Numerical Investigations of Rainfall Induced Landslide

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ABSTRACT

The geological structures and hydrological conditions are extremely complicated at landslide area and it is difficult to evaluate the rainfall induced seepage and it's accompanied stability problems of the potential sliding surface during torrential rainfall by employing conventional analysis method or simplified analysis method. This study performed two dimensional finite element seepage and deformation analyses on the A-A profile of the Lu-Shan landslide during torrential rainfall of Matsa Typhoon in 2005. At the mean time, incorporating with the limit equilibrium analysis the corresponding stability of sliding surface at each time step can be evaluated. The reliability and validity of numerical model were verified by comparing the numerical results of groundwater variation and displacement at A-A profile of Lu-Shan landslide with those from measurements. Through the analyses of groundwater variation, factor of safety, and displacement rate of Lu-Shan landslide during Matsa Typhoon (2005/8/3~2005/8/7), the evaluation equation (or \( v(t)\)~\( F(t)\) equation) can be formulated by the regression analysis which is capable of evaluating the factor of safety \( F(t)\) according to the measurement of immediate displacement rate \( v(t)\) of the slope at any rainfall time duration \( t\). In such manner, the factor of safety during rainfall can be immediately offered as a quantitative reference to the landslide warning system.

Key Words: Lu-Shan landslide, Rainfall induced seepage, Displacement rate

INTRODUCTION

The mechanism of rainfall induced landslide has been elaborately described in many works (Morgenstern and de Matos, 1975; Fukuoka, 1980; Brand, 1984; Vargas et al., 1986; Kim et al., 1991; Ocakoglu, 2002). In which, it was concluded that the precipitation is the most influential factor on the initiation of landslide. During torrential rainfall, landslides with large displacement was frequently triggered by the infiltration and seepage of rainwater in soil stratum which alternately decreases the shear strength of soil mass and increases the pore water pressure on potential sliding surface Lin et al. (2008) performed a series of numerical analyses of rainfall induced seepage and slope stability of unsaturated soil strata in Li-Shan landslide to correlate the groundwater variation with the rainfall intensity. However, in the previous studies the rainfall induced displacement of unsaturated soil stratum due to the infiltration and absorption of rainwater was excluded in the analyses.

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Lu-Shan landslide situated at the area right up the Lu- Shan hot spring and was categorized as a potential hazard slope according to field investigations. In the landslide area, slope failure frequently occurred in typhoon season and severely endangered the safety of the resident living in the hot spring sightseeing area immediate down to the landslide. In the previous rehabilitation works, the slope stability analyses were carried out by the conventional method which simplified the effect of time-dependent groundwater variation as a hydrostatic condition and the infiltration and seepage of rainwater were completely ignored in the analyses. This study adopted two dimensional finite element method and limit equilibrium method to simulate the infiltration, absorption, seepage of rainwater in soil strata. The monitoring data of groundwater variation and ground movement of Lu-Shan landslide during Matsa Typhoon in 2005 were selected for model calibration. Comparing the simulations with measurements, an evaluation equation of the factor of safety and the displacement rate of the existing potential sliding surface of landslide at any time step during rainfall can be formulated and referred for engineering practice.

FIELD INVESTIGATIONS OF LU-SHAN LANDSLIDE

Landslide area

As shown in Fig. 1, Lu-Shan landslide located at the western side of the central mountain range of Taiwan and the administrative division is delimited into Jing-Ying village, Ren-Ai township, Nan-Tou county and the boundaries of Jing-Ying village is adjacent to the Chun-Yang village and He-Zuo village. The tribal residents in the village are composed of Lu-San, Ping-Deng and Ping-He tribes. The Tai-14 highway in the landslide area is the only transportation that the tribal residents can rely on connecting with the outside area.

Further, Ta-Lou-Wan Creek and hot spring sightseeing area situated at the down-slope of Lu-Shan landslide. As a result, in addition to endangering the safety of touring area, Lu-Shan landslide causes great influence and inconvenience to the livelihood of the local residents. Lu-Shan landslide appears in a form of triangle shape with influence area of about 30 hectares, slope length of 850 m and average slope of 22°. In addition, the elevation of the landslide varied in the range of 1,495~1,085 m from northwest to southeast.

Soil strata and sliding mass

According to the field investigations (Nan-Tou branch office, Soil Water Conservation Bureau or SWCB, 2006[2] and 2007[3], and SWCB, 2008[4]) the soil strata of Lu-Shan landslide
include: (1) Surface colluvium layer composed of weathered rock mass and mixtures of sand, silt and clay materials with low cementation, (2) Slate layer (SL) is the main rock stratum of the landslide and appears dark-grey color with abundant cleavage. The openings of cleavage and the degree of weathering of the slate layer become obvious as the stratum getting closer to the ground surface, (3) Sandy slate layer (SSL) contains high percentage of sandy material and the features and characteristics are similar to sandstone. Unlike the SL layer, the SSL layer is short of cleavage and tends to be cut into blocks by joints. The stiffness of sandy slate is high and frequently in a form of outcrop appears on the ground surface.

