LANDSLIDE MODEL TEST SYSTEM AND ITS APPLICATION ON THE STUDY OF SHI LIU SHU BA O LANDSLIDE IN THREE GORGES RESERVOIR AREA

X. Q. LUO¹, H. SUN¹, L. G. THAM³ and S. M. JUNAIDEEN³

ABSTRACT

Catastrophic landslides are not uncommon in the Three Gorges area in China during rainy seasons. It is anticipated that the frequency of landslides will increase as a result of the impoundment of the reservoir of the Three Gorges Hydropower Station, and this has prompted geotechnical researchers to pay special attention to the problem. This paper introduces a landslide model test system, which allows studying of landslides induced by the combined effect of reservoir impoundment and rainfall. The system consists of a large flume with hydraulic lifting facilities, a set of computer-controlled surface sprinklers and pipes to simulate rainfall and reservoir impoundment, as well as a comprehensive instrumentation and data acquisition system. A model test carried out to study the Shi liu shu ba o landslide, which occurred in the Three Georges Reservoir area, is presented to demonstrate the potential application of the test system. It is shown that the horizontal and the vertical displacements are abruptly increasing, when the reservoir impoundment and rainfall are combined, which cause the failure of the model slope.

Key words: flume test, model test, landslide, rainfall, reservoir impoundment (IGC: E6/E14)

INTRODUCTION

According to historic records, serious geological disasters, such as landslides, occurred frequently in the Three Gorges Reservoir area. The debris of the landslide at Xintan in Zigui County blocked the Yangtze River in the year 1026 and 1542, and interrupted navigation for 25 years and 8 years, respectively. Further investigations indicate that in the Three Gorges Reservoir area more than 2000 landslides and rockfalls with a total volume of about $3.8 \times 10^{10}$ m$^3$ had occurred and more than 90 debris flow sites were identified.

Recently, there is an increase in landslide and rockfall incidents in this area. On July 17, 1982, a hill slope in Jipazi of Yunyang County slid into the Yangtze River and obstructed the navigation channel. The cost for channel dredging and landslide control was approximately one hundred million RMB. On June 12, 1985, the debris of the Xintan landslide buried a town that had a history of more than 300 years. The landslide mass also blocked the navigation channel and caused surge waves about 35 m high. The economic loss was tremendous. On July 16, 1986, a landslide in Majiaba of Zigui County occurred with a volume of about $2.8 \times 10^7$ m$^3$, shown in Table 1. Fortunately, advance warning had allowed the inhabitants to evacuate safely. Furthermore, between 1991 and 1998, there were several large scale landslides and debris flows in this area.

| Table 1. Landslides in the Three Gorge Reservoir area before impoundment |
|---|---|---|---|
| Date | Location | Topographical characteristics | Geological characteristics |
| Jipazi landslide | 1982.7.17 | Yunyang county | Fastigiated shaped, 1000–1600 m in length, 240–360 m in upper width, 700–750 m in lower width and front into the river. Bedding landslide: Sliding surface tended to Yangtze River, and sliding bed developed along mudstone. |
| Xintan landslide | 1985.6.12 | Zigui county | Horn shaped, the average slope of 23 degrees and front into the river. Collapse slope, with 30–40 m in thickness and Sliding along clay layer in the bottom |
| Majiaba landslide | 1986.7.16 | Zigui county | Long pocket shaped, 2300 m in length, 300 m in width. One-sided slope with interbedded sandstone and mudstone. |

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There were three stages of impoundment in the Three Gorges Reservoir, and the water level changed at the different stages as shown in Table 2. As reservoir impoundment will raise the water level rapidly and disturb the balance of the geology, it is anticipated that the impoundment of the Three Gorges Reservoir may cause further landslides and rockfalls, as well as erosion of the reservoir bank. Many slopes began to deform with noticeable magnitudes after the first stage of impoundment in 2003 and some landslides occurred during intense rainfalls. The Qianjiangping landslide, for example, occurred after the first stage of impoundment (started from 68 m on June 1, 2003, and reached 135 m on June 15, 2003) of the Three Gorges Reservoir. During the same period, there was heavy rainfall (162.7 mm, from June 21 to July 11) (Dai et al., 2004), while the average rainfall in the area is 1200 mm per year. As the water level of the Three Gorges Reservoir reached 156 m in 2006, and 175 m (the designed water level) in 2009, the frequency of landslides and rockfalls of the Three Gorges Reservoir area increased further. Therefore, research on landslide and rockfall in this area has become quite urgent.

