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A Systematic Review of Physical Modelling Techniques, Developments and Applications in Slope Stability Analyses

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Abstract An extensive evaluation of published articles suggests a lack of research on a systematic literature review relating to physical modelling techniques, developments and application in slope stability studies. However, there is growing interest in using physical model tests in slope stability investigations. The present study systematically reviews the methodologies and applications of physical modelling in slope stability research. The Scopus database was used to identify relevant studies which employed physical model tests in slope stability investigations. A combination of fifteen keywords was used to identify relevant articles. A PRISMA-P method for conducting a systematic review was adopted. Articles were screened and analysed, and extracted data were re-organised using an Excel sheet. Data relating to research objectives, physical model test techniques, instrumentation, scaling laws, numerical modelling, results, and findings were extracted and analysed. The systematic review highlights gaps requiring further studies, particularly in slope reinforcements using vegetation and strength deterioration of reinforcements performance under repeated loading exposures. It is found that scholars have not fully addressed the influence of loss of water on pore water regimes and its impact on stability when vegetation is applied as reinforcements. It is also found that the development of slope materials for soil slopes in physical model tests relies on the artificial development of such materials with minimal consideration of their long-term behaviour. Although other options, such as bio-cementation and desiccation techniques, which simulate the natural environment of the slopes, are neglected in slope material development, the present study recommends that future studies consider such techniques.

Keywords Slope stability · Systematic review · Physical modelling · Numerical modelling · Shaking table · Geotechnical centrifuge

Introduction

Slope stability is a crosscutting subject because of its diverse applications in civil, mining and geological engineering. Therefore, it draws various researchers and practitioners to address unique research gaps. Over the years, slope stability has been analysed using limit equilibrium methods and numerical methods. However, lately, there has been an increasing trend in the utilisation of physical modelling tests to advance knowledge of the slope instability problem. Therefore, due to the complexity of the slope stability problem, many engineers and researchers consider utilising physical model tests to obtain real-time data to help in the analyses. Physical model tests in slope stability date back to the early 1970s, with the first studies by Barton [1] and Erguvanli and Goodman [2]. To date, the physical modelling technique has received significant adoption. Physical model tests are conducted alongside the best possible theoretical calculations, particularly when researchers lack confidence in the theory [3]. Using physical models in slope stability

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has attracted increased interest in enhancing current theory and understanding. The approach requires that a critical or influencing factor(s) is being studied; these factors could be rainfall or water infiltration [4], dynamic loading such as earthquake [5, 6], joint action of rainfall and landslides [7], and static loading [8], coupled effects of rainfall and dynamic loads [9, 10], orientation of rock slope discontinuities [11], slope reinforcements [12, 13], rock block proportions and orientations in soil-rock slopes [14], failure mechanisms of soil and rock slopes [15], overburden loading [16], surcharge loading [17], slope stabilisation [18], rock joint surface shapes [19] and many more. This attests to the versatility and relevance of the physical modelling technique in slope stability research. Physical model tests generally translate to small-scale laboratory modelling, and they offer numerous advantages because they enable significant control over the model's relevant details. For example, physical model tests provide an opportunity to choose the type of geomaterials and its geo-mechanical characterisation data, choice of the boundary and loading conditions. This is helpful when developing a new theory or investigating a phenomenon with known parameters. Additionally, physical model tests involve relatively small quantities of geo-materials, shorter drainage paths and test durations and allow performing several tests to repeat observations and conduct parametric studies.

With physical modelling, complex geological formations, rock mass structures and soil slopes are investigated by down-scaling the natural proto-type using similarity theory [20]. The similarity criteria concept is satisfactorily covered in the literature and applied in geotechnical engineering research [21, 22]. For example, Wujian et al. [23] used the similarity concept and considered geometry, material density and gravitational acceleration as the fundamental variables. The study utilised a shaking table apparatus to clarify the seismic effects of loess slopes under earthquake-loading conditions. Likewise, Zhu [24] derived primary parameters for developing a physical model in investigating the anti-dip layered slope induced by the excavation toppling failure mechanism. Physical modelling has also become a common technique adopted in landslide studies by providing experimental data for numerical model validation and real-time information about slope behaviour during the test [25, 26]. For example, tiltable table tests were utilised by Alejano et al. [27] to compare the results of failure mechanisms associated with footwall slopes using limit-equilibrium, numerical and physical models. Likewise, a geotechnical centrifuge was utilised to investigate vegetation's effect on the stability of clay slopes [28]. The study used finite element numerical modelling to understand the results of the physical model tests. Large-scale physical modelling tests were used by Li et al. [15] to clarify the failure mechanisms of landslides, and the test results were examined by numerical modelling.

Different trigger factors are modelled using various equipment such as the centrifuge apparatus, shaking table tests, tilt table tests, laboratory flume tests and self-designed physical tests apparatus. Failure mechanisms of rock and soil slopes have extensively been studied using geotechnical centrifuge model tests [29, 30]. With centrifuge model tests, the effects of specific factors on the behaviour of slopes can be parametrically studied using reduced boundaries and geometries in an artificially high gravity environment. In addition, images acquired during the modelling process facilitate and assist the difficult-to-observe progressive slope failure processes from beginning to end, which are practically challenging to observe in real-time and on-site. Similarly, when earthquakes are considered a slope failure-inducing factor, shaking table tests have been employed to investigate the seismic response of slopes subjected to dynamic loading [31, 32]. In the same way, with overburden as the slope failure-trigger factor, slope failure characteristics have been investigated using physical model tests, as reported by Zhang et al. [33].

The preceding discussion suggests a rising trend in using physical models in slope stability studies. However, literature supporting the application of physical models in slope stability research has not been systematically summarised. Most reviews have focussed on landslides and slope failure triggering factors such as earthquakes and rainfall. Currently, there is no review consolidating the developments and considerations in applying physical model tests in slope stability research, and no systematic review is available on the collaborative use of physical and numerical techniques despite these gaining significant adoption. Available reviews do not consolidate the developments and considerations of physical model tests in slope stability studies. For instance, Fang et al. [34] reviewed centrifuge modelling of landslides and landslide mitigation under various triggering factors such as earthquakes, rainfall, and associated experimental techniques and requirements. However, the review did not capture the role of numerical models in validating physical solutions. The review also focussed only on studies that used centrifuge tests and ignored the shaking table and other physical modelling testing techniques that are equally gaining wide adoption. Similarly, D'Ippolito et al. [35] reviewed rain-induced landslides with a focus on hydrological and physical modelling. In the physical approach, the review addressed the effect of rainfall infiltration, its influence on pore pressure changes, and its influence on shear stresses. However, it did not address the instrumentation requirements, loading conditions, or numerical approaches. Zhang et al. [36] reviewed infiltration and slope stability analyses for rainfall-triggered slope failures. It summarised conceptual models, analytical analysis, and numerical modelling (i.e. limit equilibrium methods) but did not address the physical modelling aspect. Similarly, Mburu et al. [37] conducted a comparative review of unsaturated silty slopes under a vertical steady flow rate for identifying slope and hydraulic conditions for unsaturated slope stability analysis. The review discussed the commonly adopted computer programs for investigating rainfall seepage in unsaturated slopes. A review of the modelling approaches in slope stability was conducted by Samson et al. [38] with a focus on block toppling and highlighted milestones in the modelling techniques. However, the study emphasised chronological developments in physical, modelling and analytical methods on block toppling stability analysis, with limited attention to the methods and requirements in numerical and physical modelling in terms of slope materials, scaling laws and physical test apparatus.

It is evident that there is a lack of a systematic review for synthesised articles in the application of physical modelling techniques, developments and consideration in slope stability research. Therefore, the current work seeks to consolidate the developments and considerations in slope stability studies utilising physical model tests. In the light of this, the review intends to collate, discuss and analyse the following themes: (1) the contribution of the physical modelling approach in slope stability research, particularly when used alongside numerical modelling, (2) the experimental principles, methods, considerations, developments and applications of physical model tests in slope stability research, (3) software packages used in slope stability studies for different geological conditions. This literature summary bench marks the current state of knowledge in this research area and will help the research community address the identified gaps for future investigations. Additionally, it will serve as a guide for analysis for practising engineers and help them improve their judgement of the slope instability problem.

Materials and Methods

The present review uses the methodology proposed by the scoping review protocol guided by the *Preferred Reporting of Items for Systematic Review and Meta-Analyses Protocol* (PRISMA-P) checklist [39], which was supplemented by the *Preferred Reporting of items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews* (PRISMA-ScR) checklist reported by Peters et al. [40]. The PRISMA-P statement, as highlighted by Moher et al. [41], considers the systematic reviews and meta-analyses. In general, the systematic review section of the PRISMA-P aims to provide a comprehensive summary of the research undertaken by academics on a particular topic up to the present. However, the meta-analysis section provides the key statistical results from previously published papers. According to Welch et al. [42], the primary purpose of the PRISMA-P technique is to aid practitioners and researchers in finding a complete, simple, and clear literature review. There are several excellent examples of PRISMA-P based research from diverse domains. For example, Matsimbe et al. [43] conducted a systematic review using PRISMA-P to clarify the commonly used definitions and mix design methodologies in geo-polymers. It is noteworthy to state that many journals promote the use of the PRISMA-P in systematic reviews. It has been used in several fields, including Machine Learning in soil improvement [44], optimisation of mining productivity [45], and artificial neural networks in geotechnical engineering [46]. The PRISMA-P generally guides researchers in developing a comprehensive review of the latest published articles as a literature review [42].

