Site-specific warning system for rainfall-induced slope failure

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ABSTRACT

In New Zealand, rainfall-induced slope failures cause millions of dollars’ worth of damage annually. As a means of mitigating the associated risk, a site-specific early warning system was developed based on field instrumentation, laboratory tests and finite element modeling. The selected site is a cut slope adjacent SH-1, one of Auckland’s busiest state highways. The site consists of Northland Allochthon residual soil, known for its susceptibility to rainfall-induced landslides. In fact, a landslide occurred at the site in the winter of 2008 following a period of prolonged rainfall. Firstly, a variety of laboratory tests were undertaken on soils taken from the slope to better understand their shear strength and hydraulic characteristics. Next, a cross section of the slope about 45m from the 2008 landslide site was instrumented with 13 volumetric water content sensors installed at different depths, together with a tipping bucket rain gauge to monitor rainfall events. With the rainfall and volumetric water content readings monitored since 2010, the soil properties and boundary conditions of the monitored slope cross-section were calibrated using a transient seepage analysis program (SEEP/W). After successful validation, the matric suction/pore-water pressure profile was coupled with a limit equilibrium analyses (SLOPE/W) to simulate the 2008 landslide. For this purpose, an artificial neural network (ANN) was trained to predict the factor of safety (FoS), which successfully validated the model using the 2008 rainfall record, obtaining FoS=1.0 at the exact time the 2008 landslide occurred. Finally, the ANN-based methodology was extended to predict the FoS at the monitored site in the future, using rainfall forecasts. This can serve as basis of an early warning system as a means to mitigate the risk of rainfall induced landslides.

Keywords: rainfall, landslide, field monitoring, laboratory testing, seepage analysis

1 INTRODUCTION

Rainfall induced landslides cause millions of dollars of damage each year in New Zealand, and many of these occur in the Northland region (NIWA and GNS Science 2009; 2010), due in large part to its geological conditions (O'Sullivan 2009; Lentfer 2007), topography and climatic conditions. Mitigation of damage caused by rainfall-induced slope failures has been conventionally implemented through hard-type approaches, such as slope stabilization methods (e.g. use of retaining walls, de-watering techniques, anchor piles, etc.); however, considering the extent of potentially unstable slopes, these methods may not always be feasible due to financial and environmental constraints. Soft-type approaches, such as early warning systems (EWS), offer viable alternatives. Current site-specific EWSs rely on the measurement of parameters such as pore pressure, soil suction and displacement at a given site. Such EWSs are based on the expectation that an alarm will be issued when a predetermined level for a parameter has been reached.

As part of a project geared towards understanding rainfall-induced landslides, the authors have been monitoring since 2010 a cut slope at a site adjacent to the State Highway 1 (SH1) in Silverdale, Auckland. This site experienced a landslide in June 2008. Volumetric water content sensors and a tipping bucket rainfall gauge were installed at the site. From the monitored data, supplemented by laboratory testing and finite element modelling, a site-specific EWS was developed which provides the user with a more direct indication as to the current state of the site with regards to slope failure (i.e. the factor of safety, FoS), as well as a predicted time until failure.

2 SITE DESCRIPTION

The site being monitored is a cut slope located in Silverdale, about 40 km north of Auckland City. The site was developed in 1998 as part of an 11 m cut into the natural ground during the construction of State Highway 1 (SH 1), the longest and most significant road in the NZ’s roading network. The slope has a horizontal to vertical ratio of 4:1. The soil forming the slope largely consists of residual soil of the
Mangakahia Complex of the Northland Allochthon group, which is well-known for its susceptibility to landsliding and creep (Winkler 2003). A section of the embankment gave way in June 2008, following an extended period of heavy rainfall. Further details of the landslide are discussed by Harris et al. (2012).

3. METHODOLOGY

3.1 Soil Properties

Three separate layers have been identified at the site: a Northland Allochthon (NA) residual layer, a transition layer and a moderately weathered NA parent rock layer.

The soil-water characteristic curve (SWCC) was determined using the pressure plate apparatus (Fig. 2). The SWCC of the weathered parent rock was assumed to be the same as that of the transition zone. The model proposed by van Genuchten (1980) was used to model the permeability/matrix suction relationship. The saturated permeability of the soil was obtained using the falling head test.

