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Design method of frequency similarity relation for shaking table model test

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It is very important to determine the dynamic similarity relation in the shaking table model test. The accurate dynamic similarity relation can make the model reflect the dynamic characteristics of the prototype to the greatest extent. This paper describes the principle of similarity design for shaking table model test and reviews the related literature. According to the different research objects and purposes, four common similarity design methods including separation similarity method, artificial mass method, less artificial mass method and ignoring gravity method are summarized. Analysis of the shortcomings of the method of deriving frequency compression ratio from static factors in the design of seismic wave similarity relation. The Duhamel integral analytic expression of the structure motion equation under earthquake is analyzed. The seismic response of the structure is closely related to the natural vibration frequency of the structure. A design method using frequency as input seismic wave similarity design control quantity is proposed. The natural vibration frequencies of the prototype and the model are studied by means of the Gonza landslide field ground pulsation test and the model white noise excitation. A new frequency compression ratio design scheme is given from the perspective of dynamic similarity. It is of great reference significance to optimize the dynamic similarity design of shaking table model test and improve the accuracy of test results.

KEYWORDS

shaking table model test, principle of similitude, similarity solution, similarity design, rock slope

Introduction

Earthquake-induced building damage and secondary disasters such as landslide, collapse and mud-rock flow have attracted extensive attention because of their huge disaster causing force. China is a country with high-frequency earthquakes. In 1976, two strong earthquakes occurred in the area of Longling and Luxi of Yunnan Province, which caused serious surface damage, induced a large number of landslides and collapses. The resulting loss is far more than the earthquake itself. In 2008, a 8.0-magnitude earthquake occurred in Wenchuan, Sichuan Province. The number of earthquake-induced landslides investigated by the Ministry of Land and Resources was about 200, 000, causing huge economic losses and about 20,000 deaths (Kong et al., 2009; Xu et al., 2010). In 2010, the 7.1-magnitude Yushu earthquake triggered more than 2,000 landslides, debris flows and other geological disasters, with a total area of 1.194 km^2 (Xu et al., 2012). In 2013, a 7.0-magnitude earthquake hit Lushan, killing more than 100 people and triggering 1,678 geological disaster sites including landslides of varying degrees in Lushan and Baoxing counties, covering an area of 8.354 km^2 (Guo et al., 2014). Earthquakes and related geological disasters cause serious harm to people's lives and property. According to the existing earthquake damage data, researchers use different methods to explore the destruction mechanism of earthquake. Shaking table model test is widely used as a method to simulate earthquake damage phenomenon and study dynamic response characteristics and failure law because of its intuitiveness and authenticity.

This paper expounds the principle of similarity design, reviews relevant previous studies, and analyzes four common similarity design methods. It is pointed out that most traditional methods derive the similarity ratio of each physical quantity only from static factors in the design of similar relation. Kinematic or dynamic factors are not sufficiently considered. In order to simulate the failure characteristic and response rule of prototype better and make the test results more in line with the actual situation. Therefore, it is necessary to optimize the design method of similarity relation. We propose that the method of determining the compression ratio of seismic wave is insufficient and give a new design scheme combined with shaking table test.

Three laws of similarity

The design of similarity relation is based on the three laws of similarity (Li et al., 2007).

The discipline of sibilism dates back to 1686, when Newton discussed similar conditions for fluid motion in his book *Philosophiae Naturalis Principia Mathematica.*

In 1822, French physicist Jean-Baptiste-Joseph Fourier put forward the concept of thermal similarity when studying heat conduction. It was not until 1848 that French scientist J. Bertrand elaborated the basic nature of similarity phenomenon based on the analysis of mechanical equations and put forward the first principle of similarity. The similar second theorem was later developed by Russian scholars αelman and American scholars E. Buckingham respectively. A similar third theorem was proposed by Soviet scientists M. B. Kirpichev and A. A. Guchman in 1930. So far, the first theorem of similarity and the second theorem of similarity give the necessary conditions of similarity, the third theorem of similarity gives the sufficient and necessary conditions of similarity, and the similarity theory forms a relatively complete theoretical system.

