The Landslide Movement Process at Hsiaolin Village During Typhoon Morakot

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This study analyzes the landslide event at Hsiaolin Village during Typhoon Morakot in 2009. This landslide event resulted in 400 deaths. This event indicates that extreme rainfall conditions can alter the disaster mechanism of a landslide. The extremely high intensity and cumulative rainfall events may cause large-scale and complex landslide disasters. To study and understand the landslide event a combination of field investigations and numerical models are used. The landslide area is determined by comparing topographic information from before and after the event. Physiographic parameters are determined from field investigations. These parameters are applied to a numerical model to simulate the landslide process. And the landslide process was considered as two scenarios, a single event or a double event. For the single event, the main erosion area was the initial condition of the landslide movement. In Scenario II, the landslide process was divided into two parts. Finally, the simulation results were compared with investigation data. It shows the time of landslide movement is about 100 seconds. The deposited volume was well simulated. The deposited sediment formed a natural dam in the main channel. The minimum height of the dam is about 30 ~ 35 meter. The length of the dam is 1,100~1,600 meter.

Key words: landslide, landslide dam, typhoon Morakot, Hsiaolin village

1. INTRODUCTION

Typhoon Morakot, a medium-strength typhoon, invaded Taiwan from August 5 to 10, 2009 producing heavy rainfall. The rainfall caused a serious sediment disaster at Hsiaolin Village, which is located at southern Taiwan. The nearest rainfall station to Hsiaolin Village is the Chia-hsian station. According to the Central Weather Bureau, the cumulative rainfall was 1,911 mm during the typhoon. The maximum hourly rainfall was 94.5 mm/hr. The extremely high intensity and cumulative rainfall event caused a large-scale landslide in the morning of August 9. After the landslide occurred, the unstable sediment moved downstream and separated into two parts. One part buried the village and caused 400 deaths and another part deposited at the river channel and formed a landslide dam. The river water was stored behind the dam and formed a landslide lake. About 40 to 50 minutes later, the water overflowed and inundated Hsiaolin Village. Fig. 1 shows the satellite image after the dam break [Shieh et al., 2009].

To fully analyze this process, field investigations were insufficient. Therefore, this study proposes a numerical model along with the field investigation data to simulate the landslide process during the typhoon event at Hsiaolin Village.

2. SITE CONDITION

To analyze the sediment source and the volume, this study uses field investigation data and the Digital Terrain Model (DTM) data provided by the Aerial Survey Office, Forestry Bureau, Council of Agriculture, Executive Yuan of Taiwan, R.O.C. The DTM prior to the event was produced from aerial photography in 2006. The posterior DTM was...
produced after the event on August 21, 2009. The precision is 5 m by 5 m for both DTM. The longitudinal sections were selected based on the deposition locations of the landslide sediment. Line AA is the route for landslide sediment to move and deposit at Hsiaolin Village. Line AA' is the route for landslide sediment to form the landslide dam on the Chi-Sha River. In Fig. 3, the elevation profiles are defined by three areas, source area, transportation, and deposition.

In section AA', the sediment fills the gully and deposits at the Chi-Shan River channel forming a landslide dam. The high river flow causes the landslide dam to fail. Based on residual sediment on the west side of the Chi-Shan River, the height of the dam was estimated to be 30 m or more. The dashed line shows the estimated dam height of the landslide dam which is used to calculate the original sediment mass shown in Table 1.

Erosion and deposition areas as well as the volume of sediment are estimated by comparison between the DTM data before and after the event. Fig. 4 shows the comparison result with brown areas representing erosion areas and blue areas representing depositional areas. Erosion areas are Area A, B, and C. Depositional areas are Area I, II and III. Erosion areas are sediment sources for the sites of deposition.

Area A, where the landslide occurs, generated $22.7 \times 10^6$ m$^3$ of sediment which provided the major source of the sediment. From field investigations, Area B and C are eroded during the movement of the landslide. Area B and C generated 0.9 and 0.3 $\times 10^6$ m$^3$ of sediment respectively.