The shear strength parameters of the soil were measured using constant shear stress drained triaxial tests (Harris & Orense 2012). However, it was difficult to define a smooth failure envelope from these tests, particularly for the transition zone. This is possibly due to the effects of over-consolidation, or it could be a characteristic of the Northland Allochthon soil. As a result, the shear strengths used by the engineers to the original cut were employed (Tilsley, 1998). These shear strengths were obtained from a variety of back analyses of other landslides within the region, triaxial compression tests and from experience with similar soils in the region. These adopted shear strength parameters are shown in Table 1. The shear strength component due to matrix suction was estimated based on Equation 1, as set out by Vanapalli et al. (1996).

\[
\phi' = \left[ \left( \frac{\theta_w - \theta_s}{\theta_w - \theta_r} \right) \tan \phi \right]
\]

where \( \phi' \) is the angle of shearing resistance with respect to matrix suction (as described by Fredlund et al. 1978), \( \phi' \) is the normal angle of shearing resistance, \( \theta_w, \theta_r \) and \( \theta_s \) are the water content, saturated water content and residual water content (by volume) of the soil, respectively.

| Soil Type      | \( \gamma \) (kN/m\(^3\)) | \( c' \) (kPa) | \( \phi' \) (°) |
|----------------|-----------------|-------------|-------------|
| Residual layer | 16              | 3           | 28          |
| Transition layer | 17            | 0           | 17          |
| Parent rock    | 17              | 5           | 28          |

3.2 Field Monitoring

At this site, 13 volumetric water content sensors were installed to a maximum depth of 3m at three locations (near the toe of the slope, at mid-height near the crest of the slope). These sensors were placed along the same cross section of the site, approximately 45 m from and parallel to the axis of the existing landslide. The probes, consisting of ECH2O and MP406 sensors (ICT 2012) were installed by hand augering to the desired depth and using a PVC tube to push the sensors into the soil. The auger holes were backfilled and compacted following installation of the sensors. A tipping-bucket rain gauge, with a resolution size of 0.2mm was installed at the site to monitor rainfall events. A data logger powered by a solar panel records the data at 15 min intervals. Further details of the instrumentation, calibration and interpretation of readings are presented by Harris et al. (2014).

3.3 Finite Element Modeling

SEEP/W (GEO-SLOPE International Ltd, 2009a) was used for undertaking the finite element modelling (FEM). The hourly rainfall recorded at the site was
applied as a unit influx into the FEM. A spatial function was used to establish the initial conditions of the FEM. Counterfort drains, which were installed midway up the slope during the cut operation, were assumed to be derelict or ineffective. This assumption was based on the current condition of the pipes, and references made by Winkler (2003) to the ineffectiveness of such drainage systems in the low permeability soils of the Northland Allochthon. The boundary of the bottom and sides of the model were defined as a no flow boundaries, based on an assumption of symmetry. The model mesh was generated automatically into 1m square grids; however in the upper 2m of the model, this mesh was gradually refined into a 0.25m square grid in order to capture the advancement of the wetting front. This FEM, showing the slope profile, strata and the locations of the sensors is shown in Figure 3.

The permeability of the soil was altered in this FEM until the water content time history obtained from the FEM was in agreement with that obtained from the sensors at the site. A negative flux was also applied to the slope between rainfall events in order to achieve a good agreement between the two.

3.4 Limit Equilibrium Analyses
SLOPE/W (GEO-SLOPE International Ltd, 2009b) was used to undertake the limit equilibrium analyses. This software package allows the matric suction profile from the FEM to be directly imported into the limit equilibrium analyses. The grid and radius function was used to find the slip centre and the failure surface which resulted in the lowest factor of safety (FOS) using the Morgenstern and Price method, at each time step in the FEM.

To check the calibration of these models, the 2008 rainfall data which caused a landslide at the site was used as an input into the FEM, and the corresponding matric suction profile input into the limit equilibrium analyses. As the field monitoring was not underway in 2008, the 2008 rainfall data was obtained from three nearby rainfall stations maintained by the National Institute of Water and Atmospheric Research (NIWA). If calibrated correctly, the model should approach a factor of safety close to unity at the same time as when the landslide occurred at the site.

3.5 Artificial Neural Network
The rainfall record and corresponding factor of safety obtained for 2008 was then input as a training set into an artificial neural network (ANN). The software Matlab (MathWorks Inc 2012) was used to create the ANN. The Levenberg-Marquardt method (Mathworks Inc 2010) was used to optimize the ANN, using the mean-squared error to assess the performance of the network. The data obtained from the Limit equilibrium analysis (LEA) and the field monitoring was used to train the ANN. Because few extreme rainfall events occurred during the field monitoring period, artificial rainfall events were added to the rainfall record which was applied in the FEM and subsequent LEA. Details of the ANN-based method are discussed by Harris (2013). The 2 hour, 1 day, 2 day, 5 day, 10 day, 15 day and 20 day rainfall events were used as input parameters into the ANN. This artificial neural network was then used to predict the factor of safety for the entire 2008.

