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Evaluation of Deformation Behavior of a Natural Slope Using Particle Filter

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Abstract: This paper shows an evaluation method for landslide behavior using an elasto-viscoplastic finite element(FE) analysis and the particle filter (PF). As the elasto-viscoplastic constitutive model, the Mohr-Coulomb yield criterion with the over-stress model is adopted, and landslide displacements are simulated. The geotechnical parameters related to the creep behavior of a landslide are identified with the PF in this research. The results of the FE analysis using the identified parameters agree well with the observed data, and it is confirmed that the methodology presented in this study can be effective in the evaluation of landslides. In addition, countermeasures for landslides are discussed based on the predicted displacements; and consequently, the possibility of the proposed method's practical use is verified for the mitigation of landslide hazards.

Keywords: Landslides, Displacement prediction, Elasto-viscoplastic analysis, Particle filter

1 Introduction

Evaluating the stability of a landslide-prone slope and the ground behavior is crucial in maintenance works (Futatsugi, et al. 2018). The stability of a slopeis generally evaluated by the safety factor based on the limit equilibrium method.The method firstly assumesthe slip surface using measurements, such as those taken by inclinometers, and strain data. Then, the strength parameters, such as the angle of internal friction and cohesion along the slip surface, are determined from the measurements to perform the stability analysis.As several undisturbed samples close to the slip surface are required for a reliable determination of the strength parameters,difficultiesare encountered in the application of soil investigationsdue to budget limitations. In order to solve these difficulties, the c-tanϕ diagram, assuming a certain safety factor, is alternatively used for the determination. However, the mechanical evidencefor the experimental determination using the diagram is often inadequate for discussing the real behavior of landslides.

To monitor landslide behavior,inclinometers, extensometers, pipe strain gauges, and water level gauges are generally installed at the actual landslide site. The observation data are used to evaluate the scale and range of the landslide, to elucidate the mechanism, and to predict the collapse time. However, few works have examined the implementation of countermeasuresand accurate predictions that are basedpurely on arational interpretation of the measured data applied at the design stage.In order to logically assist in the design of effective technical countermeasures based on the field measurements, the application of inverse analyses using measurements is desirable for the calibration of numerical models by means of the identification of parameters.

This paper presents an evaluation method for landslide behavior using an elasto-viscoplastic finite element (FE) analysis, in which the strength parameters are identified by an inverse analysis based on field measurements.A two-dimensional finite element method, incorporated with the Mohr-Coulomb yield criterion, is carried out to explain the behavior of the landslide, and the parameters are identified by the particle filter. A prediction of the landslide is performed and the effects of countermeasures for landslides are numerically investigated.

2 Analysis

2.1Elasto-viscoplastic finite element method

Herein, the elasto-viscoplastic finite element method (Zienkiewicz and Cormeau 1974) is briefly described. It is firstly assumed that the total strain rate is divided into elastic and viscoplastic components.

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{e}_{ij} + \dot{\varepsilon}^{vp}_{ij} \tag{1}$$

where $\dot{\varepsilon}_{ij}$ is the total strain rate tensor, $\dot{\varepsilon}_{ij}^{e}$ is the elastic strain rate tensor, and $\dot{\varepsilon}_{ij}^{vp}$ is the viscoplastic strain rate tensor. The total stress rate is related to the elastic strain rate as

$$\dot{\sigma}_{kl} = D_{ijkl}\dot{\varepsilon}_{ij}^{e} \tag{2}$$

where $\dot{\sigma}_{kl}$ is the total stress rate and D_{ijkl} is the elasticity tensor. The following well-known Mohr-Coulomb yield criterion is adopted as the yield function:

$$F = \left(\sigma_1' - \sigma_3'\right)/2 - c'\cos\phi' - \left(\sigma_1' + \sigma_3'\right)\sin\phi' \tag{3}$$

where F is the yield function, σ'_1 is the major principal stress, $\sigma'_3$is the minor principal stress, c' is the effective cohesion, andϕ' is the effective internal angle of friction. The viscoplastic flow rule for an overstress type of elasto-viscoplastic constitutive model (Owen and Hinton 1980)is generally expressed as

