The characteristics of slope sliding under different rainfall intensities based on MEMS sensors

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Abstract. In this study, the sliding characteristics of the slope consisting of natural river sand under different rainfall intensities were revealed based on the model tests and MEMS sensors. The sensors were embedded at different locations in the slope for real-time monitoring of characteristics, such as acceleration, angular velocity, and angle under rainfall conditions. Evidently, with small rainfall intensity, the slope underwent creep deformation, and only the primary creep was observed, that is, taken the acceleration as an indicator, the change rate of the acceleration decreased with increasing time, and finally the slope turned to stability again and no slope sliding occurred; with the increase of the rainfall intensity, the change rate of the acceleration first decreased, then became stable for a short time, finally quickly increased, that is, the primary, secondary, and tertiary creeps were observed while the secondary creep stage was small, which induced the accumulated creep deformation of slope from quantitative to qualitative change (creep fracture), finally the overall slope sliding occurred. The greater the rainfall intensity, the shorter the time required for creep and slope sliding; with continually increase of the rainfall intensity, more times of slope sliding can be obtained under heavy rainfall. MEMS sensor can capture the motion characteristics of slope from creep deformation to sliding failure, which has certain application for landslide monitoring and early warning.

1. Introduction

Landslide, a common geological hazard, can be induced by rainfall, groundwater activity, earthquake, and artificial slope cutting, among which rainfall-induced landslides are widely distributed with the highest frequency and greatest harm [1]. With continuous rainfall, rainwater enters the soil to play a loading role and the pore water pressure also gradually increases. At the same time, the shear strength of the soil gradually decreases, which in turn can reduce the slope stability [2-5].

In the recent years, many researchers have revealed the relationship between macro-slump failure forms and meso-slip movement evolution of soil, the deformation, failure mechanism, and the volume characteristics of landslide surface erosion, etc. using traditional methods. [6-11], Micro-Electro Mechanical Systems (MEMS) is an interdisciplinary frontier research field in microelectronics technology, characterized by several advantages, including small size, light weight, low cost, low power consumption, and high reliability, resulting in its wide applications in civil engineering and other fields. In 2010, Liang et al. [18] used MEMS sensors for remote real-time monitoring, early warning, and forecast of the landslide by analyzing the displacement and inclination angle of the dangerous rocks in the slope. In 2013, Murakami et al. [17] realized real-time monitoring of slope damage induced by rainfall using MEMS acceleration sensors. In 2015, Towhata et al. [16] proposed a slope
displacement/deformation monitoring technology based on MEMS sensors and provided an early warning of slope failure disaster in the rainstorm. In 2019, through the model tests, Li et al. [13][14] triggered landslide by rainfall and arranged MEMS sensors inside the slope to monitor the acceleration, angle, angular velocity, and other indicators. Later, the reinforcement effect of the anchors and slope failure characteristics induced by rainfall under different slope angles were revealed. Su et al. [15] used MEMS sensors to accurately extract and locate the slope information of pavement. In 2020, Abraham et al. [12] used MEMS-based tilt and volumetric water sensors to monitor an active slope in Darjeeling. By monitoring and analyzing real-time data, including acceleration, angle, and angular velocity by MEMS sensors embedded at different positions, the characteristics of slope sliding under different rainfall intensities were explored.

2. Details of the experimental test

2.1. Model test design

In our study, based on the slope model test by Li et al. [19], the ratio of the model test box to the real slope was 1:20 with the box length, width, and height of 1500 mm, 1000 mm, and 1000 mm, respectively. The model box was spliced by acrylic plates and the joints were anchored with acrylic glue and hinges to ensure its strength. Coarse natural river sand with the initial water content of 7.4% was used for the slope preparation. The density of sand was 1400 kg/m³ and the internal friction angle was 30° obtained by the direct shear test. The top and bottom widths of the slope were 300 mm and 900 mm, respectively with the height of 600 mm and the slope angle of 45°. The 3D view of the model box, slope, and inserted sensors is shown in Figure 1. In the experiment, a single row with four sprinklers, as shown in Figure 2, was used to simulate rainfall which can spread to the top and the sides of the slope. The rainfall intensity was controlled by adjusting the water flow and measured by K24 flowmeter with the measurement accuracy of ±1%. According to different rainfall intensities, the experiments were divided into three groups, A, B, and C corresponding to the rainfall intensities of 90 mm/h, 220 mm/h and 280 mm/h, respectively.

