Comparison between landslide thrust force on double-row and single-row stabilizing piles

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ABSTRACT

It is significant in practical design that rationally analyzing and comparing the relationship in terms of magnitude between the sum of thrust in double-row piles and the thrust on single-row piles in large-scale landslide control project. According to the transfer coefficient method based on limit equilibrium principle, the sum of upslope thrust on double-row piles and upslope thrust on single-row piles, as well as the sum of net thrust upon double-row piles and net thrust upon single-row piles are analyzed and compared. Analysis results of practical examples show that the relationship between the sum of thrust on double-row piles and the thrust on single-row piles is closely correlated with the position of the rear piles, the ratio of resistance force in front of the piles over the thrust behind piles, and the load transfer factor of thrust between soil slices. If the rear piles are located at the resisting section of the slip surface, the sum of the upslope thrust on double-row piles is greater than the upslope thrust on single-row piles. If the entire slip surface is a plane, the sum of net thrust upon double-row piles does not exceed that on single-row piles.

Keywords: landslide, double-row piles, single-row piles, upslope thrust on piles, net thrust

1 INTRODUCTION

In a large-scale landslide control project, double-row piles can be used in place of single-row piles if single-row stabilizing piles are found to be technically or economically irrational (Ito et al., 1982; Zhao et al., 2009; Xiao et al., 2017). If double-row piles are found technically acceptable, their economic rationality primarily depends on the amount of material utilized for piles. Naturally, the most important influence factor of which is the magnitude of landslide thrust. Therefore, conducting a comparison analysis of landslide thrust on double-row and single-row piles becomes a key focus in actual engineering practice. A great number of studies have investigated the mechanical characteristics and contributory factors of single-row piles (Ito et al., 1981; Randolph, 1981; Poulos, 1995; Lee et al., 1995; Chow, 1996; Hassiotis et al., 1997; Cai and Ugai, 2000; Guo, 2009). Some studies have also discussed the mechanical characteristics of double-row piles and analyzed the effect of the spacing of rows on the stress of the pile body (Xiao and He, 2015; Shen et al., 2017). However, previous studies have not specifically discussed the difference in magnitude between thrust upon double-row and single-row piles on the same driving section. Therefore, the current study focuses on the difference in thrust upon double-row and single-row piles. The transfer coefficient method (imbalanced thrust force method) is a relatively simple method in determining landslide thrust (Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2012; Xiao, 2018), so this approach is adopted in the current work for the analysis. In addition, considering that the types of thrusts upon piles that are especially relevant to engineering practice are upslope landslide thrust and net thrust upon piles, which is the difference between upslope thrust on piles and downslope resistance force on piles and is the actually the effective thrust load upon piles. Hence, these two types of thrust force are examined in the present work.

2 COMPARISON OF UPSLOPE THRUST ON PILES

Single-row piles are generally located at the resisting section of the slip surface. Thus, for double-row piles, the fore piles are typically located at the resisting section, and locations of the rear piles are discussed as per the following two cases:

2.1 Rear piles at the resisting section

For the case shown in Fig. 1(a), assuming that there are \( n + 1 \) soil slices located between the A-A section and the pile, the upslope landslide thrust on the pile is expressed as \( E_n \).
For the case shown in Fig. 1(b), the upslope thrust on the fore piles $E_n'$ is as follows:

$$E_n' = E_{k-1}' + \Delta E_{kn1}$$  \hspace{1cm} (1)

where $E_{k-1}'$ is the downslope resistance force on the rear piles, and $\Delta E_{kn1}$ is the net sliding force of slide mass located between the A-A section and the piles.

Thus, the sum of upslope thrust $E$ on the rear piles and fore-row piles is:

$$E = E_k + E_n$$  \hspace{1cm} (2)

where $E_k$ is the upslope landslide thrust on the rear piles. $E_k$ is larger than $E_n$ because the rear piles are located at the resisting section. $E_n'$ is not less than zero from the perspective of engineering practice. Thus, $E_n' > E_n$.

So Eq. (3) indicates that the sum of the upslope thrust on the two rows of piles is larger than that on single-row piles.