Lu-Shan landslide can be considered as one entire sliding block with influence area on ground surface of about 30 hectares and moves from northwest to southeast as shown in Fig. 2(a). According to the boring exploration (borehole B01~B11, drilling depth 30~80 m) the thickness of colluvium is around 1.7~11.2 m, the depth of bedrock is in the range of 26.8~73.3 m and the potential sliding surface is located at a maximum depth over than 55 m. This study selected the A-A profile of Lu-Shan as a representative profile for numerical analyses as shown in Fig. 2(b) and along the A-A profile the measurements of borehole B06 (observation well of groundwater) and B09 (inclinometer of lateral movement) were used for the comparisons with simulations.
NUMERICAL ANALYSES

Methodology and analysis framework

As shown in Fig. 3, the present work performed a series of numerical investigations on the rainfall induced seepage and deformation behaviours of the sliding mass along the $A-A'$ profile of Lu-Shan landslide using the real time rainfall hyetograph of Lu-Shan rainfall gauge station. The reliability and validity of the proposed numerical model were verified by comparing the numerical results of groundwater variation and displacement rate of the sliding mass with those from measurements. In addition, a set of optimum numerical input parameters of alluvium which encompassed hydraulic and deformation parameters were determined by the optimization procedure. Eventually, a predictive equation (or $v(t)\sim F(t)$ equation) can be formulated by regression analyses to evaluate the factor of safety $F(t)$ of the exsiting potential sliding surface based on the measured displacement rate $v(t)$. 
Seepage analysis

SEEP/W

Model calibration

Pore water pressure and groundwater level variation
\( u_w = u_w(t) \) and \( h_w = h_w(t) \)

Inverse analysis and optimization of hydraulic parameters

Field precipitation monitoring data

Design rainfall pattern \( R = R(t) \)

Field measurement of pore water pressure and groundwater level

Inverse analysis and optimization of hydraulic parameters

Deformation analysis

SIGMA/W

Model calibration

Displacement and displacement rate
\( \delta = \delta(t) \) and \( v = v(t) \)

Inverse analysis and optimization of strength parameters

Stability analysis

SLOPE/W

Variation of factor of safety
\( F = F(t) \)

Correlation of displacement rate with factor of safety

\( R(t) \sim v(t) \)

Lu-Shan landslide data collection

1. relevant landslide stabilization project
2. topography, geology and hydrology data

Fig. 3 The framework of numerical investigations of Lu-Shan landslide

Numerical model, initial conditions and boundary conditions

Based on the geological investigations of Lu-Shan landslide, the soil strata of the A-A profile used for numerical analyses consisted of: (1) weathered and soft rock layer, (2) slate layer (or SL layer), (3) sandy slate layer (SSL layer), and (4) creek bed weathered slate layer. The finite element numerical model and the corresponding boundary conditions for various types of analyses were illustrated in Fig. 4. The elevations for left and right boundaries were 1,500 m and 1,110 m respectively and the bottom boundary was extended from left to right boundary for 1,000 m. For the initial conditions of rainfall induced seepage analyses, a groundwater table was firstly determined by a series of steady state analyses then the calculated groundwater table from steady state analyses was sequentially used as the initial condition of transient analyses.
For the initial conditions of rainfall induced slope stability analyses and rainwater absorption deformation analyses, the factor safety of the existing potential sliding surface \( F(t_i) \) and the displacement of the soil stratum at any time step \((t_i)\) can be determined by transient analyses using the groundwater table and pore water pressure distribution at the previous time step \((t_{i-1})\).

For the rainfall induced seepage analyses, the top boundary \( CD \) was specified as the rainfall infiltration boundary, the bottom boundary \( AB \) as no-flow-discharge \((Q=0)\) close boundary. Meanwhile, according to the field monitoring groundwater level at ordinary time (non-typhoon season), a constant total head \( H=1,089 \) m \((H=\text{elevation head } y + \text{ pressure head } p)\) was assigned to the right boundary \( BC \) whereas \( H=1,451.8 \) m for the left boundary \( AD \). In addition, for the rainfall induced slope stability and rainwater absorption deformation analyses, the bottom boundary \( AB \) was specified as hinge boundaries (or non-displacement boundary with horizontal displacement \( \Delta x=0 \) and vertical displacement \( \Delta y=0 \)) and the side boundaries \( BC \) and \( AD \) conditions as roller boundaries (partial-displacement boundary with \( \Delta x=0 \) and \( \Delta y \neq 0 \)).

