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Landslide mitigation using Anti-slide piles – A review

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Abstract. Anti-slide piles are widely used as a reinforcement technique for stabilizing slopes as part of landslide mitigation. The interaction between the anti-slide piles and sliding soil mass is best explained using the soil arching effect. The analysis of slopes stabilized with anti-slide piles can be carried out using either an uncoupled or a coupled approach. In the uncoupled approach the limiting soil pressure is obtained using an analytical, empirical, or numerical method, and this limiting soil pressure is used as an additional resistance in slope stability analysis. On the other hand, coupled analysis utilizes powerful numerical tools like 2D and 3D finite element analyses where both the pile response and slope stability are considered simultaneously. The safety and economy of anti-slide piles depend on the critical spacing and position of anti-slide piles. This article presents a detailed review of the anti-slide pile-soil interaction, the design mechanism, analysis of slope stabilized with anti-slide piles, and the parameters influencing the response of piles. The excellent landslides resistance offered by the anti-slide piles urges researchers to pay more attention to this field.
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Keywords: Landslide, Anti -slide pile, Soil arching, Slope stability.

1 Introduction

Landslide is one of the most disastrous geo-hazards which threaten human lives and leads to huge destruction of infrastructure and property all over the world especially in mountainous areas. There are many factors contributing to the cause of landslides. They occur due to natural factors like rainfall, earthquake, volcanoes, etc., or human activities like deforestation, land encroachment, construction work, farming, poor drainage, etc. The increase in frequency and risk of landslide occurrence due to the variation in climate and the intensification of natural and manmade activities have become a concern for geotechnical engineers. Numerous studies have been taking place to understand the concept, mechanism, vulnerability, and risk of landslides and to develop novel measures to control and mitigate the landslides.

Stability of slope has significant role in the formation, development, and susceptibility to landslides and can be assessed by considering the balance of between driving and resisting forces. The development of shear stresses drives a tendency for failure for most landslide types. The resisting stresses result from reactionary stresses and can be considered as the mobilized shear strength of the slope with respect to the shear stresses [1]. Slope stabilization is achieved either by reducing the forces or by increasing the stabilizing forces or by introducing both techniques. Stabilizing forces are increased by stabilization of soil by compacting the soil, by adding soil stabilizers like lime, cement, fly ash, fibres etc..., by constructing retaining structures and by using ground reinforcements. The widely used slope-retaining structures are masonry and mass concrete walls, reinforced concrete walls, gabion walls, crib walls (timber or concrete), sheet piles, king post walls, soil-nailed walls and geogrid or metal strip reinforced soil walls. Slope reinforcements in many forms using geosynthetics, soil nails, stone columns and reticulated micro piles are also implemented for slope stabilization [2]. Anti-sliding piles and micro-anti-sliding piles are widely used in slope reinforcement engineering because of their simple structure, strong anti-sliding ability, and mature construction technology [3]. These piles are usually implemented in a row with equal spacing, anchoring the unstable zone to the deeper stable layers which transfer body and shear forces from the landslide mass to underlying stable layers, maintaining the stability of the landslide. Anti-slide piles are widely used in various slope retaining projects because of their large anti-slide ability, good retaining effect, flexible pile position arrangement, and various combination forms that can be adapted according to the actual situation [4].

2 Anti-slide piles

The application of anti-slide piles to slope stabilization began in the 1930s. Countries like China, Japan has successfully implemented anti-slide piles for treating landslides. The anti-slide piles are installed through the unstable soil layer at spacing significantly larger than their diameter and embedded below the potential sliding surface in the underlying stable soil strata. The driving force of the soil mass that acts along the pile segment above the slip surface is transmitted to the lower layers, as shown in Fig 1.

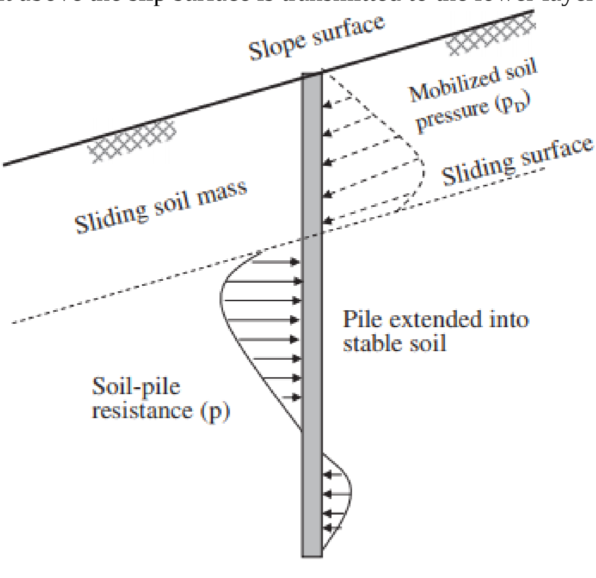

Fig 1: Driving force of the soil mass that acts along the pile segment above the slip surface [5]

According to De Beer (1977)[6], laterally loaded piles can be classified into ‘active piles’ and ‘passive piles. ‘Active piles’ are subjected to lateral loads at the pile head caused by the superstructure. ‘Passive piles’ are provided in soft soil layers where lateral pressure resulting from horizontal soil movement due to eccentric loading or unloading of the ground surface around the piles were developed. The mechanics of the mobilization of resistance from passive piles subjected to lateral soil movement can be explained with the help of the arching effect. During the process of soil arching, redistribution of internal stresses in soil occurs and the directions of the principal stresses are deflected such that the major principal stress is parallel to the arch axis and the minor principal stress is perpendicular to the arch axis [7].

