

Article

Experimental Study on the Bearing Behavior and Failure Model of Digging Hold Foundation in Rock Ground

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Abstract: The physical model test is an effective method to study the bearing behavior of digging hold foundations due to its low cost and clear boundary conditions. Here, similar materials of rocks were configured and employed to study the bearing capacity and failure model of digging hold foundations in rock ground. Firstly, sixteen groups of material proportion schemes were employed to make similar materials of rocks, and the effects of four mix parameters were analyzed. Then, similar materials of rocks were employed to perform the uplift tests of digging hold foundations. The results show that the mass ratio of fine particles and aggregate has the greatest influence on the density and internal friction angle, while the cement moisture content has the greatest influence on the cohesion and compressive strength of similar materials of rocks. During the pull-out process of the digging hold foundation, the radial cracks radiate outward from the circumferential cracks, which is different from those in the field test because the ground is small and uniform without fissures inside. The foundation drives the surrounding similar materials to be pulled up as a whole with a certain failure angle, which increases from 35.7° to 42.5° as the internal friction angle decreases from 56° to 41°. In addition, the ratio between the equivalent shear strength in Chinese Code and uniaxial compressive strength falls in the range of 0.027–0.05.



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Keywords: rock similar materials; orthogonal design; digging hold foundation; uplift test

1. Introduction

With the rapid development of China's infrastructure, more and more transmission lines are being built in mountainous and high mountain areas, where the tower foundation plays an important role in the construction of transmission lines due to limited construction space and large-scale construction equipment, such as the anchor foundation [1], conical shell foundations [2]. The digging hold foundations are quite popular for special geological conditions and harsh construction environments due to their high bearing capacity and easy construction, which has been widely applied in mountainous and high mountain areas. It is worth mentioning that the tower foundation mainly bears the uplift force due to wind, wire gravity, etc. Thus previous researches employed high-cost field tests to study the uplift-bearing capacity of the digging hold foundations in sands [3–5], clays [6–10], and rocks [11–15]. The field experimental data have been applied to engineering practice, and great practical effects have been achieved. Unfortunately, the field test is limited due to certain deficiencies, such as the extremely high cost, complex geological conditions, and uncertain boundary conditions. Moreover, it is impossible to detect the ground deformation and failure mechanism in the field ground, especially in the rock ground, which plays an important role in determining the uplift bearing capacity and developing theoretical methods.

In contrast, the physical model test seems to be an effective method to study the bearing behavior and failure models of new foundation types because of its advantages in low cost,

great repeatability, controllable geological conditions, and boundary conditions, as well as the ability to detect the ground deformation and failure mechanism in the ground, which has been widely employed in geotechnical engineering [16,17]. For the physical model test with rock ground, the preparation and selection of rock-similar materials play the most important role in obtaining reasonable experimental data. Great efforts have been made on similar materials of rocks with cheap raw materials [18–20]. For example, the MIB material similar to that of Han et al. [21] has high unit weight, low elastic modulus, and low strength characteristics. The IBSCM similar material by Wang et al. [22] can simulate most rocks with advantages in high cost-effectiveness and stable performance. Ning et al. [23] prepare similar materials with different lithologies by adding red clay. In addition, rock-similar materials have been widely used in physical model tests of rock engineering in China, such as the three-dimensional geo-mechanical model test for underground caverns [24] and the friction physical model test [23]. However, little attention was paid to the uplift bearing characteristics and failure modes of digging hold foundations in rock ground using similar materials to help design the tower foundation, which constitutes the strong motivation of the paper.

This paper employed barite powder, iron powder, and quartz sand as aggregate, water and gypsum as cementing agents, and red clay as plasticizers to prepare the rock-similar materials. A group of mixed proportion schemes of similar rock materials with the orthogonal test method was designed, where the effects of the mix parameters on the physical and mechanical properties of similar materials were investigated. Then, three similar representative materials were selected to carry out pull-out tests of digging hold foundations on rock ground, where the bearing capacity and failure modes of the digging hold foundations were analyzed in detail. The research results can enrich the repertoire of rock-similar materials and can help design the digging hold foundations in mountainous and high mountain areas.

2. Rock Similar Material

2.1. Orthogonal Design Method of Rock Similar Material

Here, the barite powder, iron powder, and quartz sand are used as aggregates, the water and gypsum are used as cementing agents, and the clay is used as a plasticizer [23]. In addition, gypsum (i.e., 3% in mass) is employed to prevent similar material from welding too fast. Note that the barite powder is 12 μm in diameter, and the iron powder is 150 μm in diameter. The grain size of quartz sand ranges from 200–420 μm , and the red clay is 420 μm in diameter.