The first principle of similarity: For similar phenomena in mechanical systems, the similarity index is equal to 1, and the value of the similarity criterion is the same. There are two conditions for examining whether the phenomena occurring in two systems are similar: 1) The ratio of the corresponding physical quantity of similar phenomenon is constant, which is the concept of similar constant. 2) All the similar phenomena can be described by the same basic equation, so the similar constants such as C_L, C_V, C_a, C_t cannot be arbitrarily selected, and they will be restricted by the similarity index K. At the same time, the proportion relation between the corresponding physical quantities in the model and the prototype should be the same and equal to a constant π, which is called the similarity criterion. The second theorem of similarity: Basic physical equations that constrain two similar phenomena can be dimensionally analyzing, and the π equations of two similar systems must be identical. The π theorem is expressed as: There are n physical quantities describing a physical system, among which k physical quantities represent the basic quantities, and the other n−k physical quantities represent the derived quantities, and these quantities all have certain factors. Since the dimensions in any physical equation are homogeneous, the n quantities can be expressed as functional relationships between similar criteria.

The third theorem of similarity: For the same kind of physical phenomena, if the single valued quantities are similar, and the similar criteria composed of the single valued quantities are numerically equal, the phenomena are similar to each other. A single valued quantity refers to a physical quantity under a single valued condition, which separates an individual phenomenon from a similar phenomenon and turns the general solution of the phenomenon into a particular one. Single—valued conditions generally include: Geometric conditions, medium conditions, boundary conditions and initial conditions.

Similarity relation design method

Many scholars in this field have done a lot of work on the similarity relationship in shaking table model test (Lu and Chen, 2001; Song et al., 2004; Zhan et al., 2015; Zhao et al., 2015; Qian et al., 2016; Niu et al., 2017; Guo et al., 2021; Zhao et al., 2022). According to the different research objects and practical problems to be solved, a variety of methods to determine the similarity relationship are put forward (Lin et al., 2000; Lin and Wang et al., 2006; Li et al., 2020). Based on relevant literature, four common similar design methods in shaking table model tests are summarized and introduced as follows:

Wang et al. (2021a) and Wang et al. (2016) pointed out the shortcomings of the traditional dimensional analysis method in the design of similarity relation of shaking table model test for the interaction of multiple structures: It is not possible to distinguish the importance degree of different parameters of the test, the difference of similar relation design of different structures, or the importance degree of the same physical quantity to different structures of the model. Taking the shaking table test of slope reinforced by anchor cable and lattice beam as an example, the separation similarity design method is proposed. By separating the functional relation between each parameter, the key to the similar design of each structure is clarified, and the similarity relation of the key parameters of each part is solved. The importance of each research parameter to the similar material design is well distinguished. The method is also applied to the similar design process of shaking table model test for dynamic interaction of soil-underground pipeline corridor (Wang et al., 2021b). The similarity design is carried out according to the characteristics of soil mass, pipe corridor, contact surface and seismic wave respectively, and the similarity of the sub-subsystem of "contact interaction between media" is realized for the first time. Zhang et al. (2020) used the separation similarity design method to obtain the third-order characteristic equation when studying the interaction law of pile-soil-structure in the inclined site under earthquakes. The similarity ratio of key parameters, relevant parameters and irrelevant parameters of soil, structure and seismic wave is derived to directly guide the test design, which provides a theoretical basis for the similar design of shaking table of non-uniform soil-pile-structure system in the inclined site.

In the similar design of shaking table model test, such as large-span structure and high-rise building, due to the size of shaking table, most cases need to adopt the scaled model. It is extremely difficult to find high density materials that satisfy the density similarity relation: $S_\rho = S_E S_l^{-1}$. In the above expression, S_ρ, S_E and S_l are the similarity ratios of density, elastic modulus, and length, respectively. Therefore, many scholars in this field put forward a variety of test methods, among which the artificial mass similarity method is widely used.

