A site specific early warning system for rainfall induced landslides

Utilisation d'un site spécifique pour l'élaboration d'un système d'alerte rapide pour les instabilités de pente induites par les pluies.

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ABSTRACT: An early warning system (EWS) to warn users of imminent landsliding caused by rainfall has been developed. The EWS is deterministic, based on a pre-determined failure mechanism present at a specific site. A prototype of the EWS was developed for a roadway embankment located in Silverdale, New Zealand. Prolonged rainfall caused a landslide at the site in 2008. Soil debris from this landslide event almost obstructed a major highway, which could have been potentially dangerous to motorists as well as causing major delays to the Auckland roading network. Volumetric water content sensors were installed at various depths and locations along the same cross section of the site. A 2D finite element model was used to replicate the response of the sensors to rainfall, using monitored rainfall events as an influx in the model. Next, a limit equilibrium analysis was used to obtain the factor of safety against slope failure for each time step in the finite element model. An artificial neural network was then trained to predict this factor of safety using the sensor readings as inputs. Thus, the factor of safety of the slope can be predicted in real time. This predicted factor of safety forms the basis of the EWS.

RÉSUMÉ : Un système d'alerte précoce (SAP) pour avertir les utilisateurs de glissements de terrain provoqués par des pluies imminentes a été développé. Le SAP est déterministe, basée sur les mécanismes de rupture pré-déterminés présents sur un site spécifique. Un prototype du SAP a été développé pour un remblai de la chaussée située à Silverdale en Nouvelle-Zélande. Des pluies prolongées ont causé un glissement de terrain sur le site en 2008. Les coulés de sol engendrées par ce glissement de terrain ont presque obstrué une route importante, ce qui aurait pu être potentiellement dangereux pour les automobilistes ainsi qu'être à l'origine de retards importants sur le réseau routiers d'Aucklande. Des capteurs volumétriques de teneur en eau ont été installés à des profondeurs différentes et à des emplacements variés le long de la section transversale du site. Un modèle par éléments finis 2D a été utilisé pour reproduire la réponse des capteurs aux précipitations, en utilisant les données expérimentales de comme données d'en trée. Ensuite, une analyse d'équilibre limite a été utilisée pour obtenir le facteur de sécurité pour la stabilité de la pente pour chaque pas de temps. Un réseau neuronal artificiel a ensuite été formé pour prédire ce facteur de sécurité en utilisant les relevés du capteur comme modèle. Ainsi, le facteur de sécurité de la pente peut être prédite en temps réel. Ce facteur de sécurité prévu est à la base du SAP.

KEYWORDS: rainfall, landslide, artificial neural network, early warning system

1 INTRODUCTION

As a means to mitigate the risk of rainfall induced landslides which cause millions of dollars' worth of damage each year in New Zealand (NIWA & GNS Science, 2010), an early warning system (EWS) has been developed. A prototype of this EWS was installed at a site in Silverdale, Northland, New Zealand. Much of the damage which incurs from rainfall induced landslides occurs in this region of New Zealand (NIWA & GNS Science, 2009).

EWSs for rainfall induced landslides started as empirical relationships which related the number of landslides in a given region to the intensity and duration of rainfall events. Examples can be seen in Dhakal & Sidle (2004), Keefer et al (1987) and Caine (1980). As technologies have developed, focus on EWSs has become more site specific. Current EWSs rely on measuring parameters such as pore pressure and displacement at a given site. Such EWSs are based on issuing an alarm when a predetermined level of these parameters has been reached (Chae & Kim, 2012; Intrieri et al., 2012). The EWS developed in this research was required to return to the user a number related to the possibility of failure, and also a timeframe for failure to occur. To achieve this, volumetric water content (VWC) sensors were installed at a variety of depths at the toe, mid-point and top of the slope. A tipping bucket rain gauge was used to monitor the intensity and duration of rainfall events. The fluctuations in VWC recorded by the sensors were replicated in a finite element model (FEM), using the recorded rainfall events as an influx into the slope. Next, a limit equilibrium analysis was used to determine the factor of safety (FOS) at each time step in the FEM. Thus, a database was created which contained values of the VWC as measured by the sensors at the site, and the corresponding FOS. This database was then used to train an artificial neural network (ANN). The ANN can thus predict the FOS of the slope in real time, using sensor readings as an input. The ANN can also predict the future FOS of the slope, using rainfall forecasts for the site as an input. The trend of the predicted FOS using the sensor data, and the future FOS obtained according to the rainfall forecast, form the basis of the EWS. Based on this information the user of the EWS can take the required action; in this case, lowering speed limits and putting detours in place.

