A Review of Slope-specific Early Warning Systems for Rain-induced Landslides

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Preface

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H.N. Wong
Head, Geotechnical Engineering Office
October 2015

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Foreword

This Technical Note summarises case histories of slope-specific early warning systems for rain-induced landslides. Geological settings of landslide sites, landslide types, instrumentation employed in monitoring schemes, and alert criteria considered in these case histories are presented. The applicability of slope-specific early warning systems in the context of Hong Kong is discussed, and potential areas worth further study are recommended.

The study is carried out as part of a review of the SafeLand's reports. SafeLand is a large-scale collaborative research project on landslide risk management. The project is funded by the European Commission, involving contributions from landslide experts of 13 European countries. Early warning of landslides is one of the major topics studied under the SafeLand project. Deliverables under Work Package 4.3 "Evaluation and Development of Reliable Procedures and Technologies for Early Warning" of the SafeLand project provide a major source of information for the present study.

This study was initially undertaken by Dr Mark H.C. Chan and later by Mr W.W.L. Shum and Dr Julian Kwan. Drafting unit of the Standards and Testing Division assisted in formatting this report. Draft of this Technical Note was circulated within GEO, and many insightful comments were received. Contributions from all parties are gratefully acknowledged.

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Abstract

This Technical Note (TN) reviews overseas slope-specific landslide warning systems which are implemented to give early warning of rain-induced slope instability. Geological settings, hazard types, parameters monitored, instrumentation used, landslide forecasting methods, triggering thresholds, means of warning dissemination and emergency preparedness plan of the systems are examined. A general overview of the current practice on the establishment and application of the early warning systems is also provided.

Overseas experience shows that slope-specific landslide early warning systems are carried out for large-scale slopes that show signs of distress or have a history of slow-moving failures. Nevertheless, forecasting when a part or the whole of a slow-moving landslide mass would turn into an uncontrolled, mobile failure remains a technical challenge.

In Hong Kong, majority of the landslides are small-scale and they usually involve brittle failures that happen with no or very little warning. Furthermore, clear targets for monitoring small-scale landslides are very difficult to identify, and there may not be sufficient lead time for emergency actions. Therefore, it is considered not practical or effective to carry out monitoring of all slopes in Hong Kong for the purpose of giving landslide warning.

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1 Introduction

Landslide early warning systems have been adopted overseas as landslide mitigation measures. The landslide early warning systems can be broadly classified into two types: (i) regional system, and (ii) slope-specific system. Regional systems have been operated in many places including Hong Kong, Japan, Italy and Brazil (Yu et al, 2004; Osanai et al, 2010; Tiranti & Rabuffetti, 2010; Ortigao, 2000). In these systems, rainfall thresholds for triggering landslide warning are determined on the basis of observed relationships between intensity and duration of rainfall and the occurrence of landslides. A regional landslide warning system usually covers a large area and it is normally used for providing general warning to arouse public awareness of landslide hazards and triggering stand-by emergency service during inclement weather. The system is not established to provide information on precise landslide locations or facilities that could be affected by landslides.

In contrast to the regional system, a slope-specific system is established to monitor a particular slope or hillside to give early warning of landslide to stakeholders (e.g. residents within the landslide hazard zone or emergency control authorities). The number of cases of using slope-specific early warning system in Hong Kong is limited, since landslides are mostly small-scale and brittle failures which occur with little pre-failure deformations. Monitoring of slow moving landslides in Tuen Mun Borrow Area 19 and Lai Ping Road slope failures are two examples in Hong Kong (Wong et al, 2006).

This report focuses on the slope-specific landslide warning system which is established to give early warning of slope instability. It serves to provide a general overview of the current overseas practice on slope-specific landslide early warning system. Reports, published papers and relevant materials pertaining to slope-specific systems which are in use overseas are reviewed. The early warning systems which are established rigorously are included. Cases where temporary early warning systems that are set up urgently during emergency repair works are not considered. Besides, site-specific early warning of debris flow hazards and monitoring for other purposes, such as health monitoring and R&D monitoring for improving understanding of ground response and slope behaviour are excluded. The cases examined in this study are by no means exhaustive due to accessibility of information.

According to Bazin (2012), a complete early landslide warning system should comprise elements including (i) knowledge of risks, (ii) monitoring and forecasting of hazards, (iii) communication and dissemination of warnings, and (iv) community response capability. In this review, geological settings, hazard types, parameters monitored, instrumentation used, landslide forecasting methods, triggering thresholds, means of warning dissemination and emergency preparedness plan of the overseas slope-specific landslide early warning systems are examined.

2 Review of Slope-specific Landslide Early Warning Systems

2.1 General

Deliverable 4.6 (Baron et al, 2012) and Deliverable 4.8 (Bazin, 2012) prepared under Work Package 4.3 "Evaluation and Development of Reliable Procedures and Technologies for

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Early Warning" of the SafeLand Project provide a major source of information for this study. In addition, relevant international journals and publications were also reviewed. The United States Geological Survey had been approached for obtaining any available information of slope-specific landslide early warning system being used in the US. Information on systems implemented in different overseas countries has been retrieved. Essential information including the potential volume of landslide failure, failure type, deformation characteristics, possible contributing factors of the potential landslide, monitoring parameters, instrumentation used and key parameters adopted in establishing alert/threshold levels for early warning purposes is summarised in Table 2.1. Details of each of the cases reviewed are presented in Appendix A. There are a few other overseas slope specific early warning systems, such as those adopted in South Korea (Chang et al, 2007) and Scotland (Winter et al, 2008), which have been reviewed as part of the study. However, they are not included in Table 2.1 because full details of these systems are not available. As those cases pertain to the subject of this study, information available has also been documented in Appendix A (see Section A.13).

2.2 Features of Slopes under Monitoring

All the slope-specific early warning systems summarised in Table 2.1 were developed for distressed slopes with precedent landslides or reported instability. The volumes of the potential landslides are massive, ranging from 25,000 m^3 to 180 Mm^3. Large scale slope stabilisation works or landslide mitigation works in these cases could not be feasible, and at the same time landslide risk could not be reduced by means of, for example, relocating facilities affected in the potential debris inundation zone.

All of the slopes, except Mt Ruapehu, New Zealand, monitored in the early warning systems have known signs of instability or deformations. Reported rates of movement, ranging from several millimetres to hundreds of millimetres per year, are used as reference for alert level of early warning system. The reported rates of movement could be considered slow and the slopes exhibited creeps rather than a brittle type of failure. However, for the Mt Ruapehu case, alert levels based on the water level of the Crater Lake were established using the data of a similar failure incident occurred before.

2.3 Monitoring Parameters

One of the crucial issues to be addressed when setting up an early warning system for a slope is to identify monitoring parameters which can indicate or predict precisely the time of failure of the impending landslide mass. Successful monitoring of these parameters could mitigate landslide hazard by triggering early warning with sufficient lead time for emergency responses. In the cases reviewed by this study, even though geotechnical investigations were carried out, the failure mechanisms and landslide triggers are still difficult to be accurately identified. This is largely due to the inherent geological variations involved in these massive-scale slopes that are not completely understood or cannot be fully revealed by limited geological investigations.

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Table 2.1 Summary of Cases Reviewed

Site	Type of Potential Failure	Potential Failure Volume	Deformation Characteristics	Major Contributing Factor	Monitoring Parameter and Instrumentation																Key Parameters Used in Establishing the Thresholds of Early Warning	Remarks
					Displacements and Deformations								Hydrogeological and Meteorological Parameters						Geophysical Parameters			
					inclinometer	crack width measurement/laser	GPS	total station/theodolite	ground based InSAR	extensometer	tiltmeter	brillouin optical time domain reflectometer	piezometer	thermometer	raingauge	flow meter	barometer	water level senor	down-hole resistivity meter	geophone		
Ancona, Italy	Deep-seated landslide in soils	180 Mm^3	Noticeable displacement after heavy rainfall (e.g. in February to April 2011, a displacement of 4 to 8 mm was recorded)	Rainfall, high groundwater level	x		x				x		x	x	x	x			x		Groundwater level	
Bagnaschino, Italy	Deep-seated landslide in soils	1.2 Mm^3	Noticeable displacement after heavy rainfall (e.g. in March to April 2009, a displacement of 700 mm was recorded)	Perched groundwater	x		x	x					x		x				x		Rainfall intensity; rainfall duration	
Casella, Italy	Deep-seated landslide in soils	30 Mm^3	Noticeable displacement after heavy rainfall (e.g. in wet season of 2004, a displacement of 13 mm was recorded)	Rainfall, high groundwater level	x								x		x						Groundwater level; displacement	
Rosano, Italy	Deep-seated landslide in soils	3.6 Mm^3	Noticeable displacement after heavy rainfall (e.g. in wet season of 2005, displacement of 4 mm was recorded)	Rainfall	x								x	x	x						Groundwater level; displacement	Temperature at sub-surface is measured to determine the location of infiltration
Ruinon Rockslide, Italy	Rock avalanche	20 Mm^3	Continuous deformation at an average rate of 300 mm/year detected	Rainfall and snowmelt		x	x		x	x					x						Rate of deformation	
Aknes, Norway	Rock avalanche	54 Mm^3	Continuous deformation at a rate of 60 - 80 mm/year detected	Rainfall and snowmelt	x	x	x	x		x	x		x	x	x					x	Rate of deformation	Geophone is used to detect ground vibration induced by rockfall
Mannen, Norway	Rock avalanche	20 Mm^3	Continuous deformation at a rate of 20 mm/year detected	Infiltration of surface water			x		x	x			x	x	x						Rate of deformation	
Turtle Mountain, Canada	Rock avalanche	5 Mm^3	Continuous deformation at a rate of 5 mm/year detected	Groundwater pressure in rock joints		x	x	x	x	x	x			x	x		x				Rate of deformation	
Illawarra, Australia	Deep-seated landslide in soils	25,000 m^3 to 30,000 m^3	Noticeable displacement after heavy rainfall (e.g. in the wet season of 2005, displacement of 2 mm/day was recorded)	Rainfall	x		x						x		x						Rainfall intensity; rainfall duration	
Wushan Town, China	Deep-seated landslide in soils	Not reported but the potential slip plane could be 30 m below ground	Continuous deformation at a rate of 24 mm/year detected	Water level of the river in front of the slope	x		x					x	x		x			x			Rate of deformation; porewater pressure; ground strain	Water level senor is used to measure the water level of the river in front of the slope
Xintan Town, China	Deep-seated landslide in soils	33 Mm^3	Continuous deformation at a rate of maximum 10 mm/year detected	Rainfall				x													Rate of deformation	
Mt Ruapehu, New Zealand	Deep-seated landslide in soils	Not reported	Deformation is closely related with the water level of the Crater lake	Water level in lake immediately adjacent to the slope														x		x	Water level in the lake adjacent to slope	Water level senor is used to measure the water level of the lake adjacent to the slope

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From the review, movement and deformation of the impending groundmass are considered as the most relevant monitoring parameters. Increase in groundwater level due to rainfall or snowmelt could also be one of the most common triggers of landslides in many of the twelve cases in Table 2.1. Therefore, deformations and hydro-meteorological parameters such as precipitation amount and pore-water pressure were monitored. In addition, study of the correlation between kinematic parameters (i.e. velocity and acceleration of deformations) and the hydro-meteorological parameters were carried out. Temperature is considered important in some of the cases involving rock slope stability, as it may control the thermal expansion and contraction of the rockmass.

