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Assessment of ground-based monitoring techniques applied to landslide investigations

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ABSTRACT

A landslide complex in the Whitby Mudstone Formation at Hollin Hill, North Yorkshire, UK is periodically reactivated in response to rainfall-induced pore-water pressure fluctuations. This paper compares long-term measurements (i.e., 2009–2014) obtained from a combination of monitoring techniques that have been employed together for the first time on an active landslide. The results highlight the relative performance of the different techniques, and can provide guidance for researchers and practitioners for selecting and installing appropriate monitoring techniques to assess unstable slopes. Particular attention is given to the spatial and temporal resolutions offered by the different approaches that include: Real Time Kinematic-GPS (RTK-GPS) monitoring of a ground surface marker array, conventional inclinometers, Shape Acceleration Arrays (SAA), tilt meters, active waveguides with Acoustic Emission (AE) monitoring, and piezometers. High spatial resolution information has allowed locating areas of stability and instability across a large slope. This has enabled identification of areas where further monitoring efforts should be focused. High temporal resolution information allowed the capture of 'S'-shaped slope displacement-time behaviour (i.e. phases of slope acceleration, deceleration and stability) in response to elevations in pore-water pressures. This study shows that a well-balanced suite of monitoring techniques that provides high temporal and spatial resolutions on both measurement and slope scale is necessary to fully understand failure and movement mechanisms of slopes. In the case of the Hollin Hill landslide it enabled detailed interpretation of the geomorphological processes governing landslide activity. It highlights the benefit of regularly surveying a network of GPS markers to determine areas for installation of movement monitoring techniques that offer higher resolution both temporally and spatially. The small sensitivity of tilt meter measurements to translational movements limited the ability to record characteristic 'S'-shaped landslide movements at Hollin Hill, which were identified using SAA and AE measurements. This high sensitivity to landslide movements indicates the applicability of SAA and AE monitoring to be used in early warning systems, through detecting and quantifying accelerations of slope movement.

1. Introduction

Landslides form one of the major natural hazards causing loss of life and damaging of infrastructure worldwide. In the seven year period between 2004 and 2010, 2620 fatal, non-seismically triggered landslides were recorded worldwide, causing 32,322 fatalities (Petley, 2012). Although the landslide frequency in the UK is comparably low (e.g. some 754 reported events between 2006 and August 2015), the economic impact is high. Failure of engineered earthworks (embankments and cuttings) or adjacent natural slopes causes interruptions to transportation and utilities networks — a process that is affected by ongoing climate change and ageing of slope materials (Dijkstra and Dixon, 2010; Foster et al., 2011; Dijkstra et al., 2014; Glendinning et al., 2015; Pennington et al., 2015).

Since one of the primary triggering mechanism for landslides is intense or prolonged precipitation (Highland and Bobrowsky, 2008), the frequency and severity of landslides are expected to fluctuate with changes in precipitation patterns (spatial and temporal variations of duration and intensity). In a context of climate change, precipitation cannot be regarded as a steady state input and it is essential to develop robust models of adequate complexity that allow evaluation of possible future changes in slope instability due to forecasted changes in

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precipitation (Dijkstra and Dixon, 2010). Mid- to high-latitude regions are likely to face an increase in precipitation of up to 20%, including increased flash floods due to more frequently appearing high-intensity rainfall events (Defra, 2012; Füssel et al., 2012). This increase in precipitation is likely to occur during the winter season, while summers will become drier (Defra, 2012). Wetter winters and drier summers will lead to an increased and deeper weathering of the topsoil, due to larger amplitudes in the wetting and drying cycles. This is likely to reduce the strength of the material and cause more frequent shallow slope instabilities. Understanding triggering mechanisms and failure potentials, to improve landslide forecasting, is therefore a major focus of research internationally.

Monitoring of kinematic, hydrological, and climatic parameters plays a significant role in supporting the development of slope stability models (e.g. Buchli et al., 2013; Springman et al., 2013), since without understanding movement patterns and responses to climate events, forecasting is not possible (Angeli et al., 2000). This requires not just monitoring of actual movements, but also environmental factors including rainfall, temperature, soil moisture content and relative (air) humidity, as well as geotechnical parameters, such as, pore water pressure. This enables the correlation of movement events with their triggering mechanisms and helps to inform the underlying causalities in the process–response models.

Previous studies have related deformation measurements by GPS/GNSS, inclinometer, extensometer or tilt meter readings to rainfall events (e.g. Malet et al., 2002; Corsini et al., 2005; García et al., 2010; Brückl et al., 2013) to study the deformation behaviour of rainfall triggered landslides. Additionally, Malet et al. (2002), Corsini et al. (2005), and Brückl et al. (2013) compare measurements of two or three of the mentioned conventional deformation monitoring techniques, showing good correlation between surface (e.g. GPS) and subsurface (e.g. inclinometer) deformations in terms of movement occurrences.

