Indian Geotech J (June 2024) 54(3):741–752
https://doi.org/10.1007/s40098-023-00848-8

STATE OF THE ART/PRACTICE PAPER

An Appraisal of the Mechanism and Research Development Status of Anti-slide Piles as Effective Technique for Landslide Risk Reduction

Dani Jose[1] · **Sreevalsa Kolathayar**[1] · **Sitaram Nayak**[1]

Received: 3 August 2023 / Accepted: 18 December 2023 / Published online: 19 January 2024

Abstract The increased frequency of landslides and associated devastations necessitates developing sustainable mitigation measures. The present paper aims to appraise the research developments in enhancing slope stability using anti-slide piles for landslide mitigation. The previous researchers made an immense effort to identify the soil–structure interaction of the anti-slide pile. The soil arching between the piles was identified as the soil–pile interaction mechanism. A detailed review of the soil arching between the piles is performed, and the observations are presented in detail. Recently, different sustainable methods for the analysis and design of anti-slide piles have been developed. An attempt was made to carry out a comprehensive review of the analysis methods and their critical features, and the observations are provided. The parameters affecting the performance of the anti-slide piles were identified, and the influence of those parameters on the behavior of piles is also discussed. Finally, the novel designs developed by researchers to overcome the limitations of conventional anti-slide piles and the utilization of sustainable materials as anti-slide piles were appreciated. The authors like to highlight that anti-slide piles are an effective solution for landslide risk reduction, and there is further scope for research in this field.

✉ Dani Jose
danijose92@gmail.com

Sreevalsa Kolathayar
sreevalsa@nitk.edu.in

Sitaram Nayak
snayak@nitk.edu.in

[1] Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, Karnataka 575025, India

Keywords Landslide · Anti-slide pile · Soil arching · Soil–pile interaction

Introduction

A landslide is a disastrous geo-hazard that can significantly impact a country's socioeconomic aspect. Landslides usually trigger without warning, giving people less time to evacuate, thus leading to a large number of causalities and deaths as well as massive destruction of infrastructure and property. Along with natural factors such as rainfall, earthquakes, etc., and illegal human intervention in the form of deforestation, obstructing natural drainage and land encroachment, steep slopes, and fragmented rocks can also contribute to the triggering of landslides [1]. In India, the mountainous regions of the Himalayas, Western Ghats and Eastern Ghats, and Northeastern hilly regions are exposed to landslides caused by several factors like natural denudation process, geology, relief, morphology, etc.

The stability of the slope, owing to the balance between driving and resisting forces, plays a vital role in the formation and development of landslides. The mobilized shear strength of the slope is generally developed from the reactionary stresses which resist the driving shear stress [2]. The mechanism behind the failure of a natural slope involves a complicated interaction between geotechnical and hydrological processes, which relies on the hydrological and geotechnical properties, boundary conditions, nature of the primary slope, and topographical deformities [3]. The slope stability can be enhanced either by decreasing the driving force or by increasing the resisting force, or implementing both. Resisting forces can be increased by the stabilization of soil by compacting the soil, adding stabilizing agents like lime, cement, fly ash, fibers, etc., and by using soil retaining structures and ground reinforcements. Slide-resisting piles such as anti-slide and micro-anti-slide piles are widely applied for slide resistance. These piles provided at equal spacing will anchor the unstable top layer to the stable deeper layer and transfer the body and shear forces in the sliding mass to the stable strata. The strong slide-resisting capability, excellent retaining effect, flexibility in arrangement, different forms, and established construction technology make anti-slide pile suitable for different projects [4, 5]. The laterally loaded piles can be categorized into 'passive piles' and 'active piles' according to De Beer [6]. In active piles, the lateral loads are induced by the superstructure, while for passive piles, it is developed by the horizontal soil movement due to eccentric loading and the unloading of the ground surface surrounding the piles.

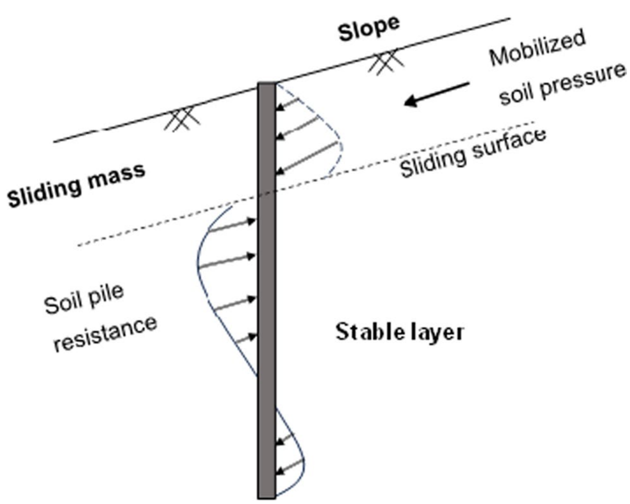

Fig. 1 Force transmission through the anti-slide pile (Redrawn by authors after Ashour and Ardalan [8])

Anti-slide piles have been successfully implemented for stabilizing slopes in different regions of the world since 1930. Countries, like China and Japan, have successfully implemented anti-slide piles for treating landslides. The anti-slide piles are installed through the unstable soil layer at a significantly larger spacing than their diameter and are embedded below the potential sliding surface in the underlying stable soil layer. Individual piles behave as a linear discrete structure that can transfer part of lateral pressure from the unstable strata to the underlying stable layer without subjecting the surrounding soil to failure [7]. The landslide thrust acting in the sliding soil mass above the slip surface is transmitted to the lower stable layers, as shown in Fig. 1.

Different types of conventional anti-slide piles used for slope stabilization are shown in Fig. 2. The common anti-slide piles are used for controlling small and medium landslides and at locations without space restrictions. The anchored anti-slide piles can resist medium and large landslides and can even be adopted at locations with space restrictions. Combined piles are adopted for resisting large landslides when sufficient anchorage rock is unavailable.

To adapt to the varying geological conditions and engineering requirements, researchers have developed different forms of anti-slide piles, such as the anchor cable anti-slide pile, the prestressed anti-slide pile, the h-type pile, and the arm-stretching-type pile [9–12].

