Research on application of new combined support structures in reinforcing rocky slopes containing weak interlayers

Fei Zhao
Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, China

Zhenming Shi
Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, China

Songbo Yu (corresponding author)
Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, China

ABSTRACT: Anti-sliding piles have good reinforcement effect in slope under earthquake. In this study, new combined piles are proposed, and models of bedding rocky slopes with different weak interlayers are established. The force characteristics, reinforcement mechanism and effect of the combined piles are analyzed. The main findings are as follows: the different mechanical mechanisms of the slope reinforced by the flexible and rigid combination of piles result in different deformation patterns; through the pre-stress of the horizontal connection structure, the h-shaped flexible structure connecting the double-row piles can reasonably distribute the squeezing pressure and shear force on the piles to realize the synergistic seismic resistance of the piles, and its reinforcement effect is better than other piles. Based on the above findings, the study of combined piles for reinforcing rocky slopes has important engineering significance.

Keywords: Rocky slope with weak interlayers, New combined anti-slide piles, Reinforcement mechanisms and effects, Earthquake

1 INTRODUCTION

In recent years, the destabilization failure of stratified rocky slopes caused by earthquakes is a common and serious phenomenon, which has become a research focus in the field of geotechnical engineering and engineering geology (Guo et al., 2017; Song et al., 2018 and 2020). In order to solve the deformation and failure of rocky slopes, a lot of research has been conducted on pile reinforcement methods (Liu et al., 2013; Lai et al., 2014; Zhao et al., 2017; Feng et al., 2018; Ma et al., 2019; Huang et al., 2020; Wang et al., 2020; Li et al., 2021). The reinforcement mechanism and effect of single-row piles, double-row piles, anchor-tension piles and crown-beam piles on supporting slopes are comparatively studied from the aspects of piles' own structure, spatial distribution and combined structure. Liu et al. (2013) and Lai et al. (2014) showed that double-row piles are more effective than single-row piles in reducing the ground vibration response of slopes and preventing the high slope landslides in strong seismic areas. Ma et al. (2019), Huang et al. (2020) and Wang et al. (2020) analyzed that the pre-stresses applied in the anchor cable can effectively suppress the displacement of pile top and improve the bearing capacity of piles, which is better than the seismic performance of single-row piles on reinforcing slopes. In particular, the use of optimized multi-anchored piles to reinforce the slope can effectively solve the failure problem of anchor-root and improve the seismic performance of pre-stressed anchored piles (Feng et al., 2018). Piles with crown beam on top of the pile can be divided into single-row piles with crown beam and multi-row piles with crown beam. Zhao et al. (2017) and Li et al. (2021) found that the crown beam connection on top of the piles can strengthen the pile connection and improve the overall bearing capacity of the anti-sliding system, and the reinforcement effect is much better than that of single-row piles. However, there is still a lack of research on the reinforcement methods of piles for bedding slopes containing weak interlayers, especially the force mechanism and reinforcement mechanism of combined piles under earthquakes. This study aims to propose several new combined support structures, compare their reinforcement effects, and analyze their reinforcement mechanisms in rocky slopes containing weak interlayers.

2 NUMERICAL MODELS

2.1 Rocky slope models

According to a highway slope in Ludian, Yunnan, a centrifuge shaking table test of single-row piles reinforcing rocky slope containing weak interlayers was carried out. In order to further study the reinforcement effect of combined piles, the bedding rocky slope models with weak interlayers were established by using FDM in this study, as shown in Figure 1. The numerical model of the slope includes bedrock, hard rock and weak interlayer, with an angle of 40°, a length of 60 m and a height of 30.60 m. According to the distribution location and number of weak interlayers in the slope, three slope models were established, namely slope model I with upper weak interlayer, slope model II with lower weak interlayer, and slope model III with two weak interlayers. The vertical height of the slope foot after excavation is 6.50 m. The width of bedrock of slope top is 17.32 m, and the horizontal distance to the right boundary is 24.14 m. Table 1 shows the geotechnical parameters of the model slope. The boundary conditions around the model are set to free boundary and the bottom boundary is set to static boundary.

