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Original Paper

Review on the Principle and Key Techniques of Centrifugal Model Test

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Abstract

The centrifugal model test, as an efficient physical simulation technique, is widely utilized in the field of geotechnical engineering, particularly in the study of soil mechanical properties and the stability of geotechnical structures. By simulating the gravitational stress under real-world conditions through a centrifugal force field, this method provides accurate experimental data on the stress, deformation, and failure mechanisms of rock and soil masses. This paper systematically outlines the fundamental principles of centrifugal model testing, with a particular focus on the similarity principle and the analysis of test errors. In light of potential error sources, such as uneven distribution of centrifugal force, boundary effects, and the centrifuge start-braking process, corresponding optimization strategies are proposed. Through a comprehensive summary and forward-looking analysis of existing technologies, this paper offers both theoretical support and practical guidance for the further development and application of centrifugal model testing in the future.

Keywords

Centrifugal Model Test, Key Techniques, Principle, Review

1. Introduction

The concept of geotechnical centrifugal model testing was first proposed by French scientist E. Phillips in 1869 (Su, 2022). This method uses centrifuges to enhance the gravity field under high speed rotation, so that the reduced model is consistent with the prototype in terms of stress and strain characteristics (Ren, Li, Yang, et al., 2022). This kind of simulation can intuitively and accurately show the mechanical behavior of soil mass in practical engineering, so the centrifugal model is considered to be one of the most similar physical models. However, due to technical limitations, this innovation was not widely used in the early days. In the 1930s, some scholars in the United States and the Soviet Union began to apply small centrifuges to study geotechnical buildings, and gradually promoted the development of centrifugal simulation technology. By the 1980s, Western European countries had also established a number of geocentrifuge laboratories, and began to be widely used in the field of civil engineering.

In China, due to historical, economic, and other constraints, geotechnical centrifugal testing started relatively late. It was not until the implementation of the "Seventh Five-Year Plan" scientific and technological research initiative that centrifugal simulation technology began to advance rapidly. After decades of dedicated efforts, China's geocentrifuge technology and related achievements have gradually reached international advanced levels. Notably, upon the completion of the "Eighth Five-Year Plan" scientific and technological research initiative, the academic accomplishments achieved using the LXJ-4-450 large geocentrifuge, developed by the Nanjing Hydraulic Research Institute, reached the forefront of international research in this field. Today, China's centrifugal simulation equipment continues to evolve, with many universities and research institutions establishing large and medium-sized geocentrifuges. This progress has significantly propelled the vigorous development of centrifugal model testing in China.

With the continuous advancement of technology, the application scope of centrifugal model testing has gradually expanded. This is particularly evident in the field of reinforced soil structures, where centrifugal model tests are widely employed to study the stability and failure mechanisms of reinforced slopes, retaining walls, and other geotechnical structures (Yang, 2018). By simulating the stress field of the prototype, these tests can reveal the interaction between reinforcement materials and fillers, analyze the deformation characteristics and failure modes of reinforced structures, and validate the rationality of design theories and methods. In recent years, driven by ongoing innovations in centrifuge technology, China has achieved significant research outcomes in various fields, including water conservancy and hydropower, road and bridge engineering, environmental studies, rock and soil mechanics, and mining. These advancements have contributed to the rapid development of related areas in geotechnical engineering (Chen, Li, Li, et al., 2022). This paper systematically outlines the fundamental principles, theories, and potential sources of error in centrifugal model testing, aiming to provide a theoretical foundation for subsequent experimental studies.