Compared with other slide-resisting structures, the anti-slide pile has many advantages. It has excellent slide resistance and supporting effect and offers little disturbance to the slopes during construction. The pile groups can also be

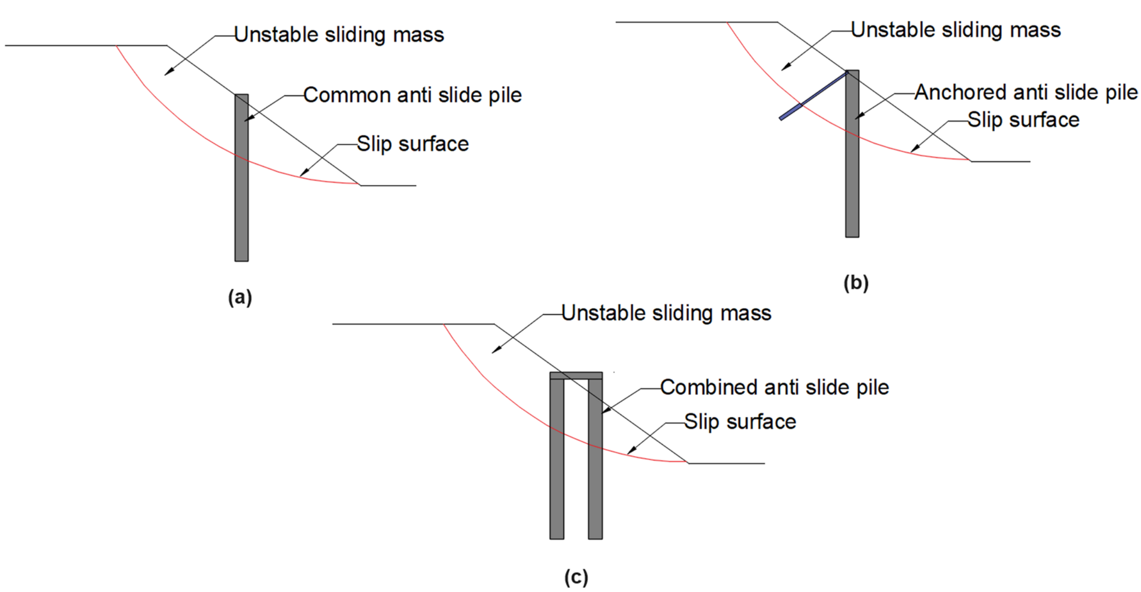

Fig. 2 Different types of anti-slide piles: **a** Common anti-slide pile, **b** Anchored anti-slide pile, **c** Combined anti-slide pile

installed simultaneously with more working area by reducing the interference and making the excavation and construction more convenient [13]. In addition to the advantages mentioned above, some disadvantages were also observed by researchers. The introduction of single-row anti-slide piles was found to be ineffective in controlling large-scale landslides [14]. It is challenging to implement anti-slide piles in projects demanding strict control over displacement. Anti-slide piles to stabilize slope is widely accepted and successfully implemented to improve slope stability in various places by overcoming its disadvantages. Much research took place to identify the mechanism and develop novel designs to satisfy the engineering requirements. The present paper attempts to appreciate the studies carried out on anti-slide piles with a prime focus on the soil–pile interaction and the methods of designing anti-slide piles. A detailed observation of the parameters affecting the performance of anti-slide piles was conducted and presented in detail. The paper also explored the novel designs of anti-slide piles developed by researchers and the latest innovations leading toward sustainability. The paper also suggests some significant research areas that must be exploited further.

Anti-slide Pile–Soil Interaction

The anti-slide pile–soil interaction is a complex phenomenon due to its three-dimensional nature, and the strength and deformation parameters of both pile and soil can influence this interaction [8]. The anti-slide pile–soil interaction can be well explained using the phenomena of the soil arching introduced by Terzaghi [15]. The soil mass slides under the action of landslide thrust, and the presence of anti-slide piles obstructs the soil movement, leading to a lack of synchronization in the displacement of soil between the piles and behind the piles. As a result, the soil between the piles forms a soil arch, which transfers the earth pressure to the pile as axial force and prevents soil flow between the piles [16]. The force transmission mechanism of the soil arch is shown in Fig. 3. Many researchers studied the effect of soil arching in anti-slide piles through numerical methods, theoretical derivations, and experimental methods. Ito and Matsui developed an analytical procedure to derive closed-form equations for calculating earth pressure experienced by the soil between the piles [17]. The results obtained from the study were helpful in understanding the arching effects in a better way.

Adachi et al. simulated the trap door test using a set of laboratory model tests and analyses using the finite element method with the imaginary viscosity method and explained the soil arching mechanism in granular soils. In the opinion of authors in granular soils, the backside pressure does not have control of the points in the arching zone (B, C, D), and the pressure acting on the front side of circular piles is less than that of equivalent rectangular piles due to the presence of an arching foothold (Zone 1) as shown in Fig. 4 [18].

The generation, propagation, and fracture mechanism of the soil arch developed was explained by Chen et al. as follows. A localized compressive zone originated in the pile backside when the landslide thrust and corresponding relative displacement are small. Once the landslide thrust increases, the compressive zone expands, and the corresponding deformation also increases. The friction between the pile and soil will restrict the relative horizontal displacement of the soil, which will lead to the generation of soil arch between the sides. The relative displacement of the soil between piles increases with the increase in landslide thrust. A soil arch is developed at the backside to resist the thrust and compensate for the soil's limited bearing capacity. The soil arch at the backside densifies owing to the compression as the landslide thrust increases. Also, an increase in relative displacement of the soil between the pile sides is observed. Gradually, cracks and fissures will occur along the arch, and ultimately, it fails due to the limited bearing capacity of the soil. Once the thrust of the slide exceeds the ultimate bearing capacity of the soil behind the pile, cracks and fissures

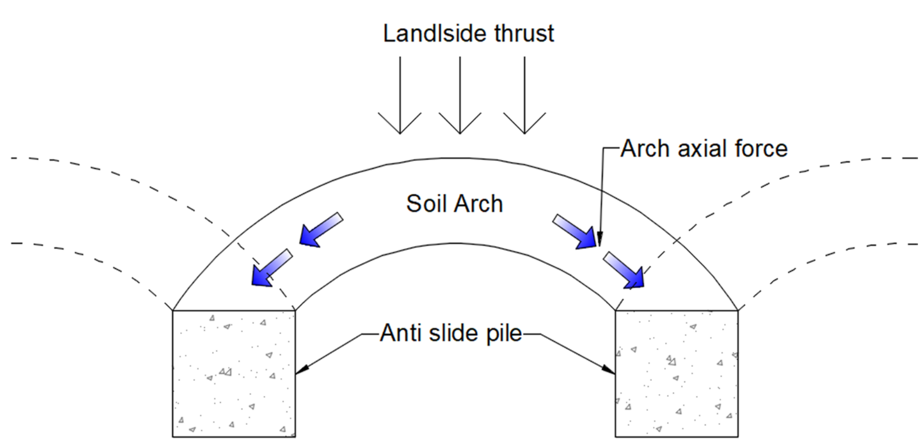

Fig. 3 Force transmission mechanism of soil arch (Redrawn by authors after Zhang et al. [16])

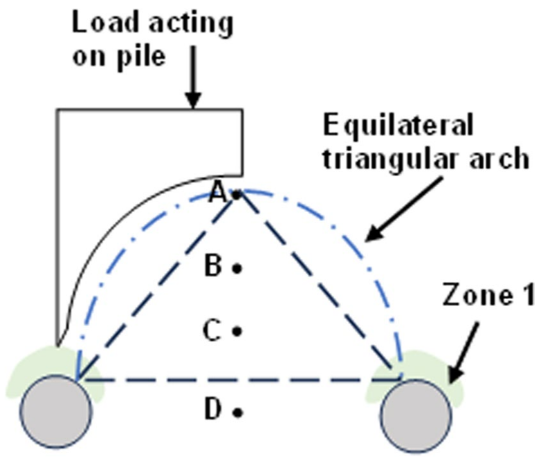

Fig. 4 Soil arching in granular soils (Redrawn by authors after Adachi et al. [18])