$$\dot{\varepsilon}_{ij}^{vp} = \gamma\left\langle\Phi\left(F\right)\right\rangle\frac{\partial Q}{\partial\sigma_{ij}} \tag{4}$$

where Q is the plastic potential, γ is the fluidity parameter, andΦ is the function of overstress. In this paper, the plastic potential is determined bythe following equation:

$$Q = \left(\sigma_1' - \sigma_3'\right)/2 - \left(\sigma_1' + \sigma_3'\right)\sin\Psi + k \tag{5}$$

where Ψ is the dilatancy angle and k is the constant parameter. The function of overstress is the monotone increasing function in terms of F> 0, and the angle brackets mean

$$\left\langle\Phi\left(F\right)\right\rangle = \Phi\left(F\right)\ F > 0$$

$$\left\langle\Phi\left(F\right)\right\rangle = 0\ F \le 0 \tag{6}$$

The function of overstress is expressed as

$$\Phi\left(F\right) = F \tag{7}$$

2.2Particle filter

The particle filter (henceforth, PF) (Gordon et al.1993;Kitagawa 1996) is one of the inverse analysis techniques.The PF can easily deal with nonlinear and non-Gaussian estimation problems, and is robust when employing the Monte Carlo method in conjunction with a numerical simulation. The PF considers the probabilistic density function of a state x_t, and the function is approximated by an ensemble consisting of a large number of discrete samples which are called particles or samples. A filtered distribution at time t-1, $p\left(x_{t-1}\middle|y_{1:t-1}\right)$, is expressed by particles $\left\{x_{t-1|t-1}^{(1)}, x_{t-1|t-1}^{(2)}, \cdots, x_{t-1|t-1}^{(N)}\right\}$ and weights $\left\{w_{t-1}^{(1)}, w_{t-1}^{(2)}, \cdots, w_{t-1}^{(N)}\right\}$ as

$$p\left(x_{t-1}\middle|y_{1:t-1}\right) \approx \sum_{i=1}^{N} w_{t-1}^{(i)}\delta\left(x_{t-1} - x_{t-1|t-1}^{(i)}\right) \tag{8}$$

where δ is Dirac's delta function and N is the number of particles in the ensemble. $y_{1:t-1}$ meansthe set $\left\{y_1, y_2, \cdots, y_{t-1}\right\}$. An ensemble approximation of the predicted distribution $p\left(x_t\middle|y_{1:t-1}\right)$ at the next observation time $t$is given from this ensemble and weights as

$$p\left(x_t\middle|y_{1:t-1}\right) \approx \sum_{i=1}^{N} w_{t-1}^{(i)}\delta\left(x_t - x_{t|t-1}^{(i)}\right) \tag{9}$$

From the predicted distribution $p\left(x_t\middle|y_{1:t-1}\right)$ and observation y_t, a filtered probabilistic density function $p\left(x_t\middle|y_{1:t}\right)$ using Bayes' theorem is expressed as follows:

$$p\left(x_t\middle|y_{1:t}\right) = \sum_{i=1}^{N} w_t^{(i)}\delta\left(x_t - x_{t|t-1}^{(i)}\right) \tag{10}$$

where weight $w_t^{(i)}$ is defined as

$$w_t^{(i)} = p\left(y_t \middle| x_{t|t-1}^{(i)} \right) \Big/ \sum_j p\left(y_t \middle| x_{t|t-1}^{(j)} \right) \tag{11}$$

