Correlation Degree Analysis of Surface Settlement Influence Factors Around the Pit

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Abstract. The excavation of city subway pit breaking the original balance of the soil, affecting the safety of existed buildings and the surface subsidence of construction are important and direct factors which react to construction impacts. Using the Gray Relational Analysis Theory, through monitoring measured data of factors, building gray correlation analysis among excavation of subway construction surface subsidence, horizontal displacement of pile top, deep displacement, the groundwater level, the support axial force, the anchor cable tension and other factors, get the collective degree of different monitoring program. The results show that, the factors, from maximal to minimum correlation degree, which affect surface subsidence includes horizontal displacement of pile top, anchor cable tension, the groundwater level, deep displacement, strut axial forces. It provides a theoretical basis for law of surface subsidence and similar monitoring program optimization for the future projects.

The excavation of city subway pit breaks the original balance of the soil. Before the excavation and construction process, in order to prevent pit deformation, measures has been taken, such as diaphragm wall, concrete support, steel support, anchor and so on. However, it does not eliminate the impact of excavation on the surrounding environment. Construction causes the movement of surrounding ground, and it leads to different degrees of surface subsidence and horizontal displacement. Most projects are located in the bustling city center, if the settlement exceeds a certain level, will cause surface subsidence, collapse pit, building damage, underground pipelines damage, etc., and it will have serious impact on personal property, the economy and life. Some scholars study the deep foundation pit bottom uplift calculation method [1], monitor excavation during construction [2], and use a theoretical model to predict the surface movement and deformation which based on geotechnical characteristics during excavation [3]. They also developed many kinds of surface subsidence model law based on measured data[4, 5, 6], such as Logistic Model, Neural Network Model, GM Gray System Model, Time Series Forecasting Model, and Gray- BP Neural Network Prediction Model [7, 8]. This paper analyzes the gray correlation excavation of the monitoring project and surface subsidence values, and distinguishes the various factors that influence the degree of surface subsidence.

Factors Affecting Excavation Subsidence

A subway station is located south of the intersection of two main roads, the original geomorphic units is second terrace of erosion ~ accumulation. The ground has been the scene of relatively flat after the several artificial transformations, the elevation is 32.21 ~ 35.44m, surrounding buildings gathers, and the terrain is not open. Terraces mainly composed of Quaternary Pleistocene silty clay, sand and gravel layer with obvious dual structure. Strata from top to bottom are: plain fill, silty clay, tine sand, gravel sand, round gravel, gravel, strongly weathered argillaceous siltstone, moderately weathered argillaceous siltstone (KS) and slightly weathered argillaceous siltstone (KS). Groundwater mainly composed of Quaternary pore phreatic water in sand and gravel layer and Quaternary fissure water in strongly-moderately weathered bedrock. Pore phreatic water depth is

1.30 ~ 7.30m, elevation is 26.43 ~ 33.26m; stable pore phreatic water depth is 1.20 ~ 6.10m, elevation is 27.71 ~ 31.82m; stable bedrock fissure water depth is 2.20 ~ 5.00m, elevation is 28.31 ~ 32.69 m. Groundwater level changes are mainly affected by climate and river waters. Each year, from April to September is groundwater accumulating period, and the water level will rise significantly; October to next March is groundwater consuming period, and the water level will drop. Changes in the magnitude is generally 5.00 ~ 8.00m.

The size of the pit surface settlement value relates to the geological conditions of excavation, outside support system, precipitation depth, and construction technology. Under the same conditions of pit geological and construction technology, pit surface subsidence relates to the following monitoring items: deep horizontal displacement of supporting pile, horizontal displacements of the pile top, the groundwater level, support axial force, the anchor cable tension. Due to the construction site complex, simultaneous monitoring of the monitoring items fails, leading to different initial observation time for each monitoring items. Therefore, we assume that each observation value occurs at the same observation time, and the previous observed value during the same observation time is the initial observation. Figure 1 shows the relationship between each cumulative value of surface subsidence and horizontal displacements of the pile top, the groundwater level, deep horizontal displacement, and the anchor cable tension. (The horizontal axis represents periods, the vertical axis represents the cumulative value of surface subsidence, mm; cumulative value of pile displacement, mm; the cumulative value of groundwater level, m; cumulative value of deep horizontal displacement, mm; cumulative value of the anchor cable tension, kN)