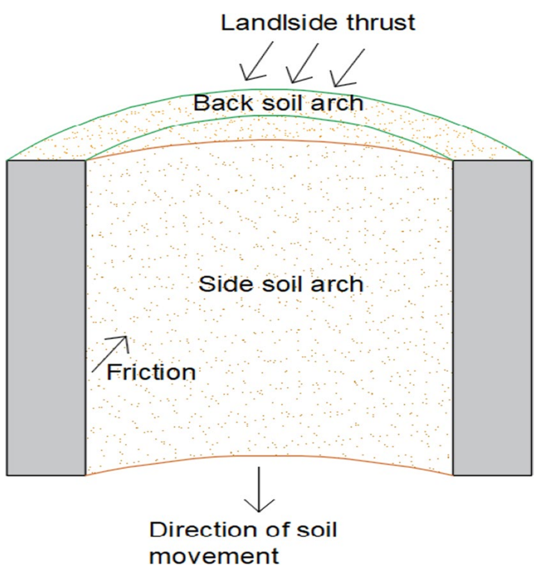

Fig. 5 The soil arch (Redrawn by authors after Chen et al. [19])

develop in the soil arch at the backside, and finally, the soil arching effect will fail completely [19]. The generated soil arches on the backside and between sides of the pile are shown in Fig. 5.

In order to incorporate soil arching in the stability analysis of slope and in the design of stabilized slopes, an extensive study on the conditions for the development of soil arching is required. Liang and Zeng performed a numerical study using the finite element method for analyzing the soil arching mechanism associated with drilled shafts. The load transfer characteristics are examined based on the relative motion between the soil mass and drilled shafts using the load transfer curves. The pile spacing, diameter and shape of the pile, angle of internal friction of cohesion less soil, and the cohesion of cohesive soil are the parameters addressed to investigate the influence on the soil. The ratio of pile spacing to the diameter of the pile was observed as the most important design parameter influencing the development of the intense arching effect. The cohesionless soil with a large friction angle will generate higher interlocking and strong arching, while for cohesive soil, a smaller cohesion value will favor the development of strong soil arches. The paper also agrees well with the numerical predictions and the previous experimental data, indicating that the finite element modeling techniques can effectively depict the soil arching mechanism [20]. Soil arching around pile groups subjected to lateral loading in granular soils and fine-grained soils was examined by Chen and Martin using the finite difference method under different soil conditions. The stress transfer from the soil to the pile is discussed by linking the pile displacement curve with the soil arching effect. The development and shape of the zone of arching depend on pile arrangement, the relative displacement between the pile and the soil, the shape of the pile, the soil dilation angle, and the interface roughness. The authors observed a double arching effect for the undrained soil condition with no dilatancy, where the stress arches around an elastic zone in front of the piles and between two piles. The increased soil dilatancy will enhance the volume around the pile while the rougher interface accelerates the arch formation. Pile group effects were observed significantly in granular soils, and the authors observed no significative effects in fine-grained soils [21]. Zhang et al. described the mechanism of pile reinforcement by explaining the evolution and propagation of two concepts: the compression effect and the anti-shear effect. To investigate the reinforcement mechanism, the authors conducted multiple centrifuge model tests on unreinforced and reinforced slopes of silty clay subjected to self-weight and vertical loads. The reinforcement effect was significant, and the compression effect was predominant in the pile vicinities. The compression effect advances upward in the slope and leads to the formation of an anti-shear effect. Near the potential slip surface in the slopes without reinforcement, the anti-shear effect predominated. [22]. Zhang et al. analyzed the parameters influencing the arching effect in the anchored anti-slide pile using model studies and numerical simulation techniques and described the evolution of the soil arch. The authors designed an indoor model test and utilized advanced digital deformation measurement technology to analyze the displacement and shear stress variations. The authors divide the soil arching mechanism behind the anti-slide pile into three stages. The first stage is the initial stage; during the second stage, the development and formation of soil arches occur, and the failure and reformation of soil arches take place during the third stage. During the initial stage, the sliding movement of soil behind the piles will be resisted by the anti-slide piles, while the soil within the piles will advance in the direction of thrust. A stable arch foot will develop since the contact force among the soil particles is increasing due to the compaction of soil resulting from these relative displacements. During the development and formation of soil arches, the relative displacement and contact forces increase further, and a stable soil arch will form. An increase in soil particle contact force and a strengthening of the soil arch effect were observed during the third stage. The soil surrounding the pile will fail when the earth pressure increases and reaches a limiting value due to the increase in sliding thrust. The soil arch will temporarily sustain damage at this point, but the soil arch will still be intact because a part of the load is transferred to the arch axis. A new soil arch capable of withstanding the increasing thrust will ultimately form. The arch formation can be improved by increasing the particle size, the particle friction coefficient, and the corresponding soil void ratio [9]. Most of the researchers explain the soil–pile interaction mechanism with the aid of soil arching. The mechanism proposed by Zhang et al. introduces a reformation stage for soil arches over the mechanism proposed by Chen et al. This reformation stage in the pile–soil interaction mechanism makes anti-slide piles stable over heavy landslide thrust and can be recommended for various projects.

Stability Analysis of Slope Reinforced with Anti-slide Piles

Efficacious designs of anti-slide piles rely on the soil pressure distribution above the piles [23]. Based on the available literature, the analysis methods of passive piles can be categorized into three: (1) pressure-based method, (2) displacement-based method, and (3) continuum-based method [24]. The pressure-based method was developed owing to the theory put forward by Ito and Matsui [17]. This method does not consider the soil arching but considers the soil around the pile to be in plastic equilibrium. Also, this method does not incorporate the actual field conditions, the flexibility of piles, finite piles, saturation, and soft soils [24–26].

The displacement-based method takes into account the relative displacement between the soil and pile and presumes the location of the slip circle. This method's main drawback is the difficulty in accurately determining lateral soil displacement, which is usually measured using an inclinometer or by using some continuum approaches or empirical co-relations [24, 26]. The reinforced slope is analyzed as a continuous elastic or elasto-plastic medium using finite elements or finite differences formulation in continuum-based methods. By incorporating the geometry of the pile, the group effect, and the interaction between the soil and the structure, this method may also be used to address three-dimensional problems and offer better results than the other approaches [24, 27].