1.1 *Site and Soil Description*

The site consists of a roadway embankment created from a cut operation during the construction of State Highway One, which runs parallel to the toe of the embankment. State Highway One is a major arterial which services Auckland city. The slope angle of the embankment is approximately 15°. A concrete dish drain is located on a bench at mid-height of the slope. The site is grassed, with some low height trees present. Debris from a landslide which occurred at the site in 2008 following prolonged rainfall almost crossed into the traffic lanes of State

Highway One, which could be potentially dangerous to motorists and cause significant disruption to the Auckland road network.

The soil at the site consists of weathered soil from the Northland Allochthon formation, which is renowned for its montmorillonite content (Power, 2005). This formation is susceptible to landsliding due to seasonal pore-pressure changes (Lentfer, 2007; O'Sullivan, 2009). The site consists of 3 strata; the underlying parent rock, a transition zone and a completely weathered residual soil. The transition zone consists of unweathered rock fragments in a silty clayey matrix. This transition zone has many slickensided shear surfaces present, and is thought to be one of the underlying factors that give rise to the susceptibility of the formation to landslides. The residual soil is a silty clay, susceptible to shrink swell movement. In general, sites in the Northland Allochthon have high ground water tables even in dry periods (O'Sullivan, 2009).

For a more detailed description of the site and soil properties, the reader is referred to Harris et al. (2012).

2 METHODOLOGY

A total of 13 VWC sensors were installed along the same cross section of the slope; at the toe, mid-height and crest. The sensors consisted of MP406s and ECH_2O probes (ICT International Pty Ltd, 2012), which were installed at approximately 0.25m depth intervals. A tipping bucket rain-gauge was used to record rainfall events. Recordings were made via a data logger at an hourly interval.

SEEP/W (GEO-SLOPE International Ltd, 2009a) was used for the FEM. The hourly rainfall captured at the site was input as an influx into the slope. A general evaporation pattern was applied to the model as a negative influx between rainfall events. This generalised evaporation pattern was based on a trial and error method to get the best agreement between the FEM results and the field monitoring results. The level of evaporation applied following a rainfall event was determined by the cumulative rainfall amount of the event. This FEM was coupled with the limit equilibrium analysis (LEA) program *SLOPE/W* (GEO-SLOPE International Ltd, 2009b). Thus at each hourly time step in the FEM, the FOS was obtained.

The soil properties used in these models are given in Table 1. The soil water characteristic curve was described using the Van Genuchten (1980) method, the parameters of which were obtained using the pressure plate apparatus. The permeability was determined using the falling head method. A variety of triaxial tests, including constant shear drained tests, were used to determine the shear strength parameters. The shear strength values used for the top soil layer were reasonably high to force the slip surface obtained in the LEA to a reasonable depth. φ^b represents the angle of shearing resistance due to matric suctions, as described by Fredlund et al. (1978)

Table 1. Soil parameters used in the models.

