A Study of a Creeping Landslide in Western Japan from Hydrological Perspective

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Abstract

Monitoring and analysis of hydrological parameters are crucial to understand the underlying causes and mechanisms of a landslide. This paper analyses hydrological parameters of an existing creeping landslide site in western Japan known as Nuta-Yone Landslide. The landslide site has been active since the last several decades. Attempts to retard the rate of landslide have been partially successful but several very expensive underground horizontal drains proved to be less effective or ineffective due to poor locations.

Groundwater flow and resulting fluctuation of pore water pressures at the slip layer of a sliding block of the landslide site were simulated by constructing a MODFLOW based three-dimensional groundwater flow model. The distributions of different parameters in the calibrated model were used to explain the reasons of ineffective drains and categorize locations for the drains that have higher potential of being effective. Local variations in pore water pressure fluctuations were used to pin-point the areas that needed dewatering. The groundwater flow model results were integrated with a two-dimensional slope stability analysis method to find local distribution of two-dimensional factor of safety within the sliding block. Fluctuation in quasi-three-dimensional factor of safety of the entire sliding block was simulated by using various methods. The study results showed the reason for the creeping nature of the sliding blocks.

Keywords: pore water pressure, landslide, factor of safety, groundwater modeling

1. Introduction

The Shikoku Island in south-western Japan (Fig. 1) consists of 80% mountains. There are four major active tectonic faults in this island, running almost parallel in the northeast and southwest directions. The fault lines serve as boundaries between different geological formations of Shikoku Island. The rainfall pattern in this area of Japan is highly seasonal; every year Shikoku Island faces several high intensity precipitation events in the Typhoon season. Due to tectonic movement in the area, the bed rocks along the fault lines are in fractured state. The effect of hydrothermal alteration phenomenon is supposed to be high in this region causing extensive mineral decomposition in the fractured bed rocks. Rainfall infiltration into the rock fractures further aggravates the rock weathering process and weakens the hill slopes. This combination of weak slopes, high intensity seasonal rainfalls, and tectonic activities has resulted in occurrence of a very high number of landslides in Shikoku Island. This paper addresses hydrological aspects of one such large-scale landslide called Nuta-Yone.

The Nuta-Yone Landslide Site (NLS) is located over Mikabu Tectonic Line (Fig. 1) at Otoyo Town in Kochi Prefecture. NLS consists of three sliding clusters, namely Tateno Cluster, Yone Cluster and Nuta Cluster; each cluster has several sliding blocks, and some of the large sliding blocks consist of several sub-blocks, as shown in Fig. 2. This study focuses on a particular sliding sub-block in Nuta Cluster.

Land displacements at NLS were noticed as early as 1950s. Historical records show that the area affected by the landslides at NLS has been increasing. Initially, the Kochi Prefecture government monitored the landslides and took some landslide preventative measures. From the 1960s, the central government of Japan has been involved in landslide monitoring and mitigation activities. NLS is an inhabited area; there are several houses, and several kilometers of service road and forest roads within the designated NLS area (Shiraishi et al., 2003).

Monitoring of landslides at NLS is conducted by a network of global positioning systems (GPS) and extensometers; the surface location of each GPS receiver station is monitored every day. Differential vertical displacement of boreholes is monitored to find the depth to the slip surface of each block and the rate of displacement at the slip surface the block.

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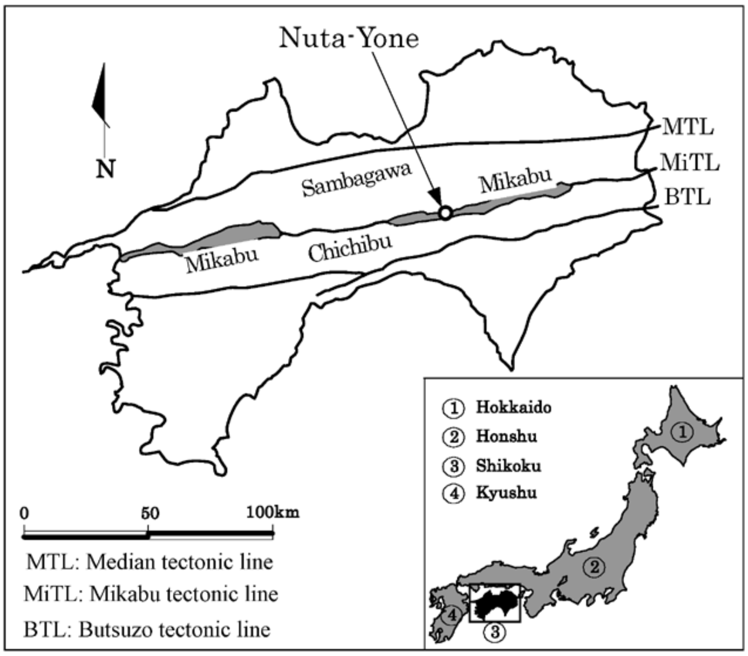