The orthogonal design method is a popular design method to study the effect of multiple factors and levels. Some representative factors from the overall test, which feature uniform dispersion, uniformity, and comparability, are carefully selected according to the orthogonality design method. Note that the physical and mechanical behavior of rock-similar materials mainly depend on their mass compositions. Thus, the mass ratio of cement to aggregate (factor A, F_A), cement moisture content (factor B, F_B), mass ratio of fine particle to aggregate (factor C, F_C), and mass ratio of iron powder to fine particle (factor D, F_D) are chosen as the main factors here, which can clearly describe the mass compositions of rock-similar material, as shown in following equation:

$$\begin{aligned} F_A &= (m_w + m_g) / (m_b + m_i + m_q) \\ F_B &= m_w / (m_w + m_g) \\ F_C &= (m_b + m_i) / (m_b + m_i + m_q) \\ F_D &= m_i / (m_b + m_i) \end{aligned} \quad (1)$$

where m_w , m_g , m_b , m_i , m_q are the weights of water, gypsum, barite powder, iron powder, and quartz sand, respectively. Ning et al. [23] showed that red clay has little effect on the mechanical behaviors of rock-similar materials, and the proportion of clay in the aggregate is chosen to be 10%. Equation (1) shows that the four factors can quantitatively describe

the mass compositions of rock-similar material. The values of the four factors are selected, as shown in Table 1, using the orthogonal design method.

Table 1. Test schemes of similar materials.

Group	F_A	F_B	F_C	F_D
	Cement/Aggregate	Cement water content	(Iron powder + barite powder)/aggregate	Iron powder/(iron powder + barite powder)
1	0.24	0.41	0.60	0.40
2	0.24	0.44	0.70	0.10
3	0.24	0.47	0.80	0.20
4	0.24	0.50	0.90	0.30
5	0.28	0.41	0.70	0.40
6	0.28	0.44	0.80	0.30
7	0.28	0.47	0.90	0.20
8	0.28	0.50	0.60	0.10
9	0.32	0.41	0.80	0.10
10	0.32	0.44	0.90	0.40
11	0.32	0.47	0.60	0.30
12	0.32	0.50	0.70	0.20
13	0.36	0.41	0.90	0.10
14	0.36	0.44	0.60	0.20
15	0.36	0.47	0.70	0.30
16	0.36	0.50	0.80	0.40

Note: The gypsum powder with a mass of 0.3% is added during sample preparation.

2.2. Sample Production

Similar materials can be prepared by the following steps: (1) Mix and stir the raw power materials according to the orthogonal design scheme in Table 1 in the mixer; (2) Add pure water and continue to stir; (3) Pour the uniform mixture into the mold and vibrate the mixture to dense; (4) Add a cover and 50 kg weight on the sample to allow the sample hardening for 24 h; (5) Remove the mold and store the samples in curing dish for 7 days to allow the sample being well cured. Note that for each group, nine samples were prepared for the axial and triaxial compression tests. Thus, a total of 144 samples are prepared, as shown in Figure 1.



Figure 1. Samples of the rock-similar material.

2.3. Material Characteristics

Then, the density, cohesion, internal friction angle, compressive strength, and elastic modulus of each group of samples are obtained by performing uniaxial and triaxial compressive tests [25]. Typical curves are provided in Figure 2. The compressive strength and elastic modulus can be calculated from Figure 2a, while the cohesion and internal friction angle can be calculated using the Mohr–Coulomb theory from Figure 2b. The calculated data are provided in Table 2. It can be found that the density falls in 2480–2910 kg/m³, the cohesion falls in 0.08–7.95 MPa, the internal friction angle falls in 38–62°, the compressive strength falls in 2.1–11.6 MPa, and the elastic modulus falls in 139–2548.5 MPa. Note that the internal friction angle is relatively large because the rocks usually exhibit an internal

friction angle of 30–60° [26]. The physical and mechanical parameters of similar rock materials are distributed in a wide range, which implies that similar materials can meet the requirements of different types of rocks.

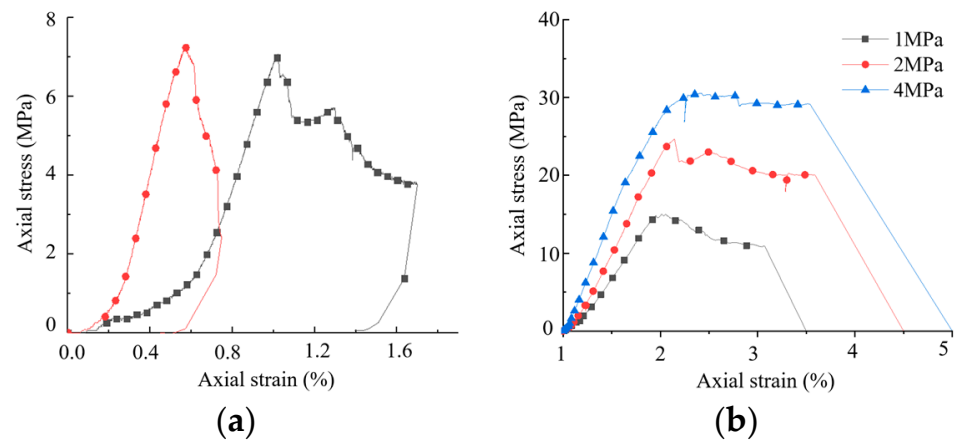


Figure 2. Typical curves of the uniaxial and triaxial compressive tests. (a) Uniaxial compressive test. (b) Triaxial compressive test.