	Van Genuchten (1980) Parameter					Shear Strength		
	k	a	n	m	θ_r	φ	φ^b	c′
	m/hr 10^{-3}	kPa^{-1}			%	°	°	kPa
Top Soil	36	608	3.27	0.69	38.5	40	20	10
Residual Soil	0.36	608	3.27	0.69	38.5	36	20	0
Transition Zone	0.036	297	5.23	0.81	37.2	21	20	3
Underlying Rock	0.0036	29	5.23	0.81	37.2	35	20	5

The ANN was developed using the software *Matlab* (The MathWorks Inc, 2012). For more information regarding ANNs and their use in geotechnical engineering, the reader is referred to Khanlari et al. (2012). The ANN was trained to predict the LEA-obtained FOS using the sensor readings from the field monitoring as inputs. The ANN was developed as a closed-loop recurrent dynamic network, where the FOS predicted by the ANN for the previous time-step was used as an input for the prediction of the FOS for the current time-step. The Levenberg-Marquardt method (Mathworks, 2010) was used to optimize the ANN, which had 10 hidden layers. The accuracy of the ANN improved when cumulative rainfall amounts were included as inputs into the ANN. Thus, cumulative rainfall amounts ranging from 2 to 200 hours were included as inputs into the ANN.

A second ANN was developed which predicts the LEA obtained FOS based solely on rainfall data. Thus the future FOS could be predicted at the site using rainfall forecasts obtained from the Meteorological Service of New Zealand (2012).

3 RESULTS

A reasonable agreement was obtained between the field measured and FEM obtained VWC. The permeability of the top soil layer had to be increased in the FEM in comparison to the underlying soil layers to obtain the required infiltration amount. Presumably this reflects the discontinuities such as surface cracks and vegetation of the soil. In some locations the agreement was very good, in others the agreement quite poor The reason for this is thought to be due to natural variability within the soil, as described by Dai et al. (2002).

To confirm this modelling process, the rainfall record obtained from the Meteorological Service of New Zealand (2012) leading up to the 2008 landslide was input into the models. As a FOS of just above unity was obtained at approximately the same time as the landslide occurred, it is assumed that the models used in the development of this EWS were reasonably accurate.

Because few extreme rainfall events occurred during the field monitoring period, artificial rainfall events were input into the rainfall record. Such artificial rainfall events can be seen in the upper graph of Figure 1, at an elapsed time of 1500 hours and 2200 hours. The comparison between the FOS obtained from the LEA, that obtained from the ANN using sensor data, and that obtained from the ANN using just rainfall data is shown in the lower graph of Figure 1. As observed, at each significant rainfall event there is a large decrease in the FOS. This FOS recovers rapidly following the rainfall event.

The ANNs are reasonably accurate at predicting the LEA obtained FOS. The mean squared error of the ANN using sensor was 0.41. Using just rainfall data, the mean squared error increased to 1.16. The FOS predicted by the ANNs is susceptible to large fluctuations, particularly during times of evaporation. This is seen at elapsed times of approximately 1600 hours and 2600 hours. Because these fluctuations occur during times of evaporation, they are not critical to the accuracy of the EWS; however they do indicate that some discrepancies occur due to the generalised evaporation pattern which was used. If a deterministic approach was used to measure evaporation, such as that described by Penman (1948), it is thought that such discrepancies will be minimised. The improvement in accuracy from the ANN which uses just rainfall data as an input, compared to the ANN which uses sensor data also, indicates that the use of the sensors provides an indication as to the actual amount of rainfall infiltration in the slope.

To provide an example of the EWS in use, the data corresponding to the point shown in Figure 1 was input into the EWS. The resulting plot is shown in Figure 2. Elapsed time = 0 corresponds to the point in time when the data was obtained from the site. The upper graph in Figure 2 shows the rainfall record obtained from the site (from an elapsed time of -24 to an elapsed time of 0). The rainfall is constant as it is obtained during an artificial rainfall event, as shown in Figure 1 (a). The rainfall record in Figure 2 from an elapsed time of 0 to and elapsed time of 5 hours is that obtained from the forecast.

The solid line in the lower graph of Figure 2 is the ANN – predicted FOS of the last 24 hours, using the sensor data as inputs. The dotted line is the predicted FOS over the next 5 hours, using the rainfall forecast data as an input. Because the ANN using the sensor data is more accurate than that using just rainfall data, this predicted FOS using rainfall forecasts loses accuracy over time. Thus, the predicted future FOS using rainfall forecast data is set to equal the FOS predicted using sensor data each time the sensor data is downloaded.