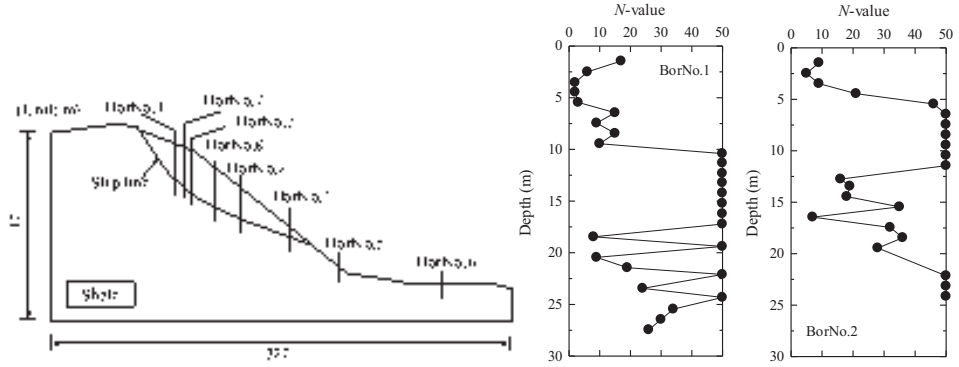
where $p\left(y_t \middle| x_{t|t-1}^{(i)} \right)$ is the likelihood of $x_{t|t-1}^{(i)}$ given data y_t.

Eq. (10) shows that $p\left(x_t \middle| y_{1:t}\right)$ is approximated based on particles weighted by $w_t^{(i)}$. A new ensemble $\left\{x_{t-1|t-1}^{(1)}, x_{t-1|t-1}^{(2)}, \cdots, x_{t-1|t-1}^{(N)}\right\}$, with a weight of $w_t^{(i)}$ for each i, is obtained by Eq. (10). This paper adopts Sequential Importance Sampling (SIS) (Doucet et al. 2000), since it is much more advantageous for nonlinear state equations, such as elasto-viscoplastic problems, than other PF methods.

3 Slope analysis for landslide site

3.1Landslide site

Figure 1 (a) presents a side view of the target slope and eightborehole locations(BorNo.1 – BorNo.8) with theslip line. A landslide with a width of 140 m, a length of 180 m, and a maximum depth of 40 m was caused, and the inclinationangle of the slope was almost 40°. Only the datafromthe standard penetration testsconducted atBorNo.1 and BorNo.2.are given in Fig. 1(b). It should be noted that when the N-value exceeds 50, the value is always set to be 50. Since there is a large variation in N-values beneath the hard strata in Fig. 1 (b), it is implied that a fracture zone due to the landslide lies there. The model consists of three strata, namely, surface strata withan N-value of almost 10, middle strata as the fracture zone, and shale with an N-value over 50.



(a) Section of slip surface at studied site. (b)Distribution of N-values in vertical direction.

Figure 1. Details of target site.

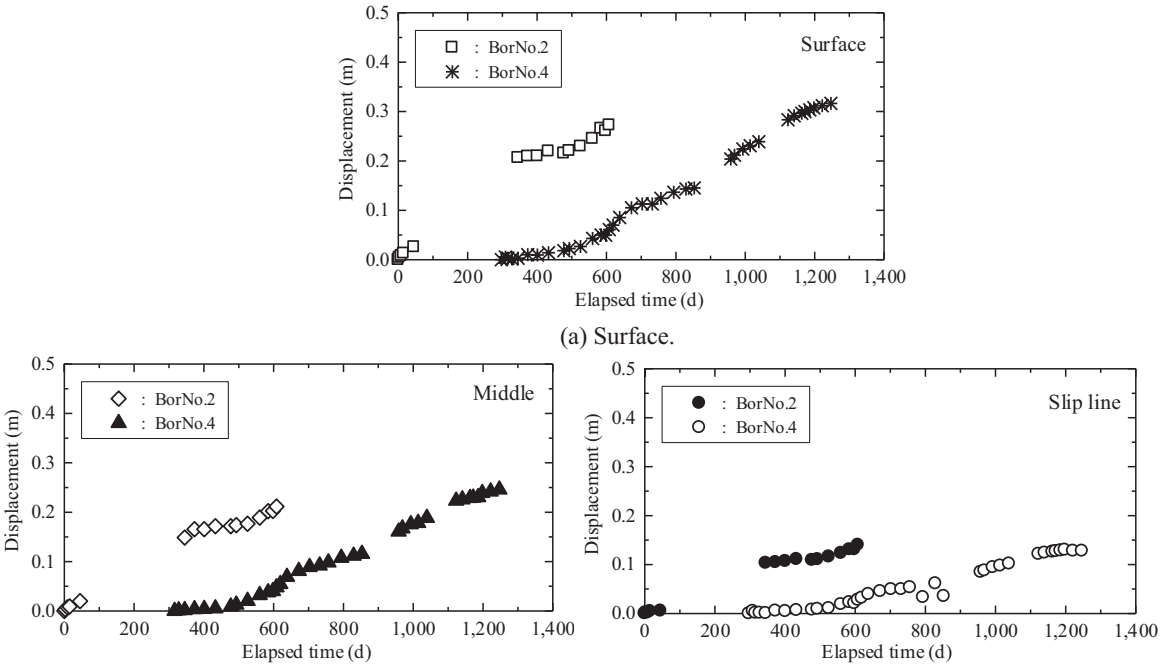
Figure 2 indicates two observed displacements for each of the three strata, namely, the surface, middle strata, and slip line, because only two observation points of displacements were available, namely, BorNo.2 and BorNo.4. The point inthe middle strata is located between the surface and the slip line.Only the displacement at BorNo.4 is used in the computation, since continuous measurement was successfully achieved at this point.