[Figure 1. Stereogram of the model box (mm) Figure 2. Rainfall simulator]

2.2. Monitoring sensor

BWT901 gyroscope sensors, based on MEMS technology, were used to capture the motions of the slope subjected to rainfall by continually monitoring the acceleration, angular velocity, angle, and magnetic field in the three orthogonal directions x, y, and z. Through the attitude fusion algorithm based on integrated high-precision Kalman filter, the highest output rate of this MEMS sensor was up to 200 Hz, and the measurement accuracy of the angle was around 0.05°. No axial drift was observed during the whole process. The return frequency of the sensor was set to 10 Hz, that is, the number of transmitted data is 10 per second.

The positive directions of the MEMS sensor in the x, y, and z axes are also illustrated in Figure 1. Before rainfall, the initial acceleration of the MEMS sensor embedded in the x direction was ~1g due to the gravity, while those in the y and z directions were close to 0.
3. The results and analysis of the experimental test

3.1. Test data acquisition

Monitoring data ranged from the beginning of the rainfall to the landslide development. The slope angle post-landslide was less than or equal to the internal friction angle (30°) of the sand, or a stable seepage was observed at the bottom of the slope, when the monitoring datum of the sensors was stable or fluctuated slightly. This indicated the end of the test as the slope did not slide further. The analysis time covering different rainfall intensities ranged from 35 to 120 min, and the number of data points ranged from about 20,000 to 70,000. The macroscopic phenomena and MEMS monitoring data during the tests are shown in Tables 1–3, wherein the side view is marked with the change of the acceleration and inclination angle measured by MEMS sensors only in y and z directions due to slight change in the x direction.

3.2. Test analysis

Combined with the macro phenomena, the failure mode and sliding characteristics of the slope under different rainfall intensities were obtained by the comparison and analysis of monitoring data based on MEMS sensors, i.e., the acceleration, angle, and angular velocity in the x, y, and z directions in different locations of the slope.

3.2.1. Test A with the rainfall intensity of 90 mm/h. The macroscopic phenomena are shown in Table 1. For the slope under a relatively small rainfall intensity, it can be seen that after 30 minutes from the start of the test, small tension cracks were observed at the back of the slope. While the whole slope had a small creep downwards, the creep deformation of the slope reached the maximum after 70 min without expanding the tension crack at the back edge. In addition, no tension crack was formed, and the slope slid down by 1–2 cm. Under low intensity rainfall, the creep deformation of the slope did not change significantly compared with that at 70 min. Therefore, inferring that the slope would not slide, the test was stopped. The variations in the acceleration and angle monitored by MEMS sensors were consistent with the macroscopic phenomena, that is, both characteristics change significantly with the Z-axis and enlarged 30 min after the test begins, especially No.3,5, and 6 sensors, which indicated that the obvious creep occurred at the bottom of the slope. After 70 minutes, the acceleration and angle did not change anymore indicating that no landslide had occurred. The change in angular velocity was relatively small in the whole process.