2. Significance of Centrifugal Model Test

In recent years, geotechnical centrifugal model test, as a new physical simulation technology, has been widely used in the field of geotechnical engineering, and has shown its unique advantages in solving problems such as discontinuous media, nonlinear deformation and progressive failure in theory and practice (Wang, Wang, Qu, et al., 2025). By enhancing the effect of gravity field, the centrifugal model test makes the stress and strain conditions between the model and the prototype more close, so that the soil behavior and the mechanical characteristics of the soil structure can be reproduced more truly. The traditional prototype small scale model can only carry out qualitative research on the whole or part, if a quantitative test of the model is to be conducted, significant investment is required to ensure the experiment aligns more closely with the conditions of the actual prototype. In geotechnical engineering, the mechanical characteristics of soil are closely related to its stress state, and the dead weight of soil is usually its main stress source. Since the dead weight stress of the main load in prototype tests cannot be effectively simulated, such tests usually cannot truly reflect the interaction between prototype soil and structure. As a result, the practical value of the research results of the prototype test has been affected to some extent (Zhang, Zheng, Liu, et al., 2025). Compared with the traditional prototype small scale model test, centrifugal test can more accurately simulate the gravity effect, stress distribution and deformation characteristics of soil mass in practical engineering, and greatly improve the reliability and applicability of experimental results, which has important research significance and practical value for solving problems in engineering design.

The research significance of centrifugal model test technology is not only reflected in theoretical verification but also plays a crucial role in engineering practice. Before the construction of a project, centrifugal tests can evaluate the feasibility and accuracy of the design scheme. By precisely controlling experimental conditions, centrifugal model tests can obtain quantitative data, providing a more reliable basis for the project. This process is of great significance for predicting the deformation characteristics, stability, and safety of the project. Particularly during the design stage, it helps identify potential risks in advance, thereby avoiding unnecessary economic losses and engineering failures (Liu, Liu, & Zhang, 2024). On the other hand, centrifugal model tests allow for the comparison of different construction schemes to meet the economic and social benefits of the project. Designers can test various construction methods and select the most suitable one, ensuring safety, reliability, and quality while achieving the goals of shortening the construction period and reducing costs. In large-scale civil engineering projects, centrifugal simulation tests provide reliable technical support, minimizing risks and losses caused by improper design or construction errors in later stages. Therefore, as an essential engineering forecasting method, centrifugal model testing plays an irreplaceable role in practice.

The introduction of centrifugal model test technology makes the design and analysis of geostructures more accurate. In the past, the complex problems often encountered in geotechnical engineering, such as soil deformation induced by earthquake and stability analysis under complex geological environment, mainly rely on numerical simulation methods. However, although numerical simulation can provide valuable information for theoretical research, it provides more accurate physical experimental data due to the simplified pseudolinear calculation and the study of elastoplastic characteristics (Wu, Chen, Meng, et al., 2024). For example, when studying reinforced soil slope, retaining wall and foundation pit supporting structure, centrifugal model test can not only simulate the real interaction between soil and structure, but also reveal the potential mechanism of structural failure, which provides a scientific basis for design optimization in practical engineering.

Centrifugal model test, as an efficient and accurate geophysical simulation technique, has been widely used in geotechnical engineering. With the continuous development of technology, centrifugal test can not only provide more accurate experimental data, but also play an increasingly important role in the solution of various complex engineering problems. In order to make centrifugal model test scientific and feasible, it is necessary to deeply understand the basic theory and potential error source of centrifugal model test, and make a scientific and reasonable test design scheme on this basis.

3. Basic Principle and Similarity Principle of Centrifugal Model Test

3.1 Basic Principle

In geotechnical engineering, gravity is the core load carried by the structure, which directly determines the stress distribution and deformation characteristics of the structure. However, since the self-gravity of traditional prototype scale model is much lower than that of actual engineering structure, and geotechnical materials often have significant nonlinear mechanical properties, there are essential differences between the model and prototype in mechanical properties, and the test results are often difficult to be directly applied to engineering practice. To solve this problem, centrifugal model test technology provides an effective solution. This technology artificially raises the stress level of the model material through the high gravity field generated by the centrifuge, so as to simulate the state of self-weight stress under actual working conditions. Specifically, the centrifugal model test uses the centrifugal force field generated by high-speed rotation to enhance the volume force inside the scaled model, so that its stress field is consistent with the prototype structure. By scaling the model scale and simulating the gravity stress of geostructures with centrifugal force, the centrifugal model test can accurately restore the stress-strain relationship of the prototype, and then provide a reliable basis for analyzing the deformation characteristics and failure mechanism of the structure.