The methods for analyzing pile-reinforced slopes can be grouped into coupled, uncoupled, and hybrid analyses. The uncoupled method neglects the soil–pile interaction and individually treats the pile response and slope stability analysis. The limiting value of soil pressure is calculated by analytical, empirical, or numerical methods, and the obtained value is treated as an additional resistance in slope stability analysis [17, 25, 28, 29]. Conversely, coupled analysis utilizes powerful numerical tools to consider the pile response and the slope stability at the same time [26]. The numerical approaches and analytical methods are combined to create the hybrid analysis method. This method involves two stages: 1. Evaluation of the lateral resistance required to keep the safety factor at the desirable level. 2. Determination of the pile's configuration provides the necessary lateral resistance for the deformation estimated in advance [30].

The slope stability is commonly analyzed using the limit equilibrium methods. This technique can analyze complicated slopes with varying soil characteristics and hydraulic conditions, differing sliding surfaces, and boundary conditions [31]. The limit equilibrium method for analyzing the stability of pile-reinforced slope was put forward by Ito et al. In this approach, the ratio between the resisting moment and the overturning moment experienced by the unstable soil mass is used to calculate the factor of safety [17]. The moment produced by the shear resistance of soil along the sliding surface and by the reaction forces from the piles contributes to the resisting moment. The resisting moment due to shear strength and the driving moments were determined using the slice method, and theoretical equations derived by Ito and Matsui were used for assessing the lateral force due to the soil movement [32]. However, this method cannot replicate the complex soil–structure interaction and is limited to homogeneous slopes. Slope stability analysis using the discrete element method was proposed by Chang, where the slope is represented using slices linked by elasto-plastic Winkler springs [33]. A dual-stage analysis incorporating the finite element method and the boundary element method was used by Lee et al. to study the behavior of piles exposed to lateral soil movements triggered by excavation. The resisting moment offered by the piles was calculated using the boundary element method by incorporating the bending moment and shear force developed in the pile at the depth of the slip surface [34]. To predict the stability of a slope reinforced with piles, Cai and Ugai used the three-dimensional shear strength reduction finite element method to predict the stability of pile-reinforced slopes. The authors have simulated the soil–pile interaction using three-dimensional, elasto-plastic interface elements of zero thickness [35]. Ausilio et al. utilized the kinematic approach of limit analysis to develop a methodology for analyzing the reinforced slopes.

In this approach, lateral forces and a moment were exerted at the potential sliding surface to account for the presence of piles. The obtained results agree well with those derived from Bishop's method and with the upper- and lower-bound solutions of limit analysis [36]. By combining the 3D finite element method with the commonly used analytical techniques, Kourkoulis et al. developed a hybrid design methodology for the anti-slide piles. The proposed method applies to the cases of pre-existing potential sliding interfaces within slopes [30]. Ho conducted a coupled analysis using a three-dimensional finite element analysis with the strength reduction method on a slope with a weak, thin layer reinforced with piles to overcome the limitations noticed in two-dimensional finite element analysis. The soil arch effect, spacing effect, boundary effect, and the soil deformation between piles are considered in the 3-D FE analysis, which cannot be adequately considered in the 2-D model [24]. An upper-bound limit analysis method was proposed by Rao et al. by incorporating the allowable rotational failure mechanism in which due consideration was given to the base failure, toe failure, and face failure [37]. A kinematic limit analysis approach for unsaturated soil slopes was suggested by Wang et al. The plastic theory put forward by Ito and Matsui [17] was adopted in unsaturated soil to evaluate the effect of suction on the lateral forces action on the stabilizing pile, and the energy dissipated due to the resistance offered by the pile was calculated using the local layer summation method. The proposed method is only adaptable for uniform slopes [38]. Mesh-less techniques like the smoothed particle hydrodynamics method (SPH), discrete element method (DEM), and material point method (MPM) are gaining popularity owing to their capability to simulate large deformations. Table 1 gives a list of various methods adopted by researchers for the analysis of anti-slide piles.

Parameters Affecting Slope Stabilization Using Piles

Researchers conducted numerous studies to identify and optimize the parameters affecting the stability of pile-reinforced slopes. The position of the pile [28, 29, 35, 42, 46, 48, 49], pile spacing [27, 35, 42, 50, 51], the diameter of the pile [29, 32, 48], fixity condition of the pile head [35, 42, 50], and pile length [29, 42] are the factors identified. Ito et al. identified that the pile spacing, diameter of the pile, length above the sliding surface, pile head fixity condition, and stiffness of the steel pipe are the factors that significantly affect the slope stability. The spacing between piles significantly influences the resistance against landslides. The safety factor gradually decreases with the increase in spacing while it is independent of the thickness of steel pipe and the length and diameter of piles [32]. Cai et al. conducted the numerical analysis using the finite element method to examine the effect of the pile spacing, pile position, fixity conditions of pile head, and bending stiffness on the factor of safety. The authors conclude from the shear strength reduction method that the bending stiffness and the pile head's nature can remarkably affect the stability of the slope. However, the results obtained from the limit equilibrium method do not agree with the same. The study recommends a restrained pile head (hinged or fixed) over the free-head piles due to the smaller factor of safety. The capability of the pile is adequately utilized due to the large relative displacements of the soil–pile interface, and it experiences more pressure when located at the middle and lower sections of the slopes. For the maximum factor of safety, the authors recommend the installation of the pile in the middle of the slopes on the basis of the shear strength reduction finite element method and slightly closer to the top based on Bishop's simplified method [35]. According to Ausilio et al., piles are very effective when placed in between the toe and middle of the slope. The optimal location was suggested nearer to the toe of slope where the factor of safety is maximum and stabilizing force is minimum [36]. Wei et al. recommended the position between the halfway slope and center of the critical slip surface of the unreinforced slope as the optimal location, and the precise location is closer to the central part of slope. The authors suggest the locations near the center of the slope and slightly toward the crest as optimum locations for sandy and clayey soil, respectively [46]. Li et al. performed a detailed investigation to determine the optimal position of piles by considering the stabilizing force required for achieving the desired factor of safety and the maximum force each pile can offer. A single-row pile-reinforced slope was analyzed using the theory proposed by Ito and Matsui [17] and limit analysis to identify the limiting lateral load on piles. Compared with the previous researchers, the authors

Table 1 List of references for various design methods

Design methods	References
Limit equilibrium method	Xu et al. [39], He et al. [40], Won et al. [26], Lee et al. [34]
Finite element method	Wang et al. [41], Abdelaziz et al. [29], Ho [42]
Finite difference method	Zhang et al. [43], Kanagasabai et al.[44]
Shear strength reduction method	Shooshpasha et al. [45], Ho [42], Wei et al.[46], Won et al. [26]
Limit analysis method	Rao et al. [37], Gao et al. [47], Li et al. [48]

tried to identify the most suitable and most effective positions and the position where the safety factor is maximum. The study reveals that for the slope under consideration, these positions vary from each other. The most suitable location varies with the required factor of safety and should be ascertained based on the force required and provided. If the highest force offered by the piles in a row is sufficiently large, the toe of the slope becomes the most effective position where the stabilizing force is minimum. For sufficiently longer piles, the upper–middle region of the slope with maximum force supply was observed as the position of the maximum safety factor [49]. Ho also concludes that pile spacing, pile position, nature of pile head, and length of pile can modify the failure mechanism of the slope. The fixed-head pile was found to be more efficient than the free-head pile, and the length-to-height (L/H) ratio greater than 0.70 is recommended as the optimum pile length. The portion at hallway of the slope is recommended as the most effective location, and the crest of the slope is the least preferred [24]. According to Rao et al., the optimal location of the pile is independent of heterogeneity and anisotropy of soil [52]. In the opinion of Wang et al., the position and geometry of the 3D critical slip surface get considerably affected by the position of pile and the spacing between them. When the position of the pile moved from the toe to the middle of the slope, the stability of the slope improved, and the shallow slip surface was observed. The slip surface, however, moved closer to the shoulder of the slope as the position of the pile got closer to it. The pile should be positioned in the middle of the slope for unsaturated slopes with a high angle of internal friction and limited width constraints [38].