### 2.2 Rear piles at the driving section

The case wherein the rear piles are located at the driving section of the slip surface is shown in Fig. 2. If there are only the fore piles reinforcing the slope, the upslope thrust on the single piles can be expressed as

$$E_n = \psi_j E_{j-1} + \Delta E_{jn1}$$  \hspace{1cm} (4)

where $\psi_j$ is the transfer coefficient of the inter-slice thrust between the $j$-th and the $j$-th slices, which can be expressed as (China Norm, 2012)

$$\psi_j = \cos(\alpha_{j-1} - \alpha_j) - \sin(\alpha_{j-1} - \alpha_j) \tan \phi_j$$  \hspace{1cm} (5)

where $\alpha_{j-1}$ and $\alpha_j$ are the dip angles of the $j$-1th and the $j$th slip surfaces, respectively; and $\phi_j$ is the internal friction angle of the $j$th slip surface. If section B-B is located at the straight segment of the slip surface, then $\psi_{j-1} = 1$. In addition, $E_{j-1}$ is the net landslide thrust on section B-B, and $\Delta E_{jn1}$ is the net landslide thrust on the fore piles, which can be expressed as

$$\Delta E_{jn1} = (\psi_j \psi_j \cdots \psi_{n-1})E_{j-1} + \Delta W_{jn}$$  \hspace{1cm} (6)

where $\Delta W_{jn}$ is the net landslide thrust generated only by the slide mass between section B-B and the fore piles.

The upslope landslide thrust on the rear piles is expressed as $E_{j-1}'$ under such an arrangement of double-row piles and that of the fore piles $E_n'$ is given by

$$E_{n}' = E_{j-1}' + \Delta E_{jn2}$$  \hspace{1cm} (7)

where $E_{j-1}'$ is the downslope resistance force on the rear piles, and $\Delta E_{jn2}$ is the net landslide thrust on the fore piles, which can be expressed as

$$\Delta E_{jn2} = (\psi_j \psi_j \cdots \psi_{n-1})E_{j-1} + \Delta W_{jn}$$  \hspace{1cm} (8)

Thus, sum of thrust $E$ on the rear and fore piles is

$$E = E_{j-1} + E_{n}' + \Delta E_{jn2}$$  \hspace{1cm} (9)

Therefore, the difference between Equations (9) and (7) is as follows:

$$E - E_n = \frac{1}{(1 + \psi_j \psi_j \cdots \psi_{n-1})E_{j-1} + \Delta E_{jn1}}$$  \hspace{1cm} (10)

If the ratio of the downslope resistance force on the rear piles over the upslope thrust on the same piles $\xi$ (called the resistance ratio of landslide thrust on the rear piles) is defined as

$$\xi = \frac{E_{j-1}'}{E_{j-1}}$$  \hspace{1cm} (11)

Then, Eq. (10) can be converted to

$$E - E_n = \frac{1}{1 + \xi (1 + \psi_j \psi_j \cdots \psi_{n-1})E_{j-1}}$$  \hspace{1cm} (12)

So, this condition can also be discussed in two cases next.

(1) General case

A comprehensive comparison between the sum of the upslope thrust on double-row piles and the upslope thrust on single-row piles can be conducted based on each transfer coefficient and $\xi$. If section B-B is located at the localized straight section of the slip surface, then...
one can get
\[
E - E_n = \left[ \xi + (\xi - 1) \psi_{j,1} \ldots \psi_{n,1} \right] E_{j-1} \tag{13}
\]

Thus, this condition can be further discussed under the following two cases.

(1) General case
A comprehensive comparison between the sum of the net thrust on double-row piles and the net thrust on single-row piles can be conducted according to each transfer coefficient and \( \xi \). However, if section B-B is located at the localized straight segment of the slip surface, then one can get
\[
E - E_n = \left( \xi - 1 \right) \psi_{j,1} \ldots \psi_{n,1} E_{j-1} \tag{18}
\]

Further judgment shall be made according to \( \xi \):

(1) If \( \xi > 0.5 \), then the upslope thrust sum on double-row piles is larger than the upslope thrust on single-row piles;

(2) If \( \xi = 0.5 \), then the upslope thrust sum on double-row piles is equal to the upslope thrust on single-row piles;

(3) If \( \xi < 0.5 \), then the upslope thrust sum on double-row piles is less than the upslope thrust on single-row piles.

3 COMPARISON BETWEEN NET THRUST UPON PILES

Considering that the downslope resistance force on the front piles of the double-row piles and that on the single-row piles are generally close to each other in magnitude in actual engineering cases, the downslope resistance force on the front piles of the double-row and single-row piles are assumed to be similar to each other and is referred to as \( R_n \) to simplify the comparison analysis.