Apart from monitoring deformations and hydro-meteorological parameters, geophysical parameters including ground resistivity and ground vibration were monitored in some of the cases. Ground resistivity was found useful for providing clues of groundwater flow path and the location of aquifer. However, as commented by Baron et al (2012), interpretation of ground resistivity data may not be straightforward, and the potential to establish thresholds based on ground resistivity for early warning purposes should be subject to further investigation. Landslide failure would induce ground vibrations, therefore, the early warning systems implemented at Aknes, Norway and Mt Ruapehu, New Zealand included geophone monitoring with an aim to providing corroborations to ascertain the occurrence of slope failure.

The monitoring schemes shown in Table 2.1 share a common feature, which is redundancy. Instruments used in monitoring were usually deployed in extreme environments and break-down of instrument was not uncommon. In addition, signals transmission may suffer from interference of noise which impairs the signal quality. The intention of redundancy is to provide different independent signal pathways for back-up purposes. In addition, readings from different monitoring stations could complement each others, and this may provide additional information for counter-checking purposes.

2.4 Monitoring Instrumentation

Response time and reporting frequency of the monitoring instruments used are critical to the success of any emergency plan. If the instruments are not sensitive to changes of the parameters being monitored, timely alert would not be given. In addition, measurement accuracy of instruments is important. Kinematic parameters (i.e. rate of deformation) including velocity or acceleration of slope deformation have been adopted as the primary warning triggering parameters in most of the cases summarised in Table 2.1. Absolute displacements, however, are seldom adopted as warning thresholds. Deformation velocity or acceleration is usually interpreted from the time series of deformation readings, which can be obtained by using instruments such as inclinometer, wire extensometer, tiltmeter, GPS sensor, total station, ground based InSAR etc.

Blikra & Kristensen (2012) compared the reliability of displacement data obtained from different sensors at Aknes, Norway. The GPS sensor was reported to be robust and reliable to provide near real-time data. GPS sensors had also been used for monitoring movements of a hillside in Hong Kong (Lau et al, 2008). The extensometers were able to capture local displacement within the landslide body and provide information of the movement to supplement the GPS data. Movements of extensometer are restricted by a

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maximum limit and beyond which the extensometer would fail. Total stations used in the Aknes site were operated using a robotic system which enables automatic data collection. However, Blikra and Kristensen reported that the total station measurements could be adversely affected by weather conditions (e.g. rain, fog, snow).

Agliardi et al (2012) reported the monitoring scheme of the early warning system for Ruinon rockslide. They commented that ground based InSAR was a high efficiency technique for monitoring surface deformations. Displacement time series extracted from ground based InSAR provides sufficiently frequent data which cover a large extent of the hillside concerned.

To facilitate accurate establishment of the rates of deformation, the monitoring frequency of the displacements has to be sufficiently high (Supper et al, 2012). To this end, accelerometer, which measures the rate of deformations direct, might provide a practical solution. The accelerometers now available in the market are low-cost, small in size and capable of transmitting measured data wirelessly. Ooi et al (2010) conducted laboratory experiments to demonstrate the applicability of accelerometers for detecting soil movements and onset of landslide. The potential of accelerometers for monitoring the kinematics of slopes may require further investigations. Besides, durability of accelerometers should also be addressed.

Yin et al (2010) presented an early warning system based on rate of deformation and ground strain. They used a relatively new monitoring technique, brillouin optical time domain reflectometer (BOTDR), for measurement of ground strain. BOTDR is a type of optical fiber sensing technique. Scattered light within the optical fiber will exhibit frequency shift when the optical fiber is subject to strain or temperature change. However, Shi et al (2008) remarked that the potential of using BOTDR for strain measurement may be constrained by the limited data resolution.

Recent research has paid attention to soil matrix suction for establishment of early warning of shallow failure of slopes. Laboratory studies on the performance of different instruments for direct or indirect measurement of soil matrix suction, including heat dissipating sensor, gypsum block sensor, TDR probe and tensiometer, have been conducted by Kwok (2011). The responses of the tested heat dissipating sensors and gypsum block sensors were slow and they could take up to 2,000 minutes to give stable readings. The response time of tested tensiometers to give a practically stable reading was in the order of 15 minutes to 30 minutes. The tested TDR probe was virtually instantaneous. However, TDR probes do not measure soil matrix suction directly. Kwok (2011) reported that the accuracy in the determination of soil suction based on the correlations with the measuring parameters by the tested TDR probe was not high. Greco et al (2010) carried out laboratory infiltration experiments on instrumented model slopes to study the hydraulic process leading to the initiation of slope failure. They reported that monitoring of soil volumetric water content seemed to be more useful than soil suction monitoring for early warning purposes, since water content increased gradually during the infiltration process while soil suction showed abrupt steep fronts.

The wireless data transmission technique becomes mature nowadays. In most of the cases reviewed, monitoring readings are transmitted from the sites using wireless system. The use of wireless system enables rapid deployment in difficult environments where cable

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laying could be difficult or even not feasible.

2.5 Establishment of Thresholds to Trigger Early Warnings

Velocity and acceleration thresholds are very often used as triggering criteria in the early warning systems (see Table 2.1). Establishment of thresholds pertains to prediction of the timing of the ultimate landslide failure (i.e. detachment of the landslide mass). In most of the cases reviewed in this study, thresholds were established based on expert judgements. Nevertheless, different theories of predicting the time of landslide failure have been proposed and applied by researchers.

Accelerating creep theory for prediction of landslide timing has been proposed by Voight (1988). Crosta & Agliardi (2003) applied the theory and the deformation data to establish the velocity thresholds for the Ruinon rockslide. The theory assumes that strain rate of the landslide mass is monotonically increasing, and that the ultimate failure would occur when strain rate shows a rising trend after a period of creeping at a constant strain rate.

The "inverse-velocity" theory described by Petley et al (2005) for examining the rate of progressive failure in cohesive materials had also been adopted for prediction of landslides. Rose & Hungr (2007) applied the theory to forecast failures of open pit mines involving landslide volume of over 1 Mm^3. The theory predicts landslide failure when the inverse of the velocity of the impending groundmass approaches zero.

Prediction of the occurrence of landslide would not be straightforward. As commented by Crosta & Agliardi (2003), although accelerating creep theory could provide physically meaningful indicators for prediction purposes, it only gives an order of magnitude of the time to failure. Any predictions provided by the theory should be supported by expert judgements taking into the consideration of the reliability of the monitoring network, the complexity of the displacement pattern and other external factors. In addition, threshold values should be subject to regular reviews taking into account relevant up-to-date observations (Moreno et al, 2011). Busslinger (2009) further cautioned that special attention should be paid to brittle materials where deformation prior to the ultimate failure could be very small, as they could make the prediction almost impossible. To this end, Baron et al (2012) remarked that early warning thresholds could only be derived at some sites.

3 Discussion

3.1 Slope Monitoring in Hong Kong

Overseas experience shows that slope-specific early warning systems are usually implemented for large-scale distressed slopes. These slopes have a track record of landslides and a majority of them are slow-moving. Long-term monitoring can track the behaviour of the slopes so that threshold values can be established and tested to set triggering levels for an early warning system. In addition to the setting up of triggering levels, a well-documented emergency plan is an essential element of the landslide early warning systems. Where possible, emergency drills should be carried out to foster the public resilience.

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Landslides in Hong Kong are mostly brittle and small-scale localised failures, although ductile mechanism is involved in some uncommon cases (e.g. the slope failure at Tin Wan Hill reported by Irfan (1986)). Brittle slope failures exhibit small or no signs of distress, which means they are lack of clear targets to monitor. Where targets for monitoring (e.g. tension cracks) are detected, small deformations are commonly encountered and they constrain the feasibility of giving early landslide warning. This is because the state of technology is still not able to reliably pick up small deformations (in the order of magnitude of several millimetres or below) precedent to brittle failure.

In addition to whether there are reliable signs of slope instability that can be detected, due consideration should be given as to whether it is practicable to initiate response actions in a timely manner. Local experience shows that slope failures could be fast-moving in nature. If the slope concerned is close to facilities, there may not be sufficient time to implement evacuation or other emergency measures after a warning is issued. Reliability of the landslide early warning system is also a critical factor that should be carefully considered. To forecast when a part or the whole of a slow-moving landslide mass would turn into an uncontrolled, mobile failure remains a technical challenge. False alarms will discredit the early landslide warning system and is detrimental to gaining the public's trust (Wong et al, 2006).

It is considered impractical and ineffective to carry out monitoring of all slopes in Hong Kong for the purpose of giving warning of impending danger. For slopes of relatively small size and in an urbanised setting with serious landslide consequence, if there are signs of instability, it would be more reliable and cost-effective to stabilise the slopes rather than adopting monitoring as a risk management strategy.

Although it may not be practical or effective to monitor all slopes in Hong Kong, monitoring of the slopes showing signs of prolonged, slow-moving deformations (i.e. ductile behaviour) and involving potentially large-scale failure that are difficult and costly to stabilize may be considered when there is significant public safety concern. However, due considerations should be given as to (i) whether a reliable early warning system and technically defensible alert criteria can be established, and (ii) whether if there is sufficient lead time to notify the affected parties for appropriate emergency responses. In addition, a well-documented emergency preparedness plan (e.g. role and responsibility of key action parties, evacuation routes, locations of gathering points, etc.) and a robust system of notification should be put in place. The affected parties should be consulted that they would accept the need to evacuate and are prepared to move when notified.

3.2 Potential Further Work

The following potential further work in the context of slope/landslide monitoring is suggested:

(a) Monitoring of slopes before implementation of upgrading/mitigation works

For slopes that are found to be not meeting the prevailing standards, before the commencement of the

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upgrading works, early warning system may be installed to monitor the stability of the slopes if the failure is ductile in nature and targets for monitoring (i.e. obvious signs of distress with slow persistent deformations) can be detected. In addition, before implementing any early warning system, key factors pertaining to the lead time for emergency actions and reliability of the warning system that can be established should be duly considered (see also the last paragraph of Section 3.1).

(b) Monitoring of debris-resisting barriers

Design of debris-resisting barriers may involve many uncertainties in parameters such as landslide debris volume, composition of debris materials and debris impact load, etc. For debris-resisting barriers that provide protection to facilities of high consequence affected by active natural hillside catchments, it would be prudent to provide alert by installation of monitoring system to detect landslide debris impacting on the barriers. The monitoring system should be carefully designed and planned such that a cost-effective monitoring scheme can be achieved. Arup (2011) discussed instrumentation which could be used for barrier monitoring.

