Promoting effect of vegetation on the initiation of landslides induced by typhoon rainstorms

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Abstract. Vegetation is widely used to prevent landslides worldwide. However, rainstorm-induced landslides frequently occur on vegetation-covered slopes during the typhoon season in the southeastern coast of China. The results of a wind tunnel test reveal the effect of typhoon-induced loads on a slope through vegetation. Under a wind speed of 17 m/s, the wind load can increase the sliding force by over 10%. Strong typhoon-induced loads cause the vegetation to exert a strong torque on the soil via roots, resulting in crack development. These cracks provide paths for rainwater infiltration and increase the soil permeability coefficient by over 10-fold when the typhoon passes. Therefore, special attention should be paid to the potential impacts of vegetation, especially large trees, on slope stability.

1. Introduction
Extreme typhoons and rainstorms have greatly increased the occurrence of landslides worldwide[1-3]. Vegetation is generally believed to play a positive role in preventing landslides as the latter are more developed in slopes with less vegetation coverage. Vegetation engineering is also considered an important project that could comprehensively control landslide disasters. In 2002, a program aiming to return cultivated land to forest and grass was implemented in China. Here, mountains were closed and grazing was forbidden in many areas along the southeastern coast of the country. Since the implementation of this project, the ecological environment has significantly improved, and the vegetation coverage has increased. However, Wang Z[4] statistically analyzed landslides during the typhoon season in the Wenzhou area and found that landslides are more likely to develop in slopes with high vegetation coverage than in bare areas. Faruk O[5] investigated landslides that occurred in NW Turkey and found that vegetation roots could hardly reach the sliding surface. Thus, vegetation may be inferred to increase the weight of the slope, which is conducive to the occurrence of landslides. The root–soil gap of trees and the macropores formed after root rot accelerate rainfall infiltration and negatively contribute to slope stability[6-9]. Furthermore, during the typhoon season, the wind load transmitted to the slope through trees will also cause slope cracking, increase the infiltration rate of the soil layer, and adversely impact landslide stability[10].
Landslide research has yet to evaluate the influence of arbor on landslide development under typhoon wind loads and study the response mechanisms of landslides to arbor, typhoons, and rainfall extensively. These topics are among the scientific challenges in the study of geological disaster mechanisms in the southeastern coastal areas of China. The present study reveals the promoting effect of vegetation on typhoon-induced landslides via in-situ rainfall experiments and a wind tunnel test.

2. Landslides induced by typhoon and rainstorm in the southeastern coastal area of China

Investigations of landslides in the Feiyun River basin along the southeastern coast of China reveal that the landslides induced by typhoon are mainly soil landslides with a small volume (~1000 m$^3$). Typhoon-induced landslides consistently demonstrate obvious binary structures involving the lower part of the bedrock and the upper part of the loose overburden. The thickness of the loose overburden is generally less than 8 m; indeed, most overburden layers are less than 5 m in thickness. The majority of the sliding mass is composed of Quaternary eluvium (or completely weathered bedrock) formed by the in-situ weathering of bedrock, which is mainly composed of clay, sandy clay, silt, sandy loam, and gravel sand. The vegetation covering typhoon-induced landslides varies and often includes two or more types of bamboo, shrubs, arbor, grasses, fruit trees, and crops. In terms of vegetation category, the slope vegetation can be roughly divided into four types, namely, arbor, shrub, bamboo, and herb. The major vegetation types on the typhoon-induced landslides that occurred in the Feiyun River basin include arbor and bamboo (Fig. 1).

![Vegetation types of landslides](image)

**Figure 1.** Vegetation types of landslides

3. Wind tunnel test

The wind tunnel test was performed in the wind tunnel laboratory of Central South University. The tunnel was made of steel with two test sections (Fig. 2). The low-speed test section was 12 m wide, 3.5 m high, and 18 m long, with a wind speed range of 0–20 m/s and turbulence of <1%. The high-speed test section was 3 m wide, 3 m high, and 15 m long, with a wind speed range of 0–94 m/s and turbulence of <0.5%. The wind tunnel laboratory was equipped with a high-frequency electronic pressure scanning valve, micro pressure sensors, dynamic data acquisition device, and an analytical system.
Figure 2. Schematic diagram of the wind tunnel laboratory of Central South University

3.1 Similarity criteria
The similarity ratio and model parameters were determined according to the experimental equipment setup and the scale, material structure, and meteorological conditions of landslides induced by typhoons and rainstorms described above. The design ratio of the model was 1:16. The specific parameters of the model are detailed in Tables 1 and 2.