Table 2. Physical and mechanical parameters of similar materials.

Group	Density (g/cm ³)	Cohesion (MPa)	Internal Friction Angle (°)	Compressive Strength (MPa)	Elastic Modulus (MPa)
1	2.52	7.95	38	11.6	2548.5
2	2.56	3.12	44	5.22	1950.5
3	2.8	2.78	56	2.1	438
4	2.91	0.3	60	2.41	301
5	2.73	4.26	55	11.49	1974
6	2.76	4.93	51	9.3	1756
7	2.82	0.08	62	10.6	1724
8	2.5	2.43	51	2.19	366
9	2.64	5.07	50	9.53	1190
10	2.88	2.83	56	2.98	577.5
11	2.54	1.14	59	2.42	247
12	2.48	2.22	51	7.2	1627
13	2.66	4.05	50	7.85	804
14	2.49	5.26	41	2.8	139
15	2.6	2.17	49	7.21	308
16	2.57	0.54	56	1.81	241.5

2.4. Sensitivity Analysis

2.4.1. Density

Figure 3 provides the average density of the samples. It can be observed that the density of the sample increases with the decreasing F_A and increasing F_B , F_C , and F_D . Note that the density of similar materials depends on the proportion of raw materials and the density of the sample after full vibration. For example, the grain size of iron powder in fine particles is similar to that of barite powder, but the density of iron powder is higher than that of barite powder. Thus, the density increases with the proportion of iron powder in fine particles F_D . F_A , F_B , and F_C will affect the final relative density of similar materials. For example, the more the fine particle content (F_C), the higher the compactness and density of the sample because the fine particle can fill the void between coarse particles. In addition, there exists an optimal moisture content, making the sample reach the maximum relative density for similar material, which is similar (i.e., nearly 47% here) to the soil [27].

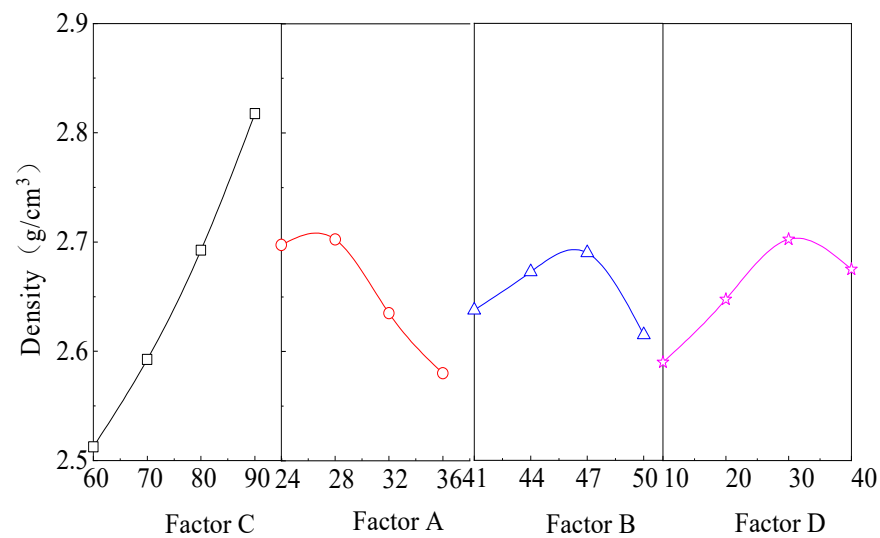


Figure 3. Influence of various factors on material density.

2.4.2. Cohesion

Figure 4 provides the effects of the four factors on the cohesion of similar materials. It can be observed that the cohesion mainly depends on the cement moisture content F_B and decreases with increasing F_B , F_C , and F_D . It can be easily understood that the higher the cement moisture content F_B , the lower the strength of the cement, which significantly affects the cohesion of the rock-similar materials. In addition, the cohesion decreases with the increasing proportion of fine particles in the aggregate. This is proper because the fine particles could be mixed with the gypsum powder, reducing the cement's strength.

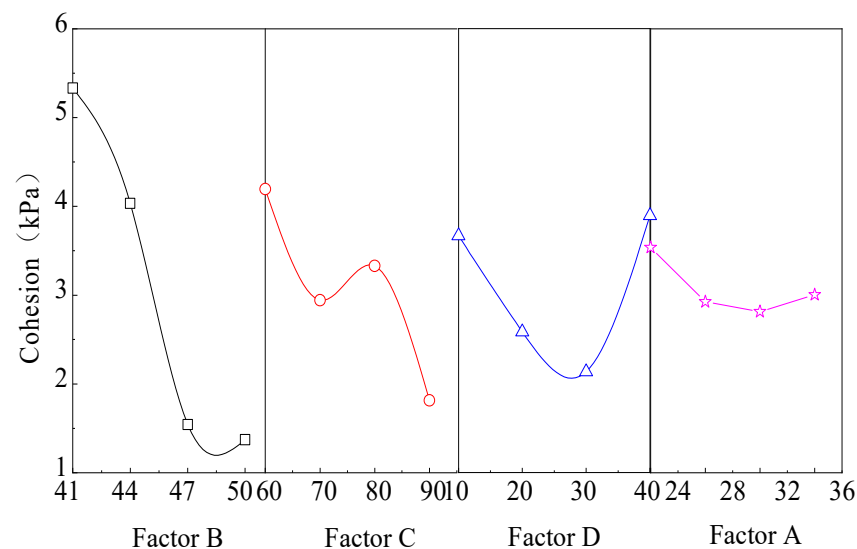


Figure 4. Influence of various factors on the cohesion.