4 RESULTS AND DISCUSSION
4.1 Finite Element Modeling
Figure 4 shows the results obtained from the field monitoring compared to those obtained from the finite element modelling. The upper graph shows the hourly rainfall recorded at the site throughout the rainy season. The middle graph shows the fluctuating water content for a sensor located at mid-height of the slope at 0.5m deep, and the lower graph shows the fluctuating water content of the soil at the same location, however at 1.75m deep. As observed in the figure, the water content at shallow depths fluctuates greatly with each rainfall event, indicating that the wetting front advances below these sensors at each significant rainfall event. However, at deeper depths there appears to be virtually no change in the volumetric water content (note the different scales used in these graphs). This is consistent with the observations of O’Sullivan (2009) and Winkler (2003), who suggested that due to the low permeability of the soil, the water table remains high, and the soil remained fully saturated throughout the entire year. This explains why the water content at approximately 1.75m deep rarely fluctuated throughout the monitoring period. Thus, the results from the FEM appear to be reasonably successful at replicating the fluctuating volumetric water content of the soil.

4.2 Limit Equilibrium Analyses
Figure 5 shows the factor of safety (FOS) obtained from the 2008 rainfall record. As mentioned earlier, the 2008 rainfall record was input into the FEM, and a limit
equilibrium analyses undertaken at each time step to predict the FOS based on the matric suction/pore pressure profile obtained. At each significant rainfall event, there is a sudden decrease in the factor of safety. Following the rainfall event, the FOS begins to gradually recover. As seen, the factor of safety reaches

Figure 4. Results obtained from the field monitoring for two sensors located at mid-height of the slope. The results obtained from the FEM in comparable locations are also shown. Elapsed time = 0 corresponds to the 19th of May 2010 at 10.00am.

Figure 5. The FOS obtained from the limit equilibrium analyses for 2008, and the corresponding rainfall events. Elapsed time = 0 corresponds to midnight on the 1st of January 2008.

Figure 6. A comparison between the limit equilibrium analyses predicted factor of safety and the predicted using an Artificial Neural Network for 2008.
a minimum of approximately 0.85 at an elapsed time of 5000 hours. According to reports, movement at the site was first noted at an elapsed time of 4400 hours, however the time it took from first movement to complete failure of the slope was unknown. The results indicate that the finite element model and the limit equilibrium analyses are reasonably calibrated to simulate the observations made at the site.

4.3 Artificial Neural Network

Figure 6 shows the predicted FOS obtained from the ANN compared with that obtained from the limit equilibrium analyses. The ANN-predicted FOS is similar to that obtained from the limit equilibrium analyses; however there are a few spikes in the ANN-predicted FOS at various times, possibly implying the ANN is susceptible to extreme rainfall events.

5 APPLICATION OF THE EWS

The use of the EWS is summarised as follows. During a heavy rainfall event the field data is downloaded from the site in real time via the internet. This field data is then uploaded into the EWS. The FOS of the previous 24 hours, using the field data, is then obtained using the ANN. Based on the rate of change of this predicted FOS, the time until the FOS will reach a FOS of unity is returned to the user.

Next, the rainfall forecast for the next 5 hours for the site is obtained from the Meteorological Service of New Zealand (2012) via the internet. This forecast can be freely obtained by the public. This forecast is based on the Weather Research and Forecasting model, using data obtained from automatic weather stations, weather radar facilities, upper air sites and marine observation stations (Bridges, 2011). The predicted FOS over the next 5 hours is obtained using this rainfall forecast as an input into the ANN. The starting FOS for this predicted FOS is the last FOS obtained using the actual sensor data. Because of the difficulty in verifying forecasts at a local scale (Hodson, 2009), both the predicted FOS according to this forecast, and the rate of change of the FOS obtained from the field monitoring data, are used to estimate when failure may occur.

If failure is predicted to occur within five hours, then a stage one warning is issued. This involves warning motorists to lower speed limits around the landslide site. If failure is to occur within one hour, then a stage two warning is issued. This puts a detour in place, so motorists avoid the site altogether. Two warnings were used because the detour route adds approximately 25 minutes to the journey. Thus this detour route is put in place as late as possible to avoid frustration with the EWS due to false alarms. Warning motorists to lower speeds around the possible landslide site in advance is intended provide a balance between minimising the cost should the landslide occur, and avoiding frustration at the delay to motorists. During periods of heavy rainfall, the EWS should be updated on an hourly basis.

6 CONCLUSIONS

Slope monitoring and numerical analyses were conducted at a site where rainfall-induced slope failure occurred during the winter of 2008. The fluctuating field-measured \( \theta_w \) during 2010 was replicated in a FEM using soil-water relationships obtained based on empirical methods. Next, the known rainfall pattern which caused slope failure in 2008 was applied as an inflow to the model and a limit equilibrium analysis was undertaken at each time step to determine the factor of safety corresponding to each rainfall event. As the factor of safety reached a minimum of 0.85 slightly after the initial movement was recorded, it is concluded that the model is still slightly out of calibration. An artificial neural network was then trained based on the results of this limit equilibrium analyses, using data from the field monitoring as inputs. This artificial neural network predicts the factor of safety of the slope, and forms the basis of the warning system. It is envisioned that this methodology can be replicated at virtually any site susceptible to rainfall induced landslides.

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