Intervisibility calculation model of monitoring hole and optimization of device installation position

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Abstract. Aiming at the laser monitoring of the strain of the underground pile foundation of buildings, this paper establishes the intervisibility calculation model of a single monitoring hole, and optimizes the installation position of the monitoring device. The results show that the calculation results of the model are basically consistent with the measured data, which solves the problem of repeatedly adjusting the laser when measuring the maximum intervisibility in the past. Finally, the sum of the maximum intervisibility of all monitoring holes is significantly increased by optimizing the installation position.

Keywords: Laser monitoring; calculation model; optimization.

1. Introduction
In order to use a laser device to monitor the strain situation of the pile foundation of a municipal project, it is necessary to build a planar distribution of borehole groups in the rock mass around the underground space, and each borehole has an intervisibility requirement, as shown in Figure 1. Limited by the performance of the equipment, the drilling axis tends to deflect to varying degrees when the hole is actually formed. By repeatedly adjusting the horizontal angle and vertical angle of the laser, a certain laser line can be found to maximize the visibility of the hole. However, this method lacks directivity, large workload and low accuracy.

Therefore, it is necessary to study a method of obtaining intervisibility to improve this problem. At the same time, it is necessary to optimize the center space coordinates used to erect the laser emitter according to the design and measured data of multiple boreholes, including the axis (horizontal angle, vertical angle) and the intervisibility, so as to meet the following requirements at the same time:

(1) The center space coordinate adjustment range is the smallest.
(2) The intervisibility reaches the maximum in the actual drilling.

2. Single-hole maximum intervisibility calculation model
Since the central axes of all boreholes are distributed in a plane and intersect at a central point $O$, the space rectangular coordinate system is established with the point $O$ as the origin, as shown in Figure 1.

As shown in Fig. 2, the actual center axis $l_i'$ of the hole $i$ with the drilling diameter $\phi_i$ ($i = 1, 2, ..., n$) has a deviation from the design axis $l_i$ (red line in the figure) of the laser emission. $a_i'$ and $b_i'$ are the
front and rear centers of the hole respectively. Taking the intersection points $a_i$ and $b_i$ of the laser and the front and rear surfaces of the drill hole as the center of the circle, make an inscribed circle in the surface. Define the intervisibility of the front and rear surfaces at this time as:

$$
\phi_{ai} = \phi_i - 2|a_i a'| \\
\phi_{bi} = \phi_i - 2|b_i b'|
$$

(1)

The intervisibility of the entire borehole:

$$
\phi_i' = \min(\phi_{ai}, \phi_{bi})
$$

(2)

Figure 1. Space diagram of drilling group.

The following analysis establishes the calculation model of the maximum intervisibility. The model uses the coordinate values of points $a_i'$ and $b_i'$ as inputs to obtain the maximum intervisibility of the borehole and the horizontal and vertical angles of the corresponding laser.

Figure 2. Schematic diagram of a single drilling hole and design axis.
Firstly, the coordinates of the actual drilling inlet and outlet center points \( a_i' \) and \( b_i' \) are read by the Total Station to represent the actual axis \( l_i' \) of borehole \( i \):

\[
\begin{align*}
  x &= x_{a_i} + (x_{b_i'} - x_{a_i}) t \\
  y &= y_{a_i} + (y_{b_i'} - y_{a_i}) t \\
  z &= z_{a_i} + (z_{b_i'} - z_{a_i}) t
\end{align*}
\]  

(3)

The straight line equation of the laser that always passes through the origin \( O \) is:

\[
\begin{align*}
  x &= \sin \theta \cos \varphi \cdot t \\
  y &= \sin \theta \sin \varphi \cdot t \\
  z &= \cos \theta \cdot t
\end{align*}
\]  

(4)

When the horizontal angle is \( \varphi \) and the vertical angle is 90°, it is the design axis \( l_i \) of the \( i \)-hole:

\[
\begin{align*}
  x &= \cos \varphi \cdot t \\
  y &= \sin \varphi \cdot t \\
  z &= 0
\end{align*}
\]  

(5)

The front end of the borehole:

\[
\begin{align*}
  A(x - x_{a_i}) + B(y - y_{a_i}) + C(z - z_{a_i}) &= 0 \\
  (x - x_{a_i})^2 + (y - y_{a_i})^2 + (z - z_{a_i})^2 &\leq (\phi_i / 2)^2
\end{align*}
\]  

(6)

The back end of the borehole:

\[
\begin{align*}
  A(x - x_{b_i}) + B(y - y_{b_i}) + C(z - z_{b_i}) &= 0 \\
  (x - x_{b_i})^2 + (y - y_{b_i})^2 + (z - z_{b_i})^2 &\leq (\phi_i / 2)^2
\end{align*}
\]  

(7)

Where \( t \in \mathbb{R} \), \( A = x_{b_i'} - x_{a_i} \), \( B = y_{b_i'} - y_{a_i} \), \( C = z_{b_i'} - z_{a_i} \).

The coordinates of \( a_i' \) and \( b_i' \) can be obtained by combining formula (5) and formula (6), formula (5) and formula (7) respectively. By substituting the results into (1) and (2), the intervisibility of the entire borehole can be obtained.

Obviously, in an ideal situation, the actual axis \( l_i' \) of borehole \( i \) coincides with the design axis \( l_i \), and the intervisibility \( \phi_i' \) is equal to the borehole diameter \( \phi_i \). The maximum value of formula (2) and the corresponding independent variable are the maximum intervisibility \( \phi_{i\text{max}}' \) and the corresponding horizontal angle and vertical angle.