Fig. 1. Map of Shikoku showing location of NLS

Various landslide preventative measures have been taken at NLS, including retaining walls, surface drains, horizontal drains, and vertical collection wells. The horizontal drains have been constructed in multi-layers to collect water from different geological formations. There are two types of horizontal drains at NLS, one with a vertical collection well and the other without the well. Some of the vertical wells go below the slip layer and hence act as a pile. Water collected from the horizontal drains is discharged into Minamidaiogawa through the surface drains; dewatering of the hills lower water table, which, in turn, reduce the pore water pressure at the slip surface of the sliding blocks and thus lowers the potential of occurrence of landslide.

Based on the availability of data, this study concentrated in the area enclosing sub-blocks N2-2 and N2-3 shown in Fig. 2. The details of the location of boreholes, springs and horizontal drains at the study area are shown in Fig. 3; the effectiveness of the drains vary, some are highly effective and some are less effective or ineffective.

Like most other sliding blocks and sub-blocks, the N2-2 and N2-3 sub-blocks have been sliding at creeping rates for the last several years. During the highest recorded 24-hour rainfall at NLS in 1998, the sliding rate of the sub-blocks increased, but the rate was still within the range of creep movement; there was no complete collapse of the hill slope despite very high intensity rainfall event.

The groundwater dynamics of the area enclosing the sub-blocks N2-2 and N2-3 were simulated by constructing a three dimensional groundwater flow model, and the results of the investigation were related to the fluctuation in pore water pressure at the slip surface of the sub-blocks and the factor of safety of the sub-blocks during August 27 to September 30, 1998. The paper discusses the results of the groundwater simulation and integration of groundwater modeling with slope stability analysis methods.

2. Methods

Available pertinent geological, hydrological, and topographical data of NLS were collected from concerned authorities. The time-series data of daily rainfall, daily fluctuations in water surface elevations (WSE) at boreholes, and daily ground surface movement (GSM) at a GPS station in N2-2 block was analyzed to see the effects of horizontal drains.

The data showed that most of the boreholes were located around sub-blocks N2-2 and N2-3. The results of a study can be only as good as availability of good data, hence the area covered by N2-2 and N2-3 sub-blocks were selected for the study.

The fluctuation of WSE at different boreholes indicated that the general direction of groundwater flow and the direction of landslides in the study area are from east to west; hence the area selected for modeling