In this study, relevant published papers were retrieved using literature searches from databases and manual searches. Li et al. [47] report that Scopus, Web of Science (WoS) and Google Scholar are the prevalent scientific databases. The Scopus database has the highest collection of citations and summaries of peer-reviewed literature [48]. Elsevier [49] reports that Scopus is a multidisciplinary database with more than 90.6 million entries and more indexed publications than the Web of Science [50, 51]. Scopus is the most popular bibliometric database owing to its comprehensive coverage [51]. As such, the Scopus database has been extensively used by many scholars, including [52–54], for systematic reviews and bibliometric analysis. Therefore, the present study adopted the Scopus database to provide a systematic review of the developments and methodologies in the physical modelling technique in slope stability studies. The most recent published articles were identified based on searching several keywords such as “physical modelling”, “shaking table tests”, “geotechnical centrifuge”, “landslide”, “dynamic response”, “earthquake”, “slope stability”, and “numerical modelling”. The articles were selected from literature which were published between 2010 and June 2023. According to our search strategy, 2718 scholarly papers were retrieved. After that, the articles were checked and duplicated articles with similar information were removed. Finally, screened papers were subjected to the eligibility criteria. Figure 1 illustrates the process flow of information according to the PRISMA-P statement. Additional and detailed data are provided as Online Resources 1–8.

Articles Eligibility

Regarding eligibility, the articles obtained from the screening stage were reviewed by assessing the full text of each publication. The authors identified relevant articles based on the research theme inter-linked to the purpose and objective of the present study in order to attain a consensus. Articles that used physical model testing techniques such as a shaking table, geotechnical centrifuge, tiltable table, laboratory flume and other specially designed equipment were selected. By nature of these studies, they covered the other relevant aspects of the current study. However, unpublished work, conference papers, book chapters, and articles in languages other than English were excluded. In addition, studies that

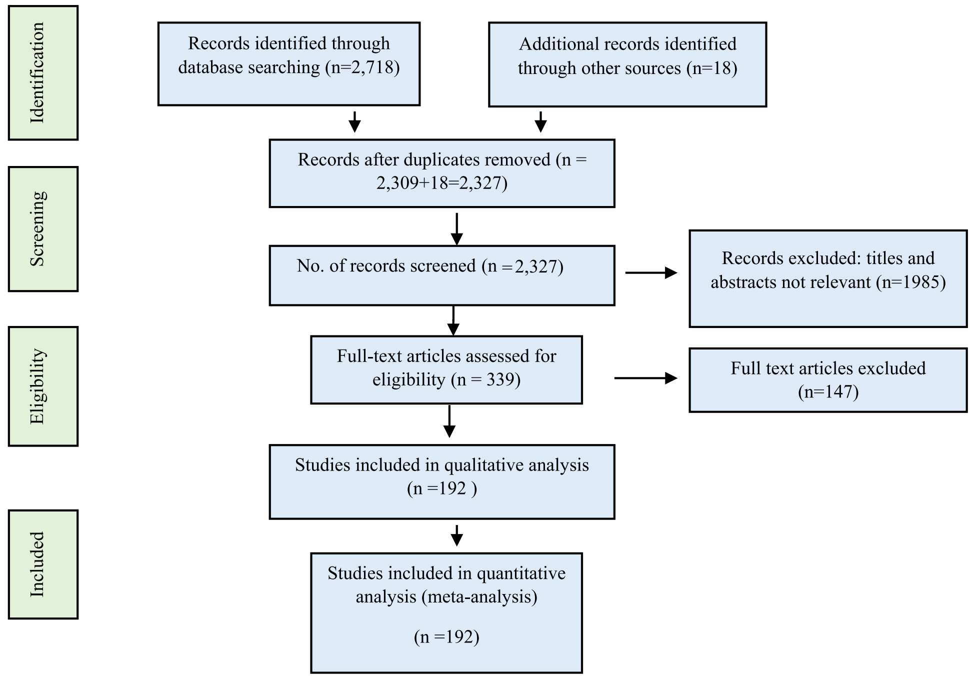


Fig. 1 PRISMA-P flowchart for the study

used numerical tests only but did not involve physical modelling tests were excluded. Implementing the inclusion and exclusion criteria resulted in 192 articles available for data extraction, summarising, curation, and analysis.

Physical Model Tests Considerations and Development

Slope Materials and Model Preparation

The selection and development of materials for physical model tests is one of the key considerations. It is a critical aspect of physical modelling because it aims to replicate the material properties and behaviour of the prototype into the model. Depending on the objectives and scope of the study, different properties and parameters are targeted for replication. For example, Rao et al. [55] developed a material composed of a high-strength substrate and a softening solution for simulating the decrease in soil strength. A model slope constructed using the substrate was immersed in the softening solution to simulate the reduction in soil strength. Slope models with reinforcements have been achieved by using anchor cables [56], geogrids for geotextile reinforced slopes [57], piles [58], fibres [59], geosynthetics [60], and vegetation [61]. Likewise, the effect of the shape and orientation of the artificial blocks on slope stability has also been widely studied to simulate a mixture of rock and soil slopes. For example, studies by Feng et al. [62] and Lianheng et al. [63] recognise the influence of the orientation and shape of artificial rock blocks in slope stability analyses. For rock slopes and toppling failure mechanics, common shapes include cuboids [64–67] and cubic blocks [68], with designated block orientations to form dipping or anti-dip slopes. On the other hand, the simulation of the soil-rock mixture (bimslopes) has varying shapes, such as ellipsoidal [14], irregular [63] and round or spherical blocks. These artificial blocks are commonly made from a range of materials, including cement [69], gypsum [70], barite powder [65], kaolinite [71], iron powder [72], and others. Interestingly, Huang [73] used 180,000 stainless steel rods of 1.96 mm diameter, rhombically stacked, to simulate the stress level of a 2 m-high prototype soil type. It is evident that the variability of materials demands different preparation methods for slope models. The studies reveal that for unsaturated slopes, soil placement is characterised by compaction in layers to meet the desired density. Some researchers prefer to compact the slope material to form a slope angle during compaction. In contrast, others compact the slope material and form a slope angle afterwards. Slope models replicating rock slopes are generally made from artificial solid blocks, and a cohesive material is used to keep these blocks together in forming a slope. It is noteworthy to state that the development of artificial model slopes consisting of soils is commonly done by the addition of cohesion content such as cement and lime into the soil mixture [74, 75] or by mixing two or more natural soils at a high temperature over a certain period [76, 77]. We have noted that none of the studies, as captured by the search query, has used any of the naturally existing soil cementation techniques, such as bio-cementation and desiccation processes.

For example, Whiffin et al. [78] proposed a two-phase bio-cementation method which involved the injection of bacteria culture and then the injection of a cementation solution into the soil to improve its shear strength and stiffness. Moreover, Cheng et al. [79] proposed a one-phase injection of a low-pH biocement solution containing ureolytic bacteria, urea and soluble calcium. On the other hand, repeated wetting and drying have been reported to improve stiffness in granitic residual soils [80]. These procedures can potentially recreate bonding in soil whose bonding structure has been disturbed due to sampling operations.

Model Containers and Materials Placement

The models are constructed using rigid boxes consisting of metallic reinforcements to withstand compaction energy during the placement of the slope material and at the implementation of loading conditions. It is worth noting that most studies use transparent glass, such as plexiglass embedded into rigid metallic frames. The plexiglass enables observations and capturing of images of the deformation behaviour of the slope material during physical modelling tests. For example, Che et al. [69] utilised a rigid, sealed box 2.8 m long, 1.4 m wide and 1.0 m high with organic glass fixed into carbon steel plates to clarify the effect of wave propagation in rock masses and its influence on slope stability. Similarly, Yang et al. [81] used a 2 m x 0.8 m x 1.5 m (L x W x H) container with two transparent sides for observing slope failure. A high-strength plexiglass was fixed on the opposite sides of the rigid portion of the container to allow imaging of in-plane deformation of the slope model. Observation points were marked on the plexiglass, and a high-resolution camera was used to capture displacement after the loading scheme. Peranić et al. [82] constructed a water-tight platform made of steel elements and transparent plexiglass placed on the sidewalls to allow observation of displacements during the tests. The platform also considered the drainage system through the plexiglass and its bottom. Different slope materials were used, including uniformly graded fine sand and a mixture of kaoline clay and clean sand. These materials were compacted during slope construction. Likewise, Munawir [83] compacted a poorly graded sand in a rigid steel container 1.5 m long, 1.0 m wide and 0.7 m high at a slope angle of 70^0, with aluminium pipes inserted in the material to act as reinforcement piles. The slope and pile configurations were adopted from limit analysis (LA), limit equilibrium analysis (LEA) and numerical methods [84].