Artificial mass similarity method is a special case based on the consistent similarity law (Zhang et al., 2003). This method changes the mass density of the model by artificially adding counterweights to the model to make it satisfy the similarity relation. Using length, elastic modulus and equivalent density as basic physical quantities, the similar relation of other parameters is derived by combining Π theorem and dimensionality analysis. Tian et al. (2017) carried out shaking table model test on a 220V large-span transmission line. Considering the large span of the pylon - line system, the design requirements of the scaled model cannot be realized under the existing test conditions, so the method of complete mass counterweight is used to balance the scaled model of the pylon - line system with large span. The proposed density similarity ratio of 1:1 is adjusted to the equivalent density similarity ratio of 20:1. Taking length, equivalent density and elastic modulus as control quantities, similar relationships of other physical quantities are derived. Several other scholars (Shi et al., 2006; Xie et al., 2014; Wei et al., 2018) also used the artificial mass method to guide the establishment of the model in the shaking table test of the large-span transmission tower-wire system.

In addition to using the above artificial mass model to solve the size and bearing capacity of the shaking table, some scholars also use the gravity ignoring similar design method to guide the experimental research. That is, the condition that the input acceleration similarity ratio is equal to the gravity acceleration similarity ratio is ignored to make the model meet the similarity requirement. Due to the lack of vertical stress, the error in the failure stage of the test is large and the gravity distortion effect is generated. Therefore, this method is only suitable for the elastic stage. Xie et al. (2019) carried out shaking table model test of steel-concrete frame structure with the ignored gravity model, and found that serious gravity distortion effect existed in the model test, leading to large errors in the test results. Wang and Li (2010) took the four-storey frame structure as an example and used the finite element software SAP2000 to carry out dynamic time-history analysis on the model ignoring gravity, and verified that the method could truly reflect the characteristics of the prototype in the elastic stage. Lu and Lu (2001) started from the Lame equation in solid mechanics and the Navier-stockes equation in Newton's viscous fluid mechanics. The dynamic similarity relation of shaking table model test of fluid-solid coupling system is deduced systematically, and a method of taking different values of three-dimensional direction of components is proposed to eliminate the gravity distortion effect.

The artificial mass model and the gravity ignoring model mentioned above solve the problems of limited size of the shaking table and difficulty in obtaining high-density materials. The former sets artificial mass to simulate the effect of total gravity and inertia force, while the latter does not set artificial mass and ignores the effect of gravity. Zhang (1997) have done a lot of research on the consistent similarity law, small-scale model similarity and nonlinear similarity, and proposed the less artificial mass method which can easily design the experimental model with arbitrary additional mass. In this method, the total weight of the model does not exceed the maximum bearing capacity of the shaking table by adding an appropriate amount of counterweight, and the method of ignoring gravity similarity design is avoided, which reduces the test error caused by gravity distortion effect. Huang et al. (1994) used two methods to deduce the dynamic similarity relationship between the model and prototype under different counterweight conditions, so as to provide a reliable quantitative method for correctly calculating the seismic performance of prototype under the condition of insufficient counterweight. Tao et al. (2010) established the equivalent density equation in order to solve the problem of structural counterweight in the shaking table test of subway structure, and studied the influence of different overlying soil thickness on the gravity effect by using the less artificial mass method. Under the premise of not changing the stiffness and mechanical properties of the structure, using the overlying soil layer and the artificial weight in the structure can improve the accuracy of the test results. Yang et al. (2007) took the three-story frame structure as an example, starting from the complete mass model, and considering the limitations of the bearing capacity of the shaking table, they adjusted the similarity relation, and derived the model similarity relation with incomplete counterweight. By comparing the derived values of the model and the calculated values of the prototype in the final test, it is concluded that under the less artificial mass method, the model and the prototype have a good similarity in the natural vibration period, the maximum acceleration of each layer, the lateral displacement, and the shear value of the structure base, which indicates that the less artificial mass model can also truly reflect the seismic behavior of the prototype in the elastic stage.

Frequency similarity ratio design

Shaking table model tests need to compress the duration of seismic waves, so the frequency of external loads and the strain rate of materials must be increased (Yin et al., 2010). However, with the increase of loading rate, the damage degree, failure mode, peak strength and deformation parameters of rock materials have nonlinear changes. Most of the similar relationships of dynamic parameters of current shaking table model tests (Zou et al., 2011; Yang et al., 2012; Ye et al., 2012a; Ye et al., 2012b; Huang et al., 2013; Hou, 2013; Li et al., 2014; Fan et al., 2015; Feng et al., 2018; Liu et al., 2019; Liu et al., 2020) are derived from static conditions of three basic physical quantities combined with dimensionality analysis and π determination, without sufficient consideration of dynamic factors.