Physical modeling is one of the common approaches for investigating landslide mechanism. Broadly speaking, such approach includes gravity model and centrifuge model tests.

Centrifuge modeling was first used in geotechnical research in 1930s (Stewart et al., 1994). In China, it was used to study the stability of dam foundations and abutments in large-scale water conservancy engineering projects since seventies of the last century (Bao, 1991; Huang and Wang, 1998). Increasing the local equivalent gravitational field increases the stresses in a centrifuge model to match those of the actual situation. Although some of the difficulties associated with scaling are overcome in centrifuge modeling, there are inevitable technical problems. For example, since the centrifugal force of soil element is directly proportional to the distance between the soil element and center of revolution, the centrifugal force acting on the soil element in the revolving bucket is unparallel and uneven. Therefore, the force field is not exactly similar to that of the weight of the soil element in the prototype where the gravitational force is vertical and even.

Gravity modeling has a much longer history. Examples include the studies conducted by a group headed by Fumagalli (1968) on engineering geological models in Italy. Ashby (1971) was the first one, to the best knowledge of the authors, to apply model technology of

### Table 2. Water levels of the Three Gorges Reservoir with three stages of impoundment

<table>
<thead>
<tr>
<th>Stages</th>
<th>Period</th>
<th>Flood frequency</th>
<th>Normal water level (m)</th>
<th>The lowest water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural state</td>
<td></td>
<td>20%</td>
<td>71.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>74.2</td>
<td></td>
</tr>
<tr>
<td>First stages</td>
<td>June, 2003—flood season, 2006</td>
<td>20%</td>
<td>135.0</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>135.0</td>
<td></td>
</tr>
<tr>
<td>Second stages</td>
<td>After flood season, 2006—before flood season, 2009</td>
<td>20%</td>
<td>156.0</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>156.0</td>
<td></td>
</tr>
<tr>
<td>Third stages</td>
<td>After flood season, 2009 (2013)</td>
<td>20%</td>
<td>175.0</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>175.0</td>
<td></td>
</tr>
<tr>
<td>The maximum flood level</td>
<td></td>
<td></td>
<td>180.4</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Photo of Shiliushubao landslide
slope platform in the research on toppling failure. Furthermore, model experiments were also carried out in Portugal, Russia, France, Germany, UK, USA, Japan and China (Baumgartner and Stimpson, 1979; Bray and Goodman, 1981; Zhang et al., 1994; Li et al., 2003). Such approaches also have limitations. For example, it is difficult to scale down the particle sizes of the test materials, and the stress levels of the models and sites could be very much different. However, the gravity model approach was still chosen here for the following reasons: (a) boundary conditions can be well defined and controlled, and (b) the size of the model is sufficiently large so that key features of the actual sites can be simulated.

This paper introduces a large landslide model testing system designed and fabricated at the China Three Gorges University. The system can be used to study landslides induced by the combined effect of reservoir impoundment and rainfall. A model test was carried out to study the Shiliushubao landslide (Figs. 1 and 2), which occurred in the Three Georges Reservoir area, and the results are presented to demonstrate the application of the test system.

LANDSLIDE MODEL TEST SYSTEM

The major factors triggering landslides, especially the old landslides, in the Three Gorges Reservoir area are reservoir impoundment and rainfall. The challenges in the landslide model test system are (a) simulating the reservoir water level and rainfall, (b) measuring the changes in moisture content and stresses, and (c) capturing the deformation pattern allowing a better understanding of the failure process.