2.4.3. Internal Friction Angle

Figure 5 provides the internal friction angles of similar materials. Figure 5 shows that the internal friction angle increases with the increasing cement moisture content F_B and the mass ratio of fine particles to aggregate F_C . This is because the internal friction angle mainly depends on the sample's relative density. As F_B and F_C increase, the sample becomes denser, and the internal friction angle becomes larger. Therefore, the four factors show similar effects on the internal friction angle with those on density in Figure 3.

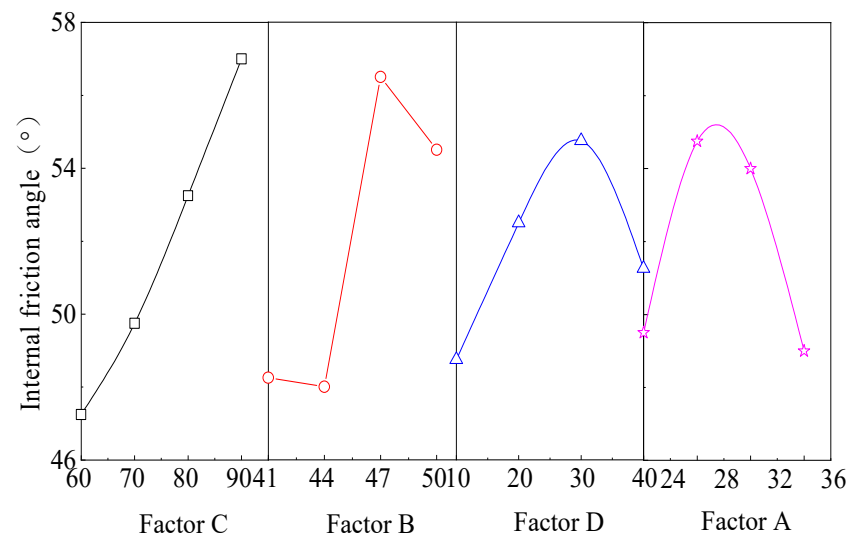


Figure 5. Influence law of various factors on internal friction angle.

2.4.4. Compressive Strength

Figure 6 provides the compressive strength of similar materials. Compared with the cohesion in Figure 4, it can be found that the effects of the four factors on the compressive strength are similar to those on cohesion, i.e., the compressive strength mainly depends on the cement strength. In addition, the compressive strength exhibits a decreasing trend with increasing F_B , F_C , and F_D .

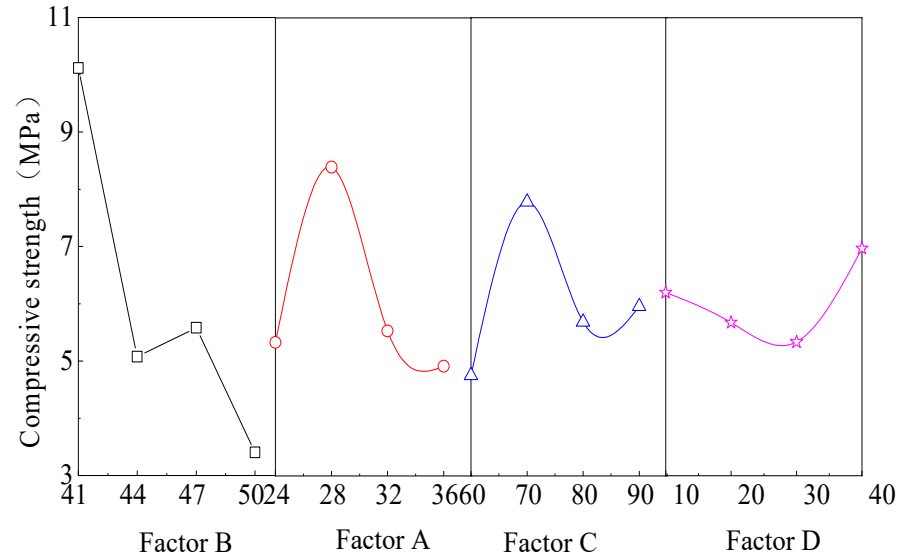


Figure 6. Influence of various factors on the compressive strength.

2.4.5. Elastic Modulus

Figure 7 provides the elastic modulus of similar materials. It shows that the elastic modulus mainly depends on the cement/aggregate mass ratio F_A and the cement moisture content F_B . The elastic modulus decreases with increasing F_A and F_B . This is because the cement exhibits a lower elastic modulus than the aggregates such as quartz sand, so the larger the proportion of cement/aggregate F_A and cement moisture content F_B , the lower the elastic modulus. In addition, when the cement moisture content F_B increases, the cement strength weakens, which results in cement breakages appearing in the sample and a large strain measured. As a result, the elastic modulus decreases with the increasing F_B .