At present, there are few studies on the dynamic response of the model under different frequency compression ratio of seismic waves. How to determine the frequency compression ratio more accurately is a problem to be further studied. Aiming at the dynamic response of slope under earthquakes, a new viewpoint on the determination of frequency similarity ratio is proposed.

Ground motion is a complex process that varies irregularly and rapidly over time. The earthquake acceleration time history is $\ddot{u}_g(t)$. The equation of structural motion under earthquake is $m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g$. The analytical expression of Duhamel integral can be used to solve the seismic response problem of linear elastic structures.The seismic equivalent load is $P_{eq}(t) = -m\ddot{u}_g(t)$. The displacement of structural seismic response is:

$$\begin{aligned} \mathrm{u}(\mathrm{t}) &= \int_0^{\mathrm{t}} P_{eq}(\tau) h(t-\tau)\mathrm{d}\tau \\ &= \frac{1}{\mathrm{m}\omega_{\mathrm{D}}}\int_0^{\mathrm{t}} \left[-\mathrm{m}\ddot{u}_g(\tau)\right] e^{-\xi\omega_{\mathrm{n}}(\mathrm{t}-\tau)} \sin[\omega_{\mathrm{D}}(\mathrm{t}-\tau)]\mathrm{d}\tau \\ &= -\frac{1}{\omega_{\mathrm{D}}}\int_0^{\mathrm{t}} \ddot{u}_g(\tau) e^{-\xi\omega_{\mathrm{n}}(\mathrm{t}-\tau)} \sin[\omega_{\mathrm{D}}(\mathrm{t}-\tau)]\mathrm{d}\tau \end{aligned}$$

In the above expression, $\omega_{\mathrm{D}} = \omega_{\mathrm{n}}\sqrt{1-\xi^2}$ is the natural vibration frequency of the damped system, ξ is the damping ratio of the structure, ω_{n} is the natural frequency of the structure.

By observing the above equation, we can see that for a given ground motion $\ddot{u}_g$, the seismic response of the structure is only related

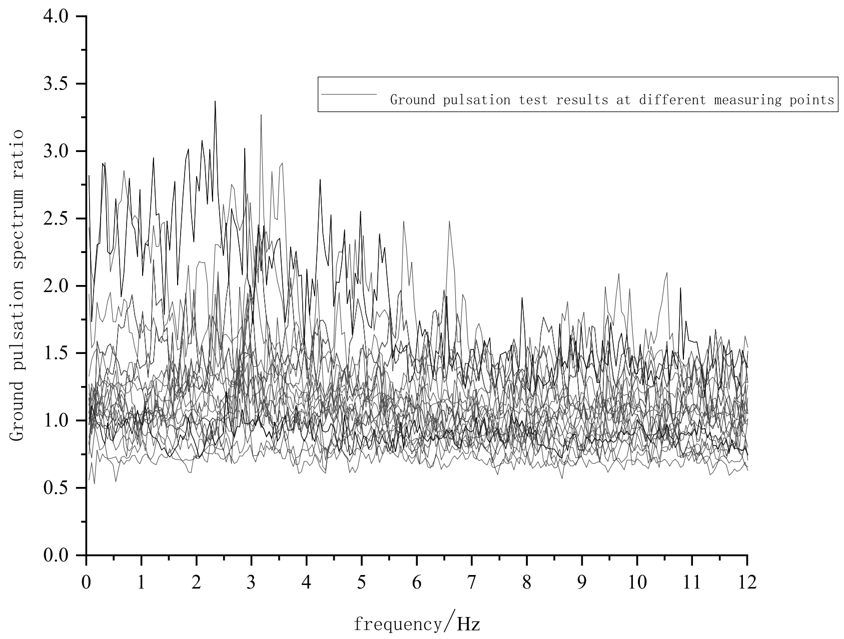

FIGURE 1
Ground pulsation test results.