3.2.2. Test B with the rainfall intensity of 220 mm/h. For the slope under a relatively high rainfall intensity, as shown in Table 2, it was found that 30 minutes after the test began, distinct tensile cracks appeared on the back of the slope and the whole slope moved down by 1–2.5 cm. 54 minutes later, a landslide occurred, the top of the slope dropped by 3–10 cm, and the front of the slope slipped out by 30 cm from the initial slope toe. After 80 minutes, a stable seepage was observed at the bottom of the slope and the final stable slope angle was ~26°. The monitored acceleration and angle by MEMS sensors were in accordance with the macroscopic phenomena of the experiment. The changes of acceleration and angular velocity indicated that the whole slope moved forward and downward. 15 minutes after the start of the test, the acceleration and angle in the Z-axis obviously increased, especially for sensors No. 2, 3, and 6, indicating obvious creep at the slope surface and toe of the slope before the landslide occurred. 54 minutes later, the acceleration, angle, and angular velocity suddenly changed, declaring a landslide.
| Time (min) | Experimental phenomenon                                                                 | Front view | Side view |
|-----------|-----------------------------------------------------------------------------------------|------------|-----------|
| 0         | Rainfall was triggered and the experiment started.                                       | ![Rainfall Image](image1) | ![Side View Image](image2) |
| 30        | Tiny cracks on the back of the slope and slope creep were observed.                      | ![Crack Image](image3)   | ![Side View Image](image4) |
| 70        | Small cracks on the back of the slope were observed and the sliding deformation of the slope was 1.0–2.0 cm. | ![Crack Image](image5)   | ![Side View Image](image6) |
| 114       | The test ended. No further development of the tensile cracks at the back of the slope was obtained and the slope became stable again. | ![Stable Image](image7)   | ![Side View Image](image8) |

**Monitored data by MEMS sensors**

| Acceleration | Angular velocity | Angle |
|--------------|------------------|-------|

(x, y, z: three directions of space)
Table 2. Experimental phenomenon of test B

| Time (min) | Experimental phenomenon | Front view | Side view |
|------------|-------------------------|------------|-----------|
| 0          | Rainfall was triggered and the experiment started. | ![Front View 0](image1) | ![Side View 0](image2) |
| 30         | Obvious cracks on the back of the slope were observed and the sliding deformation of the slope was 1.0–2.5 cm. | ![Front View 30](image3) | ![Side View 30](image4) |
| 54         | Landslide occurred: the top of the slope dropped by 3–10 cm and sliding deformation in the front of the slope was ~30 cm. | ![Front View 54](image5) | ![Side View 54](image6) |
| 80         | The test ended. Stable seepage was formed at the bottom of the slope and the slope became stable again with the final slope angle of 26°. | ![Front View 80](image7) | ![Side View 80](image8) |

Monitored data by MEMS sensors

- Acceleration
- Angular velocity
- Angle

(x, y, z: three directions in space)
### Table 3. Experimental phenomenon of test C

| Time (min) | Experimental phenomenon                                                                 | Front view | Side view |
|------------|----------------------------------------------------------------------------------------|------------|-----------|
| 0          | Rainfall was triggered and the experiment started.                                      | ![Front View](image1) | ![Side View](image2) |
| 5          | Obvious cracks on the back of the slope were observed and the sliding deformation of the slope was 0.5–2.0 cm. | ![Front View](image3) | ![Side View](image4) |
| 18         | The first landslide occurred. The top of the slope dropped 3–15 cm and sliding deformation in front of the slope was ~15 cm. | ![Front View](image5) | ![Side View](image6) |
| 28         | The second landslide occurred. The top of the slope dropped by 10–20 cm and sliding deformation in front of the slope was ~40 cm. | ![Front View](image7) | ![Side View](image8) |
| 35         | The test ended. Stable seepage was formed at the bottom of the slope and the slope became stable again with the final slope angle of 21°. | ![Front View](image9) | ![Side View](image10) |

**Monitored data by MEMS sensors**

- **Accelerations**
- **Angular velocities**
- **Angles**

(x, y, z: three directions of space)
3.2.3. Test C with the rainfall intensity of 280 mm/h. With high rainfall intensity (e.g., 280 mm/h), two or more landslides could occur and the time needed to trigger the landslide became shorter. As shown in Table 3, obvious tensile cracks on the back of the slope were observed only 5 minutes after the start of the test. Meanwhile the whole slope moved 0.5–2 cm downwards; 18 minutes later, the first landslide was produced and the top of the slope dropped by 3–15 cm while the front of the slope slid out by 15 cm from the initial slope toe; 28 minutes after the initial state, the second landslide was observed and the top of the slope dropped by 10–20 cm while the front of the slope slid out by 40 cm from the initial slope toe; 35 minutes after the start of the test, a stable seepage was formed at the bottom of the slope with the final slope angle of 21°; then, the test ended. The acceleration and angle monitored by MEMS sensors also illustrated a continual increase and a sudden change when the landslide occurred. The distinct changes of No.1, No.2, and No.3 sensors indicated that the creep near the slope surface was obvious. The reason for the two landslides may be that subjected to rainfall, the pore water pressure for the soil at the slope surface increased while the shear strength of the soil decreased, and the tensile cracks generated at the trailing edge expanded promoting the first landslide but the stable seepage had not yet formed inside the slope. With continuous rainfall, the shear strength of soil further reduced and the pore water pressure increased. When the sliding force on the potential sliding surface of soil was greater than the anti-sliding force, the equilibrium was disturbed, resulting in the second landslide.