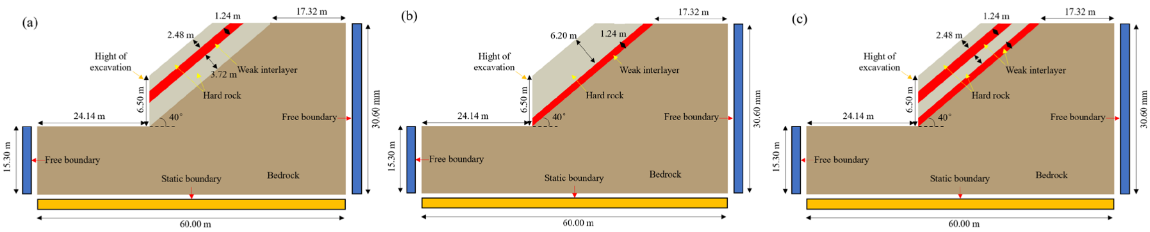

Figure 1. Numerical models for rocky slopes: (a) Slope I, (b) Slope II, and (c) Slope III.

Table 1. Physical and mechanical parameters in numerical model.

Lithology	ρ (g/cm^3)	τ (MPa)	E (GPa)	μ	c (MPa)	φ (°)
Hard rock	2.52	1.10	3.58	0.23	1.73	31.2
Weak rock	1.93	0.00	0.05	0.30	0.11	27
Bedrock	2.41	3.10	4.75	0.23	2.14	32

2.2 Combined anti-slide piles

In this study, according to the type and form of the structure connected between the double rows of piles, four types of support conditions were considered, namely, n-shaped double-row piles connected by flexible structure (n-fs-piles), n-shaped double-row piles connected by rigid structure (n-rs-piles), h-shaped double-row piles connected by flexible structure (h-fs-piles), and h-shaped double-row piles connected by rigid structure (h-rs-piles), as shown in Figure 2.

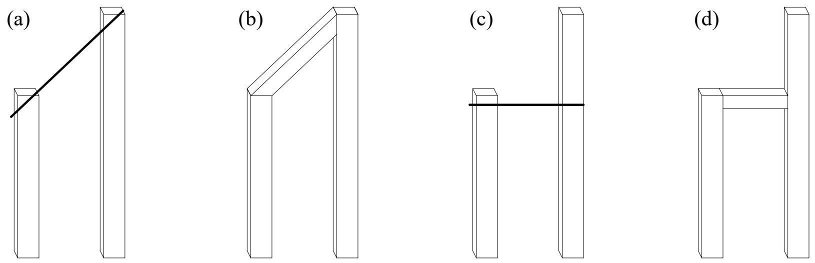

Figure 2. Four types of combined piles: (a) n-fs-piles, (b) n-rs-piles, (c) h-fs-piles, and (d) h-rs-piles.

2.3 Seismic waves

The Ludian Wave, recorded by the Ms 6.5 Ludian Earthquake in Yunnan in 2014, was used as the input wave with X-directional excitation mode in this study (see Figure 3). In order to further study the impact of different seismic intensities on the reinforcement effect of the combined support structures, three different seismic peak accelerations of 0.05g, 0.15g and 0.25g were selected.

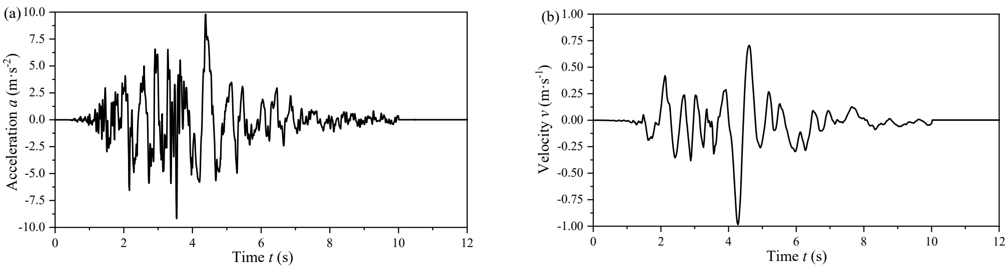

Figure 3. Ludian wave: (a) *a-t* curve, and (b) *v-t* curve.

