Numerical modelling of a creeping landslide using the finite element method: A case study

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ABSTRACT

In this study, a finite element based numerical method is considered to evaluate the creeping behavior of a creeping landslide induced by snow melt water. A novel 2D-Elasto-viscoplastic constitutive model is used to simulate the creeping behavior owing to groundwater level fluctuations of the Tomuro landslide of Gunma, Japan as a case study. Two new control constitutive parameters are incorporated in the numerical model for the first time to better understand the creeping behavior of a landslide. Such control constitutive parameters are estimated based on the relation between the total factor of safety, calculated by the various Limit Equilibrium Methods and Finite Element Method, and the field monitoring displacement rate of the Tomuro landslide. In addition, the snowfall precipitation is also considered during the calculation of total factor of safety using both limit equilibrium methods and finite element method. Others required material parameters for landslide simulation are obtained from the field investigation and laboratory tests of the collected blocked samples. The simulation results of deformation pattern and shear strain pattern are also discussed to understand the creeping behavior of the Tomuro landslide. Moreover, the predicted and measured time histories of horizontal displacement of the Tomuro landslide are compared for the validity of the proposed numerical model, and found in good agreements with each other.

Keywords: finite element simulation; groundwater fluctuation; new control constitutive parameters; creeping behavior; tomuro creeping landslide

1 INTRODUCTION

Creeping landslides are one of the major geotechnical hazards. Most of creeping landslide sites accommodate human settlement and agricultural fields, roads and highways, bridges and tunnels, nature conservation sites, and so on (Bhat et al., 2017a and 2014a). When the displacement rate of such landslides is suddenly increased and accelerated, it leads a huge mass failure, which damages human life, property, nature, and the environment. If a numerical approach to predict the creeping behavior of a landslide is possible, each damage can be prevented (Bhat et al., 2017a, and 2017b). Therefore, study of the creeping behavior of a landslide and associated Geotechnical hazard issues seems very important.

Creeping landslides are controlled by the groundwater fluctuations (e.g., Conte et al. 2014; Picarelli et al. 2004) therefore; groundwater fluctuations should be incorporated in the numerical simulation of such landslides (Bhat et al. 2017a and 2017b). However, most of previous numerical approach (e.g., Picarelli et al. 2004; Patton 1984) of soil creep and associated problems are focused on the laboratory creep tests (i.e., consolidation/oedometer test and triaxial test), which could not address the fluctuation of groundwater level. Based on the theoretical, experimental, and numerical models, a few researches (e.g., Bhat et al. 2016 and 2014b; Picarelli et al. 2004; Patton 1984) have tried to address these issues; but they are not fully understood, especially in relation to the displacement behavior of a creeping landslide. Huvaj and Maghsoudloo (2013) have simulated considering groundwater fluctuations in different phases to understand of displacement behavior of a slow-moving landslide, but the exact value of the deformation at any required point (location) couldn’t be captured perfectly. Recently, a few researchers (e. g., Ishii et al., 2012; Conte et al., 2014; Fernández-Merodo et al., 2014) have proposed a FEM-based 2D-Elasto-viscoplastic constitutive model using the field instrumentation and monitoring results, but they are only considered the single control constitutive parameter, estimate based on the trial and error method, which could not control the displacement rate of the landslide, and also far to address the realistic field problem of creeping behavior of the landslide. Therefore, the main objective of this study is to address the above-mentioned problems using a new FEM-based numerical model, and to study the creeping behavior of Tomuro landslide induced by snow melt water as a case study.

2 STUDY AREA

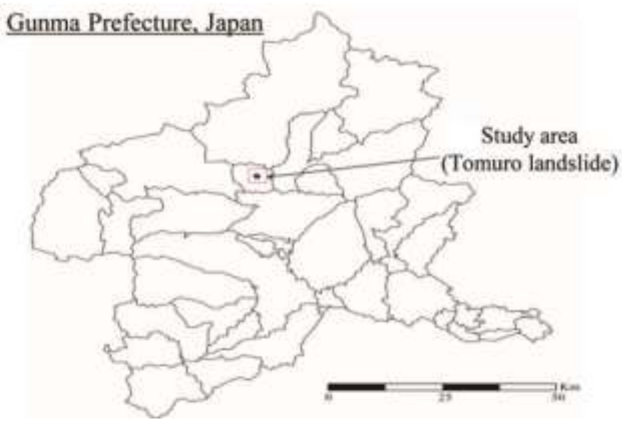

Fig. 1. Location of study area (Tomuro landslide).