(c) Monitoring for improving understanding of landslide mechanism

Majority of the rainfall-induced landslides in Hong Kong are shallow. Initiation of the shallow failures is primarily influenced by parameters such as groundwater levels, soil matrix suction, moisture content and volumetric water content in soil. Knowledge of the correlation between these parameters and the onset of shallow landslides could improve understanding on the landslide mechanism. Monitoring of changes of groundwater, soil suction, moisture content or volumetric water content at reference positions could provide useful information of general slope instability for study purposes. Furthermore, long-term monitoring of piezometers installed at strategic locations could also be carried out. The data collected would provide useful reference information on the long-term ground-water conditions and their responses to changes in rainfall patterns. These reference piezometers could serve as a tool/guide to help decision-making regarding potential landslides (particularly deep seated failures).

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4 Conclusions

Based on overseas experience, slope-specific landslide early warning systems are carried out for large-scale slopes that show signs of distress or have a history of slow-moving failures. Long-term monitoring can provide useful threshold values to be set and tested before an early warning system is developed and implemented. Landslide early warning systems can be effective on distressed slopes when there is a sufficiently long lapse of time between the on-set of threshold values and the occurrence of failure such that emergency response or action plan to mitigate the landslides can be timely executed.

In Hong Kong, a majority of the landslides involves brittle failures which happen with no or very little warning. In addition, clear targets for monitoring cannot be identified easily. Many slopes in Hong Kong are located at close proximity to densely used facilities. As slope failures could be fast-moving in nature, lead time for emergency actions could be limited. Over-generalisation of the effectiveness of slope-specific landslide early warning system could be counter-productive to a pragmatic landslide risk management strategy and damaging with respect to gaining the public's trust (Wong et al, 2006). It is therefore considered not practical or effective to carry out monitoring of all slopes for the purpose of giving landslide warning. For slopes relatively small size and in an urbanised setting with serious landslide consequence, if there are signs of instability, it would be more reliable and cost-effective to stabilise the slopes rather than adopting monitoring as a risk management strategy.

However, monitoring of large-scale distressed slopes or natural hillsides which show obvious signs of distress and continuing deformation could be given consideration where there is significant public safety concern and the rate of deformation is low; and where the scale of the problem does not lend itself to be dealt with quickly by landslide prevention or mitigation works. Before adopting monitoring as the strategy for site-specific landslide risk management, work should be carried out to establish the practicality of implementation to achieve the objective of saving lives. The implementation of an effective slope instrumentation programme calls for a good understanding of the ground model, likely failure mechanisms, proper engineering analysis and the corresponding emergency preparedness and risk management system.

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Appendix A

Examples of Landslide Monitoring and Early Warning Systems

Contents

A.1 Ancona, Italy

A.1.1 Site Description

Ancona city, Italy is located on the East coast of the Adriatic Sea (Figure A1). On 13th December 1982, the Montagnolo hill at the northern part of the city started to slide towards the sea. It damaged private houses, strategic buildings and infrastructures; about 3000 people were urgently evacuated. Railway and main roads were blocked, and gas and water supplies were interrupted. The landslide involved about 180 millions m^3 of clay and silty clay layers (Pliocene-Pleistocene), with different OCR parameters, alternated with thin sand layers. The instability was caused by a rotational slip plane 120 m below ground (Cotecchia, 2006). The landslide scarp was identified at 80 m above sea level and the landslide toe was reported to be below the level of Adriatic Sea. Records of movements of the landslide body can be traced back to 1773. The landslide is prone to reactivation. For example, the landslide was reactivated in March 2011 after a persistent heavy rainfall event.

Based on advice from geological and geotechnical experts, the local authority considered that the use of slope remediation works to stop the landslide from reactivation was impossible due to cost and environmental reasons. The Ancona Administration therefore decided to implement an early landslide warning system.

Figure A1 General View of the Slope under Monitoring at Ancona, Italy (Supper et al, 2012)

A.1.2 Monitoring Parameters and Instrumentation Used

Table A1 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Sub-surface movement (c) Tilting	• Automatic total station • GPS tracker • Inclinometer • Clinometric sensors
Hydrogeological and meteorological parameters	(d) Groundwater level (e) Temperature (f) Rainfall depth (g) Surface runoff discharge	• Peizometer • Thermometer • Raingauge • Flow meter
Geophysical parameters	(h) Ground resistivity	• Down-hole resistivity meter

A.1.3 Establishment of Threshold Values for Issue of Early Warning

According to Supper et al (2012), movement of the landslide body has been found to be correlated well with rainfall depth, groundwater level and runoff discharge rate. Cardellini & Osimani (2008) reported that trigger of the landslide warning was primarily counted on the groundwater level data. Four warning levels were established. Decision to issue a landslide warning also relies on other parameters including ground movement and meteorological data. For example, movement at 120 m below ground was once picked up by the monitoring system. However, on the basis of other monitoring data and expert judgment, it was considered that the movement could be due to the change in humidity in that particular season, and hence no early warning was issued.

A.1.4 Response Plan and Preparedness of Stakeholders

All monitoring data are transmitted every 30 minutes to the control centre in the Town Hall. Cardellini & Osimani (2010) mentioned that there is a "civil protection plan". However, details of the plan are not reported.

A.1.5 References

Cardellini, S. & Osimani, M. (2008). Living with landslides: the Ancona case history and early warning system. *Proceedings of the First World Landslide Forum*, 18-21 November 2008, United Nation University, Tokyo, Japan.

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A.2 Bagnaschino, Italy

A.2.1 Site Description

The Bagnaschino site represents a complex landslide reactivated within an old deep-seated gravitational slope deformation mass on a hillside of the Casotto Valley about 4 km away from Torre Mondovi, Italy (Figure A2). The related hillside portion had a long history of movement which was first detected in 1994. Landslide investigations commenced in 1996. The landslide site has an estimated plan area of 150,000 m^2, comprising a displaced material of about 1.2 Mm^3. The landslide could affect traffic road No. 164 at its toe.

Figure A2 General View of the Site (Supper et al, 2012)

A possible slip plane is located at about 8 m below ground. It penetrates through colluvium and tectonically densely jointed mica-schist rocks. It was considered to be a deep-seated gravitational deformation. Noticeable creeping of the impending landslide mass was detected. The maximum observed velocity of the slide was about 1 m/year in 2009. According to Supper et al (2012), the displacement could be correlated with rainfall events or snow melting. Perched groundwater was considered to be one of the triggering factors of the reactivation**.**

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A.2.2 Monitoring Parameters and Instrumentation Used

Table A2 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Sub-surface movement	• Automatic total station • GPS tracker • Inclinometer
Hydrogeological and meteorological parameters	(c) Groundwater level (d) Rainfall depth	• Peizometer • Raingauge
Geophysical parameters	(e) Ground resistivity	• Down-hole resistivity meter

A.2.3 Establishment of Threshold Values for Issue of Early Warning

Supper et al (2012) reported that the threshold rainfall intensity and duration which correlate with the onset of landslide reactivation have been established. The threshold serves as a reference for issue of early warnings. However, other monitoring data or parameters (e.g. rate of displacements and groundwater levels) will be considered holistically for making decisions.

A.2.4 Response Plan and Preparedness of Stakeholders

No details of specific response plan after the issue of landslide warning is reported. However, Supper et al (2012) mentioned that closure of the road at the landslide toe was ordered by the Province of Cuneo when a significant movement of the hillside was detected in March 2011.

A.2.5 References

Supper, R., Jochum, B., Ottowitz, D., Baron, I., Vecchiotti, F., Pfeiler, S. & Romer, A. (2012). Bagnachino (Italy). *Report on Evaluation of Mass Movement Indicators (SafeLand Deliverable D4.6)*, prepared by Ivo Baron, Robert Supper & David Ottowitz, pp 191-210.

A.3 Casella, Italy

A.3.1 Site Description

An impending landslide mass was located on a hillside in Cabella, Italy (Figure A3). The landslide has a long history of movements since 1993. The volume of the landslide was estimated to be 30 Mm^3, and the plan area of the landslide could be up to 1.2 km^2. According to Lovisolo (2012), the landslide movement could be of translational-rotational

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type. The principal sliding surface could be about 20 m below ground, which could pass through heterometric clayey and calcareous clastic in silty and clayey matrix. Noticeable movements were recorded after heavy rainfall events. For example, displacement of over 13 mm was detected in the wet season of 2004. The landslide could affect settlements and a regional highway at its toe area.

Figure A3 Overview of the Hillside at Casella; Landslide Area Outlined in Red (Lovisolo, 2012)

A.3.2 Monitoring Parameters and Instrumentation Used

Table A3 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement	• Inclinometer
Hydrogeological and meteorological parameters	(b) Groundwater level (c) Rainfall depth	• Peizometer • Raingauge

A.3.3 Establishment of Threshold Values for Issue of Early Warning

Lovisolo (2012) reported that the thresholds to trigger early warning were established using rate of slope displacements and measured groundwater levels. The rainfall threshold for the onset of landslide would be identified.

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A.3.4 Response Plan and Preparedness of Stakeholders

No specific response plan subsequent to landslide warning is given.

A.3.5 Reference

Lovisolo, M. (2012). Casella (Italy). *Report on Evaluation of Mass Movement Indicators (SafeLand Deliverable D4.6)*, prepared by Ivo Baron, Robert Supper & David Ottowitz, pp 266-233.

A.4 Rosano, Italy

A.4.1 Site Description

An impending landslide mass was located on a hillside at Rosano, Italy (Figure A4). Displacements of the related groundmass on the hillside were recorded after heavy rainfall events. According to Lovisolo (2012), the volume of the landslide body was estimated to be 3.6 Mm^3, and the plan length of the landslide mass could be up to 700 m. The geological stratigraphy of the hillside comprises silty and clayey top soils (3.5 m thick) overlaying a colluvium layer (13 m thick). It is reported that the landslide was once reactivated in 2004, which affected an inhabited area on the hillside.

Figure A4 Overview of the Hillside in Rosano; Landslide Area Outlined in Red (Lovisolo, 2012)

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A.4.2 Monitoring Parameters and Instrumentation Used

Table A4 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement	• Inclinometer
Hydrogeological and meteorological parameters	(b) Groundwater level (c) Rainfall depth (d) Temperature of groundwater	• Peizometer • Raingauge • Thermometer

The temperature of groundwater is monitored to identify potential area of surface runoff infiltration.

A.4.3 Establishment of Threshold Values for Issue of Early Warning

Lovisolo (2012) reported that the thresholds to trigger early warning were established using kinematic parameters, inferred from displacement readings and measured groundwater levels. A rainfall-displacement correlation would be developed for early warning purposes.

A.4.4 Response Plan and Preparedness of Stakeholders

An automated computer system has been set up for real-time processing of the monitoring data. When the readings exceed the pre-set threshold values, text messages will be sent to responsible personnel via mobile phones. No specific response plan subsequent to landslide warning is given in Lovisolo's report.

A.4.5 Reference

Lovisolo, M. (2012). Rosano (Italy). *Report on Evaluation of Mass Movement Indicators (SafeLand Deliverable D4.6)*, prepared by Ivo Baron, Robert Supper & David Ottowitz, pp 284-382.