2.1 Soil Structure Interaction for Anti-slide pile

The interaction behavior between pile and soil is a complicated phenomenon due to its 3-dimensional nature and can be influenced by many factors, such as the characteristics of deformation and the strength parameters of both pile and soil [5]. During pile - soil interactions, soil arches behind and between piles generate, develop, and fracture. Under the action of self-weight or upper load of soil between piles, the soil between piles produces uneven displacement, resulting in soil arch between piles. The soil arching effect was first proposed by Terzaghi and verified by the trap door test [8]. Under the action of the lateral force, the soil arching effect is an important factor in the analysis and design of the slope reinforcement mechanism [9]. The soil arches are shown in Fig. 2.

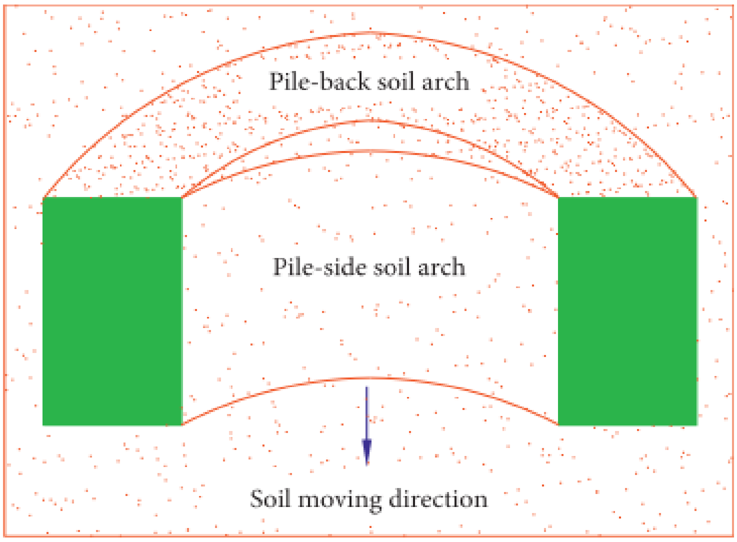

Figure: 2.3. Soil Arch

The soil arch between the pile backs governs the soil arching effect in pile soil interactions which has been proven directly through laboratory tests and practical engineering phenomena [10]. Ausilio et al. (2001)[12] developed a methodology for the stability of slopes reinforced with piles using the kinematic approach of limit analysis.

The stability of pile reinforced slopes can be assessed by various experimental, analytical and numerical methods. These methods can be grouped in three types: coupled, uncoupled and hybrid analysis. In the early years of designing and analyzing pile reinforced slopes, the uncoupled method in which the limiting soil pressure is obtained using an analytical, empirical, or numerical method, and this limiting soil pressure is used as an additional resistance in slope stability analysis. The uncoupled method ignores the pile-soil interaction and assumes that the piles only provide the resistant force. Therefore, it is not clearly known that how exactly the depth of the pile installation resists against soil movement [13–15]. On the other hand, coupled analysis utilizes powerful numerical tools like 2D and 3D finite element analyses where both the pile response and slope stability are considered simultaneously. The third category is the hybrid analysis method, which is based on combining the accuracy of numerical simulation with the simplicity of other analytical methods. This method consists of two phases: 1. Assessing the lateral resistance force required to increase the safety factor to the desired value and 2. Estimating the pile configuration which provides the lateral resistance force required for a predetermined deformation [16].

2.2 Optimization of design parameters

The stability provided by an anti-slide pile is affected by the driving force acting on the pile and the position of the pile. The estimation of the lateral force acting on the stabilizing pile due to the soil layer movement is discussed by He et al. (2015) [17]. The driving force of landslides has an important influence on determining the optimal position of the pile [4].

By considering the limit equilibrium method, Poulos (1995) [15] suggested that piles should be located in the vicinity of the centre of the critical failure wedge to avoid merely relocating the failure surface behind or in front of the piles. According to Ausilio et al. (2001) [12] the optimal location of the piles within the slope is near the toe of the slope where the stabilizing force needed to increase the safety factor to the desired value takes a minimum value. They also found out that piles also appear to be very effective when they are installed in the region from the middle to the toe of the slope. According to Li et al. (2006) [18] the optimal location of the piles within the slope is between the middle and top of the slope. The optimal pile position for slope reinforced with one row of piles is found to be located between the middle of the slope and the middle of the critical slip surface [18, 19].