It is imperative to indicate that researchers carefully design the physical tests and model containers to minimise boundary effects on the results [85]. In most cases, a flexible material is pasted on a selected side of the container boundary to limit the propagation of induced stresses and act as a damping layer to weaken the boundary effect of model containers. Some studies have utilised foam sheets, particularly on the front and back boundaries of model walls, to address this shortcoming [86–88]. In contrast, others have employed glycerin or petroleum jelly to limit the friction between slope material and container walls [89, 90]. It is worth noting that the use of mixed container boundaries (a combination of flexible band rigid boundaries) on selected sides poses concerns about the biased orientation of failure plane development and progression which is towards the flexible boundaries [91]. On the other hand, leaving all sides with rigid boundaries leads to non-uniform stresses [92]. Thus, applying flexible boundaries on all container sides eradicates concerns about preferential bias of failure planes and non-uniform stresses. However, these boundaries, including foam sheets, disturb observation and deformation data collection if image data are desired during the tests. Therefore, various material preparation methods ad considerations have emerged based on the type of materials to be used for a model in relation to a specific investigation. For example, Fang et al. [34] reported that unsaturated soil slope models are prepared by placing them in layers with the required density by tamping, whereas dry soil slope models are achieved using the pluviation technique [93, 94]. However, preparing rock slope models involves the development of artificial blocks, which is primarily achieved through casting a mixture of materials. These blocks are then stacked following a desired orientation to form a slope.

Scaling Laws

Scaling laws are used in physical modelling to reproduce the behaviour of the prototype slope in a model slope under various loading conditions. This ensures that the slope material exhibits similar fabric, structure, stress history, boundary stress state, and pore pressure distribution [34]. Meeting such requirements is not easy; hence, physical mode tests always depart from the natural conditions of the prototype slopes, but this must be kept as minimal as possible [95]. Surprisingly, not every study on physical modelling has adopted similitude laws. For example, Linfang et al. [96] proposed a novel method for estimating slope seismic stability analysis using the Yushu Airport Road 3# landslide as a case study. Similarly, Murao et al. [97] used shaking table tests to examine the progressive failure of unsaturated slopes in investigating the influence of seepage surface conditions on the fill slope. Likewise, Sun et al. [98] proposed a new limit equilibrium method for evaluating the stability of cable-reinforced high bedding rock slopes in relation to rotational bi-planar failure using tilt equipment. These studies did not use scaling laws despite adopting physical model tests. However, applying similarity laws helps to reproduce the behaviour of the slope at a different scale other than the

Table 1 Similarity laws of shaking table tests according to Zhao et al. [70]

Quantity	Physical Parameters	Similar Law	Signs
Geometric characteristics	Length	C_L	λ
	Area	C_s	λ^2
	Volume	C_v	λ^3
Material Characteristics	Density	C_ρ	$C_\rho = 1$
	Mass	C_m	$C_\rho \cdot C_L{}^3 = \lambda^3$
	Cohesion	C_c	$C_\rho \cdot C_L = \lambda$
	Friction angle	C_ϕ	1
	Poisson ratio	$C\mu$	1
	Modulus	C_E	$C_\rho \cdot C_L = \lambda$
	Stress	C_σ	$C_\rho \cdot C_L = \lambda$
	Strain	C_ε	$C_\sigma / C_E = 1$
Dynamic characteristics	Acceleration	C_a	$C_a = 1$
	Force	C_F	$C_\rho \cdot C_L{}^3 . C_a = \lambda^3$
	Velocity	C_v	$C_L / C_t = \lambda^{1/2}$
	Displacement	C_D	$C_\varepsilon \cdot C_L = \lambda$
	Time	C_t	$[C_L / C_a]^{1/2} = \lambda^{1/2}$
	Frequency	C_f	$[C_a / C_L]^{1/2} = \lambda^{-1/2}$
	Damping ratio	C_ζ	1

full scale, and they need to be used according to Buckingham's theorem and dimensional analysis [99]. Dimensional analysis is a method for deducing elements of the form of a theoretical relationship from consideration of the variables and parameters that make up that relationship. The fundamental principle is that every occurrence may be characterised by a dimensionally coherent equation connecting the fundamental and controlling parameters thereby reducing the number of factors that must be researched to comprehend a specific geotechnical problem. For example, slope stability scaling procedure is guided by the dimensionless equation [100];

$$F = f\left(\frac{C_u}{\gamma H}, \theta, \frac{D}{H}\right)$$

The parameters $c_u/\Upsilon H$ represent the stability number, Θ is the slope angle, H is the slope height, and D is the depth of the strong layer below the slope. Practically, to achieve the same margin of safety in a model and prototype, the geometry (the slope angle) and the dimensionless group ($c_u/\Upsilon H$) need to be kept constant [101]. Buckingham's theory is widely used in shaking table tests [102, 103] and a summary of similarity relationships are reported by Zhao et al. [70]. These are shown in Table 1. Similitude analysis for converting full-scale parameters into slope model parameters is illustrated and summarised by Iai [20].

Tables 2 and 3 show the similitude relationships and scaling factors for the geotechnical centrifuge and tilt table apparatus.

Zhao et al. [70] used a shaking table test to study the propagation and development of probability information, dynamic stability, slope amplification and de-amplification effects under random wave inputs. In the study, the scaling factors of the controlling parameters were length ($C_L = 25$, i.e. $\lambda = 25$), density ($C_\rho = 1$), and elasticity modulus ($C_E = 25$). In another study by Guo et al. [90], they predicted failure surface using centrifuge model tests on soil slope anchored with a geosynthetic system under seepage conditions. Soil strength parameters (cohesion and internal friction angle) and coefficient of permeability were the fundamental parameters, and their scaling coefficients were adopted from the work by Rajabian et al. [105], which was $N = 1$. Likewise, the similarity ratios for geometric size, cohesion and density were the main controlling factors for investigating the coupling effect of rainfall and earthquake in a loess slope [106]. They used similarity ratios or scaling factors of 10 for geometric size and cohesion and a factor of N = 1 for density. Similarly, Sengupta and Kumar [107] used jute thin strips on a large-scale embankment to clarify its performance as reinforcing material under varying rainfall events. The study adopted a scale of 1:10 of the actual embankment. A geometric similarity ratio of 50: 1 was used by Wang et al. [108], in which shaking table tests and numerical analysis were employed to clarify the dynamic response laws of a steep loess slope subjected to building and dynamic loads. A study investigating the influence of ground motion parameters using shaking table tests by Niu et al. [109] considered geometry, acceleration and density similarity ratios as the controlling parameters and adopted similarity constants adopted from Iai [20], using length similarity constant

Table 2 Scale factors for centrifuge model tests, White [101]

Quantity	General	1g (laboratory)	ng (centrifuge)
Length	n_l	$1/n$	$1/n$
Mass density	n_ρ	1	1
Acceleration	n_g	1	n
Stiffness	n_G	$1/n^\alpha$	1
Stress	$n_\rho n_g n_l$	$1/n$	1
Force	$n_\rho n_g n_l^3$	$1/n^3$	$1/n^2$
Force/unit length	$n_\rho n_g n_l^2$	$1/n^2$	$1/n$
Strain	$n_\rho n_g n_l/n_G$	$1/n^{1-\alpha}$	1
Displacement	$n_\rho n_g n_l^2/n_G$	$1/n^{2-\alpha}$	$1/n$
Pore fluid viscosity	n_μ	1 Or $n^{1-\frac{\alpha}{2}}$	1 Or n
Pore fluid viscosity	n_{pf}	1	n
Permeability (Darcy's Law)	$n_{pf}n_g/n_\mu$	1 Or $1/n\left(1-\frac{\alpha}{2}\right)$	n $Or1$
Hydraulic gradient	n_ρ/n_{pf}	1	1
Time (diffusion)	$n_\mu n_l^2/n_G$	$\frac{1}{n^{2-\alpha}}$ $or1/(n^{1-\frac{\alpha}{2}})$	$\frac{1}{n^2}$ Or $\frac{1}{n}$
Time (creep)	1	1	1
Time (dynamic)	$n_l\left(\frac{n_\rho}{n_G}\right)^{\frac{1}{2}}$	$1/(n^{\left(1-\frac{\alpha}{2}\right)}$	$1/n$
Velocity	$n_g n_l\left(\frac{n_\rho}{n_G}\right)^{\frac{1}{2}}$	$1/(n^{\left(1-\frac{\alpha}{2}\right)}$	1
Frequency	$\left(\frac{n_G}{n_\rho}\right)^{\frac{1}{2}}/n_l$	$n^{1-\frac{\alpha}{2}}$	n
Shear wave velocity	$\left(\frac{n_G}{n\rho}\right)^{\frac{1}{2}}$	$1/n^{\frac{\alpha}{2}}$	1

as $C_l = 1$, acceleration similarity constant as $C_a = 1$ and density similarity constant as $C_\rho = 1$. Likewise, Chen et al. [5] considered gravity acceleration ($C_g = 1$), density ($C_\rho = 1$) and geometric size ($C_l = 10$) as primary or control parameters in studying the seismic response of a model slope with a weak interlayer reinforced by a pile-anchor structure. It is important to note that the model size and accuracy increase as the geometric similarity coefficient decreases [110]. The preceding discussion depicts the relevance of scaling laws in physical model tests and the requirement to ensure that the mechanical properties of the prototype and model are kept as close as possible.