A.5 Ruinon Rockslide, Italy

A.5.1 Site Description

Repeated instabilities had occurred on a hillside at Ruinon, Italy. Signs of distress, including two main scraps and cracks, had been noticed (Figure A5). The geology of the hillside comprises fractured phyllites. Crosta & Agliardi (2003) reviewed available borehole data and found that the rocks in the hillside were highly fractured and characterised by a low rock quality designation (RQD) of 0% to 30%. The volume of the distressed groundmass

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was estimated to be exceeding 20 Mm^3. Federico et al (2012) reported that the potential slip plane could be about 100 m below ground level. Deep-seated sliding and gravitational slope deformations could be involved. It was reported that since 1997, continued and accelerated movements have been recorded. The average rate of the groundmass movement was 300 mm/year. Failure of the hillside could affect Bormio municipality which is located a few kilometers away in the down-slope direction. The displacement is associated with rainfall and snowmelt.

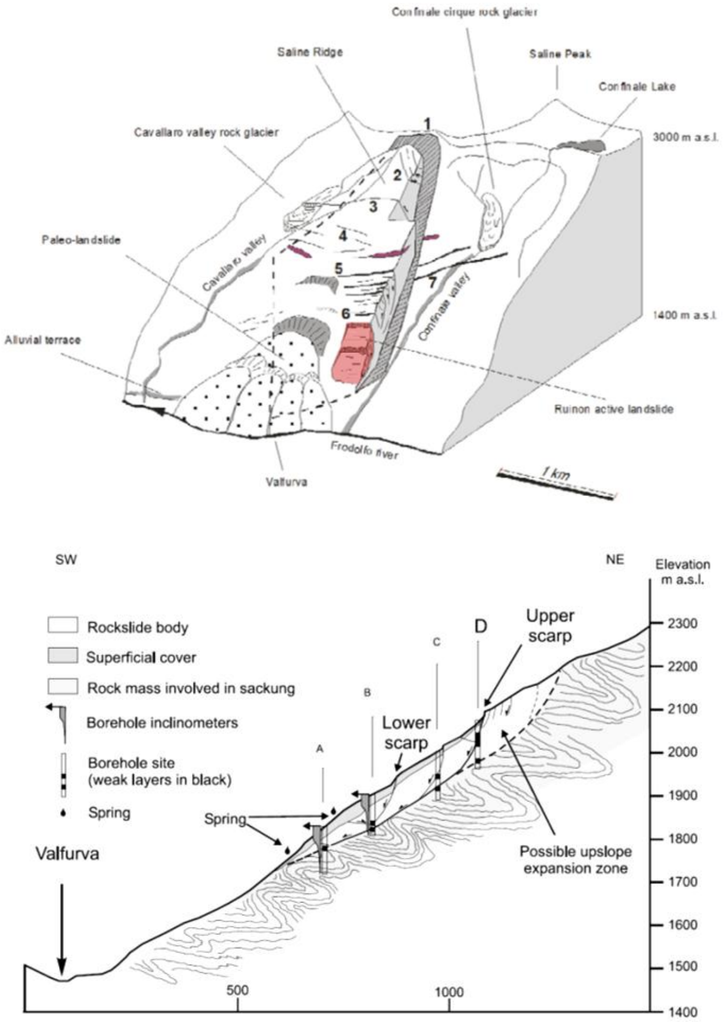

Figure A5 Sketch and Cross-section of the Ruinon Rockslide (Federico et al, 2012)

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A.5.2 Monitoring Parameters and Instrumentation Used

Table A5 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Sub-surface movement	• GPS tracker • Crack meter • Ground based InSAR • Extensometer
Hydrogeological and meteorological parameters	(c) Rainfall depth	• Raingauge

A.5.3 Establishment of Threshold Values for Issue of Early Warning

The threshold velocity for triggering early warning had been established based on the "accelerating creep theory" proposed by Voight (1988). The theory provides a basis for investigating the relationship between velocity and failure time of a creeping material. Crosta & Agliardi (2003) developed the threshold values based on 5-years' monitoring data. Three early warning threshold levels corresponding to different emergency plan actions were established (see Figure A6). Federico et al (2012) reported a study of the correlation between rainfall and displacement. However, Crosta & Agliardi (op cit) commented that the accelerating creep theory could only give an order of magnitude of the failure time and accurate forecast of slope failure may not be feasible. Therefore, the established trigger levels should be used to support judgment of experts for giving early warning.

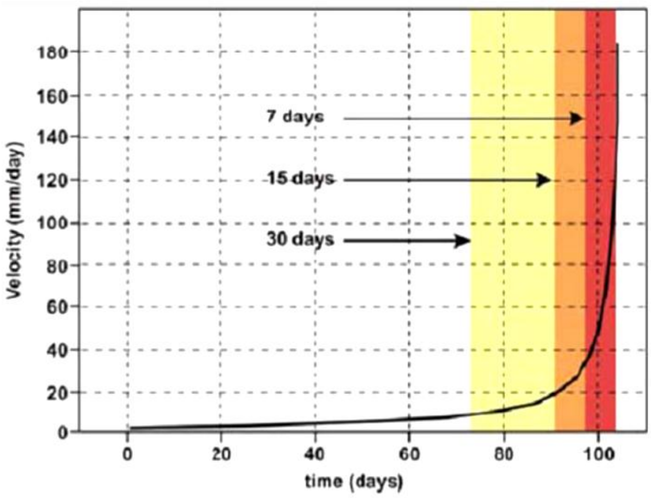

Figure A6 The Early Warning Threshold Levels Established by Crosta & Agliardi (2003)

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A.5.4 Response Plan and Preparedness of Stakeholders

No specific response plan subsequent to the issue of the landslide warning is available.

A.5.5 References

Crosta, G.B. & Agliardi, F. (2003). Failure forecast for large rock slides by surface displacement measurements. *Canadian Geotechnical Journal*, vol. 40(1). pp 176-191.

Federico, A., Giovanni, B. & Sosio, R. (2012). Ruinon Rockslide (Italy). *Report on Evaluation of Mass Movement Indicators (SafeLand Deliverable D4.6)*, prepared by Ivo Baroň, Robert Supper & David Ottowitz, pp 295-314.

Voight, B. (1988). A method for prediction of volcanic eruption. *Nature*, vol. 332, pp 125-130.

A.6 Aknes, Norway

A.6.1 Site Description

At Aknes, Norway, an early warning system of a slowing-moving rock slope is in operation. The rock slope overlooks a fjord (see Figure A7). It failed in 1940 and 1960; extensive tension cracks have been identified at the failure scrap. Accordingly to Blikra & Kristensen (2012), a series of studies, including field mapping and ground investigations, were carried out. They suggested that a rock mass within the slope had displaced and could potentially detach in the form of a rockslide. It was estimated that the volume of the impending rockslide could be as large as 54 Mm^3. Studies have indicated that if the rock mass detaches, it would fall into the fjord and trigger tsunami that could affect settlements along the fjord. According to the ongoing monitoring data, the distressed rock mass is moving at a rate of 6-8 cm/year. The rate is found to be dependent on rainfall and snowmelt.

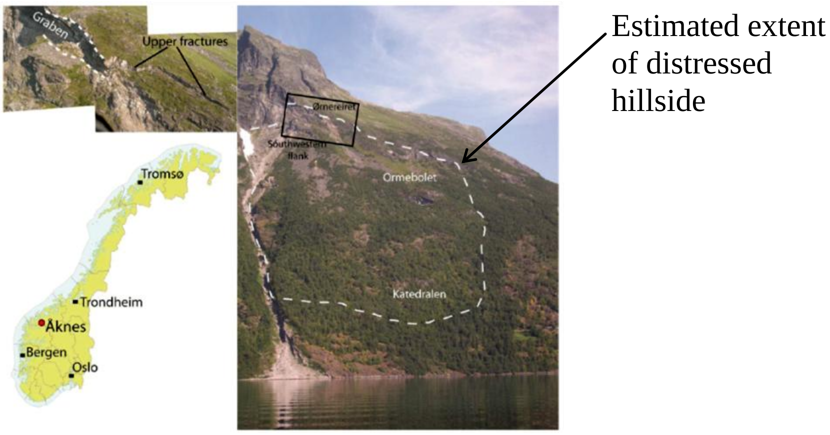

Figure A7 Location and General View of the Site (Blikra & Kristensen, 2012)

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A.6.2 Monitoring Parameters and Instrumentation Used

Table A6 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Width of fractures on the rock slope (c) Tilting of slope (d) Subsurface movement	• Automatic Total Station • GPS Tracker • Extensometer • Laser Sensor • Tiltmeter • Inclinometer
Hydrogeological and meteorological parameters	(e) Groundwater level (f) Temperature (g) Rainfall depth	• Peizometer • Thermometer • Raingauge
Geophysical parameters	(h) Ground vibration induced by localized rock detachments	• Geophone

A.6.3 Establishment of the Threshold Values for Issue of Early Warning

The early warning system is primarily based on the velocity/acceleration interpreted from the measured displacements and deformations. A five-level warning system was established. Different action parties, including police and county governor, would be informed when specified levels are reached. Different instruments have different velocity/acceleration thresholds for defining alarm levels. The thresholds were established taking into account seasonal fluctuations, for example, deformation velocity could be larger than annual average value during the snowmelt period. Therefore, other measured parameters including the hydrogeological and meteorological parameters were also considered in determining whether early warning should be issued. However, no well defined thresholds in this respect are given in available literature.

A.6.4 Response Plan and Preparedness of Stakeholders

Response plans for the five-level warning system are briefly reported by Blikra & Kristensen (2012) and Lacasse (2011). The first two levels correspond to movement comparable with the annual average movement and the seasonal fluctuations. When the third and the fourth levels are reached, the county governor would be informed by the Early Warning Centre. The country governor is responsible for the coordination of different action parties including police, government departments, costal guards and power companies. The fifth level is reached when the rock slope failure is imminent, and emergency evacuation of villages within the tsunami hazard zone would take place. It has been estimated that tsunami would arrive at the villages within five minutes. The evacuation is coordinated by the police. SMS messaging and sirens in villages are used to inform residents of the evacuation. Lacasse (2011) reported that two drills of emergency evacuation had been carried out to foster the community resilience.

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A.6.5 References

Blikra, L.H. & Kristensen, L. (2012). Aknes (Norway). *Report on Evaluation of Mass Movement Indicators (SafeLand Deliverable D4.6)*, prepared by Ivo Baroň, Robert Supper & David Ottowitz, pp 127-149.

Lacasse, S. (2011). *Learning to Live with Geohazards: from Research to Practice.* Presentation in GEO Seminar on 28 November 2011, Hong Kong.

A.7 Mannen, Norway

A.7.1 Site Description

A distress hillside, Mannen, is located in Møre and Romsdal County in western Norway (Figure A8). A continuous movement of the slope at a velocity of 2 cm/year has been recorded. The associated active groundmass is located at the peak of the hill which is about 1,300 m high. According to Blikra & Kristensen (2012), the volume of the potential rock avalanche could be up to 20 Mm^3. The distress hillside is overlooking a village with a plan distance between the peak of the hill and the village of about 2 km. It is considered that the potential rock avalanche could affect roads and residential development of the village. In addition, debris may dam up water in a river at the hill toe and this in turn may cause flooding to other inhabited areas at the downstream of the river.