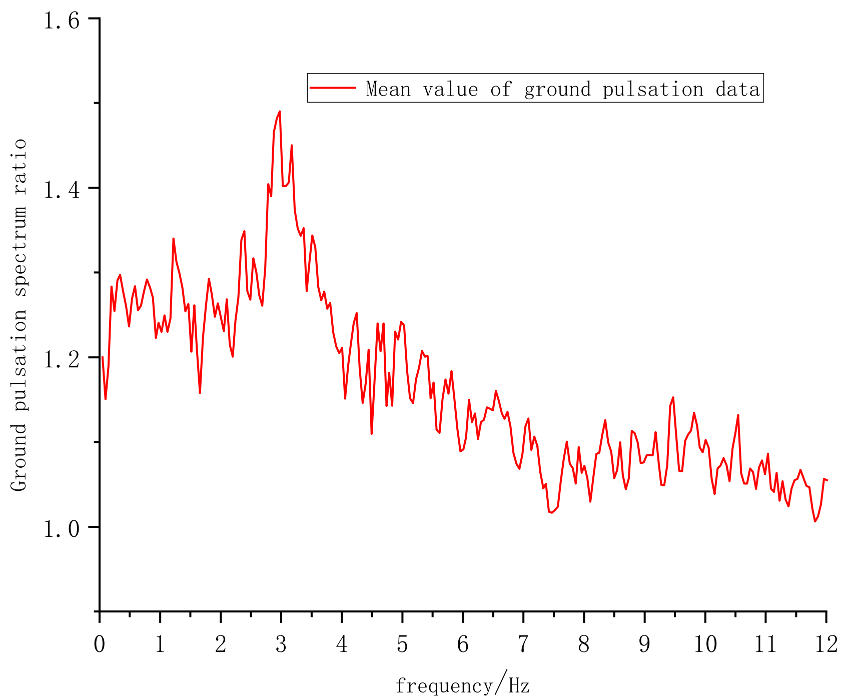

FIGURE 2
Mean value of ground pulsation test data.

to the damping ratio and the natural vibration frequency of the structure. That is, for different structures, when the damping ratio and natural vibration frequency of the structure are the same, the displacement response to the same earthquake is the same. Based on this, it is proposed that the damping similarity ratio between the model and the prototype in the shaking table test is 1 by the similarity of materials, the prototype natural vibration frequency is obtained by the field ground pulsation test or numerical simulation, and the natural vibration frequency of the model is obtained by the white noise scanning. The ratio of natural vibration frequency between the prototype and the model is taken as the frequency similarity ratio of seismic waves, and then the dynamic similarity relation of shaking