Instrumentation Requirements

Instrumentation is one of the primary considerations when conducting slope stability studies because it enables data collection during tests. Sensors are commonly applied to capture various data in physical model tests. The sensors are mostly embedded into slope models or on the surface of model containers to capture relevant information. For example, seven pressure gauges and ten acceleration sensors were buried into the slope model in a study to distinguish the dynamic response of two types of rocks subjected to seismic loads using shaking tables tests [66]. In another study by Lian et al. [86], a pile plate retaining wall was used as a reinforcement against landslides. Its dynamic behaviour was analysed using a shaking table test and time–frequency domain analysis. The study used capacitive accelerometers to record the seismic response of the model. In the study, earth pressure sensors and pull-wire displacement sensors were positioned in front and behind the piles to record the vibration response of the piles, and high-speed cameras were used to record deformations. Similarly, deformation characteristics and seismic response of double-row piles were investigated using a large-scale shaking table [89]. The study deployed accelerometers and dynamic cell pressure sensors, closely arranged in the slope model and others fixed on the anti-slide pile model. The sensor data were collected using a specially designed data acquisition system. Besides, Razeghi et al. [57] used porewater pressure transducers to collect pore pressure data at selected points to reveal the water flow in

Table 3 Various scale factors for tilting table apparatus, Amini et al. [104]

No	Parameter	Full scale/model	Scale factor	Remarks
1	Length	$\frac{L}{l} = n$	n	Model dimensions are ''n'' times smaller than the full-scale ones
2	Area	$\frac{A}{a} = n^2$	n^2	This parameter depends on two dimensions
3	Volume	$\frac{V}{v} = n^3$	n^3	This parameter depends on three dimensions
4	Mass	$\frac{M}{m} = n^3$	n^3	This parameter depends on three dimensions One
5	Gravitational acceleration	$\frac{G}{g} = 1$	1	One gravitational acceleration contributes to prototype and full scale one
6	Volumetric mass	$\frac{\rho_a}{\rho_s} = \frac{(\frac{M}{V})}{(\frac{m}{v})} = 1$	1	If one material is used for prototype and full scale one
7	Unit weight	$\frac{\gamma_a}{\gamma_s} = \frac{V\gamma_a/A}{v\gamma_s/a} = 1$	1	This parameter depends on components 5 and 6
8	Stress	$\frac{\sigma_a}{\sigma_b} = \frac{V\gamma_a/A}{v\gamma_s/a} = n$	n	This parameter depends on components 2 and 7

Table 4 Instrumentation features for selected studies from the database

Physical Testing apparatus	Trigger/Failure mechanism	Instrumentation	Reference
Laboratory scale physical model	Performance of soil slope with jute reinforcement subjected to various rainfall intensities	T5-7 tensiometers for monitoring porewater pressure/suction, laser displacement transducer for deformation monitoring, and digital tensiometers for matric suction	[12]
Geotechnical Centrifuge	Gradual increase in phreatic surface to investigate the susceptibility to hill slope debris flow for loosely deposited soils with varying particle size distribution	Druck PDCR-81 pore pressure transducers (PPTs), real-time images were captured from a video camera. Transducer outputs were collected using the built-in data acquisition system	[111]
Geotechnical centrifuge	Examining the reinforcing effect of roots in soil slope subjected to rainfall	Porewater pressure transducers (PWPs) and Accelerometers (ACCs) were used for pore pressure measurements and displacements	[61]
Tilt test apparatus	Incremental tilt angle to evaluate the slide-head-toppling failure mechanism	Displacement transducer and video recording on the sides and front of the model	[8]
Flume test apparatus	Influence of soil water content distribution and suction on slope failure (artificial rain was used)	Minitensiometers (equipped with porous ceramic cups) were used to measure soil suction, and Time Domain Reflectometry (TDR) was used to measure soil water content profiles	[112]
Shaking table	Dynamic failure of anti-dip slope model using Discontinuous Deformation Analysis (DDA)	Eight accelerometers were placed on the slope model and one on the shaking table to monitor the acceleration	[62]
	Seismic behaviour of a slope with weak interlayer and reinforced by a pile anchor structure	Nine triaxial accelerometers, ten earth pressure gauges, three strain gauges and two displacement sensors	[5]

the soil slope model in a geotechnical centrifuge. The study utilised Linear Variable Differential Transducers (LVDT); three were placed at the slope's crest to capture settlement data. Table 4 summarises physical modelling instrumentation for selected studies in the database.

Physical Modelling Test Equipment and Considerations

Geotechnical Centrifuge

Severalscholars, including Wang et al. [4], Greco et al. [110] and Ng et al.[111], have utilised geotechnical centrifuge equipment as a physical modelling tool to investigate various slope stability problems. The theory and working principle of geotechnical centrifuge have been extensively discussed elsewhere [115, 116]. The fundamental principle of centrifuge testing is to establish a stress field in the model that duplicates the prototype scenario so that observations may be made that would otherwise be possible only on full-scale prototypes [117]. This idea supports numerous ideologies taken while using the approach to solve diverse geotechnical issues. Craig [115] highlights four philosophies in which geotechnical centrifuge tests have been widely adopted to represent physical modelling. For example, the ability to model prototypes suggests that with geotechnical centrifuges, a model constructed with similar geometry and materials as the prototype can be tested at suitable increased gravity levels to achieve complete similarity in stresses and strains [118]. During centrifuge testing, the slope model is positioned at the edge of the centrifuge beam. The model is then put to an enhanced acceleration field more than the earth's gravity (g). This implies applying the centripetal acceleration of factor, Ng, to a reduced scale (1/N) model to replicate stresses in the prototype, 1 g [101]. Increasing the radius of the beam centrifuges enables the accomplishment of higher stress and strains for a model slope replicating various prototypes. This entails that replicating the prototype conditions requires deriving scaling relationships to achieve prototype parameters at a reduced scale. Figure 2 shows a schematic diagram of a geotechnical centrifuge.

Shaking Table Tests

A shaking table machine can simulate the dynamic loading imposed on the test model or structures. Japan and the USA were the first to develop shaking tables [119–121]. Over the years, there have been developments in improving the performance and capacity of shaking tables, leading to various types. Shaking tables are primarily classified depending on their method of vibration actuation, such as electrically driven, hydraulically driven and manually driven [122]. The shaking table is associated with earthquake loading conditions because many of its parameters, such as acceleration, displacement, frequency, and amplitude, are tailored to the parameters of an earthquake. Typically, test models are constructed to address the impacts of various factors and processes that contribute to the failure of prototypes in real time. It is noteworthy to indicate that if the model test is conducted

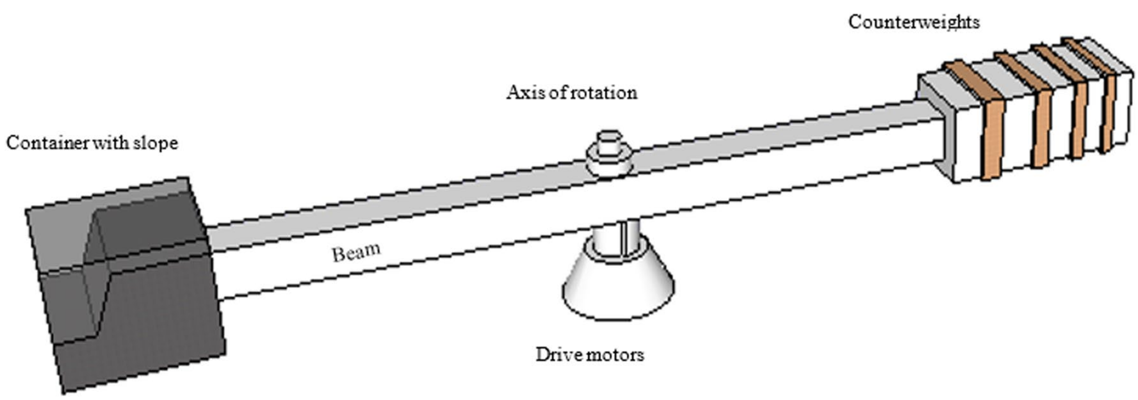


Fig. 2 Schematic diagram of a geotechnical centrifuge testing apparatus

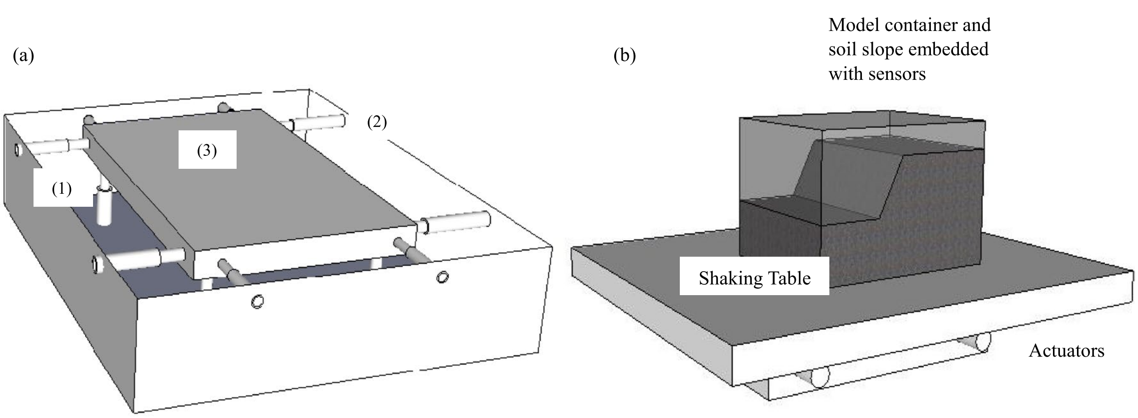


Fig. 3 Schematic diagram of a shaking table—**a** (1) vertical actuators, (2) horizontal actuators, (3) shaking table, and **b** shaking table with a slope model

in the earth's gravitational field, it is subjected to the shaking table test; however, when it is subjected to a greater gravitational field, it is under the centrifugal test. Therefore, the shaking table test is an experimental method for ensuring the validity of the theoretical estimate of the response of the geotechnical structure with its precise dynamic properties under dynamic loading conditions. In the shaking table test, specimens are carefully placed in a rigid container and fastened to the table using mechanical fasteners. The structure or model is then subjected to a procedure of shaking at a specified frequency level for a certain period. Shaking tables have gained usage globally, particularly in the simulation of seismic response of various research fields, including geohazards, structural stability, liquefaction analysis and earthquake engineering [123, 124]. Thus, shaking tables are often used for dynamic structural studies and might serve as an alternative to centrifuge testing.