The bedrock consists of Proterozoic sillimanite-bearing gneisses with inherited structural weaknesses from the tectonic deformation. The potential active groundmass consists of highly fractured rocks. Structural and geological analysis suggested that the movements of the active groundmass could be associated with translational sliding. Monitoring records revealed that the velocity of the deformation could be correlated with infiltration of surface water into the fractured rock mass. A slip plane at a level 24 m below ground surface was identified.

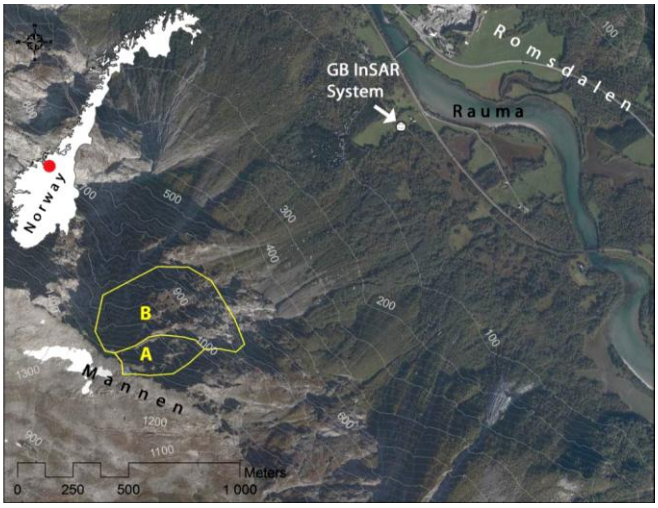

Figure A8 Location of Mannen; the Distressed Hillside is Outlined in Yellow (Blikra & Kristensen, 2012)

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A.7.2 Monitoring Parameters and Instrumentation Used

Table A7 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Crack width	• Ground-based InSAR • GPS tracker • laser sensor • Extensometer
Hydrogeological and meteorological parameters	(c) Groundwater level (d) Temperature (e) Rainfall depth	• Peizometer • Thermometer • Raingauge

A.7.3 Establishment of Threshold Values for Issue of Early Warning

The decision to issue an early warning is based on the velocity inferred from displacement data. Five levels of velocity had been set (Figure A9). They were established on the basis of normal movement rate and seasonal fluctuation recorded previously. The seasonal fluctuation was found to be correlated with snowmelt and temperature variations. The monitoring data could embed noise. Officers in the Early Warning Centre would check the overall monitoring data in a holistic manner before an early warning is issued.

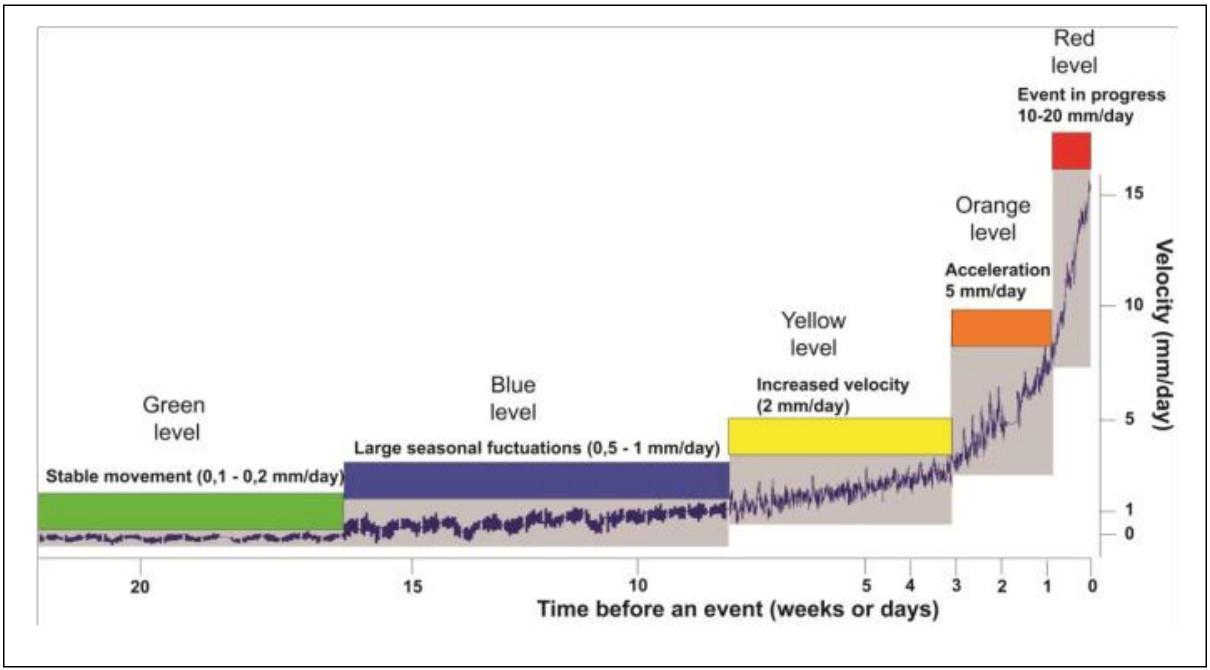

Figure A9 The Five Level of Velocity Established in the Early Warning System (Kristensen et al, 2010)

A.7.4 Response Plan and Preparedness of Stakeholders

In order to ensure the correct operation of the monitoring system, all the instrumentation and data transmission systems are checked daily. The early warning system for the Mannen rockslide involves all responsible government agencies, utility companies and residents that may be affected by the potential rockslide. These include county governor, police, and all other sectors like road authorities, health authorities, the coast guards, power companies, etc. A national emergency plan is being implemented. According to Blikra & Kristensen (2012), when the red level (Figure A9) is reached, this could imply that a catastrophic failure is imminent and an emergency evacuation would be ordered. Table-top and field-based drills have been organized.

The structure of the communication chain between the Early Warning Centre, the responsible organizations, and all involved partners are stated in documents and plans. The Early Warning Centre has the responsibility to inform the responsible organizations when the early warning level is changed. The county governor is responsible for coordinating the emergency actions during the yellow level, while the police take over this role during orange and red level. The implementation of warnings and evacuation is done by the police. The warnings would be disseminated via SMS messages. Alert to residents would be provided using electronic warning siren installed in villages.

A.7.5 Reference

Blikra, L.H. & Kristensen, L. (2012). Mannen (Norway). *Report on Evaluation of Mass Movement Indicators (SafeLand Deliverable D4.6)*, prepared by Ivo Baroň, Robert Supper & David Ottowitz, pp 271-283.

Kristensen, L., Blikra, L.H. & Hole, J. (2010). *Aknes: State of Instrumentation and Data Analysis (Aknes Report 02 2010).* Aknes/Tafjord Early Warning Centre, 43 p.

A.8 Turtle Mountain, Alberta, Canada

A.8.1 Site Description

In 1903, the east face of Turtle Mountain collapsed, sending an estimated 30 Mm^3 of rock into the valley below, burying a portion of the town of Frank, Alberta and killing more than 70 people. After the incident, a series of geological studies of the landslide revealed that a portion of the Turtle Mountain, known as South Peak, could be potentially unstable and could result in further rock avalanche (see Figure A10). Extensive cracks on the surface of the hillside were mapped. Continuous movement of this unstable rock mass of volume of about 5 Mm^3 has been recorded. The average annual rate of displacement could be 5 mm/year. Hungr (2008) carried out debris mobility analysis and the result indicated that the potential rock avalanche could reach the town of Frank and affect important transportation facilities including railway lines and highway corridors.

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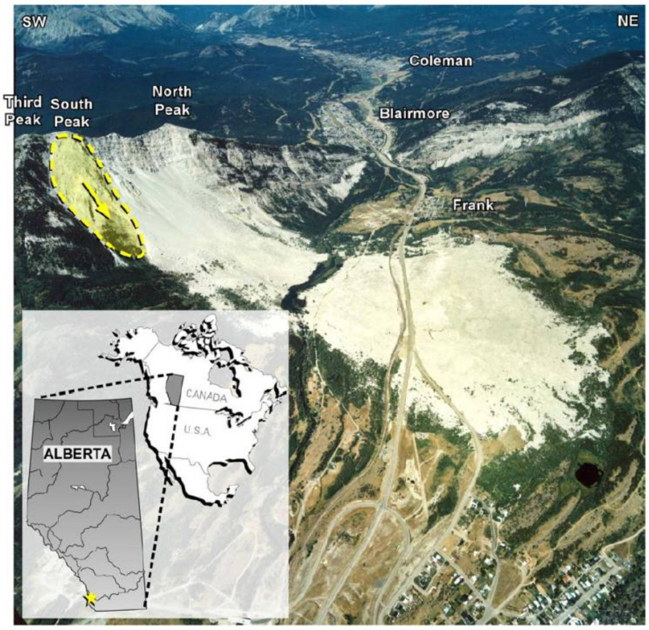

Figure A10 General View of the South Peak of the Turtle Mountain; Potential Unstable Rock Mass Highlighted in Yellow (Moreno et al, 2011)

According to Moreno et al (2011), the instability of the South Peak could be controlled by at least two steep joint sets. A geological model of the potential unstable rock mass is presented in Figure A11. Limit equilibrium stability assessment indicates that the hillside is marginally stable. Water pressure in the rock joints plays an important role in determining the stability condition of the hillside.

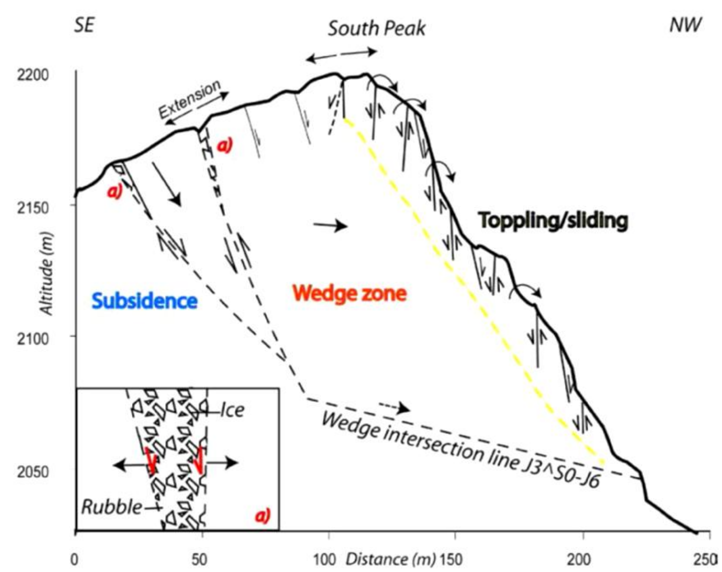

Figure A11 Geological Model of the Potential Unstable Rock Mass (Froese et al, 2009)

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A.8.2 Monitoring Parameters and Instrumentation Used

Table A8 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Crack width	• Tiltmeter • GPS tracker • Robotic total station • Crackmeter • Extensometer
Hydrogeological and meteorological parameters	(c) Temperature (d) Rainfall depth (e) Barometric pressure	• Thermometer • Raingauge • Barometer

A.8.3 Establishment of Threshold Values for Issue of Early Warning

An emergency control centre is established to monitor the near real-time data received. Personnel of the emergency control centre primarily rely on the measured displacements to determine whether early warning should be triggered. Four alert levels have been set up (see Table A9).