In this paper we introduce and compare conventional techniques, such as GPS, inclinometer and tilt meter, and recently emerging deformation monitoring techniques, such as acoustic emission (AE) monitoring using active waveguides (AEWG), and Shape Acceleration Array (SAA). To our knowledge, this is the first time that these monitoring techniques have been combined on an active landslide, providing long-term (2009–2014) measurements. This paper highlights the relative performance of these techniques focusing on different movement periods, and it provides detailed, integrated interpretations of movement, environmental, and geotechnical data of the Hollin Hill landslide. The paper reports how these long-term monitoring results have enabled a step-change in the understanding of slope dynamics, building upon previously published work.

The study site, where a Lias mudstone formation is failing, is typical for many inland landslides in lowland settings. Thus, the conclusions drawn from this study can provide guidance for researchers and practitioners for selecting and installing appropriate monitoring techniques to assess unstable slopes.

1.1. Slope monitoring instruments and techniques

There is a clear need to monitor landslides and marginally stable slopes to provide early warning of instability. This will allow for timely evacuation of vulnerable people, as well as timely repair and maintenance of critical infrastructure. The cost of remediation subsequent to landslide failure is several times higher than the cost of corrective measures and repairs if conducted prior to collapse (Glendinning et al., 2009); this highlights the importance of early warning through monitoring. Monitoring also provides: (1) the information necessary for slope stability analysis and remediation design, (2) knowledge of stability to and through construction, and subsequent to remediation, as well as (3) understanding of the condition (both serviceability and ultimate limit states) of adjacent infrastructure that has the potential to be impacted upon by slope instability (Dunnicliff, 1988; Machan and Beckstrand, 2012).

There are many different techniques and types of instrumentation typically used in slope monitoring, and numerous emerging technologies. No single technique or instrument can provide complete information about a landslide and therefore various combinations are usually employed. The primary parameters of interest are deformation and pore-water pressure. Information on these is necessary to assess the rate and magnitude of movement, as well as changes to effective stress and hence stability. Performance of monitoring techniques and instruments is usually assessed in terms of accuracy and precision, spatial and temporal resolutions, sensitivity, and reliability (Dixon et al., 2015). However, on most projects the predominant factor driving the choice of instrumentation and techniques is their cost. For this reason the majority of slope monitoring programmes comprise installation of inclinometer casings and standpipes, which are usually read at discrete and infrequent intervals of the order of months. Inclinometers allow the depth to any shear surface(s) to be identified and standpipes provide information on the ground water conditions; information that is necessary for stability assessment and remediation design. However, this mode of monitoring provides relatively low spatial and temporal resolutions, which is usually insufficient to provide early warning of instability.

Detailed in Table 1 are the monitoring instruments and techniques employed in this study, together with an indication of their spatial and temporal resolutions. The resolution of the methods is a function of the nature of the installation and the extent of the sensor network. Note that the classification shown in Table 1 specifically refers to the installation at the Hollin Hill study site. This combination of monitoring approaches was selected in order to: (1) provide relatively high spatial resolution of ground surface movements, (2) determine the depth to shear surfaces, (3) monitor subsurface deformation at localised areas with high temporal resolution, and (4) to monitor pore-water pressures at shear surface depths with high temporal resolution. This significant level of information provides the basis for a thorough assessment of each of the approaches in order to make recommendations for other landslide investigations.

2. Study site

The landslide observatory is set on a south-facing hillslope, Hollin Hill, with a mean slope angle of 12°, located south of the village of Terrington, North Yorkshire, UK (54°06′38″ N, 0°57′30″W; Fig. 1). It is set in the Howardian Hills, an undulating landscape running approximately NW–SE shaped in four bedrock formations of Lower to Middle Jurassic age and covered by superficial deposits of variable thickness (Fig. 1b). Hollin Hill is a flat-topped hill capped by calcareous sandstone and ferruginous limestone belonging to the Dogger Formation (DF). There is a sharp boundary to the underlying Whitby Mudstone Formation (WMF), the failing formation at this site (Gunn et al., 2013). The WMF, showing a thickness of about 25 m (Chambers et al., 2011), is composed of grey to dark grey mudstone and siltstone with scattered bands of calcareous and sideritic concretions (Chambers et al., 2011). It overlies the Staithes Sandstone Formation (SSF). The boundary between these two formations is represented by an upward transition from sandstone or siltstone to shaley mudstone. This change in depositional facies is marginally episodic and, although a fining upward trend persists, the boundary between the SSF and WMF is manifested by sequences of ferruginous, micaceous siltstone, with fine-grained sandstone and thin mudstone partings. The SSF is heavily bioturbated and shows local occurrences of siderite and pyrite (Gaunt et al., 1980). The formation underlying the SSF is the Redcar Mudstone Formation (RMF) that comprises grey, silty, calcareous, and sideritic mudstone with thin shelly limestones (Powell, 1984, 2010). The DF represents a potential aquifer above the WMF. Hydrogeological characterisation of the WMF and SSF is very complex as a result of variations in particle