The net thrust upon single-row piles can be expressed as
\[
E' = E_{j-1} + \Delta E_{0,1} - R_n \tag{15}
\]

The sum of net thrusts \( E' \) upon the rear and front piles of the double-row piles is
\[
E' = E_{j-1} + \Delta E_{0,2} - R_n \tag{16}
\]

For cases wherein stabilizing piles are not located at the localized straight segment of the slip surface, the upslope thrust and the downslope resistance force on the rear piles are in different directions in Equation (16). Thus, the resolution of the related forces shall be conducted by taking the direction of local slip surface in front of piles as the projection direction. In fact, the equation can stand under most of the circumstances because the majority of stabilizing piles are located at areas where the localized slip surface is approximately a plane in the actual arrangement of piles.

Then, substituting Eqs. (6) and (8) into Eqs. (15) and (16), one can get the difference value of Eq. (16) and (15) as follow.
\[
E' - E'_n = \left[ 1 - \psi_{j,2} + (\xi - 1) \psi_{j,1} \ldots \psi_{n,1} \right] E_{j-1} \tag{17}
\]

Thus, this condition can be further discussed under the following two cases.

(1) General case
A comprehensive comparison between the sum of the net thrust on double-row piles and the net thrust on single-row piles can be conducted according to each transfer coefficient and \( \xi \). However, if section B-B is located at the localized straight segment of the slip surface, then one can get
\[
E - E_n = \left( \xi - 1 \right) \psi_{j,1} \ldots \psi_{n,1} E_{j-1} \tag{18}
\]

Since \( \xi > 1.0 \), the transfer coefficient is a positive value. Thus, from the perspective of engineering significance, the upslope landslide thrust on the rear piles is generally a positive value regardless of whether the rear piles are located at the resisting or driving section. Therefore, the sum of the net thrust on double-row piles does not exceed that on single-row piles.

(2) On the condition that the entire slip surface is a plane
The transfer coefficient is 1. Thus, there is
\[
E - E_n = (\xi - 1) E_{j-1} \tag{19}
\]

Since \( \xi < 1.0 \), the sum of net thrust on double-row piles does not exceed the net thrust on single-row piles.

4 CALCULATION EXAMPLES

The cross section of a talus landslide example is shown in Fig. 3, where the slide mass and stable layer of the landslide are gravel and soil mixture and limestone, respectively. The potential slip surface is the top surface of the limestone. Main parameters of the landslide are given in Table 1. The related geometric conditions are displayed in Fig. 3. The landslide is reinforced with double rows of stabilizing piles with 5m spacing out of plane. The cross section of the rectangle pile is 2m×3m, and the pile flexible rigidity is 114750 MN.m^2.

| Unit weight | Cohesion | Internal friction | Foundation coefficient |
|-------------|----------|-------------------|------------------------|
| (kN/m^3)    | (kPa)    | angle (°)         | (MPa/m)                |
| Gravel and soil mixture | 22 | 20 (10) | 27 (24) | 23 |
| Slip surface | 22 | 20 (10) | 27 (24) | 23 |
| Limestone    | 23 | 500 | 38 | 120 |

Note: the values in brackets are residual strength parameters.
curve under specified factor of safety 1.20 can be also obtained using the method (see Fig. 4(a)). The design thrust curve indicates the rear piles are located in the driving section of the slip surface under the factor of safety 1.20. So, according to Eq. (13), one can get

\[
\frac{E - E_j}{E_{j+1}} = \left[ \psi_3(1 + \psi_4) + 1 - \psi_3(1 + \psi_4) \right] = 0.7994 > 0 \tag{20}
\]

where \( j = 4 \) and \( n = 5 \) (see Fig. 3); \( E_3 = 6227 \text{kN/m} \), \( \psi_3 = 0.9639 \) and \( \psi_4 = 0.9792 \) by the transfer coefficient method; and \( \xi = 0.8625 \) by the Xiao-He method (Xiao and He, 2015).

Therefore, Eq. (20) discloses specifically that the sum of the upslope thrust on double-row piles is more than that on single-row piles.