Fig. 1 shows the location of Tomuro landslide of Gunma, Japan. The size of Tomuro landslide has been measured approximately 135 m X 110 m. The location of Tomuro landslide on a Google map with showing the locations of sampling point, Piezometers, Extensometer, moving direction, and landslide mass are presented in Fig. 2.

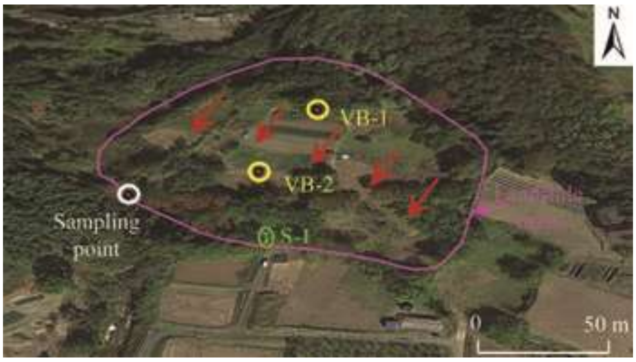

Fig. 2. Locations of Tomuro landslide on a Google map.

The Piezometers were installed at the location of BV-1 and VB-2 for monitoring the groundwater level of the landslide mass. The results of the groundwater fluctuations at the boreholes (BV-1, BV-2) are presented in Fig. 3. The Extensometer was installed at S-1 to measure the horizontal displacement ($\dot{\gamma}_{max}$) of the landslide mass. The maximum displacement rate of 9.9 mm/day was recorded on 2014/3/4, where the groundwater level was also recorded maximum at the VB-1 and VB-2. From the comparative study of groundwater level and displacement rate with various time periods, it is understood that the displacement rate depends upon the fluctuation of the groundwater level. When the groundwater level is rising, the displacement rate is also increased and vice versa. In this study, the groundwater fluctuation is considered for the stability analysis using the various limit equilibrium methods and finite element method, as well as the numerical simulation of the Tomuro landslide.

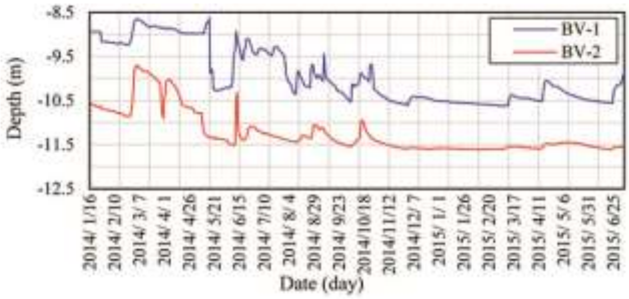

Fig. 3. Groundwater fluctuation in the boreholes (BV-1, BV-2).

3 NUMERICAL SIMULATION

In previous 2D-Elasto-viscoplastic constitutive model (e.g., Conte et al., 2014; Fernández-Merodo et al., 2014; Ishii et al., 2012), one parameter was considered, which was calculated based on trial and error method after calculating the results of displacement rate. This means that the displacement rate couldn't directly control in the previous 2D-Elasto-viscoplastic constitutive models. Moreover, such usual previous approaches are time consuming, tedious and difficult for estimating the appropriate parameters for the better simulation. However, the newly proposed numerical model has incorporated two new control constitutive parameters ($\dot{\alpha}, n$) for the first time for directly controlling the displacement rate and factor of safety of the landslide. Moreover, the newly proposed method is capable to easily estimate the exact control constitutive parameters for the better numerical simulation of the creeping behavior of the landslide, which may help for investigating the realistic field problem of a creeping landslide in the future. The details of the newly proposed model are discussed by Bhat et al., 2017a and 2017b.

The proposed numerical model is applied to study the creeping behavior of Tomuro landslide of Gunma, Japan. Fig. 4 shows the two dimensional finite element mesh used for the analysis, which is prepared based on the geological x-section of the slope of such landslide site. The major three representative materials (layers) are observed from the boreholes details of such landslide. Here, it is assumed that the creeping behavior of a landslide mass only exhibits on sliding surface/layer. Therefore, the constitutive parameters are varied for the sliding surface in the different cases of I-IV (Table 1). S-1 represents the location of Extensometer point (i.e., node 199), where the maximum displacement of the landslide mass was measured in the field (Fig. 4).