3 RESULTS AND DISCUSSIONS

3.1 Deformation of slopes

The displacement of slope foot and maximum shear strain increment of rocky slopes containing different weak interlayers reinforced by combined piles show an increasing trend at 0.05g-0.25g (Figure 4). Under the seismic load of 0.25g, the displacement of the slope foot does not exceed 0.03 m and the maximum shear strain increment does not exceed 0.01. It can be seen that all four types of combined piles have good reinforcement effects in supporting bedding slopes. This is because connecting double rows of piles by horizontal or inclined rigid or flexible structures can effectively enhance the pile connections and improve the load-bearing capacity of the combined piles. Comparing the maximum shear strain increment of the slopes reinforced with h-shaped combination piles and n-shaped combination piles, the former can better prevent the slopes from large shear deformation (Zhao et al., 2017; Li et al., 2021). This is because the tension of the inclined connection structure can be decomposed into a component parallel to the pile and a component perpendicular to the pile which is the same as the component of the horizontal connection). The component force parallel to the pile results in vertical upward tension on the front pile and vertical downward pressure on the rear pile. This is detrimental to the stability of the front pile when the connection structure is under tension. Therefore, the "h-shaped double-row pile has a better reinforcement effect.

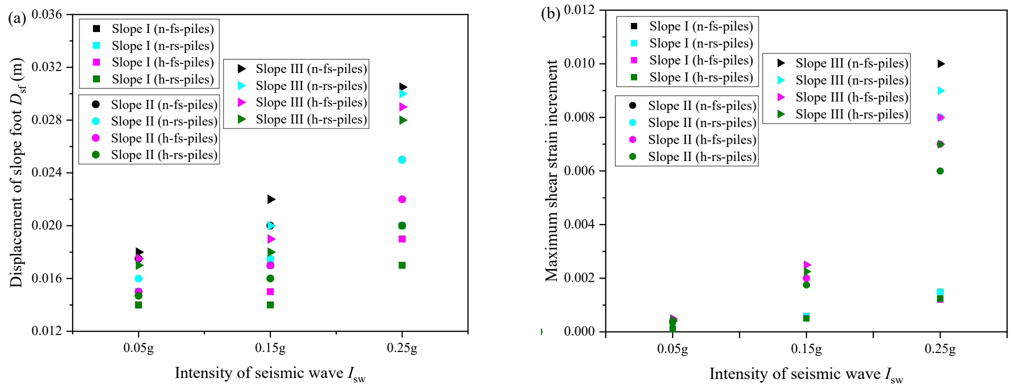

Figure 4. Deformation of rocky slopes: (a) Displacement, and (b) Maximum shear strain increment.

3.2 *Moment of piles*

Table 2 shows that the peak bending moments of the front and rear rows of the combined piles have different variation patterns under the seismic loads of 0.05g-0.25g. For slope model I, the bending moments of front piles of n-fs-piles and h-fs-piles increase with the increase of seismic load, while the front piles of n-rs-piles and h-rs-piles show a decreasing trend; the bending moments of the rear piles of n-fs-piles, h-fs-piles and h-rs-piles all increase first and then decrease, while the bending moments of n-rs-piles show an increasing trend. For slope model II, the bending moments of front piles of n-fs-piles and n-rs-piles tends to decrease first and then flatten with the increase of seismic load, while the bending moments of front piles of h-fs-piles and h-rs-piles decrease gradually; the bending moments of the rear piles show a trend of rapid decrease first and then slow decrease with the increase of seismic load. For slope model III, the bending moments of front piles of n-fs-piles and h-rs-piles show a decreasing trend with increasing seismic loadings, while the bending moments of front piles of n-rs-piles and h-fs-piles show a decreasing-increasing trend with increasing seismic loadings; the bending moments of the rear piles show a trend of rapid decrease and then slow decrease with the increase of seismic loadings.

Table 2. Peak moments of the front and rear piles.

Combined piles	Slope types	Peak moment M_{fp} (kN.m)			Peak moment M_{rp} (kN.m)		
		0.05g	0.15g	0.25g	0.05g	0.15g	0.25g
n-fs-piles	I	197	243	230	817	1190	1185
	II	486	311	302	761	444	368
	III	423	332	319	929	546	380
n-rs-piles	I	191	190	173	600	1012	1125
	II	369	267	283	671	309	181
	III	315	268	307	832	419	143
h-fs-piles	I	320	452	490	577	948	928
	II	532	448	371	592	252	206
	III	494	446	471	704	325	177
h-rs-piles	I	190	141	91	508	893	815
	II	609	367	315	558	210	207
	III	644	392	289	672	269	217