With shaking table tests, nonlinearities in soil behaviour cannot be interpreted at scales considerably larger than 1 when the stress ratio is high. However, the shaking table test may be favoured at small scales, such as between 1 and 10, depending on the nature of the research under investigation. The equipment produces two to three translational components of motion, also called degrees of freedom: vertical, horizontal, and horizontal rotation. The performance key parameters of a shaking table include platform size ($L \times W$), maximum payload (ton), maximum horizontal displacement (mm), maximum horizontal acceleration (g), maximum vertical displacement (mm), maximum vertical acceleration (g), frequency range (Hz). Figure 3 shows a schematic diagram of a shaking table with an illustration of its loading mechanism;

Tilt tests

Tilt tests are among the early developments in physical modelling. Their working principle has been covered by Stimpson [125], Barton and Bandis [126] and was applied by Alejano et al. [127] to estimate the shear strength of natural unfilled rough joints. Khorasani et al. [14] used a tilt table apparatus initially developed by Amini et al. [104] for the analysis of multi-plane and toppling failures. Amini et al. [8, 128] later utilised it for the physical modelling of circular and slide-toe-toppling failure modes in soil and rocks, respectively. The concept, design and set-up of tilt test apparatus are extensively covered by Khorasani et al. [14] and Amini et al.[100]. The latter employed a tilt-table apparatus to investigate the slope stability of bimslopes whose results were validated using the FLAC3D finite difference code.

A tilt table consists of a platform that can tilt with an adjustable angular velocity. The model slope is built on the platform to investigate geotechnical phenomena such as slopes. The slope failure is induced by increasing the plane angle to the point of model failure. Based on the design by Amini et al. [104], the parts of a tiltable table include a horse, compressor, compressed air source and fitting, angular velocity control device, device to read tilt angle and transducer to record model displacements. The tilt table apparatus does not involve external loads, and the model is expected to fail under gravity. Therefore, models subjected to tilt tests are expected to be large enough to fail due to their gravity. Tilt tests can estimate the transition from stable to unstable slope angles. However, Samson et al.[38] report that its primary disadvantage is testing steeper slope angles greater than the stable-unstable transition threshold boundary, making it unsuitable for low-lying slope angles.

Flume Tests and Other Physical Testing Apparatus

The flume test apparatus generally comprises two major sections: initiation and deposition segments [129]. It is commonly used for landslide studies, particularly for clarifying failure evolution and stability of shallow landslides. Most studies applying the flume apparatus are linked to shallow landslides triggered by rainfall [15, 130] and granular flows [131]. For instance, Qui et al. [132] conducted laboratory flume tests to clarify the influence of rainfall duration and intensity on static and seismically exposed slopes. However, some authors design and construct customised physical modelling apparatus to investigate slope failure problems. For example, Pan et al. [133] built a large gravity physical model test system to examine the influence of chair-shaped bedrock surfaces on the reaction of an ancient landslide under rainfall and reservoir water fluctuation conditions. The physical simulation model test system consisted of a hydraulic control lifting system, artificial rainfall system, observation, and data acquisition system. Likewise, the influence of intermittent rainfall on the deformation and failure characteristics of gently dipping accumulation landslides was studied using a self-designed landslide model test bench facility [134]. The study captured displacement, earth pressure and porewater pressure data using porewater pressure sensors, displacement transducers, and an image capture system. Furthermore, Vivoda et al. [135] developed an apparatus to investigate the initiation of landslides subjected to artificial rainfall. The device was equipped with photographic equipment and a complex sensor network in the slope, with water outlets for regulating the water quantity during the test. In addition, a self-designed physical model apparatus was constructed by Fang et al. [136] to investigate the deformation characteristics of arching-type slopes with varying slope angles triggered by excavation.

Laboratory flume tests and self-designed physical modelling apparatus are more suited for examining the behaviour of shallow landslides coupled with rainfall effect. Generally, landslides occur in hilly and mountainous areas, commonly associated with a mixture of soil-rock. However, the literature indicates that the flume tests and these customised apparatus are widely made of slopes consisting of soil materials, ignoring the presence of rock, which is in significant quantities in mountainous regions. Nevertheless, these devices satisfactorily address drainage of the models, unlike in tilt test apparatus.

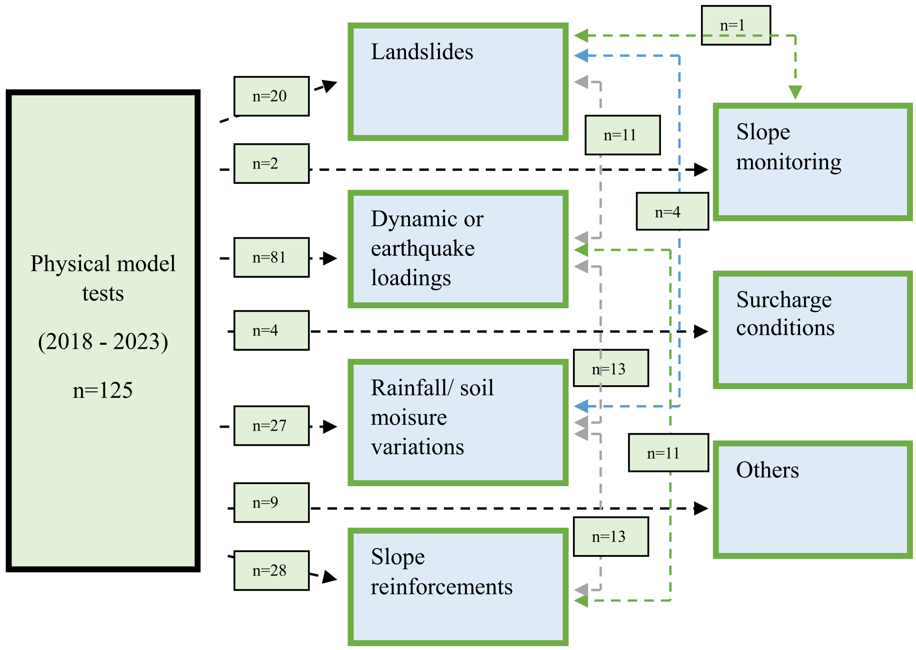
Discussion

Applications of Physical Model Tests in Slope Stability Studies

An overview of the studies cited in the preceding sections reveals the wide adoption of physical model tests in slope stability research. Physical model tests have found many applications in slope stability research and, hence, are receiving growing attention. Figure 4 presents a summary of the studies as captured by the search query during the years 2018 – 2023 regarding various applications of physical model tests in slope stability research – additional data is provided in Online Resource 9. The published articles have been classified based on the application in which the model test has been used. The figure shows the orientation of recent research outputs and the relevance of physical model tests. The category "slope monitoring" encompasses papers in which slope monitoring is the main objective or one of the objectives or where a large part of the research effort has been put into that aspect. Similarly, the same criterion has also been employed for the other categories, such as landslide, slope reinforcement, rainfall or water level variation-induced failures, dynamic/earthquake loading, and surcharge loading scenarios. The papers that have been categorized in the "others" constitute articles that have focussed on some aspects concerning slope materials, failure mechanisms, and advances in computational or analysis techniques.

The highest number of studies is on investigating the behaviour and response of slopes under dynamic loading conditions ($n = 81$), followed by the performance of various reinforcements ($n = 28$), and then the influence of

Fig. 4 Applications of physical model tests in slope stability studies



water variation in slope stability ($n=27$). Figure 4 also demonstrates a research progression in the coupling effect of rainfall and earthquakes on slope stability, as well as performance evaluation of different slope reinforcement mechanisms such as vegetation, piling, and geocomposites subjected to dynamic and precipitation conditions. Significant interlinks exist amongst these research themes where the physical model testing technique has been significantly applied.