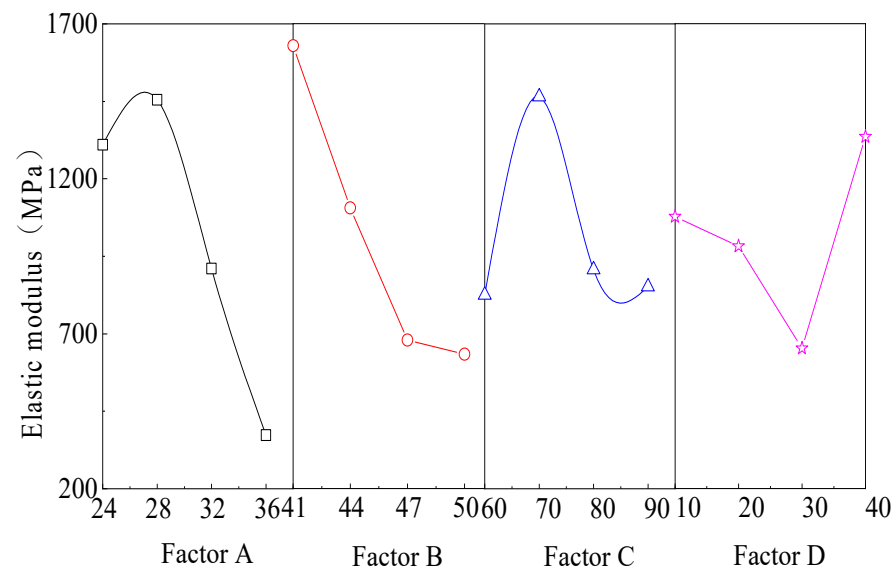


Figure 7. Influence of various factors on elastic modulus.

2.4.6. Range Analysis

The range analysis is widely used in sensitivity analysis of orthogonal proportions for rock-similar materials, where the difference between the maximum and minimum values can be regarded as the range of the corresponding physical and mechanical parameters for this factor [28]. The larger the range, the more significant the factor affects. Table 3 summarizes the range analysis of physical and mechanical parameters of similar materials under various factors. It can be seen that the density of similar materials mainly depends on F_C , cohesion and compressive strength depend on F_B , the internal friction angle mainly depends on F_C , and the elastic modulus depends on F_A and F_B .

Table 3. Range analysis of each factor.

Parameter	Factor A	Factor B	Factor C	Factor D
Density	0.1225	0.075	0.305	0.1125
Cohesion	0.7225	3.96	2.38	1.76
Internal friction angle	5.75	8.5	9.75	6
Compressive strength	3.4775	6.715	3.0275	1.635
Elastic modulus	1081.875	995.25	639.75	682.375

3. Physical Model Test

3.1. Similarity Theory

The physical model test is designed based on the similarity relationship between the research object and the model test to ensure that the physical phenomena reflected in the model test are similar to the prototype [28,29]. In the pull-out test of the digging hold foundation, the geometric similarity ratio C_L can be taken as n , and the bulk density similarity ratio can be regarded as 1. Based on the dimensional analysis, the similarity of the parameters in the prototype test and the model test can be derived, as shown in Table 4.

Table 4. Relationship between similarity scales.

Parameters	Dimension	Similarity Scale	Similarity Ratio
Size L	L	C_L	n
Density γ	FL^{-3}	C_γ	1
Cohesion c	FL^{-2}	C_c	n
Internal friction angle φ	1	C_φ	1

Table 4. Cont.

Parameters	Dimension	Similarity Scale	Similarity Ratio
Elastic modulus E	FL^{-2}	C_E	n
Compressive strength σ_c	FL^{-2}	C_σ	n
Strain ϵ	1	C_ϵ	1
Displacement d	L	C_d	n
Force F	F	C_F	n^3

3.2. Test Scheme

Figure 8 presents the test apparatus employed in this paper. First, a concrete digging hold foundation using the basic mold (Figure 8a) was constructed using C60 concrete to prevent the foundation from breaking in the uplift test. The top and bottom diameters of the foundation are 141 mm and 235 mm, and the height is 353 mm, corresponding to a prototype foundation of $1.2 \text{ m} \times 2 \text{ m} \times 3 \text{ m}$ in size, taking the geometric similarity coefficient $n = 8.5$. The experimental data can be referred to in the field conditions in Table 4. Then, the foundation is suspended in the model box (Figure 8b), and rock-similar materials are evenly mixed and filled into the model box. The size of the model box is $1 \text{ m} \times 1 \text{ m} \times 1 \text{ m}$ in length, width, and height (Figure 8c). After the filling, the rock-similar material was cured for one week before loading. The loading device consists of two jacks, a free upper crossbeam, and a fixed lower crossbeam (Figure 8d). The digging hold foundation was fixed on the free upper crossbeam through the reserved hole on the fixed lower crossbeam, and the two jacks were placed between the two crossbeams. When the jacks are loaded, the pull-out force will be transferred to the digging hold foundation, as shown in Figure 8e. During the test, a constant uplift load is applied to the upper crossbeam by two jacks on both sides, where the force sensors and dial indicators are used to record the uplift load and displacement. Note that three representative rock-similar materials (Groups 10, 12, and 14) are selected for the uplifting tests, whose internal friction angle and compressive strength parameters gradually change to study the effect of ground strength on the bearing behavior and failure models.