The basic principle of centrifugal model test is correct and scientific based on the following two key theories (Qu & Du, 2024), First, according to the modern theory of relativity, the physical effect of gravity on the object is equivalent to the inertial force, so the centrifugal inertia force received by the model in the centrifuge has the same mechanical effect on the physical effect as the earth's gravitational acceleration received by the structural prototype in the actual situation; Second, from the microscopic point of view of the material, the mechanical properties of the material are mainly determined by the electromagnetic force of the electron cloud outside the nucleus, and the influence of gravity or centrifugal force on the electromagnetic force of the material is negligible, so in the high-speed centrifugal field, the mechanical properties of the material in the centrifugal test model will basically not change due to the change of centrifugal acceleration.

Based on the above theory, the centrifugal model test under the centrifugal inertia force state will be highly similar to the prototype in the stress state, boundary conditions and self-weight effects, which include the effective stress σ', total stress σ and pore water pressure u at any point, namely:

$$\left.\begin{array}{l}\sigma_P = \sigma_M \\ \sigma_P^{'} = \sigma_M^{'} \\ u_P = u_M\end{array}\right\} \tag{1}$$

In formula (1),

M ~ The physical quantity of the model，P ~ The physical quantity of the prototype.

Self-weight stress:

$$\left.\begin{array}{l}\sigma_M = \gamma_M .h_M \\ \sigma_P = \gamma_P .h_P\end{array}\right\} \tag{2}$$

In formula (2),

γ_P ~ The bulk density of the prototype;γ_M ~ The bulk density of the model;
h_P ~ Prototype height;h_M ~ Height of model.

If the above equation (2) is substituted into equation (1), there is:

$$\gamma_M = \frac{h_P}{h_M}.\gamma_P \tag{3}$$

The geometric similarity ratio between the prototype and the model is $N = \dfrac{h_P}{h_M}$, the formula(3) is simpllied as:

$$\gamma_M = N.\gamma_P \tag{4}$$

According to the formula(4), if the size of the model in the centrifugal test is 1/N times that of the prototype, then the bulk density of the model should be made to reach N times that of the centrifugal test model, so that the centrifugal test model and the prototype can be equivalent in stress.

In the geotechnical centrifuge test, the bulk density of the model can be increased to approximate the gravity stress of the prototype by rotating the centrifuge at a high speed. If the same material as the prototype is used in the centrifugal test, then the density factor is not needed to be considered, and the following relationship can be obtained:

$$\left.\begin{array}{l}\gamma_M = \rho.a_M \\ \gamma_H = \rho.g\end{array}\right\} \tag{5}$$

In formula (5), g ~ Gravitational acceleration, a_M ~ Centrifugal acceleration.

If the equation (5) is substituted into equation (4), there is:

$$a_M = N.g \tag{6}$$

According to the above formula, when the prototype geometry is N times that of the centrifugal model, the centrifugal acceleration of Ng should be applied in the centrifugal test to achieve the equivalent of the prototype stress. At this time, the self-weight stress lost due to the size reduction of the model by

1/N can be compensated by the N times centrifugal inertia force applied by the centrifuge, so that the model and the prototype are completely consistent in stress distribution. Compared with the physical simulation under static conditions, this technology reconstructs the real stress state through the high gravity field, which can directly reveal the deformation failure mechanism and stability characteristics of rock and soil mass, and provide a more accurate test basis for engineering safety assessment.

3.2 Similarity Principle

The principle of similarity is widely used in centrifugal test models to ensure that the model test results can accurately reflect the mechanical behavior of prototype engineering. The basic core of the principle of similarity is the three theorems of similarity, which can be divided into:

1. The first theorem of similarity (positive theorem of similarity), The first theorem of similarity is a necessary condition for two systems to be similar, that is, in two systems, when their physical properties change process is the same and the similar constants meet a certain relationship, the physical phenomena of these systems will be similar. In other words, models and prototypes can only be considered similar when they meet similar criteria.