Figure 5 shows the variation of axial force in the connection structures of the four types of piles under different seismic loads. It can be seen that the axial force of the flexible connection structure shows a gradually decreasing trend with seismic loadings, while the axial force of the rigid connection structure shows a trend of increasing and then decreasing. Under the same seismic load, the variation of axial force of the horizontal flexible connection structure is smaller than that of the inclined flexible connection structure, resulting in smaller pre-stress loss and better energy dissipation effect. In addition, the change in the axial force of the connection structure also indicates that the deformation mode of the slope has changed. The increase of axial force is mainly influenced by the deformation of the lower part of the slope, while the decrease of axial force is mainly influenced by the deformation of the upper part of the slope. Therefore, for reinforced slopes with double-row piles connected by inclined rigid structures (n-rs-piles)the lower part of the slope has larger deformation under seismic loads of 0-0.15g, and the upper part of the slope has larger deformation under seismic loads of 0.15g-0.25g. Similarly, the reinforced slopes with double-row piles connected by horizontal rigid structure (h-rs-piles)have a similar deformation mode, except that 0.05g is the threshold value. However, for reinforced slopes with double-row piles connected by flexible structures (h-fs-piles, n-fs-piles), the upper part of the slopeis the main deformation location.

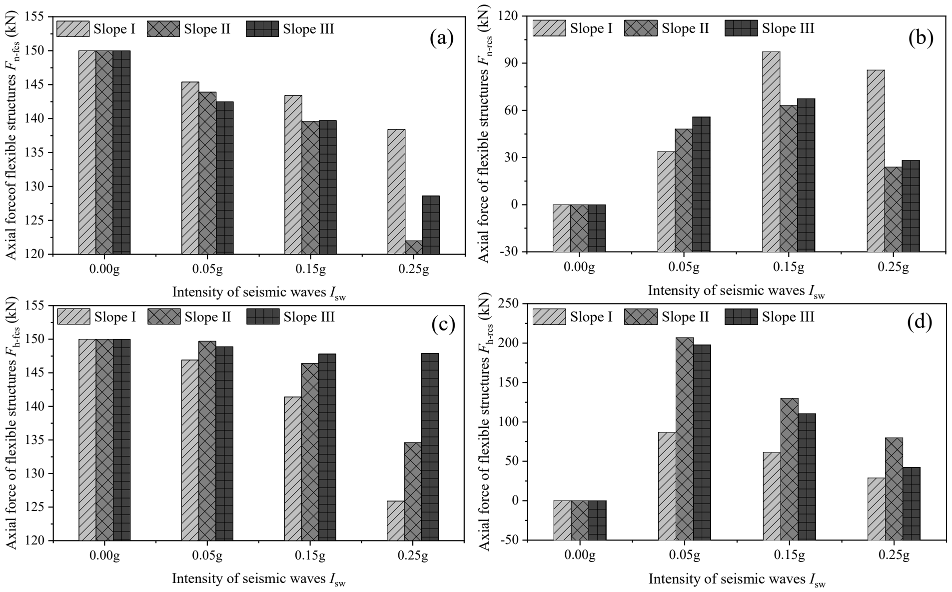

Figure 5. Axial force of connection structures: (a) n-fs, (b) n-rs, (c) h-fs, and (d) h-rs.

The force analysis of the combined piles under seismic loads shows that the mechanical mechanisms of the four combined piles on reinforcing slopes are different, resulting in different deformation patterns. The flexible or rigid structure between double row piles can strengthen the connection of piles. Among them, applying a certain amount of pre-stress to the flexible structure can change the support form of piles from passive support to active support. The rock mass between the piles is anchored as a whole tojointly resist the extrusion and shear effects of the upper rock mass, achieving the effect of consuming seismic wave energy and reducing rock mass deformation (Ma et al., 2019; Huang et al., 2020; Wang et al., 2023).

CONCLUSIONS

This study proposes several new combined piles and investigates their mechanical characteristics, reinforcement mechanism and effect by establishing the models of bedding rocky slopes with different weak interlayers. The main findings are as follows:

(1) Combined piles have good reinforcement effect on bedding slopes containing weak interlayers. Double-row piles connected by horizontal or inclined rigid or flexible structures can effectively strengthen the connection of piles and improve the bearing capacity of piles, so that the

displacement of the slope foot under a seismic load of 0.25g does not exceed 0.03 m and the maximum shear strain increment does not exceed 0.01.