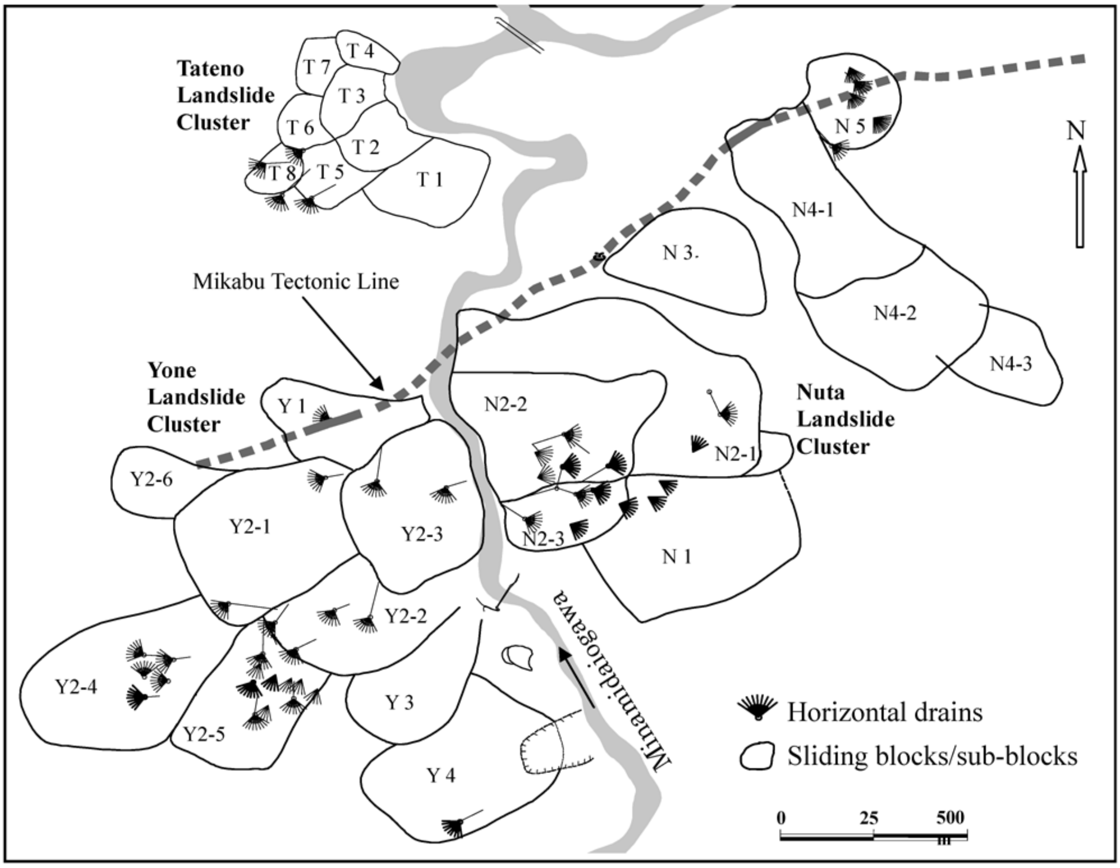

Fig. 2. Landslide clusters, sliding blocks and horizontal drains at Nuta-Yone Landslide Site

study was oriented in east-west direction (Fig. 3). The boundary conditions of the model area were set based on topographical maps, groundwater divide, expected directions of groundwater flow at the boundary cells, expected variations in groundwater table at the eastern and western boundary cells, locations of horizontal and surface drains, natural springs, and expected fluctuations in water table at the eastern model boundary. The cells located to the west of right bank of Minamidaiogawa were set as inactive cells because these cells do not affect the groundwater dynamics in the model area. The model cells in the eastern and western boundary were set as 'general head boundary' cells, the model cells in the northern and southern boundary were set as 'no flow' cells. The selection of the area for modeling was based on data availability and inclusion of complete sliding sub-blocks. The model area boundary was selected in such a way that two sub-blocks were completely within the boundary and the direction of the groundwater flow along north and south boundary were parallel to the boundary.

The horizontal discretization was based on expected rate of changes in hydraulic head; since there were no pumping or recharging wells, rapid changes in hydraulic head were not expected and hence in the horizontal direction all the model cells were made of same size. The model area was horizontally discretized into 6000 cells (80 columns and 75 rows) per layer; each cell was of size 6m $\times$ 6m. The vertical discretization of the model area was based on the changes in material properties, specifically the changes in hydraulic conductivity with depth. Different materials with similar hydraulic conductivity values were treated as same material for the modeling purpose. Similarly, materials with hydraulic conductivity values within a narrow range were treated as same material for model simplification. At most of the borehole locations the changes in material types were three or less; hence the model was vertically discretized into three layers. At specific borehole locations the cell thickness depended on the thickness of the material; in the areas between the boreholes the cell thickness was estimated based on interpolation of material thickness at the surrounding boreholes. Hence, the cell thickness changed from one cell to another.

The fluctuations in WSE at specific borehole locations within the model area were used as model calibration targets. GMS, a proprietary version of the popular finite-difference based United States Geological Survey code called MODFLOW, was used to construct and calibrate the groundwater flow model of the area