Area I is inundated by the landslide sediment. The largest depth is about 74 m and the depositional volume is $7.9 \times 10^6$ m$^3$. Deposition at Area II inundated Hsiaolin Village and the total volume of sediment is $5.1 \times 10^6$ m$^3$.

In Area III, deposition blocked the Chi-Shan River and formed a landslide dam.
dam has a height of 50 m and volume of $5.8 \times 10^6$ m$^3$. Due to river flushing, the residual sediment is about $3.7 \times 10^6$ m$^3$.

Table 1 shows the sediment yield and deposition. The sediment deposition includes model output and estimated original sediment mass obtained from field measurements. Field measurements determine the geometry of the landslide dam which is then used to estimate the original sediment mass.

The sediment volume flushed by the stream flow during the Typhoon event is about $5.1 \times 10^6$ m$^3$ based on the evaluation of the volume difference between generated sediment and deposited sediment.

<table>
<thead>
<tr>
<th>Sediment Yield</th>
<th>Sediment Deposited</th>
<th>Estimated Original Sediment Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-seated landslide area (A)</td>
<td>22.7</td>
<td>Main deposit area (I) 7.9</td>
</tr>
<tr>
<td>Side erosion area (B)</td>
<td>0.9</td>
<td>South deposit area (II) 5.1</td>
</tr>
<tr>
<td>Bed erosion area (C)</td>
<td>0.3</td>
<td>Natural dam area (III) 3.7</td>
</tr>
<tr>
<td>Total</td>
<td>23.9</td>
<td>Total 16.7</td>
</tr>
</tbody>
</table>

3. NUMERICAL MODEL

Due to high water content of the landslide mass, the landslide movement is considered as a continuous solid-liquid phase flow. The numerical model developed by Egashira and Miyamoto was modified and used in this study to simulate the movement of the landslide mass. The model is based on the balance of kinematic energy in shear flow by considering the solid-liquid mixture of the flow [Egashira et al., 1997; Miyamoto, 2002].

The governing equations include a continuity equation and a momentum equation:

**Continuity equation**

$$\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{M} = 0$$  \hspace{1cm} (1)

**Momentum equation**

$$\frac{\partial \mathbf{M}}{\partial t} + \beta (\mathbf{M} \mathbf{u}^t) \nabla = -gh\nabla H - \frac{T}{\rho_m}$$  \hspace{1cm} (2)

where $h$ is landslide thickness, $\mathbf{M}$ is the flux vector, $\beta$ is the coefficient of momentum, and $\mathbf{u}$ is depth-averaged velocity. Superscript $t$ of $\mathbf{u}$ means transverse of the corresponding vector or matrix, that is, $\mathbf{u}^t$ is the transverse vector of $\mathbf{u}$. $g$ is gravity acceleration, $H$ is the surface level of the landslide, $\mathbf{T}$ is the shear stress acting on the slip surface, $\rho_m$ is the mass density of a hyper-concentrated sediment-water mixture. The density is determined as

$$\rho_m = c \sigma + (1-c) \rho$$  \hspace{1cm} (3)

where $\sigma$ is the mass density of solid phase, $\rho$ is the mass density of liquid phase, and $c$ is the volumetric concentration of solid phase, and $\nabla$ is defined as $\nabla = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y}$, in which $i$ and $j$ are base vectors of Cartesian coordinates.

