MONITORING THE STABILITY OF SLOPES BY GPS

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ABSTRACT

The stability of slopes is a crucial problem not only in open pit mines, but also in civil engineering situations. The deformational behaviour of slopes is in general monitored during/after the excavation by carrying out field measurements where displacement measurements are commonly adopted. In monitoring the slope stability it should be emphasized that the measurement results must be properly interpreted so as to assess whether the slopes are stable or become unstable in the future. In order to interpret the data, back analysis is extremely useful.
In this paper a slope stability monitoring system is described. It consists of displacement measurements by GPS, and a back analysis of measured data. The use of GPS has a great advantage, because of the fact that continuous displacement measurements with high accuracy for a large extent of concerned area can be easily achieved. On the other hand, the back analysis can reveal the mechanical characteristics of the ground, which make it possible to assess the stability of slopes quantitatively.

1. INTRODUCTION

The Global Positioning System (GPS) can be used to measure displacements of slopes at open pit mines, landslides as well as slopes at civil engineering situations. The GPS has the great advantage to realize continuous displacement measurements with high accuracy, and to make it possible to reduce the maintenance costs related to long-term monitoring, while conventional instrumentations by using extensometers, inclinometers, and surveying methods with an electronic optical distance meter or a total station are inadequate for continuous monitoring with high accuracy. Furthermore, the conventional methods result in difficulties concerning maintenance for long-term monitoring.

A new type of GPS displacement monitoring system has been developed by the second author and his colleagues (Iwasaki et al. 2003, Masunari et al. 2003, Shimizu and Matsuda 2003). It can simultaneously measure the three-dimensional displacements of many points over an extensive area and display the results on a monitor screen in real-time. The trend model, which is a data processing method, is adopted for improving the accuracy of the measurement results, so that the system can provide highly accurate and precise measurement results comparing with conventional GPS receivers. Practical applications have already shown that the system is useful for monitoring the displacements of slopes. However, an important issue in monitoring the stability of

slopes is how to interpret the measurement results. The stability of slopes is in general assessed by a factor of safety, in such a way that the strength of materials is compared with stress occurring in a slope. For evaluating the factor of safety the strength parameters such as cohesion and internal friction angle play the most important role.
A question then arises how the strength parameters can be determined from the measured displacement data. Since displacements in general correspond directly to the deformability parameters like Young's Modulus, not to the strength parameters, a special technique must be needed. The first author developed a back analysis procedure for determining the strength parameters from the measured displacements (Sakurai and Nakayama 1999).
In this paper, the GPS displacement monitoring system is outlined together with a data processing method, and the back analysis procedure is described.

2. DISPLACEMENT MONITORING SYSTEM USING GPS

2.1. HARDWARE FOR MONITORING DISPLACEMENTS

Several types of the monitoring system using GPS has been developed (Masunari et al. 2003). Fig. 1 illustrates one of those systems used at a limestone quarry. Small antennas are set on the measurement points, and then they are connected to receivers, respectively. The receivers transfer the data transmitted from the GPS satellites through a cable to a personal computer in the control office. The cable also provides power to the receivers. The computer controls the entire system and analyzes the data in order to obtain displacements at all the measurement points. The measurement results are shown on the monitor screen in real time. The system has continuously monitored the displacements for almost ten years.

2.2. SOFTWARE FOR IMPROVING THE ACCURACY OF THE MEASUREMENTS

The precision of the measurements is commonly presented by the standard deviation (STD). The STD of the measurements using conventional GPS receivers for a baseline length of less than a few kilometers is 5-10 mm and 10-20 mm for horizontal and vertical directions, respectively. Therefore, the precision of the conventional GPS is not enough for assessing slope stability. In order to improve the precision, a data processing method is applied to the continuous monitoring results. After having tried various types of data processing methods, the trend model was found to be the most suitable for this type of displacement measuring.

The trend model is composed of a system equation and an observation equation, as follows:

$$\Delta^k u_n = v_n \tag{1}$$

$$y_n = u_n + w_n \tag{2}$$

where u_n represents the estimates for the exact values of the displacements, and y_n is the measured displacement. The measurement interval is Δt, and subscript n denotes progressing time t ($t=n\Delta t$). Δ is the operator for the finite difference ($\Delta u_n = u_n - u_{n-1}$),

and Δ^k means the rank "*k*" difference. Eq. (1) is a sort of probability finite difference equation of rank *k*. v_n and w_n are the white noise with an average value of 0 and STD τ, and the observation error with STD σ, respectively.
The trend model can yield good estimates for exact displacements from scattered data obtained from the GPS monitoring system. It was proven that the system can detect displacements of 1-2 mm and displacement velocities of 0.1 mm/day through experiments and practical applications (Shimizu and Matsuda 2003).