2. The second theorem of similarity (π theorem) : When there are n physical quantities in a physical system, the dimensions of k physical quantities are independent, then this (n-k) similar modulus and the synthesis equation formed by this must also be equal, and the equation describing the physical phenomenon is expressed as:

$$f(x_1, x_2, x_3, ..., x_n) = 0 \tag{7}$$

The expression (7) can be rewritten as:

$$\phi(\pi_1, \pi_2, \pi_3, ..., \pi_{n-k}) = 0 \tag{8}$$

Among them:

$$\left.\begin{aligned} \pi_1 &= \frac{x_{k+1}}{x_1^{\alpha 1} x_2^{\alpha 2} x_3^{\alpha 3} \cdots x_k^{\alpha k}} \\ \pi_2 &= \frac{x_{k+2}}{x_1^{\beta 1} x_2^{\beta 2} x_3^{\beta 3} \cdots x_k^{\beta k}} \\ &\cdots \\ \pi_{n-k} &= \frac{x_n}{x_1^{\varepsilon 1} x_2^{\varepsilon 2} x_3^{\varepsilon 3} \cdots x_k^{\varepsilon k}} \end{aligned}\right\} \tag{9}$$

At the corresponding time and at the corresponding point, similar phenomena require that their similar criteria always maintain the same value, in other words, all π relations related to these criteria must also be consistent, that is, :

$$\text{Model：} \varphi\left(\pi_{m1}, \pi_{m2}, \pi_{m3}, ..., \pi_{m(n-k)}\right) = 0 \tag{10}$$

$$\text{Prototype：} \varphi\left(\pi_{p1}, \pi_{p2}, \pi_{p3}, ..., \pi_{p(n-k)}\right) = 0 \tag{11}$$

Among them:

$$\left.\begin{array}{c}\pi_{p1} = \pi_{m1} \\ \pi_{p2} = \pi_{m2} \\ \cdots \\ \pi_{p(n-k)} = \pi_{m(n-k)}\end{array}\right\} \tag{12}$$

3. The Third Theorem of Similarity (Inverse Similarity Theorem), When the single-valued conditions of two physical systems are similar, and the similarity criteria composed of these single-valued quantities are numerically equal, the physical systems within the systems are also necessarily similar. This indicates that if all single-valued conditions (such as geometric properties, material characteristics, initial conditions, etc.) in the systems are similar, and the similarity criteria constituted by these conditions are consistent, then the physical behaviors between these two phenomena will also be similar.

Conducting scientific research on models through the principle of similarity allows the conclusions to be extended to practical engineering applications (Cai, Cui, Feng, et al., 2024). In the study of centrifugal model tests, to ensure that the model can effectively reveal the multi-field coupling effects of the prototype engineering and contribute to solving complex engineering problems, the model and the prototype must satisfy similarity in geometry, kinematics, and dynamics. When the model and the prototype are made of the same material, some common similarity constants, such as geometric similarity constant, stress similarity constant, and gravity similarity constant, are expressed as:

Geometric similarity constant:

$$C_1 = \frac{L_P}{L_M} = N \tag{13}$$

In formula (13), $L_P \sim \text{Prototype geometry}; L_M \sim \text{Model geometry}; N \sim \text{Times}.$

The stress at any point in the centrifugal test model is the same as the stress at the same point in the prototype, that is, the constant digit of stress similarity:

$$C_2 = \frac{\sigma_P}{\sigma_M} = 1 \tag{14}$$

In formula (14), $\sigma_P \sim \text{Prototype stress}; \sigma_M \sim \text{Model stress}.$

The similarity constant of the force is:

$$C_3 = \frac{F_P}{F_M} = \frac{\sigma_P . L_P^2}{\sigma_M . L_M^2} = N^2 \tag{15}$$

The gravitational similarity constant is:

$$C_4 = \frac{W_P}{W_M} = \frac{\rho_P . V_P . a_P}{\rho_M . V_M . a_M} = 1 \frac{a_P . L_P^2}{a_M . L_M^2} \tag{16}$$

Obviously, the formula (15) must also be satisfied by C_4, then it can be deduced:

$$n^3 \frac{a_P}{a_M} = N^2 \tag{17}$$

$$\frac{a_P}{a_M} = \frac{1}{N} \tag{18}$$

In formula (16), a_P ~ Prototype acceleration; a_M ~ Model acceleration.

