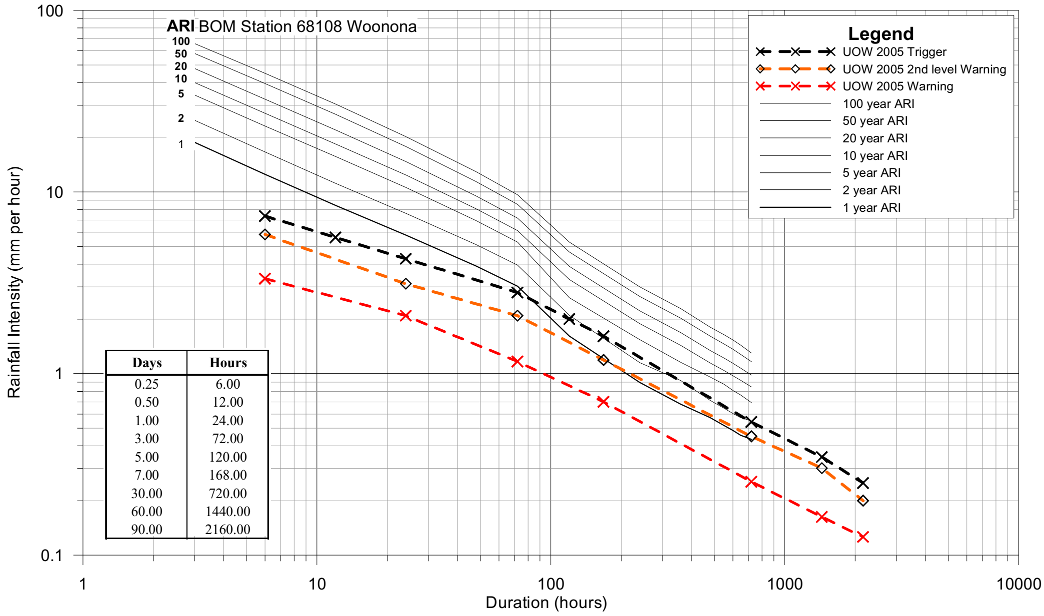


Figure 9. University of Wollongong proposed regional rainfall triggering landslide thresholds.

CRTM Web-Based Data Management and Data Display as a Risk Management Tool

Each of these five stations telephones in to a computer server housed in a temperature controlled secure room with backup power at the University of Wollongong. The incoming CRTM calls to the University computer server are managed by the Campbell Scientific Inc. 'LoggerNet' software to deposit inbound data files into designated directories on the computer server. Processing of the live data as it arrives in the server directories from LoggerNet is achieved with a range of tasks resulting in the data being assembled in a MS Access database in 'graph ready' format. Using the ASP.NET framework with a database created in MS Access, the landslide research team in collaboration with the University of Wollongong Centre for Educational Development and Interactive Resources (CEDIR) has developed web-based software to provide real-time graphical updates of the incoming data momentarily as it arrives from the field stations.

The web-based facility is available via the University of Wollongong web portal available at http://landres.uow.edu.au/ls/index.html. At present the five sites are available and the web facility enables a quick one click graphical overview of the most recent two weeks of data for each site (hourly rainfall, In Place Inclinometer cumulative displacement, In Place Inclinometer rate of shear, In Place Inclinometer Azimuth of movement, and Pore Water Pressure). Other options enable automated graphic output of all landslide performance data in the online databases.

Access to the web portal is password protected and limited to senior Geotechnical and Engineering Management staff of industry partners of this research project including the Wollongong City Council, the Roads and Traffic Authority of New South Wales, and the New South Wales Rail Corporation.

DISCUSSION

The definition and scope of an "observational approach" for landslide risk management have been outlined in this paper. This approach is part of a comprehensive research program which has been developed over 10 years with particular application to the WLGA. Details and examples of some important aspects of this comprehensive approach have been presented in this paper. Aspects of the project that have been discussed include the GIS-based Landslide Inventory, Periodic Inclinometer monitoring, Continuous real-time monitoring of landslides with real-time availability of data via the World Wide Web and the development of Landslide Triggering Rainfall Thresholds.

Due to space limitations our extensive work on the successful development of GIS-based methods and techniques for andslide Susceptibility and Hazard Mapping have not been included here. However, this is also an important component of the observational approach as the Landslide Inventory is an essential component in the development of the Susceptibility and Hazard mapping. Whilst such Susceptibility and Hazard Mapping, and indeed Risk Maps play an important role in Landslide Risk Management, such maps are not fully capable as predictive tools particularly during landslide triggering events such as extreme rainfall events. Observational techniques such as described in this paper play a key role in developing an understanding of landslide processes and triggering mechanisms. In addition, such observational techniques with real-time access to continuous performance monitoring data are essential during emergency risk management situations.

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