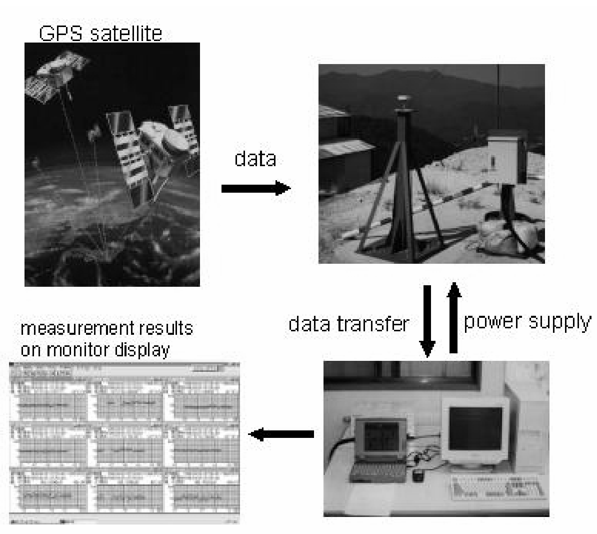

Fig. 1 The GPS displacement monitoring System

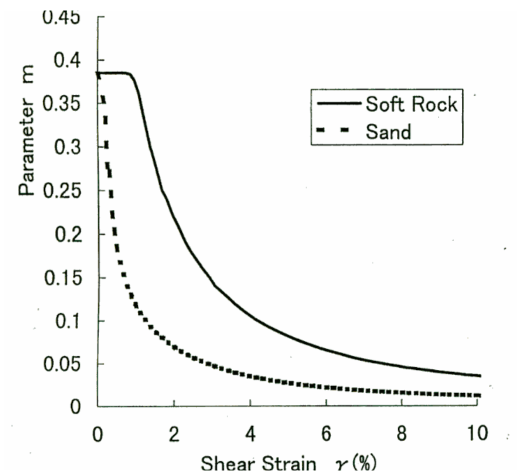

Fig. 2 Parameter m as a function of shear strain

3. BACK ANALYSIS OF MEASURED DISPLACEMENTS

Back analysis should be simple enough to apply for engineering practices. Moreover, it is important in back analysis that the mechanical model should not be assumed, but should be uniquely determined by back analysis (Sakurai 1997). This means that the conventional numerical methods such as an elasto-plastic numerical analysis cannot be adopted, because the mechanical model should be assumed before computation.
In order to fulfill these requirements, the first author proposed a back analysis procedure based on FEM, in which a strain-induced anisotropic damage parameter was introduced (Sakurai 1999). The anisotropic damage parameter can be determined by the back analysis of displacements measured by GPS.

3.1 ANISOTROPIC DAMAGE PARAMETER

The anisotropic damage parameter *d* is defined on a slip plane as

$$d = 1/2(1+\nu) - m \qquad (3)$$

where

ν : Poisson's ratio
m : The ratio of shear modulus to Young's modulus on a slip plane (Sakurai et al. 1998)

The parameter *m* for soil and soft rock is shown in Fig. 2.
Since the parameter *m* in an elastic state is $m = 1/2(1+\nu)$, the anisotropic damage parameter becomes *d* = 0, namely no damage occurs until a material reaches to the yielding point. The anisotropic damage parameter *d* then starts to mobilize on a slip plane, when the material goes in plastic state. Careful investigation of laboratory experiments reveals that the anisotropic damage parameter *d* increases monotonically with an increase of shear strain γ, so that it is expressed as follows;

$$d = 0 \qquad \text{for } \gamma \le \gamma_0$$

$$d = \left(\frac{1}{2(1+\nu)} - \beta\right)\left[1 - Exp\{-\alpha(\gamma - \gamma_0)\}\right] \qquad \text{for } \gamma > \gamma_0 \tag{4}$$

where α, β : material constants
γ_0 : critical shear strain
(Sakurai et al 1999)

3.2 STRESS-STRAIN RELATIONSHIP

Considering the above described anisotropic damage parameter, a stress-strain relationship in a local coordinate can be derived. For the plane strain condition it is expressed as follows (see Fig. 3).