To address the above issues, a large gravity model testing system was fabricated. The test system is composed of a flume and a lifting system, a set of surface sprinklers and pipes for supplying water, and a comprehensive data acquisition system (Fig. 3). The pertinent details of the setup will be discussed in the subsequent sections.

FLUME AND LIFTING SYSTEM

The flume is 8.0 m long, 0.8 m wide and 3.5 m high. The sidewalls are smooth and transparent so that deformation can be observed and recorded from either side of the flume. The base and side walls of the flume are reinforced with steel sections. A lifting system includes hydraulic pressure jacks connected to the base of the flume. The maximum specified slope angle of the flume to the horizontal is 20° (Fig. 4).
A set of sprinklers installed above the flume is used to simulate rainfall (Fig. 5). Figure 5 shows the surface sprinkling system schematically. The system consists of eight sets of sprinklers. Sprinklers with three different capacities: (five spray elements with precipitation 0.1 \( \text{mm/min} \), one spray element with precipitation 0.5 \( \text{mm/min} \), and two spray elements with precipitation 1.0 \( \text{mm/min} \)) are arranged in such a manner that one can simulate the different rainfall intensities, by composing those sprinklers. The combination can be adjusted manually or by a computer controlled system. The achievable rainfall intensity is in the range of 0.1 – 3 \( \text{mm/min} \). The maximum rainfall intensity of the Three Gorge Reservoir area is about 0.14 \( \text{mm/min} \), so the testing system can simulate the rainfall of the Three Gorge Reservoir area.

Water supply pipes set up at the lower end of the flume and a tank set up at the back of the flume is used to simulate the initial water level corresponding to the real ground (Fig. 6). The water supply pipes are supplied to simulate reservoir impoundment, whose capacity is manually controlled, and by adjusting the water capacity from the tank, then the initial water level is simulated. Marriott’s tube is used to control the water capacity and to maintain the water level.

**INSTRUMENTATION AND DATA ACQUISITION**

In addition to the use of common transducers, an optical method was used to record the displacement profile of the slope, and \( \gamma \)-ray method was used to measure the moisture content. The common transducers include piezometers, earth pressure cells, and displacement sensors. The transducers are shown in Fig. 7. There are 32 channels to be recorded.
Optical Displacement Measurement

The conventional method of measuring displacement at a few specific locations can provide only limited information on the overall deformation field. Therefore, optical method is adopted in the present study. Optical methods are superior to the conventional method in two ways: there is minimum interference to the model, and it provides comprehensive information of the deformation field.

The optical methods (Bai, 2000) can be categorized as automatic mesh method, coherent speckles measurement, laser digital method, laser direct diffraction CCD method, and high-resolution fiber optic measurement. The auto-grid method that was developed recently (Guan et al., 1996) is used. This method is based on modern electronic technique (such as CCD) and digital photograph processing technology. Figure 8 shows the optical displacement measurement of a single node. Displacement is obtained by taking photos before the start of the test and during the test. Each reference point can be treated as a mesh node, which is an “area” but not a “point” in a digit photo and it is referred to as a “speckle”. The location of each speckle can be obtained by the barycenter method (Luo et al., 2005), in which the barycenter of the grey scale of a speckle is taken as its location. The movement of each speckle can be easily obtained by the difference in the locations of the speckle before and during the test.

Compared to other methods, such method has the following advantages: rapidness, high precision, simple equipment, large measurement range, and high degree of automation.

Moisture Content Measurement by γ-ray Method

Moisture content can be measured by different methods. As the present study requires continuous measurement of moisture content, radiation approach is adopted. Radiation from a radioactive source is mainly composed of α-particle stream, β-particle stream and photon stream. The photon stream (which is also called γ-ray) is a high-energy electromagnetic wave with short wave length (<10⁻⁸ cm) and high frequency. The penetrating capability of γ-ray generally increases as the energy of γ-ray increases.