Some of the emerging research areas are the coupling effect of earthquakes and landslides, earthquakes and water level variations. Earthquakes are widely known to be one of the main trigger factors of landslides. Therefore, there is an increasing research interest in evaluating the performance of various slopes under this joint effect. In fact, the current review shows that most scholars have utilised shaking table equipment in assessing the seismic performance and behaviour of slope reinforcement techniques under different loading conditions. Various trigger factors such as landslides, earthquakes, slopes made of weak materials, influence of water content variation and stability issues in the mining industry are presented. For example, Men et al. [123] determined the dynamic response of a landslide model reinforced with micro-piles and other non-reinforced materials via shaking table testing. The research findings indicate that micropiles make a substantial anti-seismic impact on landslides. Moreover, the utilisation of micropiles reduces the acceleration response on the slope surface, specifically near the slope toe. Similarly, Gang et al. [137] determined the seismic response of a slope strengthened with double-row anti-sliding piles and prestressed anchor cables using a series of shaking table tests. They reported that these reinforcements successfully inhibited the acceleration amplification. The study also noted that the maximum lateral earth pressure exerted on the slope toe anti-sliding pile's back is considerably greater than that exerted on the slope waist anti-sliding pile's back, indicating a load-sharing ratio that fluctuates between 2 and 5. A related study by Chen et al. [138] examined the impact of anti-slide piles exhibiting varying degrees of initial damage on the mechanisms of failure of steep and high slopes subjected to seismic loads. Research outcomes indicated that the deterioration of the slope behind high-quality anti-slide piles was limited to soil sliding on the slope's upper surface, slope sliding, and overburden sliding. Topsoil sliding, slope siding, and deep integral sliding reflected deterioration in the anti-slide pile's quality. A whole slip occurred along the slip belt as a result of the slope collapse in front of the pile. Physical modelling techniques have also been applied to investigate the behaviour and stability of geosynthetically and nail-reinforced slopes. For example, Bhattacherjee and Viswanadham [60] utilised a geotechnical centrifuge to examine the impact of an innovative hybrid geosynthetic material comprising woven geogrid and non-woven geotextile on a slope model subjected to rainfall conditions and its ability to perform drainage and reinforcement functions. The findings suggested that geosynthetics can effectively maintain the stability of slopes made from low-permeable soils. The study specifically reported an average of 47% reduction in excess porewater pressure values and attributed it to the geotextile component. Likewise, comparable results were also reported by Zhang et al. [139], who examined the long-term stability of expansive soil cut slopes reinforced with geogrid through two years of field testing and monitoring. According to the study findings, geogrid reinforcement effectively minimises the formation of cracks, reduces soil deformation, and reduces soil expansion pressure. Furthermore, a physical model approach was also employed by Ayazi et al. [140] to assess and contrast the performance of soil-nailed slopes constructed with various facing materials, including geotextile fabric, coir mat, bi-axial geogrid, and geomembrane. According to the study, soil-nailed slopes without any facing material exhibited lower failure stresses than those with facing material. The study demonstrated that incorporating flexible facing material into nailed slopes enhances their strength and minimises displacement entailing improved stability. Additionally, it was stated that coir mat offers the most optimal flexible facing material, as evidenced by its minimal deformations and higher strength. Viswanadham and Rotte [141] used a geotechnical centrifuge to investigate the deformation characteristics of soil-nailed slopes supported by flexible and rigid-facing type support systems under seepage conditions. The investigation reported that soil-nailed slopes with aluminium facing type support system exhibited positive results in terms of deformation characteristics and sustained significant displacements than soil-nailed slopes with oven geotextile facing. Likewise, Ramteke and Sahu [142] employed physical model experiments and numerical techniques to establish a correlation between nail inclination and slope stability in terms of deformation under surcharge loading conditions. According to the study, soil nailing is an effective method for stabilising the soil slopes, and a 15-degree inclination of the nails with respect to the horizontal plane yields the most favourable outcome in terms of slope stability and safety factor. Another study by Sengupta and Kumar [107] reported improvements in the deformation behaviour and factor of safety of a slope, which was reinforced by jute strips under the influence of rainfall with different intensities. These results agree with those of Saurabh and Roy [12], who used jute geotextile to improve the stability of embankments subjected to rainfall. Yoshida et al. [143] evaluated the performance of soil slope reinforced with plate and flip anchors. The model was subjected to vertical loads using a rigid plate on the surface of the slope. It was revealed that both flip and plate anchors provide effective reinforcement to improve soil slope stability. Liang et al. [144] utilised juvenile plant species; Willow and Festulolium grass, both grown for two months and Gorse grown for three months, to clarify the required scaling of vegetative reinforcement between prototype and model slopes. They compared their results to previously published findings with mature field-grown species, and assessed the contribution of these juvenile plants on soil shear strength increase and determined their tensile strength and Young's modulus. The empirical evidence supports the claim that the negative power law, which is frequently applied, inadequately describes the correlation between root tensile strength and root diameter ($R^2 < 0.14$). Furthermore, when an appropriate growing period of two months and scaling factor of fifteen was chosen, it was shown that prototype root systems potentially produced from juvenile plants using geotechnical centrifugation are highly representative of the corresponding mature root systems in terms of root morphology and root mechanical properties.

Besides, Zhang et al. [145] investigated the seismic instability of a sandy cutting slope subjected to intense seismic activity using a shaking table. It was revealed that the acceleration amplification factor, which is specified by the positive PGA (i.e. PGA > 0.4 g), is more suitable for assessing the amplification effect than the one specified by the negative PGA. Similarly, Chen et al. [146] utilized a shaking table to examine the characteristics of granular landslide deposits when exposed to seismic waves. The morphology of the deposit is reportedly greatly influenced by vibration frequency, with an increased frequency corresponding to larger displacement, breadth, thickness, and area of the deposit when the vibration orientation is horizontal. Using the Yangianshan iron mine as a case study, Yang et al. [68] presented three-dimensional physical modelling methods with realistic modelling of the mechanical behaviour of rock mass. The objective of the study was to examine the impact of prominent joints on the failure and deformation characteristics of rock slopes that undergo sequential excavation as a result of mining activities. The research findings indicate, among other things, that the failure processes of rock slopes are distinct from the trumpet-shaped subsidence that is characteristic of unconsolidated soils. Efficient methodologies for investigating mining-induced stratum and surface movement in jointed rock masses were devised and emphasised in the study. Although we note limited studies on the application of physical model tests in mining related research problems; physical model tests provides an option for validation of numerical solutions for most of the mining research. Thus, data collected from instrumentation of physical model tests can check the accuracy of results from other techniques such as numeriucal and analytical solutions. For example, Cao et al. [9] investigated the dynamic response and failure mode resulting from the coupling effect of rainfall and earthquake by employing model slopes with varying moisture contents. These slopes were subjected to dynamic loads and rainfall through the utilisation of a shaking table apparatus and a rainfall simulator, respectively. The acceleration response of the model was seen to be comparatively less when saturated moisture content was present, 14–24 per cent. According to the study, when the acceleration amplitudes of the EL Centro and Wenchuan are less than 0.33 g, the acceleration amplification coefficient (AAC) in bedrock increases with increasing earthquake amplitude. Additionally, the AAC in the highly weathered layer decreases with increasing elevation and earthquake amplitude.

In their study, Nguyen and Kawamura [10] examined the post-rain seismic behaviour of embankments built with volcanic coarse-grained soils. To do this, they subjected the embankments to dynamic loads using a shaking table and simulated rainfall using spray nozzles. The findings suggested that water retention conditions inside the slope and rainfall-induced residual pore-water pressure are significant factors in determining the seismic stability of embankments in the aftermath of earthquakes. Likewise, Capparelli et al. [147] investigated the infiltration of rainfall, with variable intensity, into a sloping layered volcanoclastic deposit comprised of a pumice layer interbedded within ash layers. To clarify the effect of flow direction on slope stability, Capparelli utilized physical model tests. The results implied that for practical slopes, it is unlikely that the presence of coarse layers of pumices might induce the establishment of significant downslope subsurface drainage or the attainment of saturation in the overlying fine layers to trigger landslides in slopes with such geological formations. In their investigation, Yu et al. [148] utilised shaking table experiments to ascertain the dynamic behaviour of loess-mudstone slopes (LMS) with an anti-dip fault. According to the study, the acceleration amplification factor (AAF) was greater in loess than in mudstone and rose from the bottom to the top of the LMS. They also noted that a peak acceleration of 0.3 g is crucial for slope seismic dynamic response and failure. Similarly, Chen et al. [149] used a rain simulator and a shaking table to examine the dynamic properties of low-angle loess slopes that were exposed to rainfall before an earthquake. The research specifically examined the responses and clarified the distinctions in the manner of failure of the low-angle slope in response to varying rainfall intensities. The study reported that the acceleration amplification effect increased with increasing intensity, and the soil pressure increased with decreasing elevation under the long-term effects of rainfall before the earthquake. However, the value on the slope surface decreased under the short-term impacts of rainfall before an earthquake.

There are complexities associated with rainfall simulation when utilising geotechnical centrifuges, possibly because of space limitation, the Coriolis effect, slope surface erosion and the destruction of the slope surface due to the raindrop impacts. For example, the use of mist nozzles appears to be the most adopted and recommended technique in simulating rainfall in order to minimise damage which is caused to the slope surface when standard nozzles are used. Uniform rainfall is difficult to generate when nozzles are used because they cover a circular area. Thus, in the enhanced acceleration field, nozzles often produce a core zone with a higher rainfall intensity than the outside areas [4]. Similarly, the application of atmospheric chambers, as highlighted by Ng et al. [114], does not fully replicate rainfall conditions because the approach is based on increasing the humidity to induce porewater pressure increments within the soil voids. However, Wang et al. [4] proposed a simple rainfall device for application of physical modelling tests in a geotechnical centrifuge environment. The device, free of pressurised water connections and generating mist nozzles, was able to provide uniform rainfall with a wide spectrum of rainfall intensities (2.5 – 30 mm/hr). Additionally, Bhattacherjee and Viswanadham [117] addressed the Coriolis effect on droplet trajectory when simulating rainfall on a slope in a geotechnical centrifuge. The rainfall simulator was able to produce rainfall in the form of mist, thereby minimising slope erosion. These studies indicate a need to develop additional options and better techniques for simulating rainfall for physical modelling experiments to overcome and address challenges associated with the current approaches.