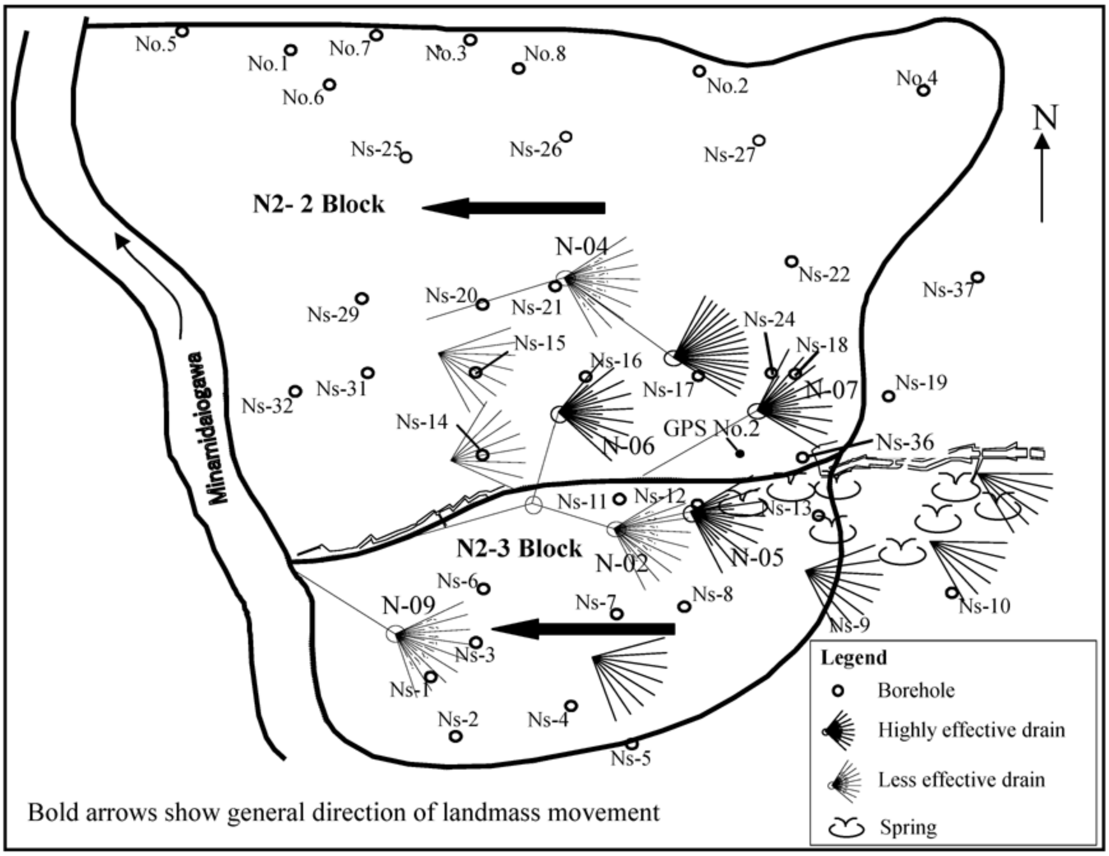

Fig. 3. Boreholes, drains and spring at the modeling site of NLS

(Harbaugh et al., 2000). MODFLOW is the most popular code for groundwater modeling (Kresic, 1997). The initial cell-by-cell distribution of various hydro-geological parameters like the hydraulic conductivity tensor, specific storage, and specific yield were based on interpolation of site specific values of the parameters at the boreholes. During model calibration the parameter distributions were changed as required, following the standard procedure of manual model calibration. Once the groundwater flow model was successfully calibrated, the model was validated by its ability to simulate fluctuations in WSE at borehole data that were not used as part of the model calibration. The sensitivity of the calibrated model to changes in different model parameters were tested by varying the parameter distribution values by specific amounts or percentages.

The parameter distributions in the calibrated groundwater flow model of NLS were used to check the reason for variations in effectiveness of the horizontal drains. The parameter distributions at locations of effective and ineffective horizontal drains were compared. Similarly, the location of the drains with respect to the general direction of groundwater flow, as indicated by the calibrated groundwater flow model, was also checked to find the reason for variations in drain effectiveness.

The variations in groundwater table during a specific period were simulated using the calibrated model of NLS. The three-dimensional (3D) representation of the slip surface of N2-2 block was obtained from differential displacement of boreholes in vertical direction. The fluctuations in groundwater table were converted to fluctuations in pore water pressure at the slip surface of N2-2 block. The N2-2 block was divided into 26 equidistant sections oriented along the east-west direction. Using Janbu's slope stability analysis method (1956), the fluctuations in two-dimensional (2D) factor of safety (FOS) of each section was estimated using the fluctuations in pore water pressure at the slip surface and other soil properties, such as dry and wet soil density, porosity, cohesion, and angle of internal friction. The spatial variations in the 2D FOS indicated the critical areas that required urgent attention for implementation of landslide preventative measures. The fluctuations in 2D FOS of each section of N2-2 block were used to obtain fluctuation in quasi-3D FOS of the entire block by using three methods; the results of the study showed the reason for lack of complete failure of the N2-2 block despite very low 2D FOS at some parts of the block.