3.2 Numerical model

Figure 3 (a) depicts the adopted finite element mesh, consisting of 515 four-node isoparametric quadrilateral elements, and the boundary conditions. Thin elements are located as the fracture zone based on the geotechnical investigations.Figure 3 (b) shows the assignment of the material parameters listed in Table 1, in which " * " indicates the parameters to be identified. Young's modulus and the angle of internal friction are deduced from the N-values, as follows:

$$E = 2{,}800N \tag{12}$$

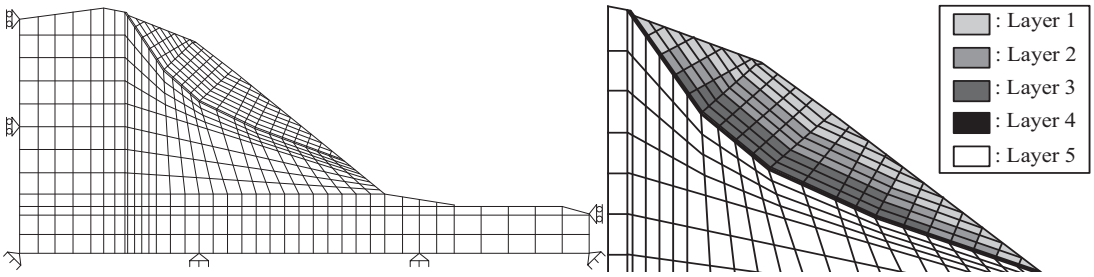
$$\phi = \sqrt{20N} + 15 \tag{13}$$



(a) Surface.

(b)Middle strata.(c) Slip line.

Figure 2. Observed displacements employed in parameter identification.



(a) Finite element mesh and boundary conditions. (b) Assignment of material parameters.

Figure 3. Description of problem for landslide.

The target parameters to be identified are the effective angle of internal friction in Layer 5 and the fluidity parameter, because these two parameters play a primary role in evaluating the creep behavior of landslides. 1,000 simulations are conducted by a Monte Carlo search over the range in parameters listed in Table 2. Each parameter is assumed to follow a uniform distribution and is generated independently. The diagonal term for the observation error covariance matrix, $\boldsymbol{R}_t$, is assumed as follows:

$$\boldsymbol{R}_t = \alpha u_i \delta_{ij} \tag{14}$$

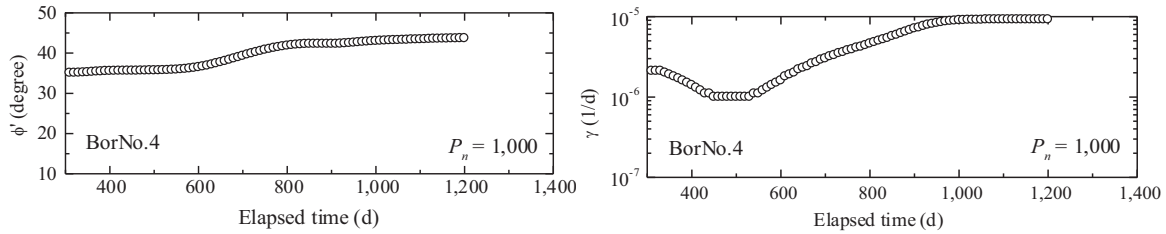
where α represents the control parameter for the covariance, u_i is the maximum value at the i-th observation point, and δ_{ij} is Kronecker's delta. The control parameter is chosen as 0.3, and the value is used when successful identification has been achieved (Shuku et al. 2012).