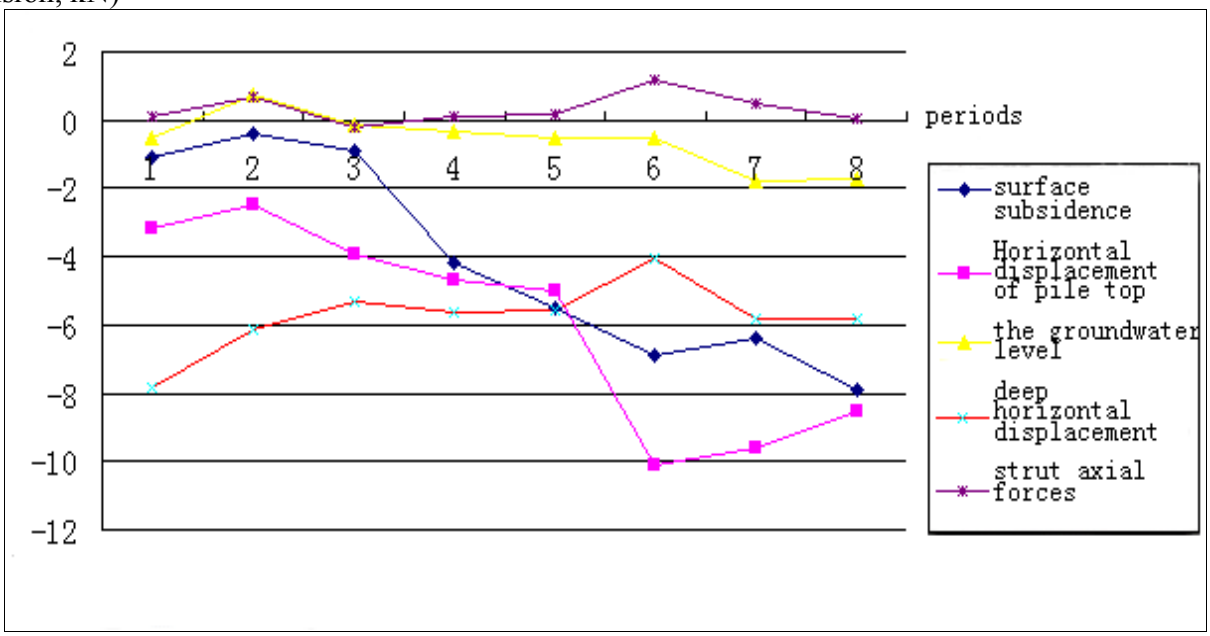

Fig. 1 Surface Subsidence Settlement of Relations with the Various Factors

Figure 2 shows the relationship between the surface subsidence and support axial force. (The horizontal axis represents periods; the vertical axis represents the cumulative size of the support axial force, kN)

Figure 1 and Figure 2 show that the horizontal displacement of the pile and the surface subsidence are positively correlated, which means as the top of the pile displacement increases, surface subsidence value increases as well. The trending of groundwater level falling and the falling of Surface subsidence are consistent, as the groundwater level falling, soil hydrophobicity consolidates and surface subsides. The support axial force and surface subsidence are negatively correlated, which means support for the role of surface subsidence has slowed. The anchor cable tension and surface subsidence are negatively correlated, which means anchor cable tension slow surface subsidence.