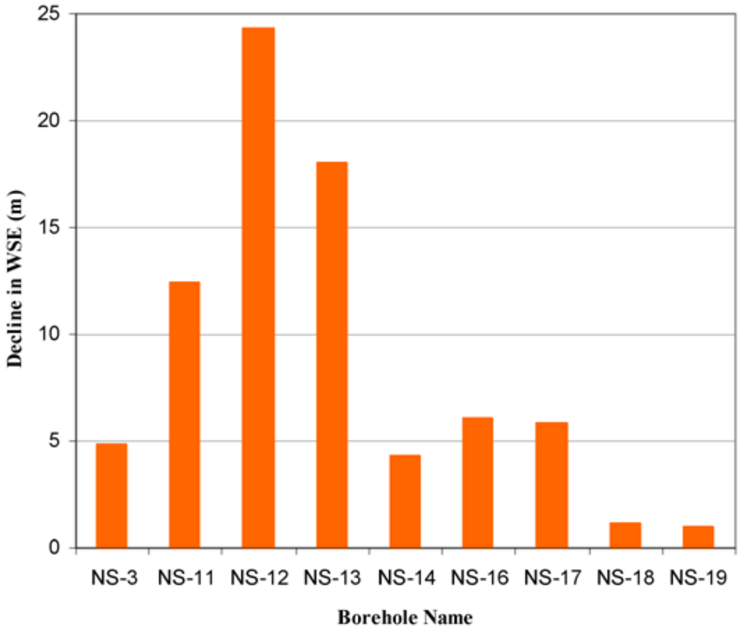

Fig. 4. WSE decline at boreholes after drain operation

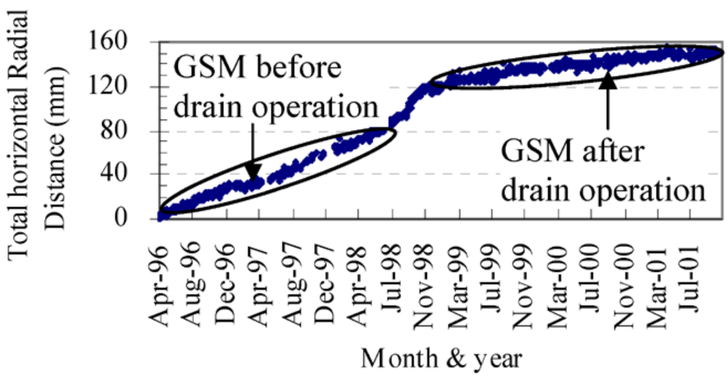

Fig. 5. Ground surface movement of GPS No. 2

3. Results and discussion

3.1. Effectiveness of horizontal drains

There are several sets of horizontal drains in the model area. The purpose of the drains was to dewater the hillside so that the WSE in the area can be reduced. The time series analysis of WSE data at different borehole locations at NLS indicated that WSE at some of the boreholes dropped significantly, up to 24 meters, after operation of the horizontal drains (Fig. 4). However, at some locations the effects of the horizontal drains on WSE were very low; WSE remained more or less constant even after the operation of the drains.

Draining of the hills at NLS caused the decline in WSE at the boreholes; the lowered water table resulted in reduced pore water pressure at the slip surface of the sliding sub blocks. As a result, the rate of landslide of N2-2 block has declined significantly, as shown in Fig. 5. The rate of GSM at NLS has declined from 4 cm/year to 0.7 cm/year, which can be considered a success in the attempt to mitigate landslide disaster at NLS.

As shown in Fig. 3, there are "highly effective" and "less effective" horizontal drains at NLS. Four more horizontal drains are planned to be constructed in the near future in the north-western part of the model area. To investigate the reasons for the variations in effectiveness of the drains and to estimate the potential effectiveness of additional drains planned for the future, a computer model of groundwater flow at the area was constructed. Fig. 6 is a 3D representation of the model domain. The groundwater flow model of the area

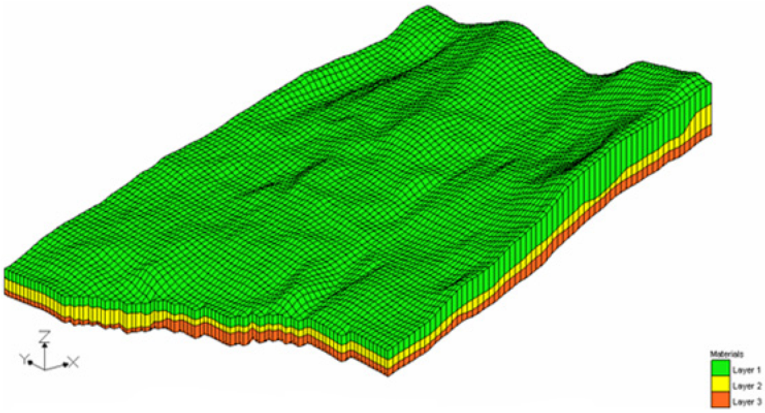

Fig. 6. 3D-representation of model domain

was calibrated based on observed WSE at different boreholes using manual calibration method. The calibrated model was verified by checking the simulated WSE with observed WSE at the boreholes; a different set of data, unused for model calibration, was used in model verification.