Table A9 Alert Levels and Response Plan

Level	Data recorded	Actions to be taken
1	Background noise or seasonal fluctuations recorded	• Continuous monitoring
2	Movements at multiple sensors detected, they are nonseasonal but only slightly above threshold levels	• Increase frequency of data review and/or data acquisition • Inform stakeholders
3	Acceleration of data trends significantly exceeding threshold values (nonseasonal) at multiple sensors recorded	• Increase frequency of data review, visit site to check conditions, communicate findings to key decision-makers, and recommend voluntary evacuation
4	High or catastrophic acceleration on several sensors recorded	• Trigger Emergency Response Plan, including evacuations and mobilization of emergency services

The thresholds of each level are established based on long-term monitoring data and judgment. The thresholds are reviewed regularly to take into account the latest data recorded. According to Moreno et al (2011), continuous revision of the thresholds is made.

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A.8.4 Response Plan and Preparedness of Stakeholders

Moreno & Froese (2009) described in detail the response plan and the roles and responsibilities of different parties involved. A brief summary of the response plan is given in Table A9. Parties including Albert Emergency Management Agency, Royal Canadian Mounted Police, Albert Geological Survey, Canadian Pacific Railway, district managers, etc. are involved in the response plan. Annual emergency exercise which validates the response plan and trains all personnel involved would be carried out (Moreno et al, 2011). There are two main types of exercise: (i) discussion based, and (ii) operation based. The discussion based exercise is conducted to familiarize staff with the planned procedures. The operation based exercise includes drills which test the communication chain and the operation of the response plan.

A.8.5 References

Froese, C.R., Moreno, F., Jaboyedoff, M. & Cruden, D.M. (2009). 25 years of movement monitoring on the South Peak of Turtle Mountain: understanding the hazard. *Canadian Geotechnical Journal*, vol. 46, pp 256-269.

Hungr, O. (2008). *Turtle Mountain, Frank, Alberta: Run-out Analyses of Potential Landslides on South and Third Peaks*. Unpublished report prepared for Alberta Geological Survey, 51 p.

Moreno, F. & Froese, C.R. (2009). *ERCB/AGS Roles and Responsibilities Manual for the Turtle Mountain Monitoring Project, Alberta.* Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-06, 22 p.

Moreno, F., Jaboyedoff, M., Pedrazzini, A., Charriere, M. & Humair, F. (2011). *Frank Slide and Turtle Mountain Early-warning System Technical Tour Guidebook (NTS 82G)*. ERCB/AGS Information Series Report 139, 15 p.

A.9 Illawarra, Wollongong, New South Wale, Australia

A.9.1 Site Description

Two unstable slopes, named as Site 113 and Site 355 respectively (see Figure A12), in Illawarra of Wollongong city have exhibited repeated instability. The two slopes are located within a landslide prone area. According to Flentje et al (2005), 17 landslides within this area have been reported in the last 50 years. The geology of the area comprises an essentially flat-lying sequence of interlayered sandstone, mudstone and coal of the Illawarra Coal Measures, overlain by interbedded sandstones and mudstones/claystones of the Narrabeen Group (Flentje & Chowdhury, 2005).

Site 113 is classified as a 3 m deep slide-category landslide having a volume of approximately 25,000 m^3. It is an active shallow slide-category landslide that has destroyed 5 houses and 1 school building in the last 50 years. Site 355 is a deep-seated slow moving ‘slide’ category landslide with a volume of approximately 35,000 m^3. Rainfall has been

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considered to be the major contribution factor which caused the ground displacement. Flentje et al (2005) reported that displacement of up to 2 mm/day had been recorded after heavy rainfall. The landslide could present a high risk-to-life to nearby residential dwellings.

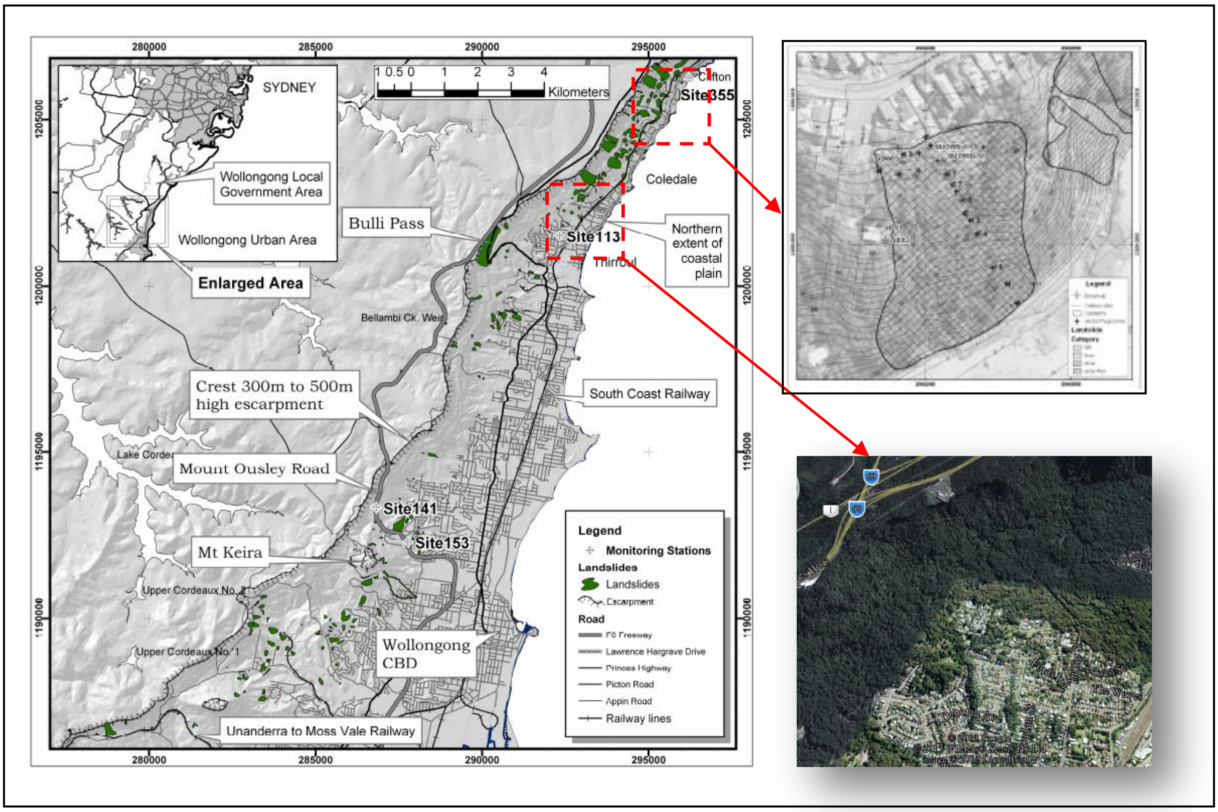

Figure A12 Locations of Site 113 and Site 355 (Flentje & Chowdhury, 2006)

A.9.2 Monitoring Parameters and Instrumentation Used

Table A10 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Sub-surface movement	• GPS tracker • Inclinometer
Hydrogeological and meteorological parameters	(c) Rainfall intensity (d) Pore-water pressure	• Raingauge • Piezometers

A.9.3 Establishment of the Threshold Values for Issue of Early Warning

The trigger of an early warning primarily relies on the rainfall intensity. Flentje & Chowdhury (2005) reported that landslide occurrence in the region is correlated with the

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rainfall intensity and rainfall duration. A curve which represents the combination of rainfall intensity and rainfall duration at which a landslide could happen has been determined. The threshold for issuing of early warning is established based on this curve with a safety margin built-in (Flentje & Chowdhury, 2006). Figure A13 shows the rainfall intensity and rainfall duration relationships. Decision to issue an early warning is also supplemented by other monitoring data e.g. inclinometer readings.

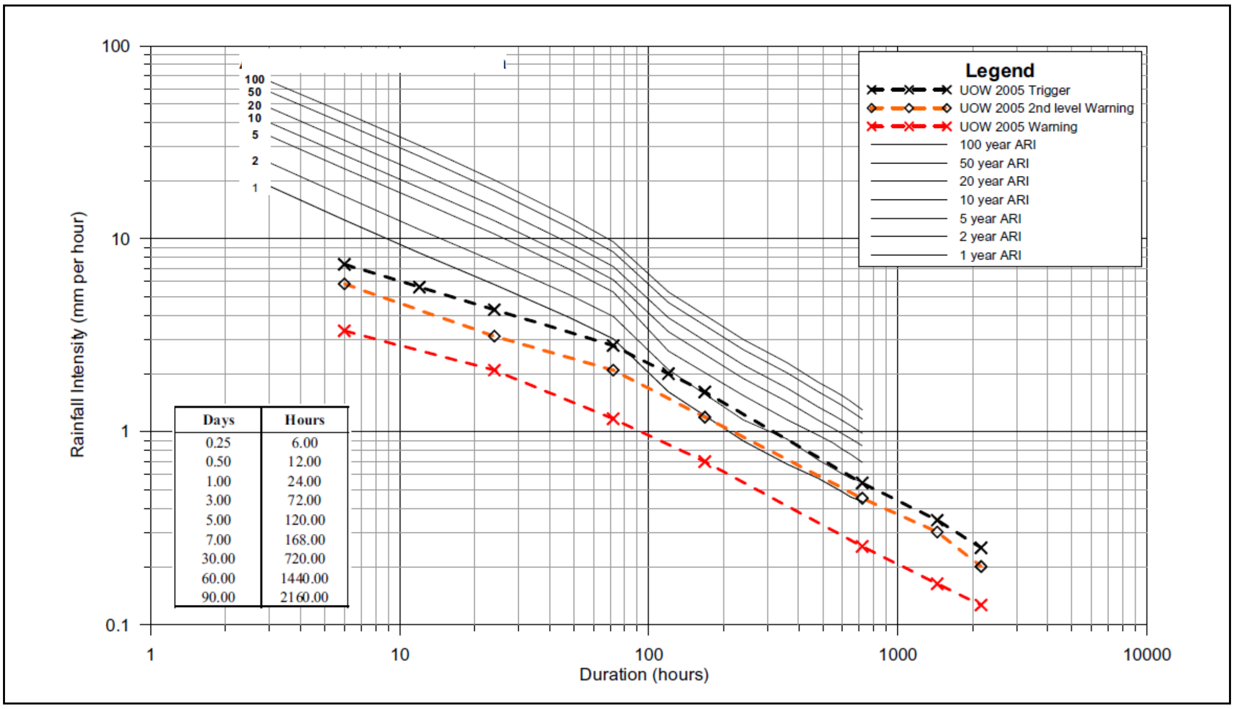

Figure A13 Rainfall Thresholds (Flentje & Chowdhury, 2006)

A.9.4 Response Plan and Preparedness of Stakeholders

Flentje & Chowdhury (2005) mentioned that the real-time monitoring system allows emergency response organizations, police force, utility and essential infrastructure managers to monitor the slope movements and take necessary action when needed. However, detailed information about the response plan and preparedness action is not given.