When γ-ray penetrates through soil, a complex interaction occurs in the soil. The interaction includes photoemission, Compton effect, and electron-twin generation. However, electron-twin generation occurs only when the energy of the photon is more than one MeV, and photoemission occurs only when the energy of the photon is low. As the energy of the radioactive source ¹³⁷Cs used in the present study is 0.66 MeV, Compton effect dominates. Due to Compton effect, a certain amount of the γ-ray energy would be absorbed while penetrating through soil. The amount of the energy absorbed depends on the initial energy of the radioactive source, the soil moisture content, and the thickness of the soil. Therefore, one can determine the moisture content of a soil by allowing the γ-ray to penetrate the soil and measure the intensity (energy) of the ray. Mathematically, the change in volumetric moisture content of the soil can then be determined from the following equation (Grismer et al., 1986),

$$\Delta u = \frac{100}{\mu L} \ln \frac{I_0}{I}$$

(1)

and

$$\theta = \theta_0 + \Delta \theta$$

(2)

where,

- $\theta$: volumetric moisture content (%);
- $\theta_0$: original volumetric moisture content (%), usually determined by the desiccation method before the test;
- $\Delta \theta$: the change in volumetric moisture content (%);
- $I_0$: the intensity of γ-ray after it penetrated through soil whose moisture content is $\theta_0$;
- $I$: the intensity of γ-ray after it penetrated through soil whose moisture content is $\theta$;
- $\mu$: mass absorption coefficient of water (cm²/g);
- $L$: the thickness of soil penetrated by the γ-ray (cm).
Note that the measured intensity of $\gamma$-ray is the combined energy of the emitted ray and the ambient ray. Therefore, one has, in the application of Eq. (2), to deduct the ambient intensity from the measured intensity. As the ambient intensity depends on the location as well as time, it has to be determined before the commencement of the test. Furthermore, the coefficient $\mu$ depends on the intensity of the $\gamma$-ray, the shield condition of the probe, the distance between the probe and the radioactive source and ambient temperature. The coefficient can be determined by measuring the intensity of the ray after penetrating soil of known volumetric moisture content.

The moisture content is measured using a dolly moving cart to control the vertical direction and a lead dot to control the horizontal direction to receive the $\gamma$-ray penetrating through the soil. The working diagram measuring the moisture content is shown in Fig. 9.

**CASE STUDY**

The Shiliushuba landslide occurred in Badong County, Hubei Province, about 65 km away from the dam site of the Three Gorges Hydropower Station. It is part of the Huanglashi landslide group. The volume of slide was $11.80 \times 10^6$ m$^3$ with an area of $250 \times 10^3$ m$^2$. The average thickness and length of the slide were 50 m and 550 m, respectively (Fig. 2). The width ranged from 350 m to 470 m. The combined effect of reservoir impoundment and rainfall is believed to have triggered the landslide. The slip zone contained aqua marl and amaranth mudstone. According to the site exploration, the failure process is primarily believed to include reactivation, creeping, and progressive movement.

The purpose of the model test was to study the failure characteristics of the landslide under the condition of the reservoir operation and rainfall. The model boundary condition was taken as plane strain one. The initial water level of the Three Gorges Reservoir was 68 m, and the impoundment of reservoir was mainly simulated using two typical conditions. Firstly the water level reached 135 m which was one third height of the slope. It was the most dangerous for slope stability when the water level of reservoir dam was one third height of the slope (Cao et al., 2005). Secondly the water level reached 175 m which was one third height of the slope. It was the most dangerous for slope stability when the water level of reservoir dam was one third height of the slope (Cao et al., 2005). Secondly the water level reached 175 m which was the designed water level. The rainfall intensity was simulated according to Fig. 10, and there was heavy rainfall when the water level was 135 m (Dai et al., 2004). Finally the reservoir drawdown was simulated.