(2) The mechanical mechanisms of the four types of combined piles for slope reinforcement are different. The connection of piles can be strengthened through flexible or rigid structure, and applying a certain amount of pre-stress to the flexible structure can change the support form of piles from passive support to active support. Compared to horizontal connections, the tension force of the inclined connection structures can be decomposed into a component force parallel to the pile and a component force perpendicular to the pile.

(3) The slopes reinforced with different combinations of piles have different deformation patterns. The axial tension of the flexible connection structure gradually decreases with the increase of the seismic load. The axial tension of the rigid connection structure shows a trend of increasing and then decreasing with the increase of the seismic load, where the seismic load is 0.15g for n-shaped piles and 0.05g for h-shaped piles.

ACKNOWLEDGEMENTS

This research was supported by the National Key Research and Development Program of China (Grant No. 2019YFC1509702). Thank the anonymous reviewers for their constructive comments.

REFERENCES

Feng, S., Wu, H.G., Ai, H., Feng, W. 2018. Seismic optimum design and experimental research on anti-slide pile with pre-stressed anchor cable. *Science Technology and Engineering* 18(12), pp. 248–255 (In Chinese) DOI:10.3969/j.issn.1671-1815.2018.12.041

Guo, S., Qi, S., Yang, G., Zhang, S., Saroglou, H. 2017. An analytical solution for block toppling failure of rock slopes during an earthquake. *Applied Sciences* 7(10), 1008. DOI: 10.3390/app7101008

Huang, Y., Xu, X., Mao, W. 2020. Numerical performance assessment of slope reinforcement using a pile-anchor structure under seismic loading. *Soil Dynamics and Earthquake Engineering* 129, 105963. DOI: 10.1016/j.soildyn.2019.105963

Lai, J., Zheng, Y..R, Liu, Y., Li, X.D., Abi, E. 2014. Shaking table tests on double-row anti-slide piles of slopes under earthquakes. *Chinese Journal of Geotechnical Engineering* 36(4), pp. 680–686 (In Chinese). DOI: 10.11779/CJGE201404012

Li, H., Wang, H., Yue, G., Zhao, F., Li, W. 2021. Arch antislide pile-wall structure system: model and optimization. *Mathematical Problems in Engineering* 2021(2), pp. 1-16. DOI: 10.1155/2021/8489627

Liu, C.Q., Li, X., Zhang, Y.P. 2013. Shaking table test and analysis of double row pile retaining structure. *China Civil Engineering Journal* 46(S2), pp. 190–195 (In Chinese). DOI:10.15951/j.tmgcxb.2013.s2.009

Ma, N., Wu, H., Ma, H., Wu, X., Wang, G. 2019. Examining dynamic soil pressures and the effectiveness of different pile structures inside reinforced slopes using shaking table tests. *Soil Dynamics and Earthquake Engineering* 116, pp. 293–303. DOI: 10.1016/j.soildyn.2018.10.005

Song, D., Che, A., Chen, Z.,Ge, X.R. 2018. Seismic stability of a rock slope with discontinuities under rapid water drawdown and earthquakes in large-scale shaking table tests. *Engineering Geology* 245, pp. 153–168. DOI: 10.1016/j.enggeo.2018.08.011

Song, D., Chen, Z., Chao, H., Ke, Y., Nie, W. 2020. Numerical study on seismic response of a rock slope with discontinuities based on the time-frequency joint analysis method. *Soil Dynamics and Earthquake Engineering* 133(4), 106112. DOI: 10.1016/j.soildyn.2020.106112

Wang, Z., Su, L., Shi, W., Ling, X. 2023. Reinforcement effect of landslide on different support structures under earthquake. *Journal of Engineering Geology*. (In Chinese). Doi: 10.13544/j.cnki.jeg.2020-487

Yin, Y.P., Zhang, Y.S., Wu, F.Q., Cheng, Y. 2014. Results and prospects of geological hazard investigation of Wenchuan earthquake. *Geological Survey of China* 1(1), pp. 1–9 (In Chinese). DOI: 10.19388/j.zgdzdc.2014.01.002

Zhao, B., Wang, Y.S, Wang, Y., Shen, T., Zhai, Y. 2017. Retaining mechanism and structural characteristics of h type anti-slide pile (hTP pile) and experience with its engineering application. *Engineering Geology* 222, pp. 29-37. DOI: 10.1016/j.enggeo.2017.03.018