$$\{\sigma'\} = [D']\{\varepsilon'\} \tag{5}$$

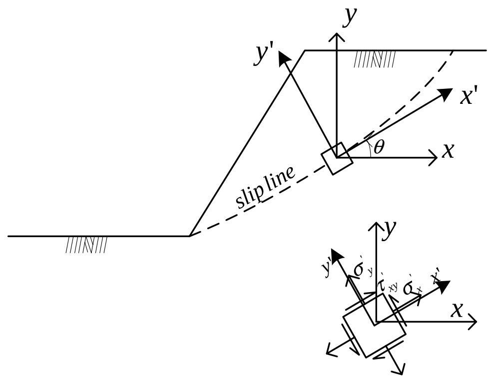

Fig. 3 Local and global coordinates

where

$$[D'] = \frac{E}{1-\nu-2\nu^2}\begin{bmatrix} 1-\nu & \nu & c_1 \\ \nu & 1-\nu & c_2 \\ c_1 & c_2 & m(1-\nu-2\nu^2) \end{bmatrix} \tag{6}$$

where E : Young's modulus
ν : Poisson's ratio
c_1, c_2 : dilatancy parameters
$m = 1/2(1+\nu) - d$

In global coordinate, $[D']$ can be transformed as,

$$[D] = [T][D'][T]^T \tag{7}$$

where $[T]$: transformation matrix

3.3 FINITE ELEMENT ANALYSIS

The relationship between the increments of external forces and displacements is expressed as,

$$[\boldsymbol{K}]\{\Delta\delta\} = \{\Delta\boldsymbol{P}\} \tag{8}$$

where

$[\boldsymbol{K}]$: Stiffness matrix
$\{\Delta\delta\}$: Increment of displacements. Some of them are measured values.

$$\{\Delta\boldsymbol{P}\} = \int[\boldsymbol{B}]^T[\boldsymbol{D}][\Delta\boldsymbol{C}]\{\sigma\}\boldsymbol{dV} + \int[\boldsymbol{B}]^T\{\sigma\}\boldsymbol{dV} \tag{9}$$

where

$$[\Delta\boldsymbol{C}] = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \dfrac{\Delta\boldsymbol{m}}{\boldsymbol{m}\cdot\boldsymbol{m}_i} \end{bmatrix} \tag{10}$$

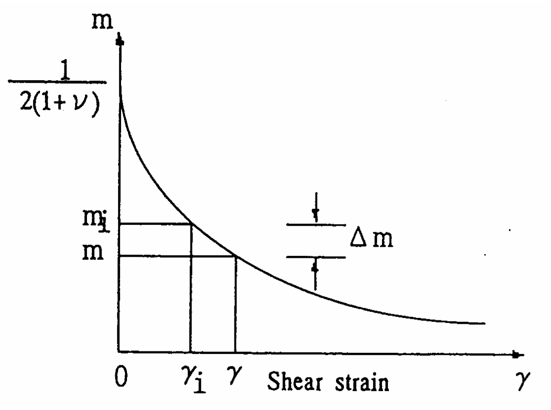

Fig.4 Relationship between increments of parameter *m* and shear strain

Eq. (9) indicates that there are two ways for the cause of displacements in slopes. One is due to the reduction of stresses caused by excavation. The other is due to the reduction of strength of materials. That is, the parameter *m* decreases with no excavation. This may be caused by weathering. In Eq. (10) $\boldsymbol{m}$ and $\boldsymbol{m}_i$ express the values of *m* at present and past at the measuring interval Δt, respectively, as shown in Fig. 4.

3.4 BACK ANALYSIS PROCEDURE OF DETERMINING THE STRENGTH PARAMETERS (COHESION AND INTERNAL FRICTION ANGLE)

(1) The parameter *m* and Young's Modulus E can be obtained by the back analysis. In this back analysis, total displacements are not needed, but only the increments of measured displacements for the time interval Δt are good enough.

(2) Shear modulus G can be calculated by the definition of *m* as follows;

$$G = mE \tag{11}$$

(3) The critical shear strain γ_0 is then estimated by considering the relationship between the critical shear strain and shear modulus G. (Sakurai et al. 1999).

(4) Shear strength τ_c can be determined by the definition of critical shear strain as follows;

$$\tau_c = \gamma_0 G \tag{12}$$

(5) Cohesion c is then determined by the following equation assuming the internal friction angle ϕ.

$$c = \frac{1-\sin\phi}{\cos\phi}\tau_c \tag{13}$$

(6) The factor of safety can be calculated by a conventional limit equilibrium method.

4. CONCLUSIONS

(1) GPS is a powerful tool for monitoring the stability of slopes in large extent of area. Both the hardware and software of GPS monitoring system have been developed for monitoring displacements and improving the accuracy of the measurements
(2) The measurement results must be interpreted properly for assessing the stability of slopes. For this purpose the strain-induced anisotropic damage parameter is proposed and introduced into back analysis procedure based on FEM.
(3) In this back analysis procedure, only the increments of measured displacements for the time interval Δt are sufficient. This means that we can start the measurements at anytime after the fracture like open cracks occurs in slopes.
(4) According to the back analysis procedure, the strength parameters (cohesion and internal friction angle) can be determined from the measured displacements. A factor of safety of slopes can then be evaluated by using a conventional limit equilibrium method.

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