A.9.5 References

Flentje, P. & Chowdhury, R.N. (2005). *Managing Landslide Hazards on the Illawarra Escarpment*. Faculty of Engineering Papers, Faculty of Engineering, University of Wollongong, Australia, 15 p.

Flentje, P. & Chowdhury, R.N. (2006). *Observation Approach for Urban Landslide Management*. IAES2006 Paper No. 522, 12 p.

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Flentje, P., Chowdhury, R.N., Tobbin, P. & Brizga, V. (2005). *Towards Real-time Landslide Risk Management in an Urban Area*. Faculty of Engineering Papers, Faculty of Engineering, University of Wollongong, Australia, 11 p.

A.10 Wushan Town, China

A.10.1 Description of the Site

Monitoring works on a continuously creeping slope on the northern bank of Yangtze River in Wushan Town have been carried out. Yin et al (2010) reported that the slope is part of the scar of an ancient landslide. The slope dips towards the Yangtze River and the creeping mass is about 435 m long and 292 m wide (Figure A14). The maximum displacement rate is about 2 mm/month.

The bedrock geology of the creeping slope comprises mainly limestone. The potential slip plane could be 30 m below ground and could daylight from the slope. Originally, the toe of the slip plane was above the water level of the Yangtze River. However, due to the increase in the water level caused by the construction of the Three Gorges Reservoir, the toe of the slip plane is now under the water level. According to Yin et al (2010), this is considered to be the triggering factor of the slope displacement. Failure of the slope would affect Wushan Town.

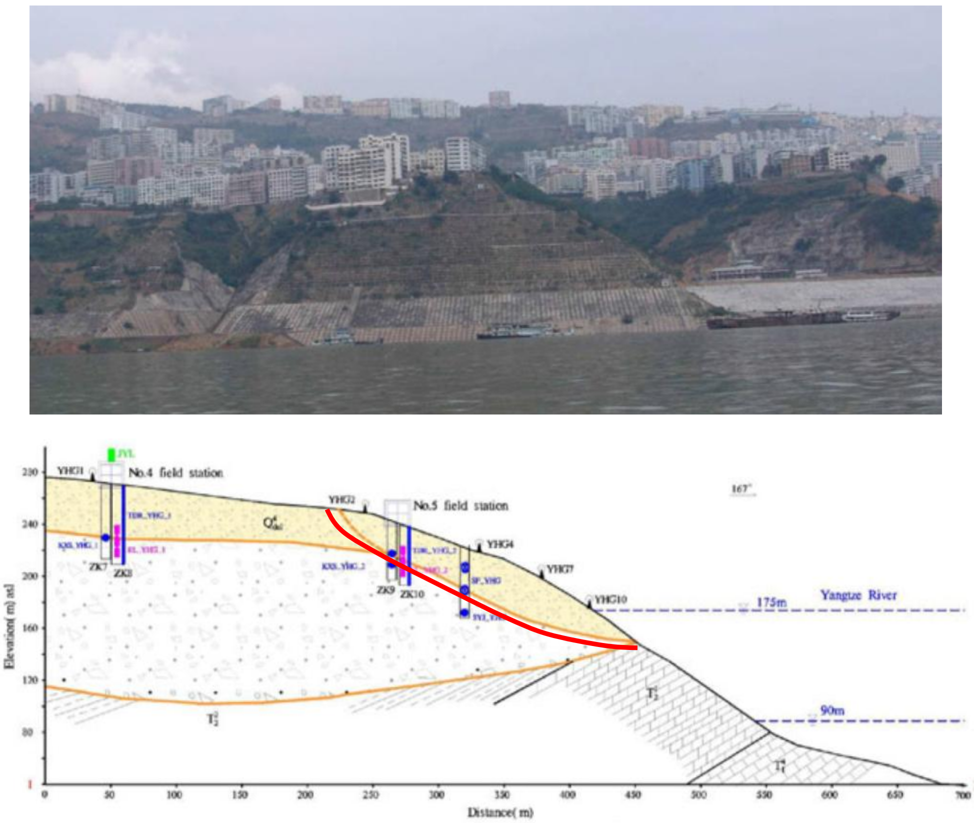

Figure A14 Overview of the Slope and a Cross-section of the Slope; Potential Slip Plane is Shown in a Red Line (Yin et al, 2010)

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A.10.2 Monitoring and Early Warning System

Table A11 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement (b) Sub-surface movement	• GPS tracker • Inclinometer • TDR • Brillouin optical time domain reflectometer
Hydrogeological and meteorological parameters	(c) Rainfall depth (d) Pore-water pressure (e) Water level of Yangtze River	• Raingauge • Piezometers • Water level sensor

A.10.3 Establishment of the Threshold Values for Issue of Early Warning

Four early warning levels (Figure A15) have been established based on studies of previous landslide cases and the threshold values are expressed in terms of the measured surface and deep ground displacements, pore-water pressures and ground strains. Details on how the threshold values were developed are not given by Yin et al (2010).

Early warning level	Color	Monitoring value: Ground displacement (mm/month)	Deep displacement (mm/month)	Pore water pressure (kPa/ month)	Ground strain (με/month)	Measures
I level	Blue	<10.0	<1.0	<10.0	50.0	Only general inspection and regular monitoring are needed. The information is issued to the group of experts
II level	Yellow	10.0~30.0	1.0~15.0	10.0~50.0	50.0~100.0	Temporal and spatial density of monitoring points must be added, and monitoring methods must be extended. The information is warned to the group of experts and decision-makers
III level	Orange	30.0~300.0	15.0~150.0	50.0~100.0	100.0~150.0	Continuous comprehensive monitoring and general inspection should be conducted 24 h/day. The emergency evacuation and fast emergency engineering work is necessary. A consultation and discussion should be carried out among experts and government decision-makers
IV level	Red	>300.0	>150.0	>100.0	>150.0	A 24-h comprehensive monitoring and general inspection, engineering stabilizing, and restricting reservoir water level fluctuation should be conducted if necessary. The risk mitigation and evacuation will be announced and conducted by the government

Figure A15 Early Warning Thresholds and Response Plan (Yin et al, 2010)

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A.10.4 Response Plan and Preparedness of Stakeholders

Actions to be carried out at each level of warning are presented in Figure A15.

A.10.5 Reference

Yin, Y., Wang, H., Gao, Y. & Li., X. (2010). Real-time monitoring and early warning of landslides at relocated Wushan Town, the Three Gorges Reservoir, China. *Landslides*, vol. 7, pp 339-349.

A.11 Xintan Town, China

A.11.1 Site Description

Wang (2009) reported a case history of implementing an early warning system of landslide in Xiling Gorge, China. The hillside was located on the northern bank of Yangtze River at Xintan. Continuous deformation of the hillside was detected back in 1977. Geological investigations revealed that the impending groundmass could cover a plan area of 33 km^2, with a volume up to 30 Mm^3. The landslide affected dwellings on the hillside.

Xintan is a landslide prone area. The bedrock of the area consists of Silurian shale and sandstone, Devonian quartz-sandstone and carboniferous limestone with coal seams, overlain by colluvial deposits up to about 86 m thick. Figure A16 shows the engineering geology map of the Xintan Landslide. In 1964, a large rock avalanche occurred at the upper portion of the hillside. Following the 1964 landslide, the deformation of the hillside began. According to Wang (2009), the main contributing factor of the continuous deformation of the hillside could be the surcharge from the 1964 landslide debris. A higher deformation rate was recorded in wet season. The landslide depth was estimated to be 30 to 100 m. From 1977, deformation monitoring was carried out with an aim to provide early landslide warning to the residents in the area. The maximum deformation rate at that period was less than 10 mm/month.

A.11.2 Monitoring and Early Warning System

Table A12 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Displacements and deformations	(a) Surface movement	• Theodolite

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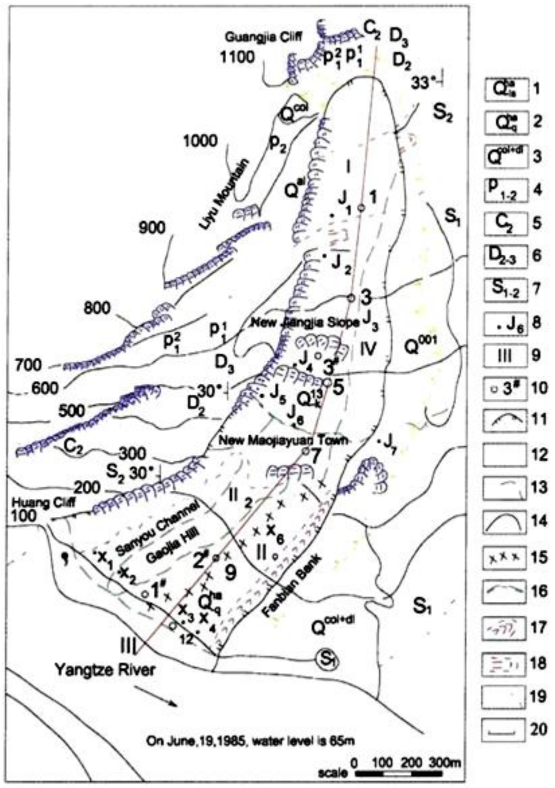

Fig. 18.5 Engineering geological map of the Xintan landslide. 1 – shiver of quaternary limestone; 2 – shiver of quaternary quartz sandstone; 3 – slope wash; 4 – Permian system; 5 – Carbonic system; 6 – Devonian system; 7 – Silurian system; 8 – survey point; 9 – divisional code of landslide; 10 – exploratory well or boring; 11 – borderline of landslide; 12 – borderline of rock fall; 13 – divisional line of landslide; 14 – borderline of underwater deposit; 15 – divisional line of shiver composition; 16 – sliding exit; 17 – ridge of debris edge; 18 – bad broken highway; 19 – debris flow valley; 20 – vertical section

Figure A16 Engineering Geology Map of Xintan Landslide (Wang, 2009)

A.11.3 Establishment of the Threshold Values for Issue of Early Warning

No threshold value was reported by Wang (2009). It is believed that an observational and judgment approach was adopted. Wang (op cit) reported that emergency evacuation was ordered in May 1985 when accelerated deformation rates at a number of stations were recorded, and significant ruptures of the hillside were noticed. Subsequent to the evacuation, the hillside collapsed.

A.11.4 Response Plan and Preparedness of Stakeholders

Wang (2009) mentioned about the communication between the monitoring team and the government agency on reporting the conditions of the hillside. However, detailed response plan, communication chain and preparedness were not given.

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A.11.5 Reference

Wang, S. (2009). Time Prediction of the Xintan Landslide in Xiling Gorge, the Yangtze River. *Landslide Disaster Mitigation in Three Gorges Reservoir*, *China*, pp 411-431.