Based on the similarity theory and combined with the above similar methods, the similarity constants of other forces can be derived. The common similarity constant relationships in centrifugal model tests are shown in Table 1.

Table 1. Common Similar Constant Relation Table

Physical Quantity	Dimension	Similarity Constant (Prototype:Model)
Geometric Dimension	L	N
Acceleration Of Gravity	LT^2	1/N
Area	L^2	N^2
Volume	L^3	N^3
Density	ML^{-3}	1
Displacement	L	N
Cohesion	$ML^{-1}T^{-2}$	1
Angle Of Internal Friction	1	1
Stress	$ML^{-1}T^{-2}$	1
Strain	1	1
Quality	M	N^3
Speed	LT^{-1}	1
Modulus Of Elasticity	$ML^{-1}T^{-2}$	1
Time	T	N^2
Slope Angle	°	1

4. Error Analysis of Centrifugal Model Test

The centrifugal model test can effectively simulate the stress distribution and characteristics of the prototype working condition, but it is difficult to accurately reflect all the details of the prototype working condition, so there are inevitably some errors. Based on the research results of previous scholars, the possible sources and potential mechanisms of errors are systematically sorted out and analyzed, so as to optimize various links in the test, reduce errors in the test process as much as possible, and improve the reliability and engineering applicability of simulation results (Liu, Chen, & Cheng, 2023).

4.1 Error Caused by Uneven Distribution of Centrifugal Force

According to modern relative theory, the physical effect of gravity on an object is equivalent to the inertial force, but under the action of centrifugal force, a different situation will occur. In the centrifugal test, suppose there is a particle *m*, the acceleration at point m is *a*, the resultant force is *F*, the Angle of rotation with the centrifuge isω, and the diameter between point m and centrifuge is R_m, then:

$$F = ma \tag{19}$$

$$a = \sqrt{\left(\omega^2 R_m^2\right) + g} \tag{20}$$

The angular velocity $\omega$of centrifuge rotation is a constant value, but R_m changes with the change of *m* point, so the centrifugal force at different points in the centrifugal model is not equal. The gravity field of the prototype is uniformly distributed. If the centrifugal force field of each point can also be evenly distributed like the gravitational field, the angular velocity ω of each point is required to rotate at different speeds. However, this is impossible to achieve, and the uneven distribution of centrifugal force will result in systematic stress deviation within the model. Theoretical analysis shows that in the test process, $\omega^2 R_m^2$ is much higher than the acceleration of gravity *g*, so the formula(20) can be expressed as:

$$a = \sqrt{\left(\omega^2 R_m^2\right)} \tag{21}$$

It can be shown that the diameter($R_{m)}$ between point *m* and centrifuge in the centrifugal model will affect the acceleration at this point. According to the existing relevant research data of Avgherinos and Schofield, the error between the centrifugal model and the prototype is inversely proportional to the rotation radius of the centrifuge. When the ratio(*H/R*) of the model height *H* to the centrifuge rotation radius *R* is less than 0.1, the error of the centrifugal acceleration can be controlled within 5%. The stress error should not exceed 2%. Further research shows that if the stress of 2/3 height of the model and the corresponding position of the prototype are the same, the error caused by centrifugal force between the two will be minimized. At this time, the stress above 2/3 of the model is larger than that above 2/3 of the prototype. The stress above 2/3 of the model is less than that above 2/3 of the prototype. The stress error function between the two parts can be expressed by the same expression as follows:

$$E_r = \frac{1}{2\left[\frac{3R}{H} - 1\right]} \tag{22}$$

Although the uneven distribution of centrifugal acceleration will lead to errors in the test results, these errors will converge with the transmission process. When the centrifugal acceleration is concentrated in the center of gravity of the model, the centrifugal test results can be considered reasonable. The height of the centrifugal test model is 33cm, and the centrifuge rotation radius R is 2m, so the error is 2.91%, which meets the error requirements, and the error caused by the uneven distribution of centrifugal force can be ignored.