Calculating the critical pile spacing considering the safety and economy is a major challenge for the design of slide-resisting piles. Excessive pile spacing may cause the soil between the soil to slip away, while smaller spacing leads to increased cost and a tedious construction process [19]. Kourkoulis et al. utilized the decoupled analysis to identify the factors influencing the behavior of piles and pile groups and to assess the effect of the thickness of stable soil mass, axis-to-axis spacing, diameter, and embedment depth. The authors considered $S = 4D$ as the most efficient and cost-effective because pile spacing of $S \leq 4D$ is needed to create soil arches, and for $S > 5D$, the piles will function as individual piles, and the soil between the piles may slide [27]. Kahyaoglu et al. assessed the influence of pile head fixity and pile spacing on the distribution of the moment and lateral earth pressure along the slope stabilized with piles and found that the behavior of the passive pile was affected by the pile head conditions. For free-head piles, a positive passive pressure is developed over a certain pile depth when the pile head's displacement exceeds the soil movement. At the same time, the soil particles in the affected zone had smaller surficial displacements than the box displacement for the fixed-head pile. Regarding pile spacing, the authors noted that an increase in the load-carrying capacity of the pile caused a decrease in pile spacing, and the pile head conditions significantly influenced the spacing. The study concludes that pile spacing more than five times the diameter of the pile is not recommended for stabilization since it will behave as a single isolated pile, and the soil will slide between them [53].

He et al. attempted to identify the order of importance of factors influencing the design of slide-resisting piles and to determine an optimal combination. For single-row piles, uniform load, pile spacing, and interfacial strength parameters were identified as the top three parameters, while pile spacing, poisson's ratio, and row spacing are the parameters for the double-row piles [51]. Abdelaziz et al. examined the effect of the position, length, inclination, and diameter of the pile on the factor of safety of pile-reinforced slopes. The slope's safety factor improves up to about twice with the increase in the angle of inclination, and for the vertical piles, the obtained value is lesser than that of inclined piles. The safety factor rises with the increment in length of the pile up to $L = 10$ m and remains constant. In addition, a comparatively less improvement in the factor of safety is noted with the increase in diameter [29]. Zhang et al. utilized the finite difference software FLAC3D to analyze the effectiveness and response of controlling parameters like post-pile filling parameters c and ϕ, pile cross-sectional shapes, pile embedding methods, and layout under two types of thrust in slope stability. Cohesion c and the angle of internal friction ϕ of the fill were determined as the main controlling parameters, and the cohesive force of the fill provided a significant impact on slide resistance compared with the angle of friction [43]. Based on the analysis of the previous literature, the preferred location for installing piles is the middle region of the slope, and a spacing of less than five times the diameter of the pile can be recommended. The order of priority of different controlling parameters has to be considered before designing piles for stabilizing the slopes.

Novel Designs and Latest Innovations Toward Sustainability

Sustainable products and practices that consume fewer resources and zero emissions must be appreciated. Currently, in the construction industry, the production of concrete and steel consumes a considerable amount of energy and causes high carbon emissions. Geotechnical engineering is a prominent field in the construction industry, and improving the sustainability of geotechnical processes can ensure sustainable development in the civil engineering field. Sustainable approaches in slope stability methods have always been an area of interest for researchers [1]. Recent research on anti-slide pile focuses on developing novel designs to overcome the present drawbacks of anti-slide piles and ensure sustainability. The h-type anti-slide pile is a combined retaining structure and can mobilize considerably greater resisting force than individual piles. The soil mass between the two piles and in front of the h-type anti-slide pile and set of two piles connected by a horizontal linking beam comprises the retaining mechanism. The landslide initially acts on the rear pile; later, it is transferred to the front pile through the linking beam and the soil mass between the two piles. The soil arching effect transfers the landslide thrust through the rear pile, and the soil mass in front of the pile resists the landslide thrust by offering resistance to structural deformation [11]. Figure 6 depicts the h-type anti-slide used for slope stabilization. In order to illustrate the mechanism of the h-type anti-slide pile, Bo et al. designed and conducted a physical model test based on the interaction between the soil and pile and found that the behavior of the proposed pile is superior to a similar traditional pile as far as the stress distribution and displacement are concerned. The less cost of construction, as well as the good retaining effect, makes the proposed structure a promising application in resisting large-scale landslides [11]. A modified design was proposed by Chen et al. to address the drawbacks of slide-resisting piles. An arm-stretching-type anti-slide pile was designed and proposed for projects requiring stringent displacement control. Unlike the design of a conventional pile, the force of the sliding body can be utilized for the design of the proposed pile. The stretching arm on the backside of the pile divides the soil mass and holds the soil mass above the arm, and reduces the earth pressure underneath and hence minimizes the overturning moment. The soil mass above the arm generates a reverse moment to counteract the driving moment due to landslide thrust. The arm on the front side of the pile offers support and utilizes the reaction force of the soil below the arm. The structure of the arm stretching pile is shown in Fig. 7. From the numerical simulations, the authors observed that the internal force of the proposed anti-slide pile is lower and evenly distributed compared with the conventional pile [54].

Wang et al. analyzed slope reinforced with polymer anti-slide piles under rainfall conditions. The proposed design has the benefits of high strength, facile construction, fast forming, minor disturbance to slope, and can meet emergency disaster relief tasks. The fluid–solid coupling analysis is carried out on an unsaturated slope under varying forms and duration of the rainfall and different positions and spacing of the pile. The results of stability analysis by the strength reduction method show that the stability of the slope undergoes gradual deterioration with the rise in peak duration of the rainfall intensity, and the recovery ability of soil mass in the slope depends on

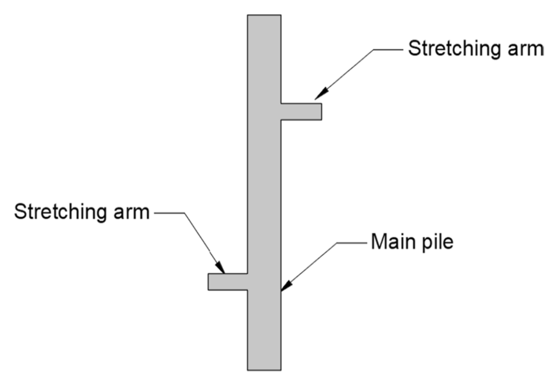

Fig. 7 Arm–stretching-type anti-slide pile (Redrawn by authors after Chen et al. [54])