**Fig. 4** Numerical model and boundary conditions of A-A profile at Lu-Shan landslide for various types of analyses

**Numerical analyses**

The rainfall induced seepage analyses consisted of two phases, namely, Phase (1): Steady state analyses were performed by specifying constant total head boundary conditions at the left and right boundaries to calculate and to fit the groundwater level at ordinary time (non-typhoon period). The calculated initial groundwater level as shown in Fig. 5(a) was then used as the initial groundwater condition of the sequential transient analyses. Phase (2): Transient analyses were carried out using the rainfall hyetograph of the duration of 2005, 07, 27~2005, 09, 06 from Lu-Shan rainfall gauge station as shown in Fig. 5(b). Subsequently, the pore water pressure \( u_w(t) \) time curve of the existing sliding surface, \( u_w(t) \) such as monitoring points P1, P2 and P3, obtained from transient analyses was used to evaluate the factor of safety \( F(t) \) time relationship, \( F(t) \) of the existing sliding surface of A-A profile. Repeatedly, the \( u_w(t) \) curve was used to calculate the deformation of soil mass due to the infiltration and absorption of rainwater and alternately the displacement rate \( v(t) \) time relationship, \( v(t) \), of the sliding mass can be determined.
Input parameters

In the present work, an inverse analysis procedure was used to calibrate the numerical parameters, \( b_i \), of both the rainfall induced seepage model (groundwater model) and the rainwater infiltration and absorption deformation model (displacement rate model) of the landslide. The calibration of both models was obtained by an optimization algorithm that minimizes the errors between computed results and measured data. The computed groundwater levels, \( h(t) \), and displacement rates, \( v(t) \), were compared with those of monitoring data \( h(t) \) and \( v(t) \) using an weighted least-squares objective function, \( S(b_i) \), which represents a quantitative measure of the error of the predictions. The objective function is expressed as:

\[
S(b_i) = [y(t) - y'(b_i)]^T \times \omega \times [y(t) - y'(b_i)] = e^T \times \omega \times e
\]

where \( b_i \) is the vector of the parameters being estimated and \( i=1\sim7 \) for seven parameters of
$c =$ cohesion, $\phi =$ friction angle, $E =$ elastic modulus, $\nu =$ Poisson’s ratio, $\gamma =$ unit weight, $k_{sat} =$ saturated hydraulic conductivity, and $\Theta_{sat} =$ saturated volumetric water content; $y(t)$ is the vector of the measurements matched by the regression; $y(b_i)$ is the vector of the corresponding computed values; $\omega$ is the weight matrix of measurement, wherein every measurement’s weight is taken as identical and $\omega$ equal to unit matrix in this study; $e$ is the vector of residuals. The values of $S(b_i)$ can be considered as a measure of the ability of the numerical procedure to correctly represent the physical process (i.e. the rainfall induced groundwater variation and the movement of landslide).

According to the objective function $S(b_i)$ curve for each parameter, it was found that the variation of groundwater level in seepage analyses is most sensitive to the $k_{sat}$ value of the surface colluvium layer as shown in Fig. 6(a). The objective function $S(k_{sat})$ in Fig. 6(a) shows enormous variation when $k_{sat} > 0.25$ m/day whereas it becomes stable when $k_{sat} = 0.01$–0.25 m/day and this implied the optimum input value of $k_{sat}$ should situate within this range. On the other hand, the displacement rate of soil mass due to the infiltration and absorption of rainwater is most sensitive to the $E$ value and then followed by the $\nu$ and $\phi$ values, whereas it is less sensitive to the $\gamma$ and $c$ values in displacement analysis. As the $S(E)$ value displayed in Fig. 6(b), the optimum input value of $E$ lays in the scope of $8 \times 10^5$–$2 \times 10^6$ kPa.

Fig. 6 Objective function of (a) saturated hydraulic conductivity (b) elastic modulus of soil stratum
Eventually a final set of input parameters listed in Table 1 were used to perform the numerical modeling.

### Table 1: Input parameters for rainfall induced seepage, displacement and slope stability analyses of Lu-Shan landslide

<table>
<thead>
<tr>
<th>Soil Types</th>
<th>$\Theta_{\text{sat}}$ ($\text{m}^3$/m$^3$)</th>
<th>$k_{\text{sat}}$ (m/day)</th>
<th>$E$ (kPa)</th>
<th>$\nu$</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$c$ (kPa)</th>
<th>$\phi$ (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colluvium</td>
<td>0.40</td>
<td>$1.00 \times 10^1$</td>
<td>$1.0 \times 10^6$</td>
<td>0.30</td>
<td>20.00</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Slate (SL)</td>
<td>0.20</td>
<td>$1.00 \times 10^4$</td>
<td>$9.0 \times 10^3$</td>
<td>0.28</td>
<td>24.00</td>
<td>10</td>
<td>34</td>
</tr>
<tr>
<td>Sandy slate (SSL)</td>
<td>0.20</td>
<td>$1.00 \times 10^5$</td>
<td>$1.0 \times 10^3$</td>
<td>0.25</td>
<td>27.50</td>
<td>10</td>
<td>35</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSIONS**