Table 1. Material parameters employed in analyses of studied site.

Layer	*N*-value	γ_t (kN/m^3)	E (kN/m^2)	c' (kN/m^2)	ϕ' (degree)	γ (1/d)
1	10	18	28,000	0.0	29	*
2	50	22	140,000	0.0	47	*
3	25	20	70,000	0.0	37	*
4	5	20	14,000	0.0	*	*
5	50	23	200,000,000	10,000	0	*

Table 2. Ranges ofparameters.

Parameter	Range of particle generation
ϕ' (degree)	25.0 ~ 45.0
γ (1/d)	1.0×10^{-7} ~ 1.0×10^{-5}

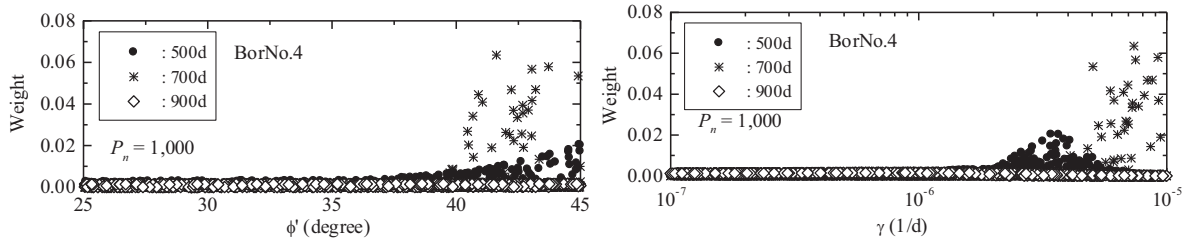


(a)Effective angle of internal friction.(b) Fluidity parameter.

Figure 4. Time evolution of identified parameters.

3.3Identification of geotechnical parameters

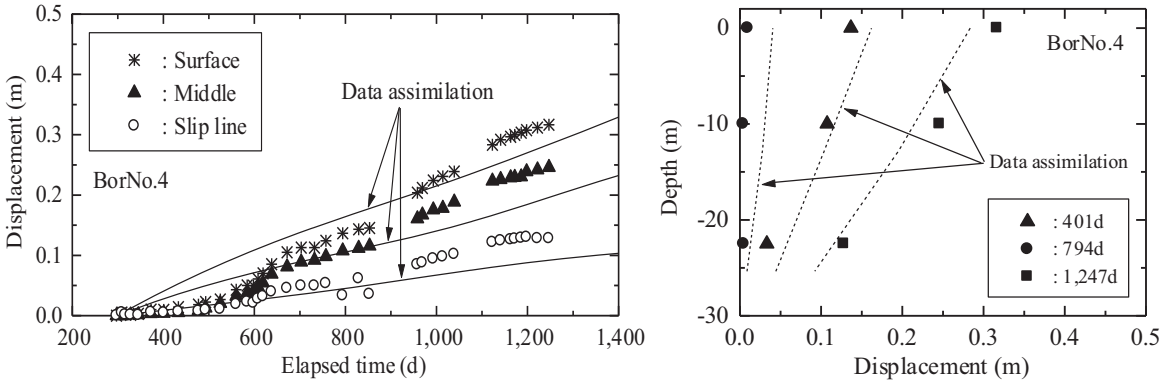
Figure 4 shows the time evolution of the identified parameters, which are obtained by the weighted average of the particles using the computed weight distribution in Eq. (11) at each time.In Fig. 4(a), the effective angle of internal friction stays almost constant before a lapse onthe 600th day, then slowly changes along the path occurring after the 600th day, and remains constant with the passage of time after the 800th day.Figure 4 (b) shows the significant changes caused before the 600th day, the identified fluidity parameter moderately increasing up to the 950th day, and then an almost constant value until the 1200th day. Eventually, the effective angle of internal friction and the fluidity parameter indicate 43.7° and 9.2×10^{-6} d^{-1}, respectively.Figure 5depicts the filtered probability density functions of the weight of the identified parameters. The distribution is updated following themeasured data.