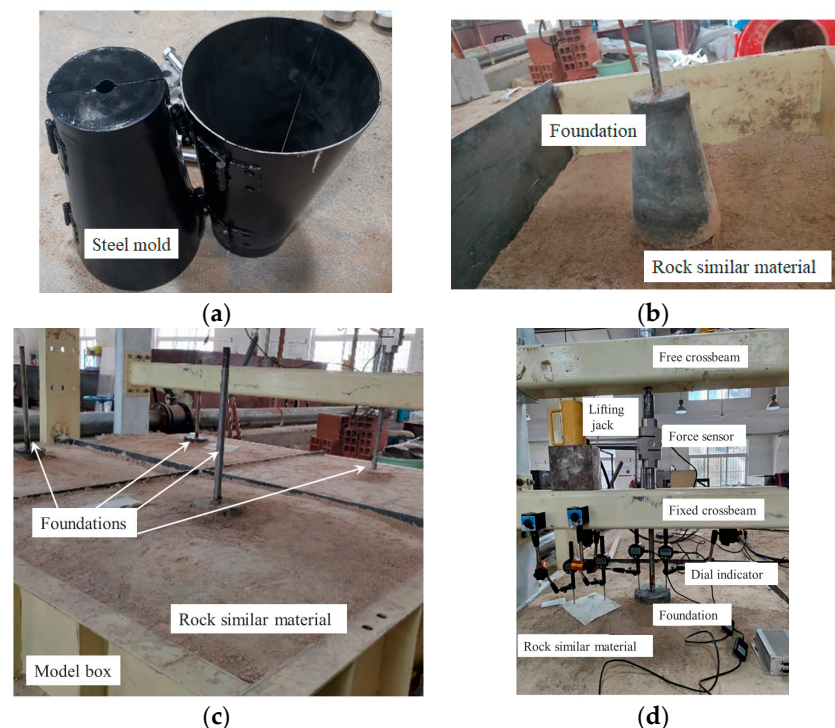


Figure 8. Cont.

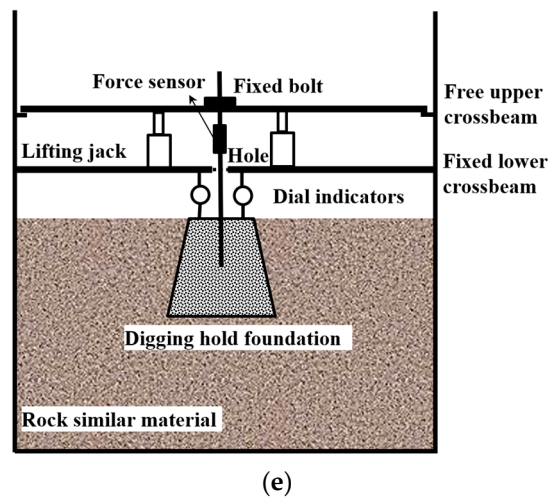


Figure 8. Test apparatus. (a) Mold; (b) ground filling; (c) soil bin; (d) loading device and measuring device; (e) loading diagram.

4. Test Results

4.1. p - s Curve

Figure 9 shows the load–displacement curve of the digging hold foundations on three different grounds. It can be observed that the load–displacement curves evolve in a similar trend under different grounds, which is also consistent with the p - s curve in field tests [11]. At the beginning of uplifting, the displacement and load increase approximately linearly, where the ground exhibits elastic deformation. As the uplift load continues to increase, the displacement required for each level of load gradually increases, which results in the p - s curve showing a nonlinear increasing trend. Such observation implies that plastic deformation occurs in the ground. When the uplift load reaches the peak, the displacement continues to increase and cannot be stabilized, which implies that rock failure appears in the ground. The corresponding ultimate uplift loads when the ground failure appears are 22.56 kN, 30.02 kN, and 16.05 kN, respectively.

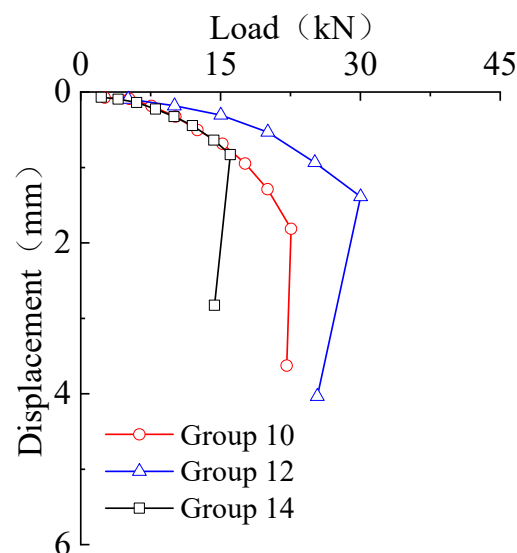


Figure 9. Load-settlement curve.