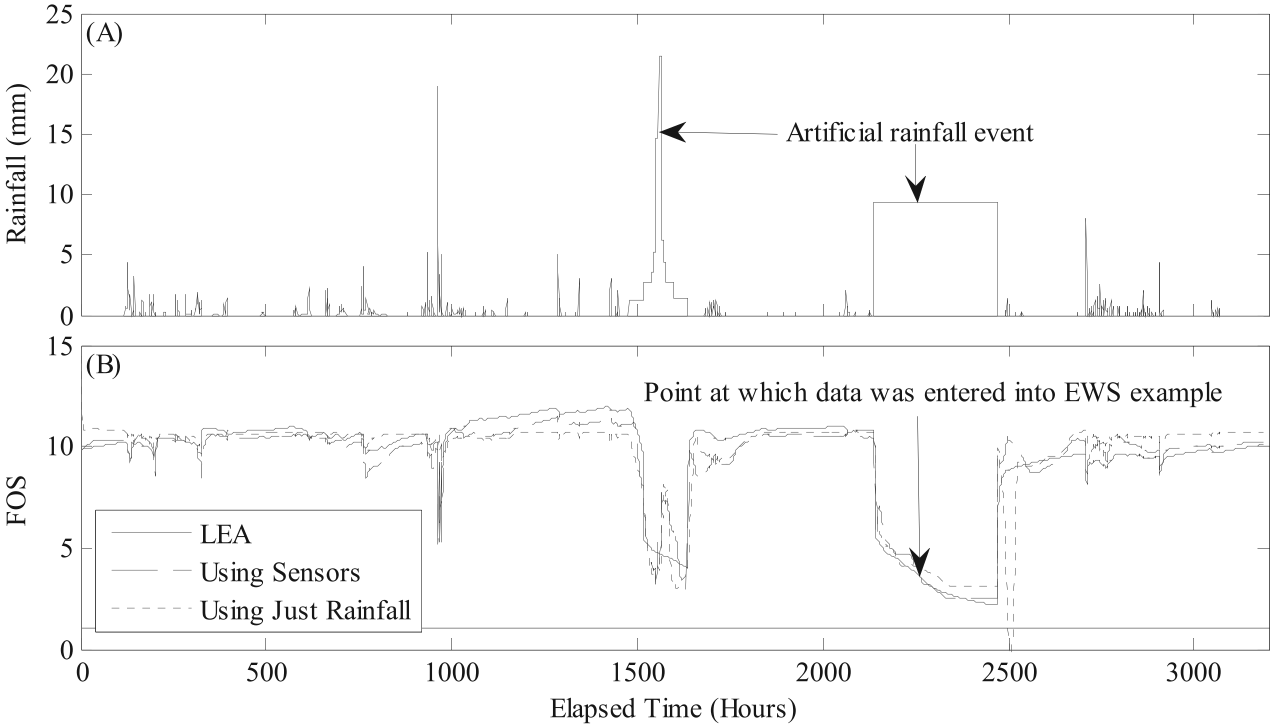

Figure 1. (A) Rainfall events input into the FEM and (B) corresponding FOS obtained from LEA, the ANN using field measured data, and the ANN using only rainfall events. The black line shows a FOS of unity (i.e. when failure will occur).