Table 1. Geometric parameters of the landslide model

| Model parameter          | Length (m) | Width (m) | Soil depth (m) | Vegetation height (m) | Vegetation root depth (m) |
|--------------------------|------------|-----------|----------------|-----------------------|--------------------------|
| Geometrical ratio        | 16         | 16        | 16             | 16                    | 16                       |
| Size                     | 1.56       | 1.00      | 0.25           | 0.60                  | 0.15                     |

Table 2. Physical and mechanical parameters of residual soil in the landslide model

| Physical and mechanical parameters | Density (g/cm³) | Cohesion (kPa) | Internal friction angle (°) | Water content (%) |
|------------------------------------|-----------------|----------------|-----------------------------|-------------------|
| Similarity ratio parameters        | 1               | 16             | 1                           | 1                 |
| Parameters                         | 1.8             | 2              | 28                          | 15%               |

3.2 Model materials
3.2.1 Slope model. Our experiment focused on the effect of vegetation and the residual soil layer on landslides. The bedrock impact was neglected in the experiment, and the building board was directly used to simulate the interface between the bedrock and residual soil layer. The residual soil in the slope model was composed of a mixture of river sand, expansive soil, clay, and barite powder. Several groups of geotechnical tests were conducted in the laboratory until the physical and mechanical parameters of the material met the similarity ratio specified in Table 2. Finally, the mass ratio of river sand, expansive soil, clay, and barite powder was determined to be 39:10:39:12. The physical and mechanical parameters of the model slope material are shown in Table 3.

Table 3. Physical and mechanical parameters of the model slope material

| Density (g/cm³) | Water content (%) | Cohesion (kPa) | Internal friction angle (°) | Hydraulic conductivity (m/s) |
|-----------------|-------------------|----------------|-----------------------------|-------------------------------|
3.2.2 Vegetation model. A large number of studies have shown that arbor exerts a great impact on wind force and is highly unfavorable to landslide stability. Thus, we selected arbor as the model vegetation in the present experiment. Model trees that met the required height and root depth provided in Table 1 were selected (Fig. 3). We arranged 12 model trees on the slope model by establishing four rows with three trees in each row. The distance between tree rows was 0.3m, and the spacing between tree columns was 0.4m.

![Vegetation model](image)

**Figure 3.** Vegetation model

3.3 Model construction
The model slope was constructed from a box with a steel frame; the side walls were made of Perspex plates, and the bottom surface was made of building wood. River sand, quartz, clay, barite powder, and water were placed in the box and mixed well according to the material ratio and moisture content specified in Section 3.2.1. The model box was then filled with the mixed slope material, which was shaped into a slope (Fig. 4).

![Model construction](image)

**Figure 4.** Construction of the slope model

The roots of the vegetation were first placed in the model area, and then covered with soil. The model slope was completely filled and compacted from bottom to top. A total of 12 trees were established in the model; these trees were numbered 1~12 from the top to the foot of the slope.
Particulate matter was not allowed in the wind tunnel laboratory used in this study. Thus, we covered the surface of the landslide model with plastic film prior to the experiment to prevent particle generation due to excessive wind speed and vegetation damage. The final slope model is shown in Fig. 5.

3.4 Test conditions
Four scenarios with different wind forces were selected in this experiment to simulate a tropical storm (8–9 m/s), typhoon (12–13 m/s), super typhoon (16 m/s), and extreme typhoon (>16 m/s); the corresponding experimental wind speeds were set to 8.3, 10.3, 13.4, and 17 m/s, respectively. The experimental duration of each working condition was 1 h. After the experiment, the soil was tamped once more, and the vegetation on the slope was restored to its original state. The details of the four typhoon conditions are shown in Table 4.

| Condition | Typhoon level (m/s) | Actual wind speed (m/s) | Test wind velocity (m/s) | Time (h) |
|-----------|---------------------|-------------------------|--------------------------|----------|
| 1         | 8–9                 | 33                      | 8.3                      | 1        |
| 2         | 12–13               | 41                      | 10.3                     | 1        |
| 3         | 16                  | 53                      | 13.4                     | 1        |
| 4         | Extreme             | 65                      | 17                       | 1        |

4. Results and discussion

4.1 Structural damage of the slope
The dumping angle of the vegetation was measured after the experiment (Table 5). Statistical results revealed that a total of seven trees were dumped on the slope. All of the trees in the first two rows (Nos. 7–12) and one tree in the last row (No. 3) collapsed. The toppling angle of the first row of trees reached 10°, and the angle of the second row of trees was approximately 5°. The wind pressure on the crown of tree No. 3 in the last row was the highest, and the toppling angle of the tree was 8°.