In Eq. (1), deposition and erosion are assumed not to occur during the landslide movement so the right side of the equation is set to zero, Egashira et al. [1997] assumed that shear stress $\mathbf{T}$ acts on the slip surface and can be expressed as:

$$\mathbf{T} = \mathbf{T}_s + \mathbf{T}_d + \mathbf{T}_r$$  \hspace{1cm} (4)

where $\mathbf{T}_s$ is the static inter-granular contact, $\mathbf{T}_d$ is the particle-to-particle collision, and $\mathbf{T}_r$ is the interstitial liquid phase.

$$\mathbf{T}_s = \alpha c(\sigma - \eta \rho) gh \cos \theta \tan \phi_s \cdot \mathbf{u} / |\mathbf{u}|$$  \hspace{1cm} (5)

$$\mathbf{T}_d = 25/4 \cdot k_s \sigma (1 - \epsilon) \frac{1}{3}(d/h)^{2/3} |\mathbf{u}| \mathbf{u}$$  \hspace{1cm} (6)

$$\mathbf{T}_r = 25/4 \cdot k_f \rho (1 - c) \frac{1}{3}(d/h)^{5/3} |\mathbf{u}| \mathbf{u}$$  \hspace{1cm} (7)

where $\alpha = (c/c^*)^{1/5}$, $\phi_s$ is the friction angle, $\epsilon$ is the restitution coefficient, $c$ and $c^*$ are the concentrations of the solid phase in volume in the flow and at a packed state, $d$ is the diameter of particles of the solid phase, $k_s$ and $k_f$ are constants, $k_s = 0.0828$ and $k_f = 0.25$, and $\theta$ is the gradient of the slip surface, $\eta$ is the coefficient of the effect of buoyancy and takes a value from 0 to 1. $\mathbf{T}_s$ and $\mathbf{T}_d$ may change according to the speed of the sediment movement. When the sediment is moving slowly, $\mathbf{T}_s$ has larger impact than $\mathbf{T}_d$. Otherwise, it will be the other way around. Therefore, the given internal friction angle is updated automatically during the calculation.

The dynamics of the landslide mass is determined using the revised momentum equation. The revised momentum equation can be written as:

$$\mathbf{M}^{n+1} = \mathbf{M}^n - \left[ \beta (\mathbf{M}^n \mathbf{u}^n) \nabla + (\mathbf{T}^n_s + \mathbf{T}^n_d + \mathbf{T}^n_r) / \rho_m + gh^n \nabla H^n \right] \mathbf{M}$$
where \( n \) denotes the present time step and \( n + 1 \) denotes the next time step. As shown in the equation, the dynamics is determined not by the friction but the value of \( M \). When \( M > 0 \), the mass is in motion. On the other hand, the mass is not in motion when \( M < 0 \). For more details, refer to Miyamoto [2002].

There are two limitations for the proposed model. First, the erosion of the slide surface due to the movement of landslide mass is not considered in the model. Second, the water content of landslide material is constant. In this case, the soil mass is saturated during the landslide event.

In this paper, the model is applied to the landslide movement process and the deposition area. Fourthly, the shape of natural dam is also considered.

4. SIMULATION SCENARIOS

Based on the site investigation results, the landslide movement could be considered as a single or a double event. The double event (Scenario II) is based on the field data of area around Hsiao village. There are mount landslide occurred in the evening of 8/8. It shows the possibility of the 1st collapse. With compared with a geology map, there was a fault evident crossing the landslide area at E.L. 800 m. This is the possible boundary of the 1st collapse.

Hence, two scenarios are considered in this study. In scenario I, the soil mass in Area A was set as the initial area and moved only once. In scenario II, area A was divided into the upper and lower parts. The lower part of the soil mass in area A moved first and triggered the movement of the upper soil mass in scenario II. Fig. 5 and Fig. 6 present the initial condition of scenario I and II. In scenario I, the volume of landslide mass is \( 23.9 \times 10^6 \) m\(^3\). There is \( 22.5 \times 10^6 \) m\(^3\) for the main part in scenario II. The volume in first step is \( 1.5 \times 10^6 \) m\(^3\).

The parameter of the landslide material is set as shown in Table 2. The parameters include friction angle, average particle diameter, concentration of landslide mass and specific weight of fluid and particles.