4.2. Ground Failure Model

Figure 10 shows the distribution of surface cracks at the end of the test under three different grounds. The cracks can be observed using white paint near the cracks. It can be found that surface cracks in field and model tests can be divided into radial cracks and

circumferential cracks. The circumferential cracks are the main cracks of ground failure. In field tests, radial cracks first appear around the foundation, gradually extending outward and finally forming a penetrating circumferential crack, causing the foundation to be pulled up. However, radial cracks diverge outward from the circumferential cracks in the model tests. This is because the ground in the field test is large and uneven, with fissures inside. The ground is first compressed and damaged, and then the entire foundation is pulled up. In the model tests, the ground size is small and uniform without fissures inside. When the foundation is pulled up, the foundation drives the surrounding similar materials to be pulled up as a whole, causing large deformation and cracks near the pull-out ground.

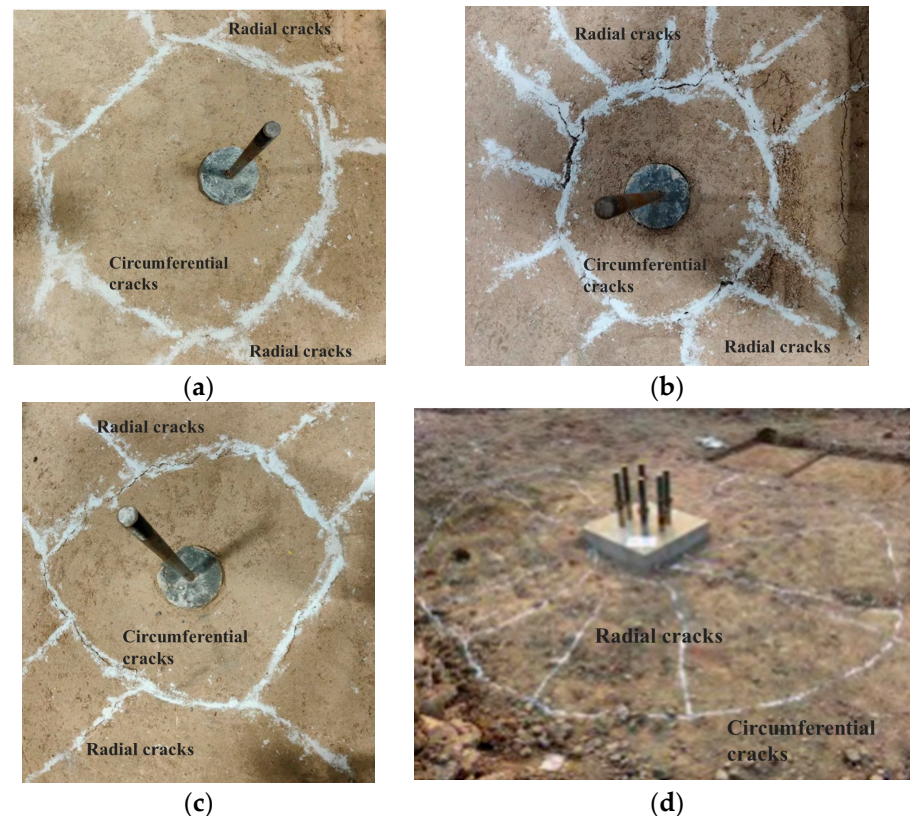


Figure 10. Ground failure model. (a) Group 10; (b) Group 12; (c) Group 14; (d) cracks in the field test [11].

4.3. Failure Surface

Figure 11 shows the cross-sectional and top views of the pull-out ground at the end of the test (e.g., Group 14). It can be observed that the pulled-out foundation is in the shape of a circular cone, and the failure surface presents a linear one, which extends towards the ground surface at a certain angle. Such observation is consistent with existing specifications' assumptions [30]. Note that the surface of the circular cone is elliptic, with a long diameter of 34.3 cm and a short diameter of 28.4 cm instead of a circle, as shown in Figure 11. Thus, the circumference of the circumferential crack is calculated for the equivalent diameter, which can be used to calculate the failure angle. The calculation results are shown in Table 5. It can be found that different grounds have different failure angles, which vary around 45° , which is the assumed one in the specification [30]. The relationship between the failure angle and the internal friction angle of similar materials is provided in Figure 12. It can be found that the failure angle decreases with the increasing internal friction angle of rock-similar materials. More physical model tests will be performed to quantitatively describe the relationship between the failure angle and internal friction of the ground in the future.