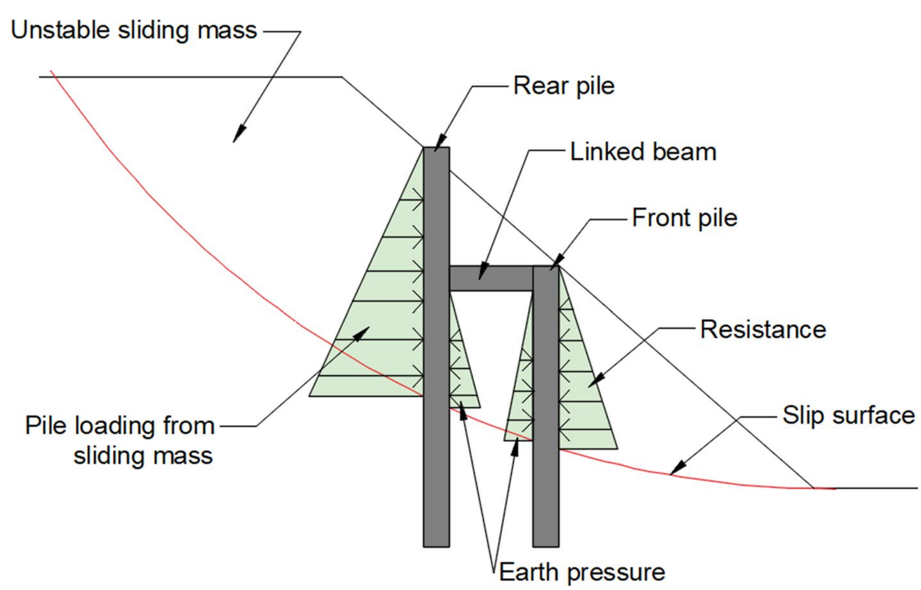

Fig. 6 h-type anti-slide pile (Redrawn by authors after Bo et al. [11])

this peak duration. The optimum location is 1/2–3/4 L and 1/4L-1/2L distance away from the foot of the slope for non-rainfall and rainfall conditions, respectively. Reduction of pile spacing will improve the reinforcement effect under non-rainfall conditions. While under rainfall conditions, it can reduce the reinforcement effect and can affect the seepage rainwater flow and discharge [55]. The novel designs developed by the researchers can reduce the utilization of construction materials and can be used as an emergency relief for disaster mitigation. Researchers also focus on developing anti-slide piles using eco-friendly materials. Davila et al. suggested bamboo as an environment-friendly pile material for slope stabilization. Finite element analysis was carried out using Plaxis 2D and 3D to analyze the reinforcement mechanism of the bamboo anti-slide by varying the pile position, inclination, diameter, and spacing. The authors observed an increase of 4.99% in the factor of safety when the piles were placed at the lower position of the slope. Piles inserted normal to the slope perform better than vertical piles, and an average increase of 1–2% in the factor of safety is obtained for a 5% increment in diameter [56]. Gidon and Sahoo carried out a comprehensive analysis of the current state of the art of bamboo as a landslide stabilization technique and highlighted the use of bamboo as an anti-slide pile [1]. An analytical model for bamboo-reinforced slopes was developed by Kumar et al. using the ordinary method of slices. They carried out analytical and numerical studies on slope reinforced by bamboo piles as vertical reinforcement along the length of the slope at uniform spacing. The case study conducted by the authors yielded a significant improvement in safety factor, with an increase of 17% in sandy slopes and 8% in clayey slopes [57]. Chakrabortty et al. made an effort to develop a limit equilibrium method by modifying the bishop method of slices. Two case studies were considered, where the stability analysis of a sandy slope and the effect of slope angle on the factor of safety were addressed. There was an improvement in safety factor on the utilization of bamboo piles. The analytical method gives a safety factor less than numerical analysis by 47.2%. The authors recommended that the proposed equation can also be used for other materials [58]. Ngudiyono and Sulistyowati conducted the 2D numerical analysis using ABAQUS with bamboo pile reinforcement. Piles are placed perpendicular to the slope, and an increase in the factor of safety by 17% was observed [59]. The above-mentioned research highlights that bamboo piles can be used as a sustainable material for slope stabilization as anti-slide piles. Further studies to understand the mechanism in detail and to optimize the design parameters for the effective utilization of bamboo anti-slide pile as a slope stabilization technique are essential.

Concluding Remarks and Future Scope

The utilization of anti-slide piles for improving slope stability began in 1930, and much research was going on in this field. Most of the work focuses on studying the soil–pile interaction, soil arching between piles, developing design methods, and parametric study. Researchers are also interested in developing novel designs to overcome the present drawbacks of anti-slide piles. Among the various methods for controlling landslides, anti-sliding piles are widely used because of the following advantages. It has strong slide-resisting capability, excellent retaining effect, flexibility in arrangement, small sections and different forms, and established construction technology with little disturbance to the sliding mass.

Based on the review conducted on the previous literature, the soil arching between piles mainly governs the soil–pile interactions. The soil arch developed between the piles resists the landslide thrust and enhances slope stability. The capability of the soil arch to resist the landslide thrust depends on the spacing between the piles. The practical and economical design lies in selecting proper spacing between the piles to aid the development of soil arching between the piles. Researchers have developed numerous analytical and numerical methods for designing piles; among them, the limit equilibrium method is extensively used. Earlier, the computational time made the task of analyzing difficult. The progress in computing techniques and the development of powerful software tools make numerical methods more attractive, and the finite element method combined with shear strength reduction methods are commonly used now for slope stability analysis. Mesh-less techniques like the smoothed particle hydrodynamics method (SPH), discrete element method (DEM), and material point method (MPM) are gaining popularity owing to their capability to simulate huge deformations.

The position of the pile, pile spacing, diameter of the pile, fixity condition of the pile head, and pile length were identified as significant parameters affecting the stability of the pile-reinforced slopes. Calculating the critical pile spacing considering the safety and economy is a major challenge for the design of slide-resisting piles. Excessive pile spacing may cause the soil between the soil to slip away, while smaller spacing leads to increased cost and a tedious construction process. Most of the researchers suggest a spacing of S = 4D such that the design will be economical and the soil arching will also be present at that spacing. Based on the analysis of the previous literature, the favorable location for installing piles is identified as the middle region of the slope, and a critical pile length should be adopted such that the pile can be embedded in the stable strata. The order of priority of different controlling parameters should be kept in mind before designing anti-slide piles for stabilizing the slopes. The focus on the development of sustainable materials like bamboo as an anti-slide pile was also noticed in various studies. Developing anti-slide piles incorporating the capability of soil between the piles also attracted researchers. The development of sustainable materials and designs can reduce the impact of the conventional practices of slope stabilization on the environment.