Under a wind speed of 17 m/s, the slope surface near the root systems of tree Nos. 10 and 11 in the first row heaved. The root–soil structures of these two trees were damaged, and the heave height was approximately 2 cm.

| Condition | Typhoon level (m/s) | Actual wind speed (m/s) | Test wind velocity (m/s) | Time (h) |
|-----------|---------------------|-------------------------|--------------------------|----------|
| 1         | 8–9                 | 33                      | 8.3                      | 1        |
| 2         | 12–13               | 41                      | 10.3                     | 1        |
| 3         | 16                  | 53                      | 13.4                     | 1        |
| 4         | Extreme             | 65                      | 17                       | 1        |
| Tree No. | Dumping angle |
|---------|---------------|
| 3       | 8°            |
| 7       | 6°            |
| 8       | 5°            |
| 9       | 4°            |
| 10      | 10°           |
| 11      | 8°            |
| 12      | 12°           |

Under a wind speed of 17 m/s, cracks appeared near the roots of tree Nos.10~12 in the first row and tree No.3 in the last row of the model slope. The cracks were distributed in front of the trees and radiated around the tree roots; these cracks measured 5–12 cm in length and 2–5 mm width (Fig.6).

**Figure 6.** Crack distribution around tree roots

The soil around the roots of vegetation in the front and last rows was likely to be destroyed because the front row of vegetation is directly affected by the wind and the vegetation at the top of the slope experiences the greatest wind load.

### 4.2 Variation in sliding force under different wind speeds

When the wind speed was 13.4 m/s, the safety factor of the model slope began to decrease to <1. When the wind speed was increased to 17 m/s, the safety factor of the model slope decreased to 0.9, and the model slope demonstrated instability. Moreover, when the wind speed reached 17 m/s, the residual thrust of the slope increased to −44, −106, and −22 N, respectively (Fig.7).

**Figure 7.** Variation curve of the residual sliding force of the slope

**Figure 8.** Safety factors of different wind speeds
4.3 Variation in the permeability coefficient of the slope material

At the end of each experiment, undisturbed soil samples were collected from the top of the slope into iron cylinders. The cylinders had a diameter of 15cm and height of 20cm, and samples were obtained at a depth of 15cm (Fig. 9).

![Figure 9. Collection of undisturbed soil samples into iron cylinders](image)

Under wind speeds above 17 m/s, the vegetation on the slope clearly inclined and generated a drag force, resulting in the formation of a large number of cracks in the rock and soil mass. The permeability of the soil in this case sharply increased to over 10-fold that of the original slope, causing significant impacts to slope stability.

![Figure 10. Variations in permeability coefficient under different working conditions](image)

An in-situ rainfall experiment was carried out to verify the effect of preferential flow on slope stability.

When all of the cracks and pores on the slope are filled, the infiltration intensity of the slope is highest when the soil is dry. During rainfall, the water content of the soil gradually increases, and the infiltration capacity of the slope gradually decreases to approximately $1 \times 10^{-4}$ cm/s.
The moisture content of soil at a depth of 125 cm below the ground surface was greatly affected by rainfall and varied periodically with the rainfall intensity. By contrast, the moisture content of soil at depths of 200 and 300 cm below the ground surface was only slightly affected by rainfall.

The infiltration capacity of the slope increased rapidly without landfill measures, and the cracks generated on the slope created paths favoring water infiltration. The infiltration intensity of the whole slope increased to approximately three times that of the original slope.
runoff, and the water content in fissure-affected areas decreased. In summary, the water content around cracks and the displacement of the slope dramatically changed during rainfall.

5. Conclusions
In this study, we performed an in-situ rainfall experiment and wind tunnel test and discussed the results. The main conclusions can be drawn as follows:
1) The typhoon-induced load exerted on a slope through vegetation is non-negligible. Under a wind speed of 17m/s, the wind load can increase the sliding force by over 10%.
2) Vegetation exerts a strong torque on the soil via roots under the influence of a severe typhoon-induced load, resulting in crack development.
3) Typhoon and vegetation can increase the intensity of rainfall infiltration. Thus, special attention should be paid to the potential effects of vegetation, especially tall trees, during typhoons.

6. References
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