Although the preceding discussion indicates numerous studies on the application of physical modelling tests in slope stability research. In terms of reinforcement applications, we note that insufficient attention is given to the performance of slopes reinforced with multiple anti-slide piles undergoing deterioration due to repeated seismic loads. One of the few studies was conducted by Chen et al. [138]. The cumulative influence of the structurally damaged piles on slope stability over time needs to be quantified for the purpose of monitoring overall slope stability. We also note that research on the influence of vegetation on slope stability is complex because of the multiple and changing relationships between vegetation and the immediate environment, making it difficult to have full control of some variables. However, well-instrumented physical model tests have simplified the complexity of such research due to the ability to collect real-time data. Thus, the influence of water losses through transpiration and evaporation when vegetative or plant root reinforcement is used has been neglected in the majority of the studies. Furthermore, the strength degradation of slope reinforcements due to repeated loading conditions has not been adequately studied. For example, interactions between slope materials and reinforcements due to load transfer mechanisms potentially affect the entire slope-reinforcement system. These interactions vary and affect reinforcements differently for each phenomenon. On model preparation, first, we note that the influence of boundary effects on failure plane development and propagation is not accounted for. Most scholars ignore the impact of boundary effects on selected sides of the model container on the orientation of the failure plane when the model is subjected to loads. Besides, most scholars prefer preparation of slope materials by the addition of different types of cohesive materials such as cement, lime, gypsum, barite powder, kaolinite and others in various proportions to achieve the desired engineering properties of the prototype slope. However, other techniques, such as desiccation and bio-cementation methods, which simulate the long-term exposure of the slope material, are not being adopted and advanced. Apparently, repeated wetting and drying can induce bond recreation, stiffness and strength development in some soils. For example, Liu et al. [80] reported improvements in the stiffness of granitic residual soils, whereas other scholars have reported a decrease in strength [150], suggesting a variation in the behaviour of soils at different wetting and drying cycles. Additionally, detailed presentation on the preparation of cohesive beds, particularly on studies involving slope instability of embankments, is lacking, as evidenced elsewhere [151–153]. It is necessary that in such studies, the preparation of cohesive beds (stiff or soft) needs to be clarified, particularly where reinforcements or foundations are embedded into the slope.

Comparison of the Use of Physical Modelling Apparatus

The present study reveals that slope stability research significantly uses physical model tests. For example, 56.63% (n = 339) were considered relevant based on the application of various types of physical modelling apparatus. As shown in Fig. 5 and detailed data provided in Online Resource 10, 55% ($n = 106$) of the studies used a shaking table test, followed by self-designed physical model apparatus, 18% ($n = 35$) and then centrifuge model tests, 16% ($n = 30$).

The lead in the use of the shaking table test apparatus could be attributed to its advantages, such as well-controlled large amplitude, multi-axis input motions and easier experimental measurements [154]. Shaking table tests are mainly used to validate numerical models or vice-versa and when the failure mechanisms of geotechnical infrastructure are of interest [155, 156]. However, higher gravitational stresses cannot be reproduced in a shaking table test [34]. On the other hand, the geotechnical centrifuge apparatus is capable of replicating the stress–strain states of soil. This is achieved by subjecting the model to an elevated gravitational acceleration provided by the centripetal acceleration ($R\omega^2 = \text{ng}$), where R is the radius and ω is the angular velocity of the centrifuge [154]. Comparatively, the leading use of shaking table apparatus revealed in this study is also highlighted elsewhere [157, 158]. Additionally, the design and development of customised physical model apparatus is receiving significant adoption, as indicated by the findings from this study and others [159, 160]. For example, most of the self-designed equipment addresses slope reinforcements [83, 100], slope failure evolution and behaviour of slopes [161, 162], excavation-induced slope failures [24, 136], static and surcharge loading [163, 164], landslide monitoring [165].

Numerical Approaches

Numerous numerical methods have been developed to investigate the stability of soil and rock slopes, such as those discussed by [166, 167]. Possibly due to their simplicity, Limit Equilibrium Methods (LEMs) have been widely adopted by the geotechnical community. In the category of LEMs, several methods exist, such as those by Bishop [168], Morgenstern and Price [169], Janbu [170], and Sarma [171]. In particular, LEMs assume the slope's failure surface and use the static equilibrium concept to evaluate the system.

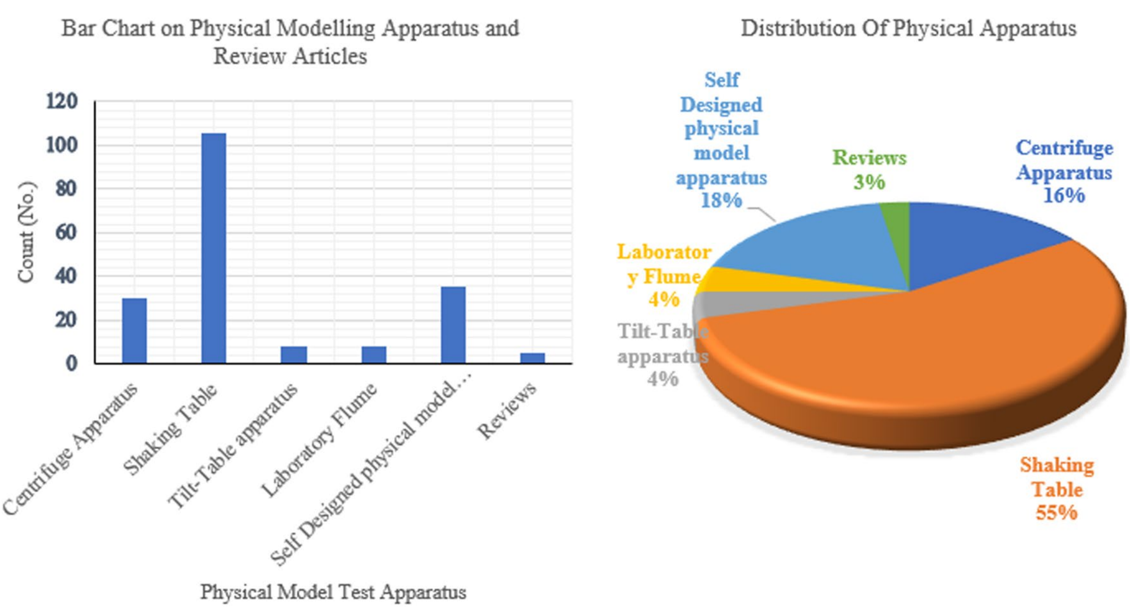


Fig. 5 Usage comparison for various physical modelling apparatus

With LEMs, the sliding mass is divided into equal slices, and each slice's equilibrium of force, moment, or combination is satisfied. Mohr Coloumb failure criterion is applied to calculate the safety factor. As highlighted by Pasternack and Gao [172], some of the disadvantages of LEM methods include: (a) the normal stresses on the potential failure surface are determined using arbitrary assumptions to meet a condition of static equilibrium but do not reflect the relationship with the actual stresses, (b) they do not address the development and propagation of slope failure, (c) failure plane is assumed. Consequently, other numerical techniques were developed to address the limitations of LEMs. These methods can analyse complex geometries, loading schemes, materials properties and models. According to Sinha and Walton [173] and Zheng et al. [174], numerical methods are categorised into two broad families, namely continuum-based methods (CM) and discontinuum-based methods (DM). CM treats soil mass as a continuous material in evaluating factors influencing slope failure. Continuum methods are limited in capturing and evaluating influential geomechanics properties such as joints and faults; hence, the methods are unsuitable when these properties are critical. Two commonly used methods under CM include Finite Element Methods (FEM) and Finite Difference Methods (FDM). On the other hand, DMs are more applicable to slope stability problems with complex geological conditions or when the slope's behaviour is governed by structural features such as rock joints, faults and bedding planes. Therefore, DM can reflect the influence of structural features on slope behaviour, and its use requires detailed rock mass properties information such as fracture orientation and discontinuity properties.

With regards to slope stability studies, the application of numerical solutions addresses several issues in the profession, including the ability to visualise and provide a better perception of the behaviour of geomaterials under varying loading conditions and minimise funding requirements associated with comprehensive field and laboratory experiments. Numerical simulation is an effective and economical tool for revealing mechanical behaviour and solving geotechnical problems [175]. In most cases, numerical methods are conducted to supplement or compare with other solutions, such as physical tests or analytical solutions [124, 176]. This research reveals extensive utilisation of numerical methods alongside physical modelling. This is illustrated in Table 5, which presents a summary of existing numerical methods that have been used as extracted from the database.