Most of the studies on anti-slide piles focus on numerical and analytical studies, and a lack of experimental studies using flumes is observed in the literature. Experimental studies using flumes will help to simulate the real-time scenario, to understand the mechanism, and to develop novel designs. Can apply advanced numerical methods like mesh-less methods to understand the behavior of anti-slide piles. Also, it can further exploit the applicability of anti-slide piles for controlling rainfall and seismic-induced landslides for risk reduction. Developing novel designs to suit various field conditions and utilizing eco-friendly materials are also identified as the future scope. The tremendous development in artificial intelligence has also affected civil engineering. These developments point toward the opportunity of utilizing these tools for encountering slope stability problems. Numerous data available from the field can be used for the optimization of parameters of anti-slide piles and for developing some warning systems with the aid of machine learning and artificial intelligence.

Acknowledgements Not applicable

Author Contributions The second author, Dr. SK, and the third author, Dr. SN, had the idea for the article. The first author, DJ, carried out the majority of the literature search and drafted the paper. All the authors critically revised the work. Thus, there was contribution from all three authors to the paper.

Funding This work is not financially supported by any source of funding.

Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no competing interests. The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

References

1. Gidon JS, Sahoo S (2020) Rainfall-induced slope failures and use of bamboo as a remedial measure: a review. Indian Geotech J 50:766–783. https://doi.org/10.1007/s40098-020-00409-3
2. McColl ST (2015) Landslide Causes and Triggers. Landslide Hazards, Risks, and Disasters. Elsevier, Amsterdam, pp 17–42
3. Sorbino G, Nicotera MV (2013) Unsaturated soil mechanics in rainfall-induced flow landslides. Eng Geol 165:105–132. https://doi.org/10.1016/j.enggeo.2012.10.008
4. Wang H, Wang P, Qin H et al (2020) Method to control the deformation of anti-slide piles in Zhenzilin landslide. Appl Sci 10:2831. https://doi.org/10.3390/app10082831
5. Zhu H-H, Naveen BP, Wang J et al (2022) Research Status and Prospect of Anti-slide Piles for Slope Stabilization. In: Zhu H-H, Garg A, Zhussupbekov A, Su L-J (eds) Advances in Geoengineering along the Belt and Road, BRWSG 2021. Lecture Notes in Civil Engineering, Springer, Singapore, pp 223–236
6. De Beer E (1977) Piles subjected to static lateral loads. In: Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering, Special Session No. 10. Tokyo, pp 547–558
7. Lirer S (2012) Landslide stabilizing piles: experimental evidences and numerical interpretation. Eng Geol 149–150:70–77. https://doi.org/10.1016/j.enggeo.2012.08.002
8. Ashour M, Ardalan H (2012) Analysis of pile stabilized slopes based on soil–pile interaction. Comput Geotech 39:85–97. https://doi.org/10.1016/j.compgeo.2011.09.001
9. Zhang S, Li C, Qi H et al (2021) Soil arch evolution characteristics and parametric analysis of slope anchored anti-slide pile. KSCE J Civ Eng 25:4121–4132. https://doi.org/10.1007/s12205-021-1612-6
10. Chen H, Zhang G, Chang Z et al (2021) Failure analysis of a highway cut slope with anti-slide piles. Geofluids 2021:1–15. https://doi.org/10.1155/2021/6622214
11. Bo Z, Yun-Sheng W, Yu W et al (2017) Retaining mechanism and structural characteristics of h type anti-slide pile (hTP pile) and experience with its engineering application. Eng Geol 222:29–37. https://doi.org/10.1016/j.enggeo.2017.03.018
12. Chen G, Guo F, Zhang G et al (2023) Anti-slide pile structure development: New design concept and novel structure. Front Earth Sci 11:1–9. https://doi.org/10.3389/feart.2023.1133127
13. Tan S, Yong R, Zhong Z (2021) Interaction mechanism of the anti-slide pile and sliding mass based on the soil arching effect. IOP Conf Ser Earth Environ Sci 861:062043. https://doi.org/10.1088/1755-1315/861/6/062043
14. Xie Q, Cao Z, Shi X et al (2021) Model test of interaction between load-caused landslide and double-row anti-slide piles by transparent soil material. Arab J Sci Eng 46:4841–4856. https://doi.org/10.1007/s13369-020-05256-1
15. Terzaghi K (1943) Theoretical Soil Mechanics. John Wiley & Sons Inc
16. Zhang S, Yang Z, Liu Q et al (2023) Analysis of influence factors of anti-slide pile with prestressed anchor cable based on bearing and deformation characteristics of pile body. Sustainability 15:10549. https://doi.org/10.3390/su151310549
17. Ito T, Matsui T (1975) Methods to estimate lateral force acting on stabilizing piles. Soils Found 15:43–59. https://doi.org/10.3208/sandf1972.15.4_43
18. Adachi T, Kimura M, Tada S (1989) Analysis of the preventive mechanism of landslide stabilizing piles. Numer Model Geomech NUMOG III:691–698
19. Chen G, Zou L, Wang Q, Zhang G (2020) Pile-spacing calculation of anti-slide pile based on soil arching effect. Adv Civ Eng 2020:1–6. https://doi.org/10.1155/2020/7149379
20. Liang R, Zeng S (2002) Numerical study of soil arching mechanism in drilled shafts for slope stabilization. Soils Found 42:83–92. https://doi.org/10.3208/sandf.42.2_83
21. Chen CY, Martin GR (2002) Soil - Structure interaction for landslide stabilizing piles. Comput Geotech 29:363–386. https://doi.org/10.1016/S0266-352X(01)00035-0