4. Characteristics of slope sliding under rainfall

Based on the experimental results of tests A, B, and C, it was found that the sliding characteristics of slopes are different under different rainfall intensities. The MEMS sensors can capture the sliding characteristics. Considering the change rate of the acceleration as an indicator, the creep behavior of the slope before landslide conforms to the that of general materials. As shown in Figure 3, the primary, secondary, and tertiary creeps were obtained. The creep behavior was different under different rainfall conditions. The greater the rainfall intensity, the shorter the time needed for creep and landslide and the greater the damage degree of the slope.

Subjected to relatively low rainfall intensity (e.g., 90 mm/h, Test A in Figure 3), the deformation of slope was mainly creep, obvious in the interior and toe of the slope, and the creep deformation cannot develop into a large-scale landslide. The change rate of the acceleration decreased first and then stabilized around 0. Only primary creep was found for the slope deformation. The slope can reach a new balance under this rainfall condition and no large-scale landslide occurred.

When the rainfall intensity was higher (e.g., 220 mm/h, test B in Figure 3), obvious deformation at the slope surface and toe were observed and the accumulated creep deformation varied from quantitative to qualitative change eventually inducing a landslide. The primary, secondary, and tertiary creep were observed. The related change rate of the acceleration first decreased, then became stable, and finally increased again. Distinguished from other materials,
such as metal, the sustained time for the secondary creep was short for the slope occupied by granular material.

Under heavy rainfall intensity (e.g., 280 mm/h, test C in Figure 3), the slope experienced two landslides, even more related rainfall intensity. The deformation near the slope surface were more obvious. Corresponding to the two landslides, two whole processes of creep were also obtained. That is, change rate of the acceleration first decreased, then became stable, and finally increased indicating the first landslide; after the first landslide, the slope reached to a new balance and the change rate of the acceleration decreased, eventually stabilizing. With continuous rainfall, it suddenly increased again and the second landslide occurred.

5. Conclusion

The MEMS sensors were used to continually monitor the acceleration, angle, and angular velocity of the slope under different rainfall intensities. The main conclusions are as follows:

(1) When the rainfall intensity is small, the deformation is obvious in the interior and toe of the slope and the accumulated deformation cannot develop into a landslide. The change rate of acceleration for the slope gradually decreases with time, i.e., only the primary creep can be found under this condition.

(2) With the increase of rainfall intensity, a landslide occurs. MEMS sensors can capture the creep deformation before and after the landslide. The change rate of acceleration for the slope covers the primary, secondary, and tertiary creep properties. That is, the obvious decrease in the change rate of acceleration is observed first, then becomes stable for a short time, and finally increases again indicating the landslide emergence. Under heavy rainfall, two or more landslides can occur. The change rate of the acceleration for the slope also goes through two or more cycles of variations.

(3) The greater the rainfall intensity, the shorter the time required for the creep and landslide, the more the sliding time, and the greater is the damage to the slope. There are two limited rainfall intensities, \( R_0 \) and \( R_1 \). When the rainfall intensity is less than \( R_0 \), no landslide can occur; when the rainfall intensity is greater than \( R_0 \) and less than \( R_1 \), only one landslide occurs. When the rainfall intensity is greater than \( R_1 \), two or more landslides can happen. MEMS sensor can capture the creep process before the occurrence of landslide and the movement characteristics of the landslide, which in turn can play an important role in the damage prevention for the slope.

6. References

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