Pile-spacing is a crucial parameter and a key problem in the design of anti-slide piles, which involves the safety and economy of anti-slide piles. Making full use of the soil arching effect between anti-slide piles can achieve the purpose of economy and efficiency. If the pile spacing is designed to be excessively large, soil between the anti-slide piles will slip away; if the pile-spacing is designed to be excessively small, the investment would be high, and the construction process would be difficult [10]. When the pile spacing is great, the piles cannot take advantages of the arching effect and are less effective in controlling sliding mass. The behavior of the passive pile was significantly influenced by pile head conditions. In case of free head pile, pile head movement exceeds the soil movement, resulting in positive passive pressure on the piles over a certain depth [20]. When pile spacing exceeded more than five times the pile diameter the force acting on the stabilizing pile decreased and the piles behaved almost as single isolated piles and the soil could flow between them. Hence, such an arrangement cannot be recommended for the purpose of slope stabilization [21]. The bearing capacity of the soil arches decreases with the increase of the pile spacing. And the increase of the soil compaction can efficiently increase the bearing capacity of the soil arches [22]. Reasonable pile spacing is an important practical problem in engineering design [23]. Pile spacing has a significant effect on landslide displacement control. Too small pile spacing causes a shielding effect and too large pile spacing causes the phenomenon of flow around the rear pile, in double row anti slide piles [24].

2.3 Anti-slide piles in multiple rows

With the increase in large scale landslides in nature and when the sliding mass is large, the most common measure to control large scale landslides is using pile rows. The double row anti-slide pile is developed from the single row anti-slide pile, which retains the mature theory and technology of single row anti-slide piles, and new structural support forms are developed. The new structural forms of double-row anti-slide piles mainly include two categories coupling beam double-row piles, and non-coupling beam double-row piles. The front and rear piles form a whole structure by connecting the top of the front and rear piles with rigid beams in the coupling beam double-row piles, such as gate-type anti-slide pile and h-type anti-slide pile. However, when the coupling beam double-row piles is used, the coupling beam constructed by the concrete is very easy to crack at the corner under the action of the massive bending moment and landslide thrust. The non-coupling beam double-row piles are commonly used, especially in the complex environment of landslide topography and landform [24]. There are two kinds of arrangement forms of non-coupling beam double-row piles, parallel arrangement, and staggered arrangement [25]. In the design of two rows of piles, the stress borne by the back row in parallel piles is less than the stress borne by the back row in staggered piles, and some leakage stress among front piles in parallel piles occurs. However, leakage stress from the back row in staggered piles can be borne by the front row. Therefore, the staggered piles are better at controlling slides. For multiple rows of piles, a staggered pile design type is better than a parallel design type [26].

3 Conclusion

Landslides are one of the most disastrous calamities which leads to huge destruction of infrastructure and human life. Among the various methods for controlling landslides anti-sliding piles and micro-anti-sliding piles are widely used in slope reinforcement engineering because of their simple structure, strong anti-sliding ability, and mature construction technology. The anti-slide pile is designed to install through the potentially sliding mass at a spacing significantly larger than their diameter and embedded below the potential sliding surface in the stable soil/rock strata. The soil arching effect is an important factor in the analysis and design of the anti-slide piles. Studies were conducted worldwide to assess the suitability of anti-slide pile for controlling and mitigating the landslides. The stability of pile reinforced slopes can be assessed by various experimental, analytical and numerical methods. The stability provided by an anti-slide pile is affected by the driving force acting on the pile and the position of the pile. The calculation of the critical spacing of anti-slide piles is a key problem in the design of anti-slide piles, which involves the safety and economy of anti-slide piles. Compared with other kinds of anti-slide structures, the anti-slide pile has many advantages; it has a large anti-slide resistance and good supporting effect; the pile has a small section and little disturbance to the stability of the sliding mass; pile groups can be constructed at the same time with more working surfaces, thereby reducing the interference, thus it is more convenient for excavation and construction. Besides, the anti-slide pile does not disturb the stability of the slope during the construction process. The anti-slide pile is an effective tool for controlling landslide, which was successfully implemented in different parts of the world. The application of advanced numerical methods to study the interaction mechanism and development of novel designs for overcoming the present disadvantages of anti-slide pile has been taking place. Also, numerous researches are taking place in this area to understand the mechanism and to expand its applicability for controlling rainfall and seismic induced landslides. Studies on utilization of anti-slide piles to control landslides due to rainfall and earthquake will be helpful for developing methods which are economical and advantageous over the current practices. Investigation on utilization of these piles in Indian scenario will be an advantage for our country. The assessment of the influencing parameters and their optimization will help in the development of economical pile design. Development of pile design using ecofriendly materials can be suggested as a future scope of this field.

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