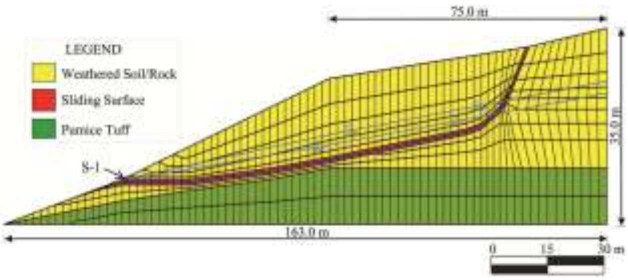

Fig. 4. Finite element model of Tomuro landslide.

In this study, the parametric study has been done to obtain the two new unknown control constitutive parameters ($\dot{\alpha}, n$). Initially, the total factor of safety (F_s) is calculated using the various Limit Equilibrium Methods (LEM) based on the slices and Finite Element Method (FEM). In LEM, three frequently used methods are used to calculate F_s of Tomuro Landslide of Gunma, Japan. At first, the ordinary method of Slices (Fellenius 1936) is used, which is referred as "Case I". Bishop's method (1955) has used to address the limitation of the ordinary method of slices, which is referred as "Case II". Again, Janbu's Simplified method (1973) is also used to incorporate the drawback of the Bishop's method (1955), which is referred as "Case III". Finally, the FEM is also used to address the drawback of the LEM, which is named as "Case IV". In FEM method, Shear Strength Reduction Method (SSRM) is used.

Table 1. Material parameters for landslide simulation.

Materials (→) / Parameters (↓)	Weathered Soil/Rock	Sliding Surface				Pumice Tuff
		I	II	III	IV	
Young's modulus, E (kN/m²)	5000	1000				50000
Poisson's ratio, ν	0.40	0.30				0.45
Cohesion, c′ (kN/m²)	50	0				5000
Internal friction angle, ϕ′ (deg.)	35	15.2				30
Dilatancy angle, ψ (deg.)	0	0				0
$\dot{\alpha}$ (day^-1))	-	0.00089	0.000489	0.00023	0.0011	-
n	-	53.398	46.4900	55.833	67.233	-
Unit weight, γ (kN/m³)	24	20				26

Matsuura et al. (2003) have reported that snow melt water and/or rain water are closely related to groundwater level and landslide displacement. Therefore, the snowfall precipitation is also considered during the calculation F_s of the landslide mass. After the calculation of F_s, the relations between $\dot{\gamma}_{max}$ and F_s have been established for the cases I-IV. After that, the general equations are obtained based on the well fitted curve between $\dot{\gamma}_{max}$ and F_s. Than, the unknown two new control constitutive parameters ($\dot{\alpha}, n$) were estimated by solving of these general equations for each case. The other required material parameters for the landslide simulation (Table 1) are estimated based on field investigation results and laboratory test results. The summary of the material parameters for landslide simulation is tabulated in Table 1.

4 SIMULATION RESULTS AND DISCUSSION

Fig. 5 shows the results of deformation pattern at the end (i.e., 2015/7/6) for the case II as a representative result. The red dot line shows the result of a maximum deformation pattern of each node at the end of the numerical simulation with compare to without the deformation (i.e., initial condition). The maximum deformation of 0.26735 m was recorded at node 199 (i.e., S-1). Similarly, the maximum deformation of 0.26921 m, 0.26683 m, and 0.26921 m were obtained at the same node 199 in the cases I, II & IV respectively. From the comparative analysis of the results of deformation pattern in the cases I-IV, it was found that the value of the deformation of node 199 is almost the same. Moreover, the maximum deformation was occurring at the same node 199, where the maximum displacement of the landslide mass was recorded during field monitoring. Hence, any one case (method) among these four representative cases (i.e. I-IV) can be used to understand the deformation pattern of a creeping landslide in the future.