Considering the effect of impoundment and rainfall, based on the above information on the reservoir operation and rainfall pattern, the test was carried out in the following stages:

1. The initial condition: the water level was 68 m above sea level (a.s.l.).
2. The first impoundment: the water level was raised from 68 m a.s.l. to 135 m a.s.l. in 15 days.
3. The second and third impoundment: the water level was directly raised from 135 m a.s.l. to 175 m a.s.l. at a rate of about 1.05 m/day.
4. The rainfall as defined in Fig. 11 was assumed to occur when the reservoir level was 135 m a.s.l.
5. Simulation of the reservoir drawdown: the rate of drop was about 2 m/day, and it took 15 days to drop from 175 m a.s.l. to 145 m a.s.l.

In the modeling, the parameters include dimension $l$, density $\rho$, acceleration of gravity $g$, cohesion $c$, friction angle $\phi$, deformation modulus $E$, Poisson’s ratio $\mu$, stress $\sigma$, strain $\varepsilon$, displacement $u$, permeability coefficients $k$, time $t$, velocity $v$, suction $s$, moisture content $\theta$, rainfall intensity $q$, and lateral pressure $p$. The ratio of prototype parameter to model parameter for each parameter can be obtained and they are denoted by:

\[
\frac{l^*}{l^m} = \frac{\rho^*}{\rho^m}, \quad \frac{g^*}{g^m} = \frac{c^*}{c^m}, \quad \frac{\phi^*}{\phi^m} = \frac{E^*}{E^m}, \quad \frac{\mu^*}{\mu^m}, \quad \frac{\sigma^*}{\sigma^m}, \quad \frac{\varepsilon^*}{\varepsilon^m}, \quad \frac{\theta^*}{\theta^m}, \quad \frac{\sigma^*}{\sigma^m}, \quad \frac{q^*}{q^m}, \quad \frac{\rho^*}{\rho^m}.
\]
where $\phi$, $\mu$, $\varepsilon$, $\theta$ are non-dimensional parameters, and the following sets of parameters have same dimension (1) length—$l$, $u$, $s$; (2) Force/length$^2$—$c$, $E$, $\sigma$, $\rho$; and (3) Length/time—$k$, $v$, $q$.

Based on the second similarity law (Fumagalli, 1968), the parameters that correlated with the landslide are expressed by the following equations,

$$F(l, \rho, g, c, E, \mu, \sigma, \varepsilon, u, k, l, v, s, \theta, q, p) = 0$$

or

$$\phi(\pi_1, \pi_2, \pi_3) = 0$$

Choosing $l$, $g$, $\rho$ as the independent parameters, one can show readily that Eq. (4) can be re-written in terms of three non-dimensional scaling parameters, that is:

$$\phi(\pi_1, \pi_2, \pi_3) = 0$$

where

$$\pi_1 = \frac{c}{\rho l}$$
$$\pi_2 = \frac{k}{(lg)^{1/2}}$$
$$\pi_3 = \frac{l}{f^{1/2}g^{-1/2}}$$

If we let $g^*$ as well as $\rho^*$ equal unity and $l^*$ equals $n$, the other scaling parameters can be easily obtained as follows:

$$\phi^* = \mu^* = \varepsilon^* = 1$$
$$u^* = l^* = n$$
$$c^* = E^* = \sigma^* = \rho^* = n$$
$$k^* = v^* = q^* = \frac{1}{n}$$
$$\rho^* = \rho^* = n$$

In the model test, the slip band and slip mass were mainly simulated, and the physical and mechanical parameters of prototype slip slope were obtained from the physical and mechanical tests, shown in Table 3, and the parameters of model slip band and mass were obtained from the similarity theory and then the materials were made using the mix proportion tests (Cheng et al., 2002).

Before placing the soil sample in the flume, the glass walls were lubricated to reduce the frictional effect of the sidewalls. Figure 11 shows the layout of the optical measurement points. Based on the water level, the points were mainly distributed on the three sections of slope, such as the foreside (at about 135 m height), central (at about 175 m height) and back of the slope. The locations of piezometers, earth pressure and surface displacement transducers were mainly distributed on the three sections of slope, shown in Fig. 12. The layout of moisture content measurement points was averagely distributed on the slope, 200 mm away from each column, 100 mm away from each line, shown in Fig. 13. The test results are presented in Figs. 14 to 19.