22. Zhang G, Wang L, Wang Y (2017) Pile reinforcement mechanism of soil slopes. Acta Geotech 12:1035–1046. https://doi.org/10.1007/s11440-017-0543-3
23. Tang H, Hu X, Xu C et al (2014) A novel approach for determining landslide pushing force based on landslide-pile interactions. Eng Geol 182:15–24. https://doi.org/10.1016/j.enggeo.2014.07.024
24. Ho I-H (2015) Numerical study of slope-stabilizing piles in undrained clayey slopes with a weak thin layer. Int J Geomech 15:06014025. https://doi.org/10.1061/(asce)gm.1943-5622.0000445
25. Jeong S, Kim B, Won J, Lee J (2003) Uncoupled analysis of stabilizing piles in weathered slopes. Comput Geotech 30:671–682. https://doi.org/10.1016/j.compgeo.2003.07.002
26. Won J, You K, Jeong S, Kim S (2005) Coupled effects in stability analysis of pile-slope systems. Comput Geotech 32:304–315. https://doi.org/10.1016/j.compgeo.2005.02.006
27. Kourkoulis R, Gelagoti F, Anastasopoulos I, Gazetas G (2011) Slope stabilizing piles and pile-groups: parametric study and design insights. J Geotech Geoenviron Eng 137:663–677. https://doi.org/10.1061/(asce)gt.1943-5606.0000479
28. Poulos HG (1995) Design of reinforcing piles to increase slope stability. Can Geotech J 32:808–818. https://doi.org/10.1139/t95-078
29. Abdelaziz A, Hafez D, Hussein A (2017) The effect of pile parameters on the factor of safety of piled-slopes using 3D numerical analysis. HBRC J 13:277–285. https://doi.org/10.1016/j.hbrcj.2015.06.002
30. Kourkoulis R, Gelagoti F, Anastasopoulos I, Gazetas G (2012) Hybrid method for analysis and design of slope stabilizing piles. J Geotech Geoenviron Eng 138:1–14. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000546
31. Yamin M, Liang RY (2010) Limiting equilibrium method for slope/drilled shaft system. Int J Numer Anal Methods Geomech 34:1063–1075. https://doi.org/10.1002/nag.852
32. Ito T, Matsui T, Hong WP (1981) Design method for stabilizing piles against landslide - one row of piles. Soils Found 21:21–37. https://doi.org/10.3208/sandf1972.21.21
33. Chang CS (1992) Discrete element method for slope stability analysis. J Geotech Eng 118:1889–1905. https://doi.org/10.1061/(ASCE)0733-9410(1992)118:12(1889)
34. Lee CY, Hull TS, Poulos HG (1995) Simplified pile-slope stability analysis. Comput Geotech 17:1–16. https://doi.org/10.1016/0266-352X(95)91300-S
35. Cai F, Ugai K (2000) Numerical analysis of the stability of a slope reinforced with piles. Soils Found 40:73–84. https://doi.org/10.3208/sandf.40.73
36. Ausilio E, Conte E, Dente G (2001) Stability analysis of slopes reinforced with piles. Comput Geotech 28:591–611. https://doi.org/10.1016/S0266-352X(01)00013-1
37. Rao P, Zhao L, Chen Q, Li L (2017) Limit analysis approach for accessing stability of three-dimensional (3-D) slopes reinforced with piles. Mar Georesources Geotechnol 35:978–985. https://doi.org/10.1080/1064119X.2016.1273982
38. Wang L, Sun D, Yao Y et al (2020) Kinematic limit analysis of three-dimensional unsaturated soil slopes reinforced with a row of piles. Comput Geotech 120:103428. https://doi.org/10.1016/j.compgeo.2019.103428
39. Xu X, Xing Y, Guo Z, Huang Y (2021) Stability analysis of rainfall-triggered toe-cut slopes and effectiveness evaluation of pile-anchor structures. J Earth Sci 32:1104–1112. https://doi.org/10.1007/s12583-021-1474-3
40. He Y, Hazarika H, Yasufuku N et al (2015) Estimation of lateral force acting on piles to stabilize landslides. Nat Hazards 79:1981–2003. https://doi.org/10.1007/s11069-015-1942-0
41. Wang Y, Han M (2022) Optimal design of slope reinforcement by a new developed polymer micro anti-slide pile in case of emergency and disaster relief. Nat Hazards. https://doi.org/10.1007/s11069-022-05212-2
42. Ho IH (2017) Three-dimensional finite element analysis for soil slopes stabilisation using piles. Geomech Geoengin 12:234–249. https://doi.org/10.1080/17486025.2017.1347286
43. Zhang S, Zhang G, Zhang X et al (2020) Influences on antislide piles used for slope reinforcement: numerical simulation based on the soil arching effect. Math Probl Eng 2020:1–15. https://doi.org/10.1155/2020/7651080
44. Kanagasabai S, Smethurst JA, Powrie W (2011) Three-dimensional numerical modelling of discrete piles used to stabilize landslides. Can Geotech J 48:1393–1411. https://doi.org/10.1139/t11-046
45. Shooshpasha I, Amirdehi HA, Kharun M (2020) Factors influencing the critical piles length in reinforced slope. J Phys Conf Ser 1687:012018. https://doi.org/10.1088/1742-6596/1687/1/012018
46. Wei WB, Cheng YM (2009) Strength reduction analysis for slope reinforced with one row of piles. Comput Geotech 36:1176–1185. https://doi.org/10.1016/j.compgeo.2009.05.004
47. Gao Y, Ye M, Zhang F (2015) Three-dimensional analysis of slopes reinforced with piles. J Cent South Univ 22:2322–2327. https://doi.org/10.1007/s11771-015-2757-6
48. Li XP, He SM, Wang CH (2006) Stability Analysis of Slopes Reinforced with Piles Using Limit Analysis Method. In: Advances in Earth Structures. pp 105–112
49. Li X, Pei X, Gutierrez M, He S (2012) Optimal location of piles in slope stabilization by limit analysis. Acta Geotech 7:253–259. https://doi.org/10.1007/s11440-012-0170-y
50. Kahyaoglu MR, Onal O, Imançlı G et al (2012) Soil arching and load transfer mechanism for slope stabilized with piles. J Civ Eng Manag 18:701–708. https://doi.org/10.3846/13923730.2012.723353
51. He G-F, Li Z-G, Yuan Y et al (2018) Optimization analysis of the factors affecting the soil arching effect between landslide stabilizing piles. Nat Resour Model 31:e12148. https://doi.org/10.1111/nrm.12148
52. Rao P, Zhao L, Chen Q, Nimbalkar S (2019) Three-dimensional limit analysis of slopes reinforced with piles in soils exhibiting heterogeneity and anisotropy in cohesion. Soil Dyn Earthq Eng 121:194–199. https://doi.org/10.1016/j.soildyn.2019.02.030
53. Hajiazizi M, Mazaheri A, Orense RP (2017) Analytical approach to evaluate stability of pile-stabilized slope. Sci Iran. https://doi.org/10.24200/sci.2017.4218
54. Chen G, Zhang G, Guo F et al (2022) New arm-stretching-type anti-slide pile design and verification. Front Earth Sci 10:846616. https://doi.org/10.3389/feart.2022.846616
55. Wang Y, Han M, Lin X et al (2021) Influence of rainfall conditions on stability of slope reinforced by polymer anti-slide pile. Front Earth Sci 9:774926. https://doi.org/10.3389/feart.2021.774926
56. Davila AMJ, Romanel C, Ghavami K (2019) Numerical analysis of bamboo piles for slope stability. Geotech Eng Xxi Century Lessons Learn Futur Challenges. https://doi.org/10.3233/STAL190144
57. Kumar P, Chakrabortty P (2020) A Simple Analytical Model for Bamboo Reinforced Slope Using Ordinary Method of Slices. Lecture Notes in Civil Engineering. Singapore, Springer Singapore, pp 269–283
58. Chakrabortty P, Srivastava LS, Kumar P (2023) A simple analytical model for bamboo-reinforced slopes using modified Bishop method. Front Built Environ 9:1–10. https://doi.org/10.3389/fbuil.2023.1080318
59. Ngudiyono ST (2023) Numerical Simulation of Slope Stability for Soil Embankment Reinforced with Inclined Bamboo Piles.

Lecture Notes in Civil Engineering. Singapore, Springer Nature Singapore, pp 287–295