(a) Effective angle of internal friction.(b) Fluidity parameter.

Figure 5. Distribution of weight for each parameter.

Figures6(a) and (b) comparethe observed displacements and the results of the direct analysis using the identified parameters to be described as ‘data assimilation’. Although a small discrepancy appears between the computed results and the observations, a good agreement is shown. The results suggest that the methodology is a highly effective approach for use in geotechnical practice.



(a) Time history of displacements. (b) Displacements against depth.

Figure 6. Results of analysis using identified parameters.

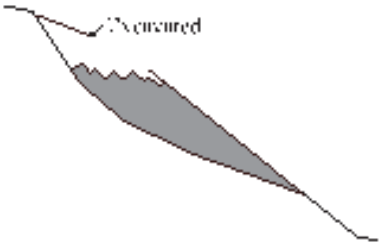
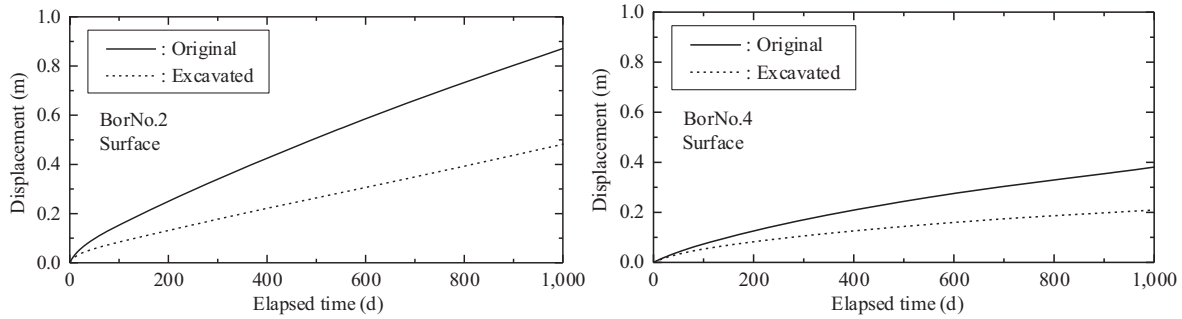


Figure 7. Earth removal work.

3.4Simulation of countermeasures

To discuss the effect of countermeasures for landslides based on the simulated results using the identified parameters, a numerical simulation of the earth removal work is carried out. A direct analysis with the identified parameters, using 0 forthe unit weight of the excavated soil, is shown in Fig. 7. Figures 8 (a) and (b) explain the time-displacement relationship of the slope surface with the earth removal work at BorNo.2 and BorNo.4. The broken line is the calculated displacement due to the earth removal work, whereas the solid line indicates the results without any countermeasures. The figures display that the computation can predict the displacement of the landslide and that the removal of soil decreases the displacement. The resultsverify the potential of the proposed method's practical use for the mitigation of landslide hazards.



(a) Displacement at BorNo.2. (b)Displacement at BorNo.4.

Figure 8. Time-displacement relationship of slopesurface with earth removal work.

4 Conclusion

This paper proposed an evaluation method for landslide behavior based on an elasto-viscoplastic finite element(FE) analysis using the identified parameters, namely, the effective angle of internal friction and the fluidity parameter. Theparticle filter (PF)was employed to identify the geotechnical parameters based on the field measurements. A good match was found between the simulation using the PF approach and the observations. The results imply that the proposed procedure using the PF is an effective method for use in geotechnical practice for predicting landslidehazards.

In order to discuss the effect of countermeasures for landslides, a numerical simulation of earth removal work using the identified parameters was conducted. The results show that the calculation can predict the displacement of a landslide and that the removal of soil decreases the displacement, thus verifying the potential of the proposed method's practical use for the mitigation of landslide hazards.

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