As shown in Table 1, the borehole with a design horizontal angle of \( \pi/6 \) is measured to obtain the coordinates of \( a_i' \) and \( b_i' \). After repeated adjustment of the laser axis, the maximum intervisibility was measured to be 175mm, at this time the horizontal angle was 0.519 and the vertical angle was 0.175.

| Length(m) | Diameter(mm) | \( a_i' \)       | \( b_i' \)       |
|-----------|--------------|------------------|------------------|
| 10        | 305          | (8.6160, 5.0094, 0.0915) | (17.4146, 9.9315, 0.0930) |

Substitute the coordinates of points \( a_i' \) and \( b_i' \) into the above calculation model. The calculation results of the front-end and rear-end intervisibility are shown in Figure 3, and the entire borehole...
Intervisibility is shown in Figure 4. It can be seen from the figure that $\phi_i'_{\max}$ of the hole is 175.6mm, the corresponding horizontal angle is 0.5206, and the vertical angle is 0.1756.

**Figure 3.** Intervisibility of the front-end and rear-end of the borehole (design horizontal angle $\pi/6$).

**Figure 4.** Borehole intervisibility with design horizontal angle of $\pi/6$ and its maximum value.
Considering the measurement error, through the measurement and calculation of many other boreholes, it is found that the calculated results of the model are consistent with the measured results, so the model is established correctly.

3. Optimization of device installation position

As mentioned before, in order to achieve the maximum intervisibility in all boreholes, the spatial coordinates of the device installation position need to be further optimized.

Based on the measured coordinates $a_i'$, $b_i'$ ($i = 1, 2, ..., n$) and the maximum intervisibility $\phi_i'$ calculated by the model, the spatial rectangular coordinate system with the origin of $O_0$ is re-established, as shown in Figure 5.

![Figure 5. Spatial coordinates before and after optimization of equipment installation position.](image)

Suppose that the coordinate value of $O_0$ in the original coordinate system $O$ is $p_{OO_0}(\Delta x, \Delta y, \Delta z)$. The optimization goal is to find a point $p_{OO_0}$ in the space to maximize the sum of the maximum intervisibility of each borehole.

According to the theory of the representation of position and the roll-pitch-yaw representation of rotation [1], the coordinates of the points in coordinate system $O$ in coordinate system $O_0$ meet the formula:

$$
\begin{bmatrix}
q_{O_0} \\
1
\end{bmatrix} = R_{OO_0} \begin{bmatrix}
p_{OO_0} \\
0 \\
1
\end{bmatrix}$$

(8)

Where $R_{OO_0}$ is the roll-pitch-yaw representation of an arbitrary rotation matrix of coordinate system $O_0$ relative to coordinate system $O$:

$$
R_{OO_0} = 
\begin{bmatrix}
c_\phi c_\theta & -s_\phi c_\theta + c_\phi s_\phi s_\theta & s_\phi s_\theta + c_\phi s_\phi c_\theta \\
-c_\phi s_\theta & c_\phi c_\theta + s_\phi s_\phi s_\theta & -s_\phi c_\theta + c_\phi s_\phi c_\theta \\
-s_\phi & c_\phi s_\phi & c_\phi c_\phi
\end{bmatrix}
$$

For simplicity of calculation and without loss of generality, the $O_0$ coordinate axis is parallel to the $O$ coordinate axis and the direction is consistent, then $R_{OO_0}$ is the identity matrix.

The specific optimization solution flow is shown in Figure 6.
Limiting the variable space of the center point is a cube centered at $O$ point and with a side length of 0.2m. The data in Table 2 is used as an input for optimization calculation. The results are shown in Figure 7.

Table 2. Borehole data before optimization.

| Number | Horizontal angle | $a'_i$         | $b'_i$         | $\phi'_{i_{\text{max}}}$ |
|--------|------------------|----------------|----------------|--------------------------|
| 1      | 0                | (10.062, 0.081, -0.074) | (20.082, 0.026, -0.080) | 0.1970                   |
| 2      | $\pi/6$          | (8.616, 5.009, 0.091) | (17.414, 9.931, 0.093) | 0.1740                   |
| 3      | $\pi/2$          | (0.091, 5.997, 0.060) | (-0.071, 11.984, 0.091) | 0.1317                   |
| 4      | $2\pi/3$         | (-3.935, 6.967, 0.031) | (-7.036, 12.214, -0.092) | 0.1657                   |
| 5      | $\pi$            | (-6.093, 0.031, 0.069) | (-11.012, -0.065, 0.086) | 0.2112                   |
| 6      | $4\pi/3$         | (-5.062, -8.683, 0.035) | (-9.941, -17.267, 0.051) | 0.2240                   |
| 7      | $7\pi/4$         | (4.989, -5.002, 0.048) | (9.029, -8.958, -0.021) | 0.2106                   |
Figure 7. Optimization calculation results.

In the results, the points less than 1.3142 (the sum of the maximum intervisibility before optimization) are represented by blue o, the points greater than 1.3142 are represented by yellow + and the red * is the maximum after optimization. It can be seen from Figure 7 that after optimization, the sum of the maximum intervisibility is 1.5379m, the coordinates of the optimized center point are [-0.023, 0.1, 0.062], and the average maximum intervisibility of each hole is increased by 31.9mm, achieving the optimization effect.

4. Conclusion
The intervisibility calculation model of a single monitoring hole is correct. Using this model to calculate the maximum intervisibility is more time-saving and labor-saving than repeatedly adjusting the laser axis. The optimization algorithm has a significant effect on the installation location optimization of the monitoring device, and the sum of the maximum intervisibility of all monitoring holes is significantly increased.

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