A.12 Mt Ruapehu, New Zealand

A.12.1 Site Description

Mt Ruapehu is an active volcano in northern New Zealand. The Crater Lake, located over the actual vent of the volcano. The 1995-96 eruptions of Mt Ruapehu left a 7-metre high dam of tephra, consisting of volcanic ash and rocks, around the rim of the Crater Lake (see photograph and cross-section in Figure A17). Failure of tephra dams could lead to debris flows which threatened the safety of residents below. Similar event happened in 1953, in which the debris flow travelled down the mountain, causing more than 150 fatalities.

Subsequent to the 1995-96 eruption, the lake was refilled. The stability of the tephra dam became a concern, since if the dam collapses, a sizeable debris flow could be triggered. In 2000, the central and local governments decided to plan, design and implement an early warning system to monitor the stability and give early warning to stakeholders. A series of investigations was carried out on the tephra dam. The geology of the tephra dam comprises mainly inter-layered medium dense, slightly silty sand and dense to very dense, sandy gravel. Stability condition of the dam was considered pertinent to the water level of the Crater Lake.

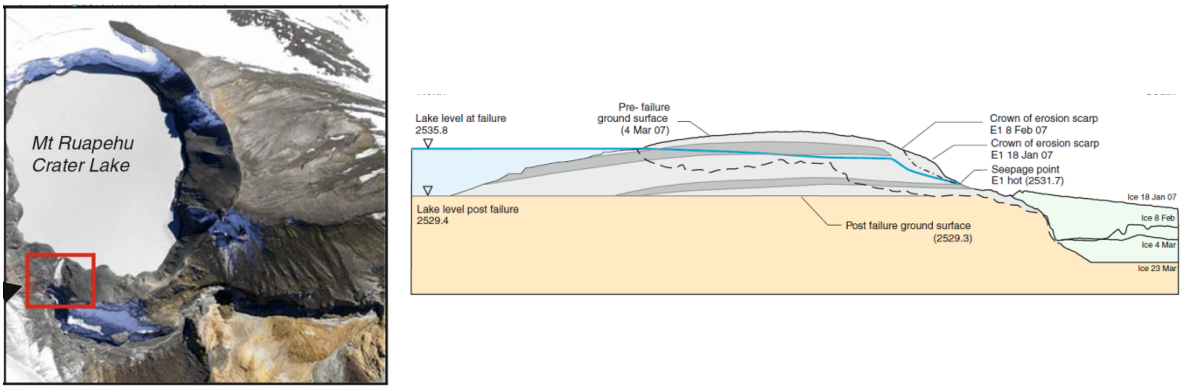

Figure A17 (Left) Plan View of the Tephra Dam Enclosed in Red Box
(Right) Cross-section of the Tephra Dam (Massey et al, 2009)

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A.12.2 Monitoring and Early Warning System

Table A13 Summary of Monitoring Scheme

Parameters Monitored	Details	Instrumentation
Hydrogeological and meteorological parameters	(a) Water level in Crater Lake	• Water level sensor
Geophysical parameters	(b) Seismic signal at downstream of Crater Lake	• Geophone

A.12.3 Establishment of the Threshold Values for Issue of Early Warning

Massey et al (2009) gave the alert levels used in the early warning system (see Table A14). The alert levels were established based on water levels of the Crater Lake with reference to the previous dam failure events. Geophones included in the warning system provide independent corroboration of the presence of debris flows. The last column of Table A14 is a forecast of time required for a water level of one alert level to elevate to the next alert level. This provides a sense of the lead time to dam failure.

Table A14 Alert levels (Massey et al, 2009)

Level of readiness (warning level)	Lake level (msl)	Simplified explanation (conditional probability of dam failure based on Gillon et al. 2006)	Actions (mostly agency response time)	Anticipated time for lake to rise to next level (in summer, based on fill rates 2000–2005)
Normal	Below 2,527 m	Base level of readiness as per normal civil defence planning	Planning, preparation, and training	
Level 1	2,526.5 m	Critical trigger point, 3 m below the new rock overflow level. (Waves caused by small eruptions or landslides could overtop tephra barrier but resulting lahar would be small)	Planning largely completed. Response capability available. Response within 30 min	1 to 6 months to fill from Alert Level 1 to 1b
Level 1b	2,529.5 m (Lake 100% full)	Lake reaches to the buried rock rim outlet level at the base of the tephra dam. Probability of dam failure at this level is still very low	Planning completed. Full response capability available and ready	1 to 6 months to fill from Alert Level 1b to 2
Level 2	2,533 m	Sudden collapse could produce a lahar equivalent to the 1975 event (largest historic eruption lahar) which passed under downstream road and rail bridges without significant damage. Conditional probability of dam failure at this level is 1–2%	Response within 20 min (for example, this required one local police sergeant to always be within 20 min of base from this time on)	0.7 to 1.9 months to fill from Level 2 to 3, or 7.8 months to drop to Level 2 from Level 3, depending on infill rates. Variation due to the possibility of filling spanning fast and slow filling rates, and seepage. Slow fill rates will probably result in net drops in lake level above about 2,532 m
Level 3a	2,535 m	Equivalent to a large moderately fast lahar. Conditional probability of dam failure at this level is 5–10%	Response within 10 min	0.4 to 0.6 months to fill from level 3 to 3b, or 3.2 months to drop to level 3 from 3b
Level 3b	2,536 m	Conditional probability is 50–60%		0.2 to 0.3 months to fill from level 3b to 4, or 1.1 months to drop to level 3b from 4
Level 4	2,536.5	Equivalent to a large, fast lahar. Conditional probability is 90%	Response within 5 min	0.2 to 0.3 months to fill from level 4 to 5, or 0.7 months to drop to level 4 from level 5
Level 5	2,536.9	Lake at top of the tephra dam. Conditional probability is 100%		

A.12.4 Response Plan and Preparedness of Stakeholders

According to Keys & Green (2004), an emergency plan was implemented. Response actions included provision of warning signal to road users, activation of automatic road barriers and notification of local police force. Stakeholders involved in the emergency plan included District councils, The Ministry of Civil Defence and Emergency Management,

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Power Stations, railway operator, highway authority, etc. Training and exercise had been provided which familiarized different agencies with the response plan.

A.12.5 References

Keys, H. & Green, P. (2004). The Crater Lake Issue - a Management Dilemma. Department of Conservation, New Zealand, 8 p.

Massey, C.I., Manville, V., Hancox, G.H., Keys, H.J., Lawrence, C. & McSaveney, M. (2009). Out-burst flood (lahar) triggered by retrogressive landsliding, 18 March 2007 at Mt Ruapehu, New Zealand - a successful early warning. *Landslides*, vol. 7, pp 303-315.

A.13 Other Cases Histories

A.13.1 South Korea

Many non-engineered steep cut slopes were formed as part of road construction in South Korea during the 1970s and 1980s. According to Chang et al (2007) and Chang & Ho (2008), a real-time monitoring system was designed to monitor some of these slopes for the purpose of giving early landslide warning. The system comprises a newly developed instrumentation called Translation, Rotation and Settlement (TRS) sensors which are interconnected with tension steel wires and installed at designated points along the profile of a slope. Each TRS sensor consists of a precision potentiometer for measuring of linear displacement up to a range of 200 mm and a pair of orthogonally arranged inclinometers for measuring vertical tilt in directions parallel and perpendicular to the slope profile. Monitoring data can be transmitted via SMS and/or internet to a control centre. When the pre-determined threshold levels are reached, warning signals will be issued through traffic control signals (Figure A18). Trial use of the TRS system had also been conducted in one of the LPMit sites in Lantau and an account of the trial is given by Lau et al (2009).

Figure A18 Warning is Issued Via Traffic Control Signals (Chang et al, 2007)

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A.13.2 Scotland, UK

In August 2004, Scotland experienced a long lasting and intense rainfall resulting in a large number of landslides. Although there were no major injuries or casualties involved in these landslides, the economic and social impacts were huge. A landslides study comprising two parts was commissioned by Transport Scotland. The first part collated and presented the background information and developed a plan for the second part. The second part of the landslides study presents the proposed means of landslide management on the trunk road network.

According to Winter et al (2008), Transport Scotland developed two approaches to the management and mitigation of landslide hazards: (i) hazard reduction, which includes engineering measures that protect the roads, reduce the opportunity for debris flow to occur or involve realignment of the roads, and (ii) exposure reduction, which comprises for example education, warning, signage and road closure. The exposure reduction calls for the provisioning of early landslide warning systems, which include:

> ***Detection*** - identification of either the occurrence of an event (e.g. by instrumentation/monitoring or observation) or by the measurement and/or forecast of precursor conditions e.g. rainfall;
>
> ***Notification*** - notification of either the likely or actual occurrence of an incident to the authorities, including the Police, Traffic Scotland and the relevant operating companies; and
>
> ***Action*** - proactive process to reduce the exposure of the road user to the hazard, by for example road closure or traffic diversion. This also includes the dissemination of hazard and exposure information by for example, signs, media announcements and may be "landslide patrols" in marked vehicles.

Figure A19 shows some of the means of reducing exposure of road users to the landslide hazard.

A.13.3 References

Lau, K.W.K., Sun, H.W., Millis, S.W., Chan, E.K.K. & Ho, A.N.L. (2009). Application of innovative monitoring techniques at four selected natural hillsides in Hong Kong. *Proceedings of the 2008 HKIE Geotechnical Division Annual Seminar*, HKIE, Hong Kong, pp 161-170.

Chang, K.T., Han, H.S., Wang, J.F., Ho, A. & Mothersille, D. (2007). Predicting Slope Failure using Real-time monitoring technology and the TRS Sensor. *Proceedings of The 2007 International Forum on Landslide Disaster Management*, pp 579-586.

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Chang, K.T. & Ho, A. (2008). On-line risk management for slopes using FOS and TRS. *Proceedings of The State-of-the-art Technology and Experience on Geotechnical Engineering in Korea and Hong Kong*, pp 122-144.

Winter, M.G., Macgregor, F. & Shackman, L. (2008). *Scottish Road Network Landslides Study: Implementation.* Transport Scotland, 270 p.

	
A variable message sign located along a truck road that can be used to warn road users of landslide hazards	A gate that can be used to effect road closure following landslide events or close the road in case of an anticipated landslide event

Figure A19 Means of Disseminating Warning to Road Users (Winter et al, 2008)

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土力工程處刊物及訂購資料

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土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 302 p. (English Version), (Reprinted, 2011).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2007).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.
Geoguide 7	Guide to Soil Nail Design and Construction (2008), 97 p.

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

GEO PUBLICATIONS

GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/2006	Foundation Design and Construction (2006), 376 p.
GEO Publication No. 1/2007	Engineering Geological Practice in Hong Kong (2007), 278 p.
GEO Publication No. 1/2009	Prescriptive Measures for Man-Made Slopes and Retaining Walls (2009), 76 p.
GEO Publication No. 1/2011	Technical Guidelines on Landscape Treatment for Slopes (2011), 217 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

TGN 1	Technical Guidance Documents

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