Theoretical Analysis on Soil Pressure Acting on End-Suspended Pile Supporting Structure to Foundation Pit in Soil-Rock Mixed Stratum

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Abstract. By taking Sanshandao Gold Mine Foundation Pit Supporting Project as an example, targeting at the end-suspended pile supporting structure applied in soil-rock mixed stratum common in mountainous and hilly area, this paper introduces unified strength theory and revised Hoek-Brown strength criterion to calculate and analyze active soil pressure, passive soil resistance and overall stability of supporting structure, during which not only the influence of intermediate principal stress, but also the influence of structural surface, weathering degree and disturbing degree of the rock can be taken into consideration. Therefore, theoretically speaking, it is much more scientific than traditional soil pressure theory, and the results are closer to actual engineering properties, thus being of critical theoretical significance and engineering reference value to perfecting design calculation theory of end-suspended pile supporting structure and optimizing design of foundation pit supporting structure.

1. Introduction
In terms of foundation pit with pure soil conditions, design theories, specifications and software for its supporting structure have developed to be rather mature. In terms of foundation pit in soil-rock mixed stratum in mountains and hilly area, though the special “end-suspended pile” supporting structure to foundation pit has been successfully used in many projects, the research on its design calculation theories and methods is far lagging behind needs of engineering practice. At present, the research of Chinese experts and scholars[1-3] on end-suspended pile is mainly to build numerical model, or design calculation model with several given conditions relying on projects cases, and then design it by virtue of both theories and experience based on the design calculation theory of soil slope, with no relevant specifications on how to judge the safety of such supporting structure to follow. Of course, no matter what kind of calculation model and method are selected by the designer, the priority is to rationally ensure the soil pressure acting on supporting structure. As is well-known, in all kinds of numerical analysis and design software, the soil pressure shall be determined according to the traditional soil pressure theory, namely, soil pressure calculation method specified in Mohr-Coulomb strength criterion, and the influence of intermediate principal stress $\sigma_2$ on soil-rock mass strength is never considered. This paper, by relying on End-Suspended Pile Supporting Project to Sanshandao Gold Mine Foundation Pit, based on the unified strength theory, with the influence of intermediate...
principal stress on soil-rock mass strength taken into consideration, discusses rules of soil pressure changing along with intermediate principal stress coefficient \( b \), and calculate passive soil resistance by virtue of revised Hoek-Brown strength criterion. The research findings can serve as theoretical support for optimized design of “end-suspended pile” supporting structure.

2. Support Model and Soil Pressure Calculation

2.1. “End-suspended pile” support model

Other than pile-anchor supporting system to mere soil or soil-rock foundation pit, “end-suspended pile” Supporting structure’s design calculation model shall not be designed through single calculation model since its pile foot is not buried below the foundation pit bottom, and shall be calculated according to the actual conditions by stages after foundation pit excavation. When excavating the upper soil layer, it can be designed and calculated according to the common pile-anchor support model since the pile foot of support pile is fixed in the embedded section, as shown in Figure 1.

![Figure 1](image1)

Figure 1. Schematic diagram of row pile model.

When excavating from the rock-embedded plane to deeper foundation pit bottom, the pile foot of supporting pile, due to loss the protection of rock embedded section, can only be supported by feet-lock anchor and reserved rock shoulder, which turns the support model into “end-suspended pile” supporting structure, as shown in Figure 2.

![Figure 2](image2)

Figure 2. Schematic diagram of end-suspended pile model.

2.2. Soil pressure calculation

Soil pressure refers to the principal lateral pressure acting on foundation pit supporting structure, and it also the main reason of deformation of supporting structure. Therefore rationally determining the soil pressure close to the the most actual press state during the excavation of foundation pit is critical to engineering safety and economy.