Comparing the water levels with the estimated ground water tables (Luo et al., 2001) when the water levels of

### Table 3. Comparison between the prototype material parameters and model material parameters

<table>
<thead>
<tr>
<th></th>
<th>Slip Mass</th>
<th>Slip Band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prototype</td>
<td>Model</td>
</tr>
<tr>
<td>Bulk unit weight (kN/m$^3$)</td>
<td>20.2</td>
<td>20.1</td>
</tr>
<tr>
<td>Saturated unit weight (kN/m$^3$)</td>
<td>22.4</td>
<td>22.3</td>
</tr>
<tr>
<td>Coefficient of permeability (m/s)</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>Friction angle (degree)</td>
<td>38.6</td>
<td>38.5</td>
</tr>
</tbody>
</table>
Yangtze River are 68 m, 135 m, and 175 m, respectively (Fig. 14), and the slope profile obtained during the simulated rainfall when reservoir level is at 135 m with the computed ones (Luo et al., 2001) (Fig. 15), shows good agreement, demonstrating the potential of the physical model in the study of large-scale landslides.

Rainfall caused the change in moisture content (Fig. 16). The moisture content at the thin back layer of slope increased quickly and connected to the ground water after the rainfall, but at the centre of the slope, only the moisture content of shallow layer increased and did not connect to the ground water.

Now we discuss the deformation characteristics of foreside (Point 14), central (Point 10) and back (Point 4) of slope during the testing (Figs. 17–18). Deformation at Point 14 occurred distinctly at the beginning of testing and increased the most quickly during the period from when the reservoir water level was at 68 m to 135 m. It is shown that the foreside of slope is the most sensitive to the change in water level of reservoir when the water level reached 135 m from 68 m. However, deformation at Point 10 increased the most quickly during the period from when the reservoir water level was at 135 m to 175 m, showing that the central part of slope is the most sensitive to the change in water level of reservoir when the water level reached 175 m from 135 m. Deformation at Point 4 increased slowly with impoundment, showing that the back of slope is not sensitive to the change in water level.

Deformation development of the slope was similar to the change in water level during the impoundment. That is to say, deformation increased with raise in water level, and deformation rate became slow when the water level was constant. At the same time, the deformation of slope
mass occurred more slowly than the change in water level. When the water level of reservoir was down to 145 m abruptly from 175 m, the landslide completely appeared (Fig. 19). Deformation increased quickly at the most part of slope. Therefore, the change in water level of reservoir had a strong influence on the landslide.

Rainfall had an influence on the landslide too. Horizontal displacement changed at small degree (Fig. 17), but vertical displacement of slope increased quickly which was caused by the rainfall (Fig. 18).

Based on the tests, it is presented that landslide is distinctly motivated by impoundment of reservoir and rainfall.

SUMMARY AND CONCLUSIONS

The large experimental setup, which has been fabricated by the China Three Gorges University, allows the study of landslides induced by the combined effects of reservoir impoundment and rainfall. The setup consists of a large flume with hydraulic lifting facilities, a system of computer-controlled surface sprinklers and pipes to simulate rainfalls and reservoir impoundment, and comprehensive data acquisition systems. The instrumentation includes piezometers, earth pressure transducers, and conventional displacement transducers. The moisture content and movement were determined by γ-ray and optical approaches, respectively. The potential application of the flume is demonstrated through a model study conducted to investigate the Shiliushubao landslide which occurred in the Three Gorges Reservoir area. The test results show that moisture content and displacement measurements can be effectively made using the γ-ray method and optical method, respectively.

Furthermore, it can provide experimental data for understanding the failure mechanism so that engineers can plan necessary mitigation measures. Based on the tests, it is shown that the horizontal and the vertical displacements abruptly increase, when the reservoir impoundment and rainfall are combined, which cause the failure of the model slope.

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