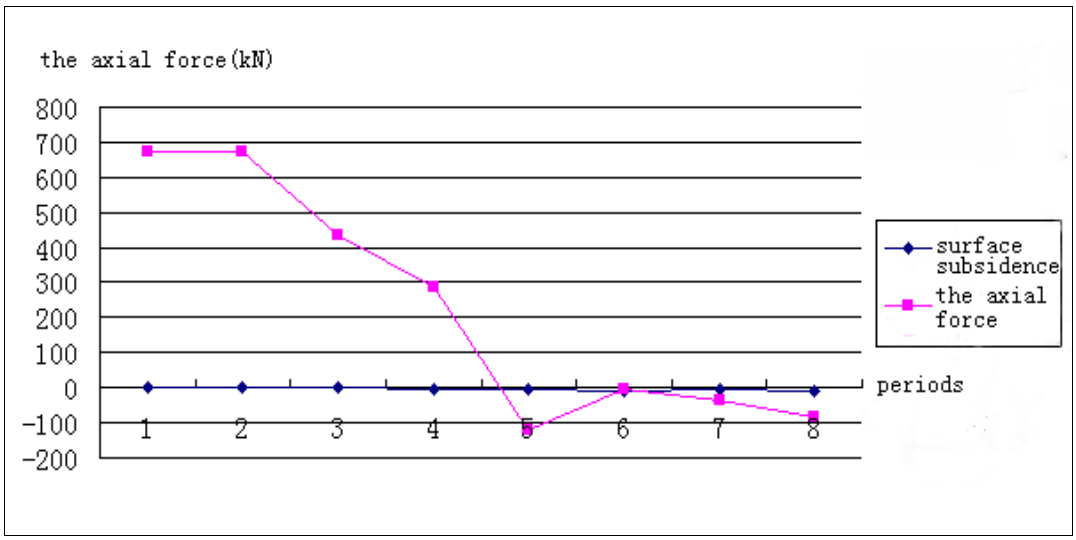

Fig. 2 the Surface Subsidence and the Axial Force

Analysis of Correlation

Gray Relational Analysis Theory

Correlation indicates that the relative changes between the various factors in system development process. It represents the degree of change, direction, speed and other indicators of relevance. The correlation of sequence A and sequence B is regarded as lager if they have the same relative change during their developing process [9]. Gray relational analysis is a method which can describe and compare dominant factor and underlying factor. Clarify the relationship between systems and factors before the entire system, and then we will have more comprehensive understanding [10]. Gray relational analysis includes the following steps: transform raw data; calculate the correlation coefficient; calculate correlation; sort correlation; lists the correlation matrix. Has m periods, subsequence is $\{X_1^{(0)}(t)\}, \{X_2^{(0)}(t)\}, \{X_3^{(0)}(t)\} \ldots \{X_m^{(0)}(t)\} = 1,2 \ldots N, m = 1,2,\ldots, N$ [11], $\{X_1^{(m)}(t)\} = \{m, x_1^{(m)}, x_2^{(m)}, x_3^{(m)}, \ldots, x_n^{(m)}\}$, parent sequence is $\{X_0^{(0)}(t)\} = 1,2,\ldots,N$ [12].

Transform Raw Data. Due to various factors dimensional inconsistencies, such as subsidence in millimeters, the force in kN, the water level in meters, etc.; we must eliminate the dimension of the original series and convert it into a sequence comparison. Transformation happens in the following forms: the mean transformation, initialize transformation, standardization transformation.

Mean transformation: calculating the mean of each sequence, then each raw data is divided by the corresponding average value to obtain mean sequences. Initialize transformation: each raw data is divided by the first number to obtain new multiple sequences. Standard transformation: calculating the mean and standard deviation of each sequence, then all the raw data subtract the average value, after that divide by the standard deviation to obtain standard sequences.

Calculate the Correlation Coefficient. After the data conversion, parent sequence is $\{X_0(t)\}$, subsequence is $\{X_i(t)\}$. When at t = k, Correlation coefficient $L_{0i}(k)$ is

$$L_{0i}(k) = \frac{\Delta_{\min} + \rho\Delta_{\max}}{\Delta_{0i}(k) + \rho\Delta_{\max}} \tag{1}$$

where, $L_{0i}(k)$ is the absolute difference between the two compared sequences when the K time, $\Delta_{0i}(k) = |x_0(k) - x_i(k)| (1 \le i \le m)$; $\Delta_{\max}, \Delta_{\min}$ are respectively the maximum and the minimum of all the absolute difference at each time in the compared sequences; ρ is resolution.

Calculate Correlation. If the two columns are completely coinciding at any time, correlation coefficient is 1, correlation is also 1. If the two sequences are not perpendicular at any time, correlation coefficient greater than 0, correlation is also greater than 0, correlation formula is:

$$r_{0i}=\frac{1}{N}\sum_{k=1}^{N}L_{0I}(k) \tag{2}$$

where, r_{0i} is correlation of parent sequence 0 and subsequence *i; N* is compared sequences' length.

Sort Correlation. The correlation of m subsequences and the same parent sequence are arranged in order of size, and consist of association sequence $\{X\}$. The $\{X\}$ directly reacts the relationship between each subsequence and parent sequence. If $r_{0a}>r_{0b}$, for the parent sequence $\{X_0\}$, $\{X_a\}$ is better than $\{X_b\}$; if $r_{0a}=r_{0b}$, for the parent sequence $\{X_0\}$, $\{X_a\}$ is the same as $\{X_b\}$; if $r_{0a}<r_{0b}$, for the parent sequence $\{X_0\}$, $\{X_a\}$ is worse than $\{X_b\}$.

List the Correlation Matrix. If there are n parent sequences $\{Y_1\}$, $\{Y_2\}$,…, $\{Y_n\}$, m subsequences $\{X_1\}$, $\{X_2\}$,…, $\{X_m\}$, the correlation of each subsequence and parent sequence $\{Y_n\}$ are $[r_{n1}, r_{n2},..., r_{nm}]$, Correlation matrix R is,

$$R=\begin{bmatrix} r_{11}, r_{12},..., r_{1m} \\ r_{21}, r_{22},..., r_{2m} \\ ..... \\ r_{n1}, r_{n2},..., r_{nm} \end{bmatrix} \tag{3}$$

Analysis of the Gray Correlation

Since the initial observation time of each monitoring project is different, set each observation value as the same observation time, and set previous monitoring observation during the same time as the initial observations. Table 1 is the monitoring data.