2.2.1. Soil pressure calculation in row pile mode

(1) Determination of soil mass strength parameters

This paper introduces shearing strength parameters \((\phi, c)\) according to the unified strength theory[4-5]
\[
\varphi_i = \sin^{-1}\left[ \frac{b(1-2\nu) + (2 + b + 2b\nu)}{2 + b(1 + \sin \varphi_0)} \right]
\]

\[
c_i = \frac{2(1+b)c_0 \cos \varphi_0}{2 + b(1 + \sin \varphi_0)} \cos \varphi_i
\]

In which, \(b\) is the intermediate principal stress, \(\nu\) is Poisson's ratio, \(\varphi_0\) is soil-rock mass internal friction angle, expressed in degree, \(c_0\) is soil-rock mass cohesion, expressed in kPa.

2. Passive soil resistance

In order to calculate the lateral resistance provided by embedded rock mass in the lower section, the revised Hoek-Brown Strength Criterion[6-8] is applicable. The corresponding calculation results will be closer to the true stress state. Hoek-Brown Strength Criterion based on the unified strength theory is expressed as below:

\[
\sigma_i = \sigma_3 + \frac{2(1+b)}{2+b} \sqrt{m_i \sigma_c \sigma_3 + s \sigma_c^2}
\]

\[
m_i = m_i \exp\left( \frac{GSI - 100}{28 - 14D} \right)
\]

\[
s = \exp\left( \frac{GSI - 100}{9 - 3D} \right)
\]

In which, \(\sigma_1\) and \(\sigma_3\) represent the maximum stress and minimum stress respectively, expressed in kPa; \(\sigma_c\) is the uni-axial compressive strength of rock, expressed in kPa; \(m_i\) and \(s\) are the constant value of rock mass materials, \(m_i\) reflects the hardness of rock and \(s\) represents the fragmentation degree of rock mass, with the value range being 0-1, 0 representing severely fractured rock mass, and 1 representing the perfect intact rock; \(GSI\) is the geological strength indicator of rock mass; \(D\) is disturbance coefficient, with 0 representing no disturbance on rock mass and 1 representing severe disturbance.

2.2.2. Calculation of soil pressure in “end-suspended pile” mode

This paper analyzes the passive soil resistance of certain thin stratum from rock shoulder during the “end-suspended pile” stage, with the stress shown in Figure 3.

![Figure 3](image)

Figure. 3 Schematic diagram of force analysis of rock shoulder.

This thin stratum is loaded with gravity \(G\) and supportive of lower rock stratum \(F_h\) in the vertical direction, both being mutual balanced, as well as friction between upper and lower interfaces \(f\) and passive soil resistance \(F_x\) in the horizontal direction. According to the force balance in the horizontal direction,
In Formula (6), \( \gamma \) reflects the weight of rock stratum, expressed in kN/m³; \( z' \) and \( z'' \) represents the distance from the upper interface and lower interface of thin stratum to the rock embedded plane respectively, expressed in m; \( \varphi \) represents the internal friction angle of soil-rock stratum, expressed in degree; \( c \) represents the adhesion of rock stratum, expressed in kPa; \( B' \) and \( B'' \) represents the width of upper and lower thin stratum respectively, expressed in m.

3. Application Examples and Analysis

The foundation pit of Laizhou Sanshandao Gold Mine is 33.0m in depth. Wherein, No.3 section applies anchor secant end-suspended pile + slop-cut support, with the profile designing of support shown in Figure 4. The diameter of plain concrete secant piles is 1,000mm, and the pile spacing is 1.7m, and the pile body is driven through the upper soil layer and strong weathered rock stratum only. The diameter of reinforced concrete piles is 1,200mm, and depth of pile end into intermediary weathered sericitolite shall be no less than 3.0m, and pile spacing shall be 1.7m. There shall be a 3.0m-wide platform at the lower part of anchor secant end-suspended piles, the natural slope ratio of intermediary weathered sericitolite in the lower stratum shall be 1:0.2. There shall be 7 pre-stressed anchor cables with horizontal spacing being 1.7m and vertical spacing being 3m. More information about the stratum in this area, please refer to Table 1.