During the landslide event, water is mixed with fine sand which results in a density increment. In addition, the concentration is reduced due to the decrease of fine sand. Before the landslide event, the concentration is 0.65, the porosity is 0.35, the specific weight of sediment is 2.65, and the specific weight of water is 1. During the landslide event, the concentration reduced to 0.46 and increased to 1.59 for the soil-water mixture.

The model starts at the time of landslide occurrence. The time step interval in this simulation is 0.001 second. The grid size is 10m by 10m. The total time period of the simulation model is 200 seconds. In scenario II, the simulated time is 100 seconds and 200 seconds.

5. SIMULATION RESULTS

The simulation results include three parts: (1) the velocity of landslide movement; (2) deposition condition of landslide; and (3) the shape of natural dam. The results are listed as follow.

5.1 The velocity of landslide movement

Fig. 7 shows the average velocity over time of the two scenarios. The movement process of the landslide is about 100 seconds. The maximum
velocity of the movement is 36.6 m/s in Scenario I, and 40.5 m/s in Scenario II. The result is close to the broadband seismometer monitor of Academia Sinica recorded [Shieh et al., 2009].

5.2 Deposition condition of landslide

The terrain changes are shown in Fig. 8 and Fig. 9. The green areas show depositional areas. In Scenario I (Fig. 8), deposition is modeled to occur at the northern part of Hsiaolin village and on the main channel. The max height of the natural dam would be about 60 m. In Hsiaolin village, the deposited depth would be about 20 m.

For scenario II (Fig. 9), the depositional areas include that downstream of Hsiaolin village. In this result, the height of the dam would be about 50 m, and the deposited depth in village would be 20 m. The deposited depth in the southern part of Hsiaolin village is 10 m.

5.3 The shape of natural dam

To discuss the shape of the dam, two profiles were chosen. Fig. 10 shows the frontal view of the natural dam. The longitudinal profile of the dam is shown in Fig. 11.

Fig. 11 shows the result of the longitudinal profile of the dam. The dash line is the original terrain, and the grey line is the remnants of the dam. The green line is the topography of river after the dam breach.

From the result, the shape of the dam could be well understood. The length of the dam is about 1,100 to 1,600 m.

Table 3 shows the volume of the depositional area from the simulation result. It shows that Scenario I is much closer to the field investigation result.

Table 3 Simulation result of deposit sediment (Unit: million m$^3$)

<table>
<thead>
<tr>
<th>Deposition Area</th>
<th>Estimated Original Sediment Mass</th>
<th>Deposition Area of Scenario I</th>
<th>Deposition Area of Scenario II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main deposit area (I)</td>
<td>7.9</td>
<td>7.0</td>
<td>5.1</td>
</tr>
<tr>
<td>South deposit area (II)</td>
<td>5.1</td>
<td>4.6</td>
<td>3.8</td>
</tr>
<tr>
<td>Natural dam area (III)</td>
<td>5.8</td>
<td>5.7</td>
<td>4.4</td>
</tr>
</tbody>
</table>
6. CONCLUSION

To discuss the movement process of the landslide at Hsiaolin village, field investigations and numerical simulations are applied in this paper. Based on field investigations and the topographic map, the largest depth of the landslide was 74 m. The landslide mass was $2.39 \times 10^6$ m$^3$. The mass deposited at the original river channel formed a landslide dam of 30 m or more. The depositional areas were also evaluated around the village.

The numerical model is based on sediment-water mixture movement. This is proper for the movement of the landslide at Hsiaolin Village. The result of the simulation includes the deposition condition and the landslide movement process. The process of landslide movement was well simulated by the numerical models.

The landslide process was considered as a single or double event. With this result, the movement process and the deposition conditions are well described in both scenarios. When compared with the survey data, Scenario I is more in line with the current investigation. From the result, it shows that the landslide movement was probably a single event. The survivors could evacuate because a part of the village was not buried by the landslide event.

Furthermore, the shape of the natural dam was evaluated in the model. This result is important for hydraulic analysis in the main stream.

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REFERENCES