Tab. 1 Monitoring Data

Factors	First	Second	Third	Forth	Fifth	Sixth	Seventh	Eighth
Surface subsidence	-1.1	-0.4	-0.9	-4.2	-5.5	-6.9	-6.4	-7.9
Horizontal displacement of pile top	-3.2	-2.5	-3.9	-4.7	-5	-10.1	-9.6	-8.5
The groundwater level	0.1	0.66	-0.19	0.08	0.14	1.16	0.49	0.04
Deep horizontal displacement	671.2	671.2	436.5	284.6	-120.8	-3	-34.1	-84.8
The anchor cable tension	-0.546	0.728	-0.173	-0.316	-0.517	-0.553	-1.759	-1.73
Strut axial forces	0.58	0.48	-0.97	2.18	3.83	-5.02	-0.72	-7.22

According to the principle of gray correlation analysis, using the average of the initial treatment, the mean transform results show in Table 2, the absolute difference between the surface and the other factors show in Table 3, relations sequence of surface subsidence and other factors show in Table 4, correlation matrix of each factor sequence and surface subsidence sequence show in Table 5.

Tab. 2 Mean Transform Results

Horizontal displacement of pile top	The groundwater level	Deep horizontal displacement	The anchor cable tension	Strut axial forces	Surface subsidence
0.5389	0.3226	2.9490	0.8977	-0.6764	0.2643
0.4211	2.1290	2.9490	-1.1969	-0.5598	0.0961
0.6568	-0.6129	1.9178	0.2844	1.1312	0.2162
0.7916	0.2581	1.2504	0.5195	-2.5423	1.0090
0.8421	0.4516	-0.5308	0.8500	-4.4665	1.3213
1.7011	3.7419	-0.0132	0.9092	5.8542	1.6577
1.6168	1.5806	-0.1498	2.8919	0.8397	1.5375
1.4316	0.1290	-0.3726	2.8442	8.4198	1.8979

Tab. 3 Surface with Other Factors, the Absolute Difference

Factors	Relations							
Horizontal displacement of pile top	0.2747	0.3250	0.4406	0.2174	0.4792	0.0434	0.0793	0.4663
The groundwater level	0.0583	2.0329	0.8291	0.7509	0.8697	2.0843	0.0431	1.7689
Deep horizontal displacement	2.6848	2.8529	1.7016	0.2414	1.8521	1.6708	1.6874	2.2705
The anchor cable tension	0.6334	1.2930	0.0682	0.4895	0.4713	0.7485	1.3544	0.9463
Strut axial forces	0.9406	0.6559	0.9150	3.5513	5.7878	4.1966	0.6979	6.5219

Tab. 4 Surface Subsidence and Other Factors Associated Sequence

Factor	Relations
Horizontal displacement of pile top	0.7133
The anchor cable tension	0.5123
The groundwater level	0.4925
Deep horizontal displacement	0.3039
Strut axial forces	0.2861

Tab. 5 Correlation Matrix

Correlation matrix	Horizontal displacement of pile top	The groundwater level	Deep horizontal displacement	The anchor cable tension	Strut axial forces
Surface subsidence	0.7133	0.4925	0.3039	0.5123	0.2861

From Table3, the max differenceΔmax=6.52193. From correlation matrix, the greatest correlation is surface subsidence and horizontal displacement of pile top, the correlation coefficient is 0.7133; following with deep displacement, the correlation coefficient is 0.5123; next one is the underground water level, the correlation coefficient is 0.4925; the smallest correlation is surface subsidence and strut axial forces, the correlation coefficient is 0.2861. From those data, it is clearly that horizontal displacement of the pile has the greatest impact on surface subsidence, following with deep displacement, and strut axial forces with minimal impact. Therefore, we should focus on relationships among horizontal displacement of pile top, the groundwater level, and the anchor cable tension in the analysis of surface settlement, also need to maximize the accuracy of the instrument.

Conclusion

By analyzing the impact of the relationship between a subway excavation monitoring of surface subsidence and horizontal displacement of pile top, deep displacement, strut axial forces, the anchor cable tension and the groundwater level, combining with gray correlation analysis theory, and using the measured data to analyzing correlation of surface subsidence and horizontal displacement of pile top, deep displacement, strut axial forces and The anchor cable tension, conclude that surface subsidence and horizontal displacement of the pile top have the highest correlation, and strut axial force has the lowest correlation. Accordingly, the method can provide the basis and way for the similar engineering design optimization: when similar geological conditions, should control the horizontal displacement of the pile to reduce surface subsidence, thereby reducing surrounding buildings (structures) hazards that are caused by excavation.

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