| No. of soil layer | Name of soil layer       | Average thickness / m | Poisson’s ratio | Severe / (kN·m⁻³) | Modulus of compression / MPa | Internal friction angle / ° | Adhesion / kPa |
|-------------------|--------------------------|-----------------------|-----------------|-------------------|----------------------------|----------------------------|----------------|
| ①                 | Plain fill               | 3.40                  | 0.35            | 19.0              | 5.15                       | 15.0                       | 5.00           |
| ②                 | Medium sand              | 5.00                  | 0.30            | 18.5              | 15.0                       | 29.9                       | 0.00           |
| ③                 | Silty clay               | 2.00                  | 0.35            | 19.6              | 6.05                       | 13.14                      | 24.87          |
| ④                 | Strong weathered rock    |                       |                 |                   |                            |                            |                |
| ⑤                 | Intermediary weathered rock |               |                 |                   |                            |                            |                |

Figure 4 Support profile schematic diagram of zone 3.
3.1. Soil pressure in row pile mode

The foundation pit can be excavated along with the decrease of underground water, ensuring that the level of underground water within the pit is 0.5m under the excavation face. Considering that foundation pit is excavated quite deep, and the level of underground water is relatively high, it’s necessary to take the influence of underground water on soil pressure of supporting structure into consideration. Before calculating the soil pressure, convert the value of $c$ and $\phi$ from soil parameters to $c_t$ and $\phi_t$, with the converted parameters in Table 2 and Table 3, and value of equivalent internal friction angle in Table 4.

| $b$       | 0   | 0.25 | 0.5  | 0.75 | 1   |
|-----------|-----|------|------|------|-----|
| Plain fill| 15.00 | 17.19 | 18.87 | 20.21 | 21.30 |
| Medium sand| 29.90 | 33.09 | 35.48 | 37.35 | 38.85 |
| Silty clay| 13.14 | 15.75 | 17.78 | 19.39 | 20.71 |
| Strong weathered rock | 30.00 | 33.55 | 36.22 | 38.32 | 40.00 |
| Intermediary weathered rock | 45.00 | 48.29 | 50.73 | 52.62 | 54.13 |

| $b$       | 0   | 0.25 | 0.5  | 0.75 | 1   |
|-----------|-----|------|------|------|-----|
| Plain fill| 5.00 | 5.46 | 5.82 | 6.12 | 6.36 |
| Medium sand| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Silty clay| 24.87 | 27.27 | 29.19 | 30.77 | 32.09 |
| Strong weathered rock | 20.00 | 21.88 | 23.42 | 24.73 | 25.84 |
| Intermediary weathered rock | 200.0 | 219.0 | 234.9 | 248.6 | 260.4 |

| $b$       | 0   | 0.25 | 0.5  | 0.75 | 1   |
|-----------|-----|------|------|------|-----|
| Plain fill| 16.83 | 19.25 | 21.11 | 22.61 | 23.83 |
| Medium sand| 29.90 | 33.09 | 35.48 | 37.35 | 38.85 |
| Silty clay| 22.15 | 26.03 | 29.11 | 31.62 | 33.70 |
| Strong weathered rock | 43.23 | 47.9 | 51.38 | 54.08 | 56.23 |
| Intermediary weathered rock | 81.45 | 83.11 | 84.20 | 85.00 | 85.52 |

Figure 5 shows the distribution of active soil pressure strength under row pile mode with different values of $b$. As shown in the figure, the active soil pressure strength in the rock-embedded surface is maximum, and along with the increase of $b$, active soil pressure strength at different soil layer interfaces will decrease gradually.
Figure. 5 Influence of $b$ value on active earth pressure strength of row pile.

Table 5, Table 6 and Table 7 respectively show calculation results of total active soil pressure, passive soil resistance and safety factor of global stability of slope under the row pile mode and different values of $b$.