The present research gives insights into the wide use of FEM in slope stability studies. In particular, more studies have used the finite element program PLAXIS. For example, Munawir [79], Yoshida et al. [138] and Rawat and Gupta [156] employed the FEM using the PLAXIS software program alongside physical model tests in slope stability investigations. PLAXIS can handle various geotechnical issues, including tunnels, deep excavations, earth structures, retaining walls, and slopes [183]. Notably, the database reveals a significant number of researchers [184–188] implementing the FDM using FLAC2D/3D computer program. Likewise, Geostudio software based on the FEM has also been

Table 5 Selected studies utilising numerical modellings alongside physical model tests

Broad Category	Method	Application in Physical Model Studies
LEM	Fellinius, Bishop, Janbu, Morgenstern and Price, Spencer, Sarma	Geostudio programmes (Seep/W and Slope/W) were used for a parametric study whose results were validated by a geotechnical centrifuge [177]. Likewise, Aqib et al. [152] used a Geo-studio program to clarify the effect of vegetation, degree of compaction and rainfall intensity on railway embankment of semi-high speed trains. Other studies using Geostudio include [12, 57]. Rajabian and Viswanadham [90] used SLIDE software to supplement results obtained from centrifuge tests
CM	FDM	Nasiri and Hajiazizi[153] investigated the performance of geotextile-encased stone columns on sandy embankments using the finite difference method. Likewise, centrifuge tests and FLAC 2D simulation were used to investigate the amplification effects and deformation conditions in a dormant loess-mudstone landslide [176]. Dynamic response and failure mode were also investigated using shaking table tests and FLAC3D [178]
	FEM)	Sobhanmanesh et al. [151] proposed a numerical simulation using PLAXIS 2D based on the dimensions of a centrifugal model under varying incremental acceleration fields. Clayey sand was used as slope material. Similarly, PLAXIS 2D was also used by Liang et al. [179] in modelling the performance of vegetated slopes
DM	Discrete Element Methods (DEM)	Slide-head-toppling failure was investigated using tilt tests and verified by Universal Distinct Element Code (UDEC) software [64]. UDEC was also adopted by Deng et al. [180] to study the dynamic stability evaluation of bedding rock under repeated micro-seisms. Other studies using DEM include [68, 98, 181]
	DDA	2-D numerical mode of DDA method was adopted by Irie et al. [182] alongside shaking table tests to investigate the effect of shear resistance on landslide mechanisms. Similarly, Feng et al. [62] used it to study the dynamic response of anti-dip rock slope

Table 6 Comparison of results from physical and numerical simulations for selected studies

References	Numerical Simulation	Physical Model Test	Comparative Output
[37]	PLAXIS 2D	Full-scale landslide flume test conducted by [192]	The review reports that the FOS from the numerical simulation dropped below 1 (i.e. FOS = 0.97) at the same time the slope failed in the experiment, suggesting agreement with the results
[57]	SLOPE/W	Centrifuge models	The FOS analysis by Bishop, Morgestern-Prince and Spencer were all in agreement with the observations made in the geotechnical centrifuge
[187]	FLAC3D	Shaking table tests	The failure pattern and mechanisms in the numerical and physical models were close, i.e. the length of crack propagation and sliding shear plane, respectively
[182]	DDA simulation	Shaking table tests	The DDA simulation results agreed well with the ones obtained from the laboratory shaking table tests
[153]	3D finite Difference method (3DFDM)	A laboratory scale slope model box	The comparison of loads at failure for the numerical model and physical test differed by 4.4%, i.e. the load at failure for the experimental model was 10.04 kPa. For numerical analysis, it was 9.61, indicating close agreement
[181]	LEM and DEM (implemented using particle flow code, PFC3D)	A laboratory scale slope model box	Similar in the location of the sliding failure surfaces between the physical model tests and numerical simulations
[188]	FLAC3D	Shaking table tests	There are similarities in failure mechanisms implemented in both the FLAC simulation and the physical model test
[98]	UDEC	Tilt tests	Agreement in failure characteristics (rotational bi-planar sliding shear failure)
[90]	SLIDE software (rocscience 2005)	Centrifuge model tests	Numerical simulations (Modified Bishop, Modified Janbu, Spencer, Morgenstern-Price) gave an FOS around 1, which was in good agreement with observations from physical model tests
[100]	Finite Difference programme (implemented by the Strength Reduction Method)	A laboratory scale slope model box	Results obtained from numerical models were similar to those from physical model tests; a close agreement in soil displacement values was noted

significantly used in these studies [57, 107, 113, 189]. Using Geoslope, SEEP/W is primarily employed for seepage analysis, whereas SIGMA/W has been employed for stability analysis.

Comparison of Numerical and Physical Modelling Results

The present study indicates that the application of both physical and numerical techniques in slope stability research has been in existence for more than a decade. Scholars[138, 190, 191] report that model tests and numerical simulations are common research methods in slope instability studies. However, it is important to relate the results obtained from these techniques when they have been used in the same study so that their credibility is checked. Therefore, the comparison of results from physical and numerical modelling techniques for various studies is key because it provides a guide on the suitability of various numerical solutions for specific research problems. This is achieved by exposing the trends, disparities and agreements in results for key parameters to guide the reliability of such approaches. In slope stability studies involving physical and numerical modelling, such validity checks are done by comparing failure mechanisms, patterns and factors of safety (FOS) in the physical and numerical simulations. Failure of the physical model implies a factor of safety (FOS) of less than 1, and stability indicates otherwise. Table 6 presents a comparison of results for selected studies in this work.

Limitations of the Review and Future Research Areas

The review has comprehensively covered the developments, practices, considerations, merits and demerits of physical modelling test techniques used in slope stability; however, it also has some limitations. For example, the articles have been extracted from the Scopus database, ignoring other databases such as Web of Science and Google Scholar. This suggests a possibility of leaving relevant sources out of the study. Additionally, the keywords used in the search engine to collect the articles do not guarantee retrieval of all relevant articles. Finally, excluding non-English articles limits all the results to one language; however, consideration of other languages could increase the number of articles to be included in the review.

The review highlights the following gaps in the literature and recommends the following areas for further studies;

(a) There is a lack of research on the physical modelling of tropical residual soils, which is inherent in countries experiencing tropical climates. This is despite the complex behaviour of tropical residual soils.
(b) Further studies are required to improve the understanding of the influence of water content variation on the bonding structure of selected soils, such as tropical residual soils. The closest study by Yang et al. [81] investigated the effect of variation of moisture content in unsaturated soil slopes (they used sandy clay, USCS classification) under dynamic loading conditions.
(c) Other techniques, such as desiccation and bio-cementation, should be explored in recreating the bonding structure of soil slopes to simulate the natural environment to which the slopes are subjected. It is evident that the current practice is to develop model slope materials artificially. However, the prolonged behaviour of such materials in the natural environment, for example, recurrent wetting and drying, is not considered. The closest study by Postill et al. [193] investigated the progressive failure of clay slopes due to seasonal ratcheting.
(d) Studies on the coupling effect of rainfall and earthquakes for tropical residual soils should be conducted.
(e) There are limited studies validating physical model tests using two or more numerical solutions to improve the results' acceptability and reliability.
(f) There is a need for comparative studies on the performance of various data-capturing sensors commonly used in physical modelling studies.
(g) There are limited studies on understanding the application of vegetation as a slope reinforcement technique considering water uptake or loss and its effect on matric suction and soil shear strength. Based on the database, the closest study was conducted by Ng et al. [113].

Conclusion

The systematic review has highlighted the developments, considerations, and practices many researchers adopt when conducting slope stability studies using physical model tests. The systematic review has involved the analysis of 192 articles which have utilised physical model tests and extracted relevant data to address the objectives of this review.

There is research progress towards the use of vegetation for slope reinforcement; however, we note that there are some grey areas requiring further research in the spirit of promoting "green technology" engineering solutions. For example, minimal studies are available on the influence of transpiration, evaporation and other water losses in soil/rock slopes on porewater variations and regimes, matric suction and soil bonding and their respective effects on slope stability. Additionally, there are inadequate studies on the strength degradation of reinforcements and slopes subjected to repeated loading conditions and how such exposures affect the future performance of the same.

Furthermore, most researchers have utilised the mixing of various types of soils or the addition of additives such as lime, kaolinite, barite powder, cement, gypsum, iron powder and others in the development of artificial soil slope materials or the manufacturing of rock blocks to mimic practical slope materials. Whereas these approaches deal with disturbed slope material, we observe that other methods of replicating undisturbed soil slope structures targeting inherent engineering features such as cementation and bonding are not being adopted. Although wetting and drying cycles replicate the natural environment of slopes, there are very few slope stability applying physical modelling tests adopting the strength development of reconstituted soils using this approach. Additionally, we have noted that most of the scholars have targetted strength and geological structure replications with limited attention to other relevant parameters such as permeability of slope material, which significantly affects groundwater regimes, porewater pressure and saturation status, which are pertinent parameters of slope stability studies.

Finally, despite the fact that the foam material is usually used on the boundary containers to minimise the influence of boundary conditions on the accuracy of test results, further attention is required in selecting foam thickness for various test container sizes to improve the quality of studies. This concern also borders on the extent of attenuation or the damping ability of these foams, particularly for physical model tests involving dynamic loads. The boundary materials, particularly foams, also absorb water, affecting the desired moisture content of the model. None of the studies has paid particular attention or taken into account moisture absorption by the foam material. Furthermore, the difference in stiffness between the foam and slope materials induces stresses between the boundary material and the slope material. This causes "biases" in the orientation, development and propagation of failure planes within the slope particularly when the flexible boundaries are used in selected container sides. It is important that this effect should be taken into account when flexible boundaries are used on selected sides of container boundaries.

Therefore, the present study will help researchers interested in using physical modelling in designing their studies and consider the areas that have not been adequately addressed. In particular, physical modelling allows one to sufficiently study the application and influence of external factors, such as vegetation and reinforcements, which may not be well addressed with numerical solutions. In return, this will advance understanding of slope behaviour and performance under various loading conditions and help progress the agenda of slope failure prediction and development of early warning systems.

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Declarations

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