4.2 Errors Due to Boundary Effects

In centrifugal model tests, there is a huge difference between the size of the model box and the prototype structure. Compared with the actual working conditions, the interface friction resistance generated by the contact surface between the side wall of the model box and the soil mass will significantly change the boundary conditions of the centrifugal model, resulting in certain differences from the boundary conditions of the prototype structure, and then cause the stress field and deformation mode distortion (Zhu, Cai, Huang, et al., 2021). In order to reduce the impact of such effects on the results of centrifugal model tests, Malushitsky changed the size of the model box. The study showed that only the middle region of the model met the mechanical similarity conditions, and the strain distribution was closer to the prototype conditions, indicating that the side wall constraints of the model box had a significant impact on the test results. By changing the interface friction coefficient between the centrifugal model and the model box and the aspect ratio of the model, Santamarina studied the influence of interface friction resistance and model geometry scale on the acceleration when the model was damaged. It was found that the effect of coarser interface friction resistance on the model box was greater, while the increase of the width of the model would significantly reduce the acceleration when the model was damaged. It proves that the influence of side wall constraint is weakened. Therefore, in centrifugal tests, Vaseline should be applied on the side walls of the model box to ensure smooth side walls and reduce errors caused by boundary effects.

4.3 Error Caused by Centrifuge Start-Stop Process

In the centrifugal model test, the starting and braking process of the centrifuge will cause the change of tangential acceleration, which is expressed as follows:

$$a_r = R \cdot \omega \tag{23}$$

In formula: a_r ~ All-directional acceleration; R ~ Radius; ω ~ Angular acceleration.

The centrifuge, on the other hand, has zero tangential acceleration when moving at a constant speed. Due to the limitations of the existing technology, the acceleration process required for centrifuge loading and unloading to reach the test takes a certain time, during which tangential acceleration will have an impact on the geotechnical model. If the time used in the model loading process is too short, the foundation of the centrifugal model will not be fully consolidated under the action of centrifugal force field, which may cause large deformation of the model, and then affect the accuracy of the test results. Conversely, if the model is used less during unloading, the stability of the centrifugal model may be adversely affected by the inertial force field. The results show that when $t \leq Ng$, the acceleration or deceleration process of centrifuge has negligible effect on the results of centrifuge model test. Therefore, in order to ensure the accuracy of the test results, the appropriate starting acceleration should be selected according to the specific needs of the test, so as to reduce the influence of tangential acceleration on the test results during the starting and braking of the centrifuge.

5. Conclusion and Prospect

As an important experimental method in geotechnical engineering research, centrifugal model test has achieved remarkable results in many fields, and provides accurate data support for solving complex engineering problems. However, there are still some problems in the test, such as error sources, uneven distribution of centrifugal force, boundary effect and instability in the operation of the equipment, which need to be further optimized. With the continuous development of centrifuge technology and test equipment, future centrifuge model tests will be able to provide more accurate simulation data in a larger range and more complex engineering conditions.

In future research, the precise control and correction of centrifugal model test errors should be strengthened. Especially in the process of test design and implementation, problems such as how to better prepare the foundation soil to reflect the real situation and how to minimize the influence of the data acquisition system on the test errors should be solved, and more accurate schemes should be adopted to improve the reliability of the experimental results. At the same time, with the integration of big data and artificial intelligence technology, the combination of centrifugal model test and numerical simulation technology will become an important trend in the future development. Through more in-depth experimental research and numerical analysis, centrifugal model test will play a greater role in the reinforced soil structure, slope stability, earthquake engineering and other fields, and promote the innovation and progress of geotechnical engineering technology.

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