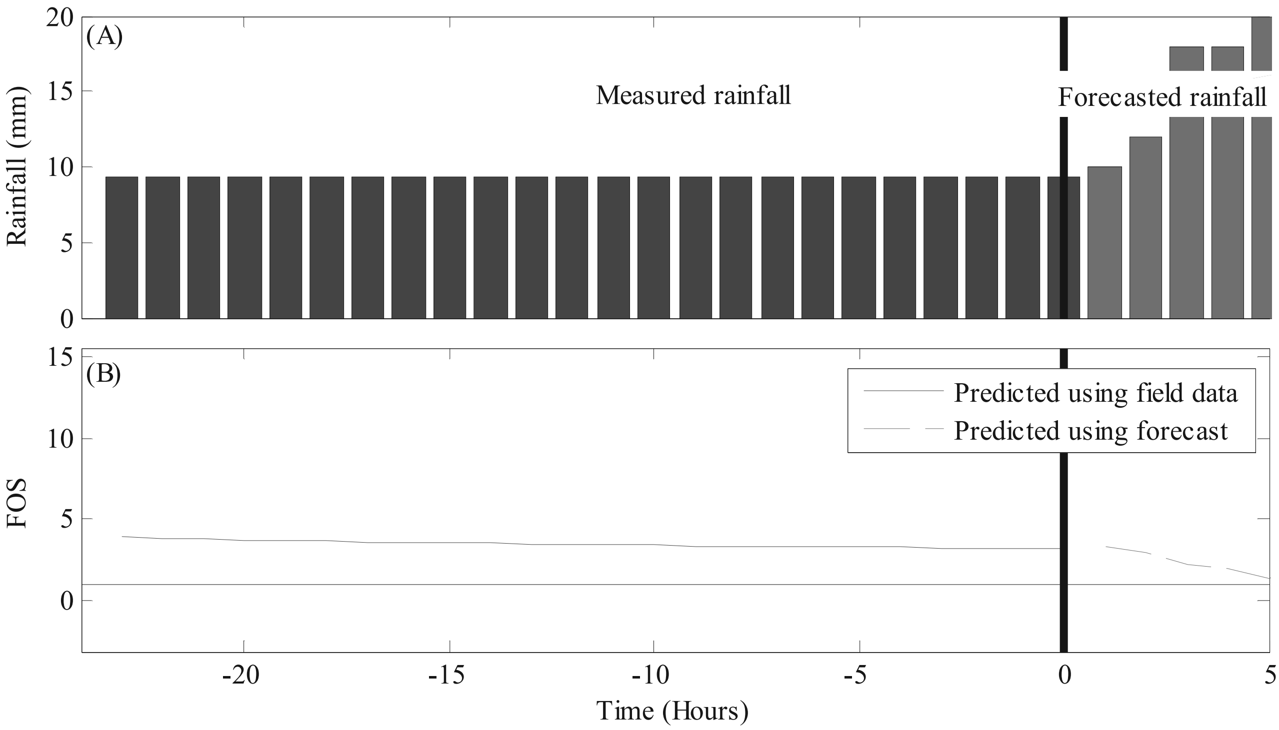

Figure 2. Example of the EWS in use. Elapsed time = 0 corresponds to the point in time at which the data was downloaded from the site (shown in Figure 1). The upper graph (A) shows the rainfall recorded at the site, and the forecasted rainfall at the site. The lower graph (B) shows the predicted FOS using the field data, and the predicted future FOS using the rainfall forecast. A FOS of unity is shown by thing black line.

4 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.

5 CONCLUSIONS

A site specific EWS for rainfall induced landslides has been developed. The EWS is based on the ability to predict the current FOS of the site using ANNs, rainfall forecast data and real time field measurements. The EWS proves to be useful at predicting when failure might occur, and also returns to the user a parameter related to the possibility of failure (the current FOS).

A FEM was used to replicate the field response of the site to rainfall events. This FEM was coupled with a LEA to predict the FOS at each time-step. The results of this modelling process were reasonably accurate, considering discrepancies caused by natural variation within the soil and the generalised evaporation pattern which was applied within the model.

The ANN which uses field measured data could predict the LEA obtained FOS with good accuracy; a mean squared error of 0.41 was obtained. To predict the future FOS, an ANN using just rainfall forecast data was developed. This ANN was less accurate, with a mean squared error of 1.16 obtained.

It is envisioned that the methodology used to develop this EWS can be replicated at a variety of sites as a means of risk reduction for rainfall induced landslides.

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