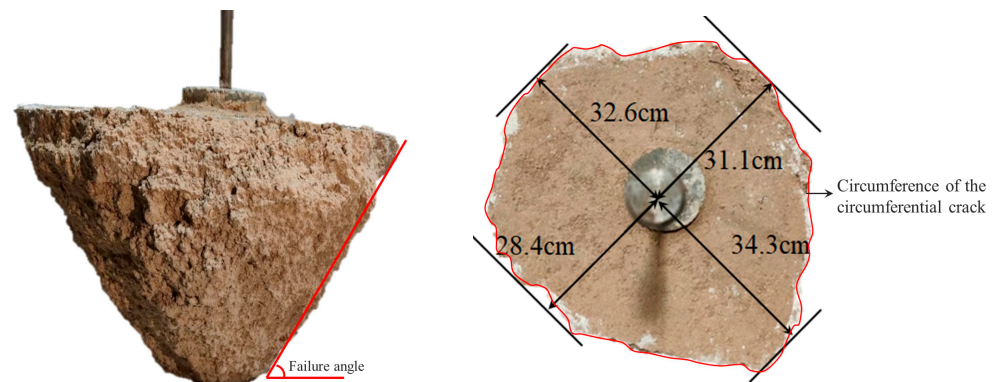


Figure 11. Typical failure surface.

Table 5. Information of circumferential crack perimeter.

Rock Similar Material	Group 10	Group 12	Group 14
Circumference of the circumferential crack (cm)	194	208	230
Equivalent diameter (cm)	61.78	66.24	73.25
Side area (cm ²)	14,140	15,890	18,900
Failure surface (°)	35.7	38.5	42.5

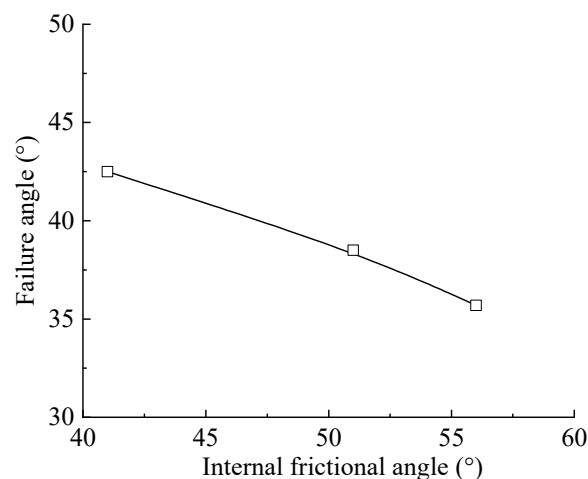


Figure 12. Relationship between the failure angle and internal friction angle.

4.4. Equivalent Shear Strength

According to the code for the design of the foundation of an overhead transmission line in China [30], the uplift load T_K can be calculated using the following equations:

$$T_K = \frac{\pi h \tau_s (D + h \tan \theta)}{K_1} + \frac{G_f}{K_2} \quad (2)$$

where K_1 and K_2 are the safety factors, D and h are the foundation bottom diameter and height, θ is the failure surface (i.e., 45° as the suggested value), and G_f is the self-weight of the foundation. Note that τ_s is the equivalent shear strength along the failure surface, as shown in Figure 11, which can only be determined empirically. Here, the τ_s can be calculated using Equation (1), as shown in Table 6, along with the uniaxial compressive strength of rock-similar materials. It shows that the ratio between the equivalent shear strength τ_s and uniaxial compressive strength falls in the range of 0.027–0.05 with an average value of 0.35.

Table 6. Equivalent shear strength.

Rock Similar Material	Group 10	Group 12	Group 14
Equivalent shear strength (MPa)	0.15	0.19	0.085
Uniaxial compressive strength (MPa)	2.98	7.2	2.8
Ratio	0.05	0.027	0.03
Average ratio		0.035	

5. Conclusions

This paper employed barite powder, iron powder, and quartz sand as aggregates, water and gypsum as cementing agents, and clay as a plasticizer to prepare similar materials, where the effects of four factors were analyzed, e.g., the mass ratio of cement to aggregate (factor A, F_A), cement moisture content (factor B, F_B), mass ratio of fine particle to aggregate (factor C, F_C), and mass ratio of iron powder to fine particle (factor D, F_D). Then, rock-similar materials were employed to study the uplift bearing behavior and failure models of digging hold foundations on rock ground. The main conclusions are as follows:

- (1) As for the rock-similar material, the density and internal friction angle mainly depend on F_C , the cohesion and compressive strength depend on F_B , and the elastic modulus mainly depends on F_A and F_B .
- (2) In the pull-out test, the foundation drives the surrounding similar materials to be pulled out as a whole, causing large deformation and cracks near the pull-out ground.
- (3) The failure surface evolves from the foundation bottom extending towards the surface along a certain angle, which increases from 35.7° to 42.5° as the internal friction angle decreases from 56° to 41° .
- (4) The ratio between the equivalent shear strength in Chinese Code and uniaxial compressive strength falls in the range of 0.027–0.05.

In the future, more experimental tests will be performed to further study the effect of foundation size on the bearing behavior and failure model and to better help design the digging hold foundation in mountain areas.

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Conflicts of Interest: Author Wenxiang Zhang was employed by the company Power China Fujian Electric Power Engineering Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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