The distribution of horizontal hydraulic conductivity (K) around each horizontal drain, as represented in the calibrated model, was checked to find the reasons for variations in effectiveness of the drains. The location of the horizontal drains with respect to general direction of groundwater flow in the model domain was also checked to find favorable locations of effective drains. Fig. 7a shows the K distribution around "effective" drains (N-03, N-05, N-06 and N-07) and "less effective" drains (N-02 and N-04); Fig. 7b shows the K distribution around "ineffective" drain (N-09). The arrows in the figures 7a and 7b show the direction of groundwater flow. Analysis of K distribution around the drains of different effectiveness showed that at the "effective" drains compared to the discharge side the K values in the cells in the recharge side were higher. The effective drains N-03, N-05 and N-07 have higher K in the recharge side and lower K in the discharge side (Fig. 7a). On the contrary, the "ineffective" drain N-09 has relatively lower K in the recharge side and relatively higher K in the discharge side (Fig. 7b). At the locations of "effective" drains the higher K in the recharge side allowed more water to flow rapidly towards the drains and the lower K in the discharge side impeded the water to flow downwards; hence the water gets collected at these locations and the "effective" drains were able to withdraw the collected water. Analysis of the location of the horizontal drains with respect to the general direction of groundwater flow indicated that the drains located on the pathway of the groundwater flow were effective, and the drains located away from the pathway were less effective or ineffective. It was thus found that the effectiveness of the horizontal drains was influenced by (a) the K distribution around the drains and (b) the location of the drains with respect to the groundwater flow pathway.

3.2. Pore water pressure distributions

Rise in pore water pressure in the hillside is one of the basic causes of landslides. The slip surface of the N2-2 block was determined from variation in horizontal displacement in each borehole; the portion of the borehole above the slip surface displaces more than the portion of the borehole below the slip surface. Fig. 8 shows the 3D view of the slip surface of N2-2 block from the bottom; as indicated in the figure, the bottom surface of some parts of the slip surface are not horizontal across the section. Such sections were mostly in the north and south edges of N2-2 block. Due to the inclined bottom surface across the section the actual area available for development of resisting force against landslide is higher than the projected area.

The pore water pressure distribution at the slip surface of N2-2 block during low rainfall period and high rainfall period were simulated using the calibrated groundwater flow model. The results of the simulation indicated the critical locations within the N2-2 block that have higher pore water pressure even during low rainfall periods. The circles in the figures 9a and 9b show the high pore water pressure area during high intensity rainfall and low intensity rainfall, respectively. Such areas can be considered prime locations for implementation for future dewatering activities. Comparison of figure 9a with 9b shows the rise in critical areas in terms of high pore water pressure due to high intensity rainfall at the study area.