In the case of the peak state of the slip surface, the natural factor of safety of the landslide is 1.30. The related practical and design landslide thrust curves under specified factor of safety 1.35 are shown in Fig. 4(b), which indicates the rear piles are located in the resisting section of the slip surface under the design condition. According to the transfer coefficient method, one can get \( E_3 = 5516 \text{kN/m} \) and \( E_5 = 3297 \text{kN/m} \). So, the sum of the upslope thrust on double-row piles must be more than that on single-row piles as expected.

Altogether, for the landslide example, the sum of the design upslope thrust on double-row piles is more than that on single-row piles no matter whether the rear piles are located in the driving or resisting section of the slip surface.

5 CONCLUSIONS

The sum of the landslide thrust upon double-row piles and the thrust upon single-row piles can be analyzed and compared approximately with the application of transfer coefficient method. The primary conclusions of the comparison and analysis are drawn as follows:

(1) Generally, the relationship in magnitude of the two thrusts depends on the location of the rear piles, the ratio of resistance force before over thrust force behind the piles, and the thrust transfer coefficient between soil slices.

(2) Under the circumstance that the rear piles are located at the resisting section of the slip surface, the sum of the upslope thrust on double-row piles is greater than the upslope thrust on single-row piles.

(3) If the entire slip surface is a plane, the sum of net thrust upon double-row piles does not exceed the thrust on single-row piles. However, if the rear piles are located at the driving section of the slip surface, the sum of upslope thrust on double-row piles does not exceed the upslope thrust on single-row piles only if the resistance ratio of landslide thrust on the rear piles does not exceed 0.5.

(4) If the rear piles are located at the localized straight segment of the slip surface, the sum of net thrust upon double-row piles does not exceed the thrust on single-row piles.
thrust upon double-row piles does not exceed the net thrust upon single-row piles. However, if the rear piles are located at the driving section of the slip surface, the relationship in magnitude between the sum of the upslope thrust on double-row piles and the upslope thrust on single-row piles are uncertain.

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REFERENCES

1) Cai, F. and Ugai, K. (2000): Numerical analysis of the stability of a slope reinforced with piles, Soils and Foundations, 40(1), 73-84.
2) Chow, YK. (1996): Analysis of piles used for slope stabilization, International journal for numerical and analytical methods in Geomechanics, 20, 635-646.
3) Guo, WD. (2009): Nonlinear response of laterally loaded piles and pile groups, International journal for numerical and analytical methods in Geomechanics, 33, 879-914.
4) Hassiotis, S., Chameau, JL., and Gunaratne, M. (1997): Design method for stabilization of slopes with piles, Journal of Geotechnical and Geo-environmental Engineering, 123(4), 314-322.
5) Ito, T., Matsui, T. and Hong, WP. (1981): Design method for stabilizing piles against landslide—one row of piles, Soils and Foundations, 21(1), 21-37.
6) Ito, T., Matsui, T. and Hong, WP. (1982): Extended design method for multi-row stabilizing piles against landslide, Soils and Foundations, 22(1), 1-13.
7) Lee, Y., Hull, TS. and Poulos, HG. (1995): Simplified pile-slope stability analysis, Computers and Geotechnics, 17, 1-16.
8) Poulos, HG. (1995): Design of reinforcing piles to increase slope stability, Canadian Geotechnical Journal, 32(5), 808-818.
9) Ministry of Housing and Urban-Rural Development of the People’s Republic of China (2012): Code for design of building foundation (GB50007-2011), ISBN 1511221656, China Architecture & Building Press, Beijing, China, 58-60 (in Chinese).
10) Randolph, MF. (1981): The response of flexible piles to lateral loading, Geotechnique, 31(2), 247-259.
11) Shen, Y., Yu, Y., Ma, F., Mi, F. and Xiang, Z. (2017): Earth pressure evolution of the double-row long-short stabilizing pile system, Environmental Earth Sciences, 76, 586.
12) Xiao, S. and He, H. (2015): An approximate analytical method for calculating thrust on double-row stabilizing piles, Rock and Soil Mechanics, 36(2), 376-380 (in Chinese).
13) Xiao S., Zeng J. and Yan Y. (2017): A rational layout of double-row stabilizing piles for large-scale landslide control, Bulletin of Engineering Geology and the Environment, 76(1), 309-321.
14) Zhao, S., Zheng, Y., Li, A., Qiu, W., Tang, X. and Xu, J. (2009): Application of multi-row embedded anti-slide piles to landslide of Wulong county government, Rock and Soil Mechanics, 30(Supp.1), 160-164 (in Chinese).