Table. 5 Total active earth pressure of row pile mode.

| $b$   | 0     | 0.25  | 0.5   | 0.75  | 1     |
|-------|-------|-------|-------|-------|-------|
| Active soil pressure/ (kN·m$^{-1}$) | 1679.3 | 1515.4 | 1406.0 | 1328.0 | 1270.0 |

Table. 6 Passive soil resistance of row pile mode.

| $b$   | 0     | 0.25  | 0.5   | 0.75  | 1     |
|-------|-------|-------|-------|-------|-------|
| Passive soil resistance/ (kN·m$^{-1}$) | 1693.2 | 1881.3 | 2031.8 | 2154.9 | 2257.6 |

Table. 7 Overall stability safety factor of row pile mode.

| $b$   | 0     | 0.25  | 0.5   | 0.75  | 1     |
|-------|-------|-------|-------|-------|-------|
| $k$   | 2.94  | 3.23  | 3.45  | 3.67  | 3.90  |

According to previous research, Mohr-Coulomb Criterion is an exception of the unified strength theory when the intermediary principal stress coefficient $b=0$, and for loss soil mass and rock mass, when $b=0.5$ and $b=1$, the calculated soil pressure is in line with the engineering practice[9-10]. When comparing the calculation result in Table 5 and Table 6 with $b=0$ and $b=0.5$, the total active soil pressure calculated according to Mohr-Coulomb Strength Criterion is 19% larger than that calculated according to the unified strength theory, which means that the active soil pressure of upper soil layer calculated according to traditional soil pressure theory is conservative; the passive soil resistance when $b=0.5$ is 20% larger than that when $b=0$. As a result, the passive soil resistance calculated according to Hoek-Brown Strength Criterion based on the unified strength theory can make better play of the embedded effects of rock stratum.

Table 7 shows the calculation result of safety factor under row pile mode by applying Lizheng Deep Foundation Pit Software. According to Table 7, the safety factor of global stability of supporting structure will increase along with the increase of $b$.

3.2. Soil pressure in “end-suspended pile” model

When excavating to the bottom of foundation pit, the support model turns to become “end-suspended pile” supporting structure. When calculating the active soil pressure of rock-embedded section, the internal friction angle shall be equivalent internal friction angle in the stratum. As shown in Table 4, the equivalent friction angle of intermediary weathered stratum is quite large, and the calculated active soil pressure is quite small, almost being zero.
The calculation results of passive soil resistance and safety factor of global stability of slope under the end-suspended mode and different values of $b$ are shown in Table 8 and Table 9 respectively.

Table 8 Passive soil resistance of end-suspended pile pattern.

| $b$ | 0   | 0.25 | 0.5  | 0.75 | 1   |
|-----|-----|------|------|------|-----|
| $F_x/(kN\cdot m^{-1})$ | 1927.6 | 2398.3 | 2853.0 | 3312.4 | 3698.9 |

Table 9 Overall stability safety factor of grading.

| $b$ | 0   | 0.25 | 0.5  | 0.75 | 1   |
|-----|-----|------|------|------|-----|
| $k$ | 1.83 | 2.02 | 2.18 | 2.32 | 2.44 |

According to the calculation results of passive soil resistance at this stage after analyzing the stress of reserved rock shoulder under “end-suspended pile” mode, the calculation result, when $b$ is 0, is 52% of that when $b$ is 1. Therefore, the strength of rock mass will be fully exerted after taking the influence of intermediary principal stress on mechanical parameters of rock mass.

Same to the rules that the safety factor of global stability in row pile mode, the safety factor of slope in lower bed rock stratum increases along with the increase of $b$. When $b=0$, the safety factor of global stability is 1.83, which means that the intermediary weathered stratum is quite intact, and the lower rock bed stratum can be directly excavated without erecting supports when excavating to the soil-rock interface.

4. Conclusion
(1) In soil-rock mixed stratum in mountains and hilly areas, “end-suspended pile” supporting structure has been successfully applied to protect foundation pits of urban architecture, water utilities, mining and other many projects, but its design calculation theory is quite immature, without relevant specifications to follow, resulting in great blindness and experience-based practice in design.

(2) It’s quite complex to calculate the soil pressure of supporting structure. Determining soil pressure based on the unified strength theory with the influence of intermediate principal stress into consideration, theoretically speaking, is much more scientific than classic soil pressure theory proposed by Rankine and Coulomb. The calculation results based on these classic soil pressure theories are quite conservative, which cannot be used for optimized design of supporting structure to foundation pit.

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