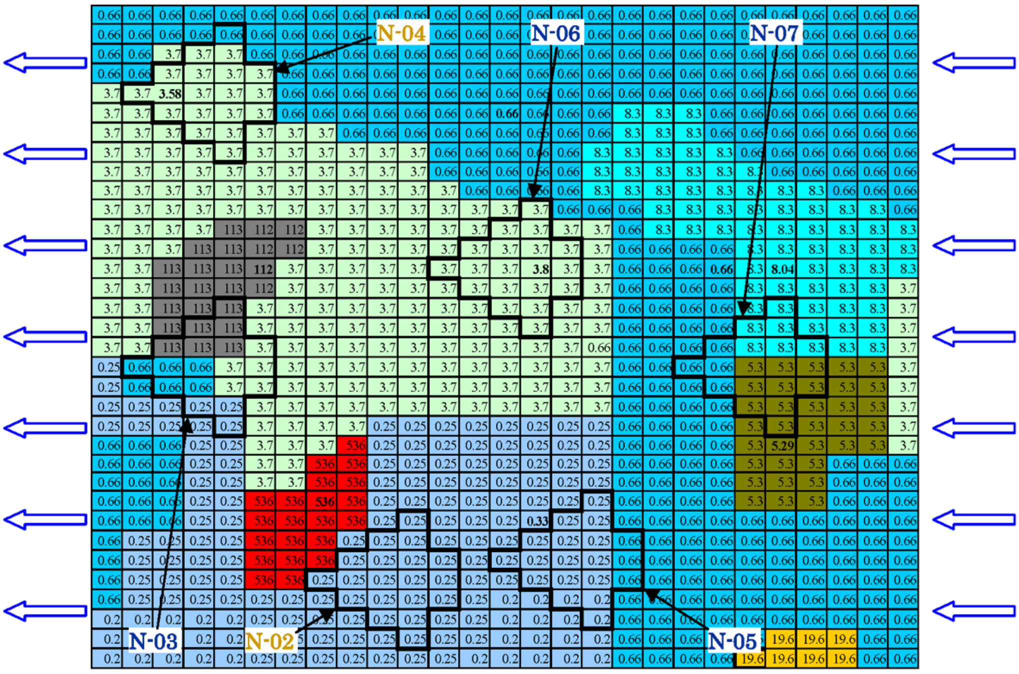

Fig. 7. a K distribution around "effective" and "less effective" horizontal drains

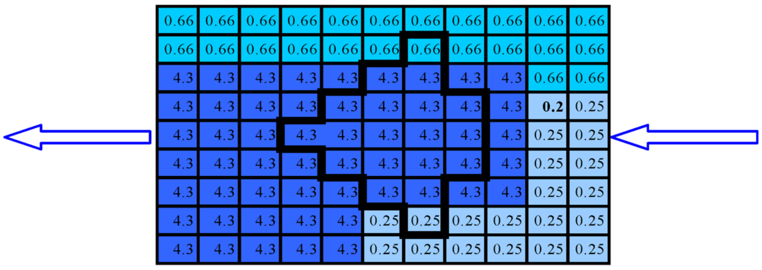

Fig. 7. b K distribution around "ineffective" horizontal drain

3.3. Factor of safety (FOS)

The fluctuation in the FOS of the N2-2 block was simulated by considering the local soil properties. Researchers in Japan have found that in the absence of site specific data, the cohesion (c') can be approximated by the relation $c' = 0.981z$, for soils in Japan, where z is the depth of the slip surface from the ground surface in meters (Fujita et al., 1985). The internal angle of friction ($\phi\prime$) was obtained from previous studies involving soil samples from the model area. The $\phi\prime$ value of soil samples at the slip surface of NLS range from 22.5 to 29.4 degrees (Bhandary et al., 2001). As the internal angle of friction increases, the soil resistance to shear failure also increases. To be on conservative side, a value of $\phi\prime = 23$ degrees was assigned to all the slices. The N2-2 block was divided into 26 sections oriented parallel to the direction of landslides. For the particular scenario of high rainfall of September 1998, using Janbu's method (1956), the 2D FOS of each section was calculated separately for each day of simulation. The variation in 2D FOS of each section showed the critical locations in the model area. At some locations the 2D FOS of some sections were below 1 for certain duration; however, no complete failure of the N2-2 block occurred. Local FOS values of 1 or less do not necessarily mean that a slope is unstable.

The quasi-3D FOS of the entire N2-2 block was calculated by using three methods — Sherard et al. method (1963), Lambe and Whitman method (1979), and Loehr et al. method (2004). In Lambe and Whitman's method, the quasi-3D FOS is calculated by weighting the two-dimensional FOS of each section by the area of the section. In Sherard et al.'s method the total resisting force is divided by the total driving force of all the sections; it is assumed that the role of each two-dimensional section in overall slope stability of three-dimensional sliding block is equal. In Loehr et al.'s method the factor of safety are weighted based on the total equilibrium shear force along each two-dimensional slip surface, corrections are made for difference