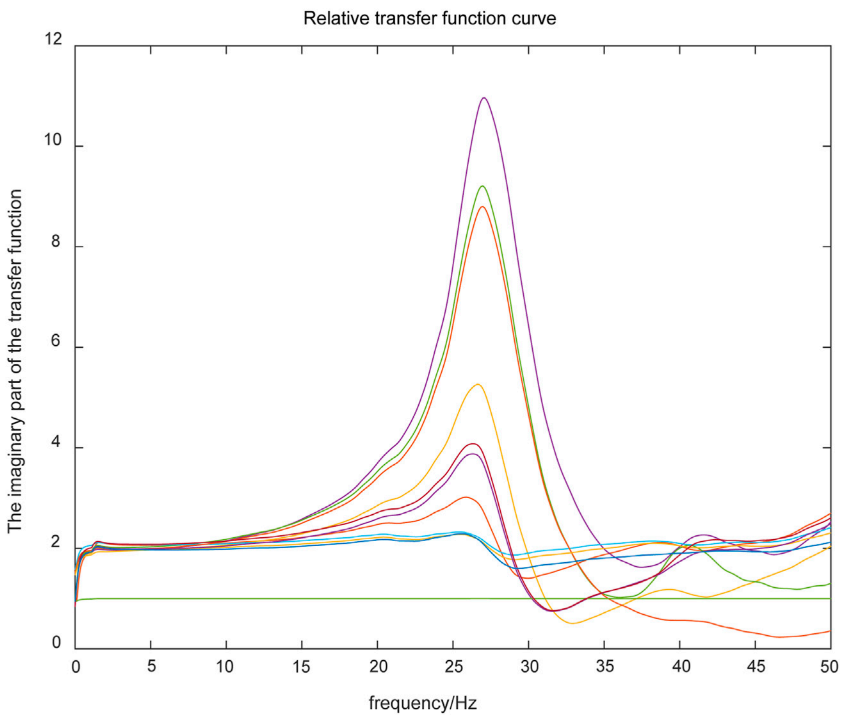

FIGURE 3
Relative transfer function curve.

TABLE 1 Similarity constants of similarity factor.

Name of physical quantity	Physical quantity symbol	Similarity factor
Length*(controlled quantity)	L	$C_L = 100$
Density	ρ	$C_\rho = C_\omega{}^{-2}C_L{}^{-1}$ =0.83
Gravitational acceleration* (controlled quantity)	g	$C_g = 1$
Duration	t	$C_t = C_\omega{}^{-1} = 9.09$
Amplitude	a	$C_a = 1$
Frequency	ω	$C_\omega = 0.11$

table model test is determined, which can reflect the dynamic response characteristics of the prototype under real earthquake more truly.

The author completed a shaking table model test with Gonza landslide in Soduoxi Township, Mangkang County, Qamdo Prefecture, Tibet Autonomous Region as the prototype. The author takes this landslide as the research object to carry out field measurement of ground pulsation, and uses Matlab program to carry out data extraction, separation, filtering and analytical calculation, so as to draw ground pulsation spectrum of the prototype of Gonza landslide, as shown in Figure 1. The average value of multiple ground pulsation data is obtained as shown in Figure 2. And according to the frequency corresponding to the maximum point, the natural vibration frequency of the landslide prototype is determined to be 2.97 Hz. The experiment was carried out in the structural mechanics Laboratory of Beijing University of Technology. The model was made, the measuring point was arranged and the ground motion input was completed. At the beginning of the experiment, we input 0.1g white noise to scan the model, test the dynamic characteristics of the model at the initial stage and use Matlab relative transfer function to process the data. As shown in Figure 3, the natural vibration frequency of the model after excitation is determined to be 27.1Hz according to the peak value of the curve. The ratio of natural vibration frequency between the prototype and the model is 0.11. In the processing stage of test results, the similarity design of seismic waves is carried out by combining the separation similarity design method. Length(L), gravity acceleration(g) and frequency(ω) are selected as basic physical quantities to derive the similarity relationship of other physical quantities. The specific values are shown in Table 1. The similarity relationship determined by this method provides a valuable reference for the follow-up experiment.

Conclusion

(1) This paper summarizes four common similarity design methods, separation similarity design method, artificial mass method, gravity ignoring similar design method and less artificial mass method. When determining the similarity ratio, the similarity

design method should be selected reasonably according to the research purpose and equipment condition. For the shaking table model test of the interaction of various structures, the separation similarity design method can be selected. For the large-span structure model or high-rise structure model, the artificial mass method can be selected when the shaking table bearing capacity is high, and the less artificial mass model can be selected when the shaking table bearing capacity is insufficient. For the shaking table test to study the seismic response of the elastic stage of the model, the gravity ignoring similar design method can be chosen.

(2) Based on the field ground pulsation test and shaking table model test data of Gonza slope, the frequency similarity ratio between the prototype and the model is determined to be 0.11. Length, gravity acceleration and frequency are selected as control quantities to satisfy geometric similarity, kinematic similarity and dynamic similarity, and the similarity ratio of each physical quantity of seismic wave determined by the new design method is derived. The new method makes up for the shortcomings of dynamic similarity design in shaking table model tests, provides a new idea for determining the frequency similarity ratio of seismic waves, and is of great significance for optimizing the similarity relationship and improving the accuracy of test result.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, MG; investigation, XC; writing—original draft preparation, MG and XC; writing—review and editing, MG, XC, and JZ; supervision, JZ; and funding, JZ. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The 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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