This study carried out a series of rainfall induced seepage, displacement and slope stability analyses using the cumulative daily rainfall record in the duration of 2005/7/27~2005/9/6 of Lu-Shan rainfall gauge station. Based on the rainfall hyetograph in Fig. 5(a), the input rainfall data for transient seepage analyses can be given as Fig. 7. Figure 8 indicates the computed groundwater variation of borehole B06 (at the mid-slope of landslide) is in good coincidence with the observations in between the depth of 15 m and 25 m. Comparing the Figs (7) and (8), the numerical results is capable of reflecting the time lagging for the groundwater to reach its maximum uplifting level. Moreover, this implies that after the time of peak daily precipitation it needs to take about one day for the seepage flow to completely response the variation of groundwater level. The groundwater level can only change as the soaking line moves downward and links up the phreatic line. The uplifting groundwater level during Matsa Typhoon (2005/8/3~2005/8/7) is obvious and leads to the abrupt drop of the time-dependent factor of safety $F(t)$ as shown in Fig. 9 and this also implied the pore water pressure on the existing sliding surface may increase simultaneously in this duration.

![Fig. 7 Daily precipitation in the duration of 2005/7/27~2005/9/6 used as input data for transient seepage analyses](image-url)
Fig. 8 Comparison of groundwater variation between measurement and simulation of borehole B06

Fig. 9 Variation of factor safety of the potential sliding surface of A-A profile during rainfall

As shown in Fig. 10, the P1, P2 and P3 represent the numerical monitoring points of pore water pressure at up-slope, mid-slope and down-slope respectively along the existing sliding surface (see Fig. 5(a)). The point P1 at up-slope with negative pore water pressure in the entire rainfall period denotes the groundwater level is never beyond the elevation of point P1 and where always situates at the unsaturated condition. Moreover, the point P2 at mid-slope merely exhibits positive pore water in the duration of 2005/08/08~2005/08/09 after Matsa Typhoon (2005/08/03~2005/08/07). This indicates that a large quantity of seepage flow of rainwater will accumulate at the point P2 after Matsa Typhoon. Eventually, the point P3 at down-slope shows an increasing positive pore water pressure after 2005/08/06 and lasts to the end of simulation time. This implies the infiltrated rainwater flow at upper slope during rainfall may immediately seeps down to the slope toe and accumulates along the existing sliding surface.
Figure 11 presents the lateral movement of soil strata of inclinometer B09 at two time points of 2005/8/9 and 2005/9/5 after the torrential rainfall of Matsa Typhoon (2005/8/3–2005/8/7). It is shown that the lateral movement of soil stratum at shallow depth is larger than that at deep depth due to the infiltration and absorption of rainwater at ground surface. Although the lateral movement at deep depth is underestimated in simulation, nevertheless the tendency of simulation profile is coincident with measurements to a certain extent. In addition, the simulated lateral movement profile also indicates the potential sliding surface may locate at a depth of 25~30 m and this is in good agreement with the actual sliding surface situates at 28 m deep underground.
Figure 12 presents the displacement rate \( v(t) \) (mm/day) at different depth (-0.5 m, -14 m, -25 m, -40m) of inclinometer B09 in the duration of 2005/7/27~2005/8/9. Using the simulated values of \( v(t) \) and \( F(t) \), the \( v(t) \sim F(t) \) relationship of Lu-Shan landslide can be set up in Fig. 13. The regression equation of \( v(t) \sim F(t) \) enables an evaluation of the factor of safety based on the measured displacement rate of Lu-Shan landslide during torrential rainfall and it also demonstrates that the displacement rate may largely increase as \( F(t) < 1.01 \).
CONCLUSIONS

The proposed numerical procedures are capable of modeling the rainfall induced seepage and deformation behaviors of Lu-Shan landslide. An inverse analysis procedure was used to calibrate the numerical parameters and a final set of input parameters can be determined and referred for the advanced analyses of Lu-Shan landslide. It was also found that the rainfall induced seepage analysis and deformation analysis are very sensitive to the saturated hydraulic conductivity and elastic modulus of the colluviums, respectively. Conclusively, a displacement rate \( v(t) \sim \) factor of safety \( F(t) \) evaluation equation (or \( v(t) \) (mm/day) = \( 4471[F(t)]^2 - 9078[F(t)] + 4608.4 \)) was formulated and capable of evaluating the factor of safety \( F(t) \) according to the measurement of immediate displacement rate \( v(t) \) of the slope at any rainfall time duration \( t \).

REFERENCES