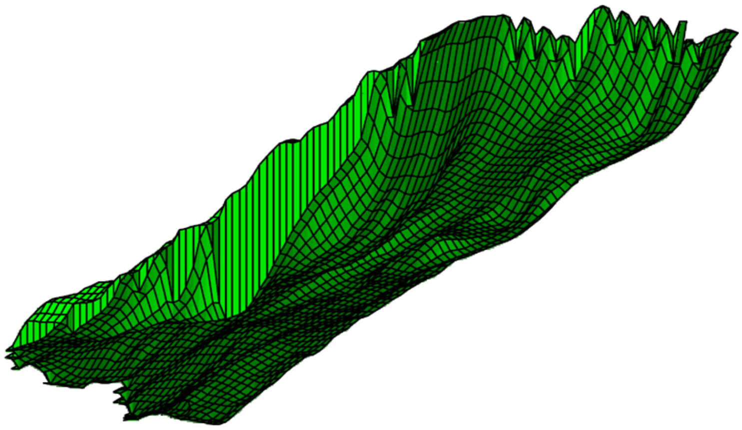

Fig. 8. D-view of slip surface of N2-2 block from bottom

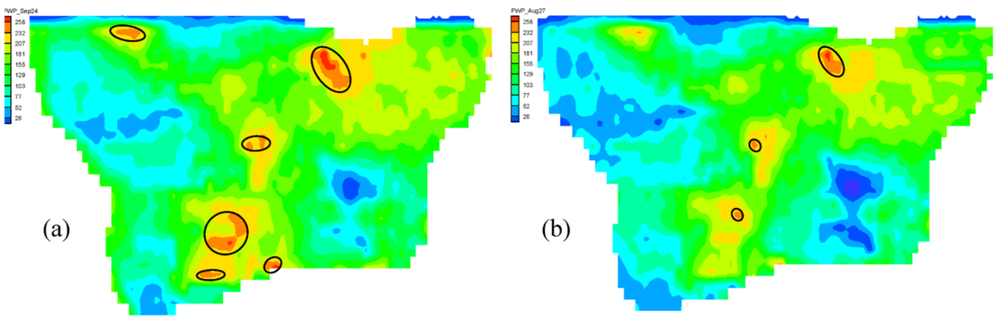

Fig. 9. Spatial distribution of pore water pressure at the slip surface of N2-2 block

between projected area and real area of slip surface. When the bottom of the slip surfaces is not horizontal the actual area over which the resistance force develops is larger than the projected area. As shown in Fig. 8, the bottom of many sections of the N2-2 block was not horizontal; hence, as shown in Fig. 10, the total resistance force developed and the resulting FOS of the N2-2 block calculated using Loehr et al.'s method (represented by triangles) was higher than the results of the Sherard et al.'s method (represented by diamonds) and Lambe and Whitman's method (represented by squares). Due to the higher pore water pressure and larger sectional area at the central portion of the N2-2 block, the quasi-3D FOS value calculated by using the Lambe and Whitman's method fluctuated in the unstable zone, indicated by shaded area in Fig. 10, for two days within the simulation time; however, as mentioned before, no complete collapse of the block occurred. The results of the quasi-3D FOS calculations showed that the FOS of the entire N2-2 block fluctuated in the creep movement zone (Fig. 10). The average quasi-3D FOS of N2-2 block, represented by the bold line in Fig. 10, fluctuated between 1 and 1.05 for the duration of simulation, which resulted in creeping movement of N2-2 block. Patton (1984) pointed out that a landslide block tends to move at creep rate as long as the FOS of the block is slightly above 1. Siqing (1999) also mentioned that the factor of safety of creeping landslides calculated by using limit equilibrium methods is above 1. The N2-2 block is sliding at creep rate and the results of the study indicated the reason for the creeping nature of the slide. The simulation result was, thus, able to represent the reality of creeping movement of N2-2 block at NLS.

4. Conclusions

The results of the study showed that the horizontal drains are effective in lowering the water surface elevation of a hillside; however the location of the drains should be determined based on groundwater dynamics of the area. Locations with comparatively higher hydraulic conductivity in the recharge side and lower hydraulic conductivity in the discharge side are generally suitable for locations of horizontal drains. Similarly, the horizontal drains should be located in the general pathway of the groundwater flow in the area. Groundwater flow modeling can be effectively used in finding the critical locations of a hillside in terms of high pore water

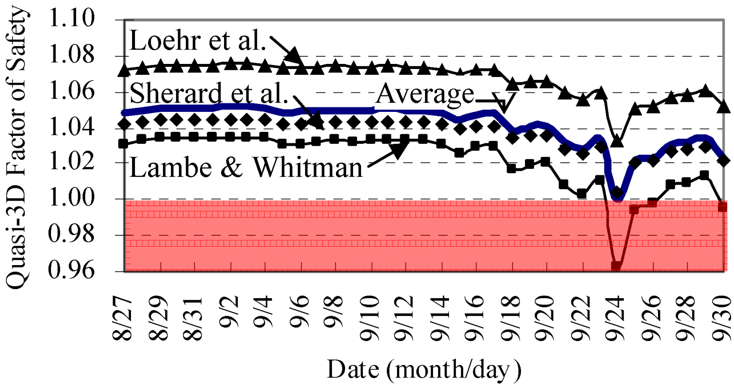

Fig. 10. Fluctuation in quasi-3D FOS of N2-2 block

pressure; application of groundwater flow model was able to locate the time-dependent areas of high pore water pressure at the Nuta-Yone Landslide Site. The results of the groundwater flow model can be easily integrated with the two-dimensional slope stability methods, which, in turn, can be used to estimate the fluctuations in quasi-three-dimensional factor of safety of a hillside.

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