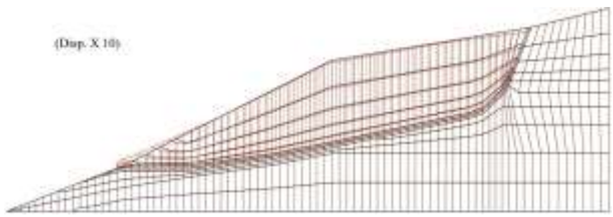

Fig. 5. Results of deformation pattern (Case II).

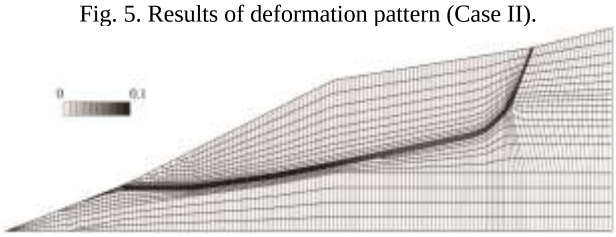

Fig. 6. Results of shear strain pattern (Case II).

Fig. 6 show the results of the shear strain pattern at the end for the case II as a representative result. The maximum shear strain of 0.91059 was obtained at element 278 at the end of the numerical simulation in the case II. The maximum shear strain of 0.92647, 0.90419, and 0.93865 were found at the same element 278 in the cases I, II & IV respectively. Based on the comparative study of the results of shear strain pattern in the cases I-IV, it was found that the maximum shear strain has exhibited along the sliding surface of the Tomuro landslide. Moreover, the results of overall shear strain trends of each case were found almost same. The maximum shear strain value is also almost same and occurred at the same element 278, where the maximum displacement rate of the landslide mass was recorded during the field monitoring. Therefore, any one case among the four representative cases (i.e., I-IV) can be applied to study the shear strain pattern of a creeping landslide in the future. From the overall comparisons of the results of the deformation pattern and shear strain pattern, it clearly shows that the maximum shear strain and maximum deformation occur along the sliding surface.

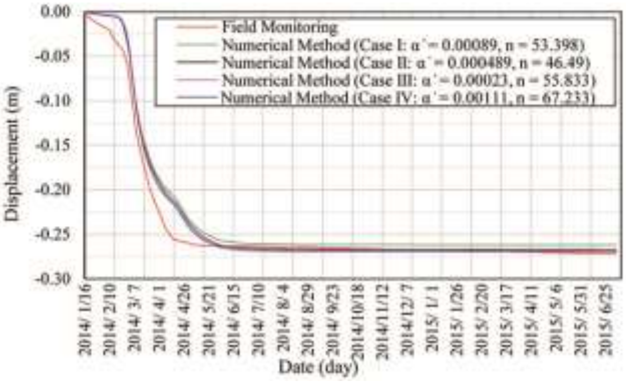

Fig. 7. Comparison of predicted and measured time histories of horizontal displacement at S-1.

Fig. 7 shows the comparison of predicted time histories of displacement in model and measured displacement in the field. Here, the predicted time histories of displacement were measured at the same point S-1, where the displacement was measured in the field. Moreover, the horizontal component of displacement was considered for predicting time histories of displacement in the model. The maximum horizontal displacement of 0.2717 m was recorded at the end of the field monitoring. Similarly, the maximum displacement of 0.2617 m, 0.2673 m, 0.2668 m, and 0.2692 m was obtained by the numerical method in the cases I-IV respectively. In numerical method, the results of maximum horizontal displacement at the same point is almost same and they are also following the similar trends with respect to time (Fig. 7). Therefore, any one case among the four representative methods can be used to understand the creeping behavior of the landslide in the future.

5 CONCLUSIONS

In this study, the creeping behavior of Tomuro landslide induced by snow melt water has been studied using the finite element method. A 2D-Elasto-viscoplastic constitutive model is used to simulate the creeping behavior of clayey soil along the sliding surface of Tomuro landslide. Two control constitutive parameters are incorporated for the first time to perform the realistic field problem of the landslide. The simulation results of deformation pattern and shear strain pattern have been presented to evaluate the creeping behavior of clayey soils along the sliding surface of Tomuro landslide owing to groundwater level fluctuations by snow melt water. Finally, the results of predicted and measured time histories of horizontal displacement at S-1 have been compared, and found in good agreements with each other. Therefore, it is believed that this model can be applied as a replicable numerical model/tool to understand the creeping behavior of a landslide induced by snow melt water in the future.

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