Monitoring and Analysis of Deep Foundation Pit Construction of Structural Loess in Northwest China

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Abstract. To investigate the internal force and deformation characteristics of the supporting structure of structural loess foundation pit, 15 field monitoring data of foundation pits in Shaanxi, Gansu and Ningxia, were collected. The lateral movement of the supporting structure, settlement of soil behind piles and axial force of supporting point were studied on the basis of induction and systemize. The results show that: (1) due to the influence of spatial effect, the pile lateral displacement, surface settlement at the corner of foundation pit were significantly smaller than the middle of foundation pit; (2) the pile maximum lateral displacement at the middle of foundation pit ranges from 0.8‰ ~ 2.0‰ of excavation depth, the pile top lateral displacement ranges from 0.2‰ ~ 0.6‰ of excavation depth, the lateral displacement at the corner of foundation pit decreased by 60% ~ 70%; (3) the maximum surface settlement in the middle of the foundation pit can reach 0.35‰~1.2‰ of the excavation depth, and the maximum settlement at the corner of foundation pit decreased by 60% ~ 70%; (4) the position of largest axial force of supporting point occurs near the maximum lateral displacement, between 0.4 ~ 0.8 of excavation depth, the maximum measured axial force of the supporting point reached 35% ~ 80% of the designed axial force, indicated that many foundation pits were too conservative in the design process, the structural characteristics of loess in northwest area should be considered, and the design scheme of the foundation pit should be optimized to save the cost of foundation pit engineering to avoid unnecessary waste.

Keywords. Foundation pit, the pile lateral displacement, surface settlement, axial force of supporting point, spatial effect.

1. Introduction
There is a large range of structural loess distributed in northwest China. However, due to the significant structure of loess, its mechanical properties are quite different from those of other soils. After being wet by water, the structure of the soil will be damaged, resulting in the decrease of its carrying capacity, and then collapse. With the development of urban construction, foundation pit accidents are also increasing. In 2009, the foundation pit site of Minan building in Xi’an collapsed; in the same year, the foundation pit collapsed at Shajinqiao station of Xi’an metro line 1 due to continuous rainfall; in 2013, the collapse accident occurred between Hujiamiao station and Tonghuanmen station of Xi’an metro line 3. It can be seen that the understanding of the structural characteristics of loess is still not perfect, and further research is needed to provide a basis for the design and management of the foundation pit in this region. Current studies on loess are divided into the following two directions: (1) to study the mechanical properties of loess structure from the perspective of microstructure. In the 1860s, academician Dongsheheng Liu summarized the effects of the particle distribution of loess and the content of main mineral components (calcium carbonate) on loess
characteristics [1]. With the emergence of a large number of advanced technologies, scientists began to observe the change rules of the pores and structure of the loess in the test process by scanning electron microscopy, and improved the structure of the loess with the help of acidic solution, so as to reduce the probability of collapsibility of the loess [2-4]. (2) The structural characteristics of loess were studied by the classical soil mechanics research methods such as unconfined compression test and triaxial test. Based on the laboratory tests, Zuiqiang Hu and Zhujiang Shen, et al. established a constitutive model of unsaturated loess to simulate its mechanical properties in the loading process by studying its damage evolution rule [5-10]. Few of foundation pit monitoring data for the actual project summarized, therefore this article combined with the northwest loess region 15 actual foundation pit monitoring results, were studied under the condition of the pile anchor supporting foundation pit retaining structure of the lateral and internal force of retaining structure, the surface subsidence rule of foundation pit, the monitoring scheme to optimize the region, can also be used as a reference of foundation pit supporting design.

2. Basic Information of the Monitoring Project

In the current excavation of deep foundation pits in the northwest region, most of them use retaining piles + anchor cable support, as shown in figure 1 (a), this is an active support system, which combines the pile body and the anchor cable into one Overall, the passive earth pressure below the pile body and the frictional resistance of the anchor cable and the soil behind the pile are used to maintain the stability of the foundation pit. For foundation pits with a narrow excavation width, enclosing piles + internal support are used, as shown in figure 1 (b). This is a passive support system. When the soil body moves laterally behind the pile, the support structure begins Forced to prevent the development of deformation.

The research object selected in this paper is enclosing pile + anchor cable support enclosing pile + internal support. Because the physical and mechanical parameters of the soil in the survey report may not be consistent with the actual geological conditions, and soil may appear during the excavation. The water content of the layer and the changes in the load around the foundation pit, combined with the influence of various human factors, have carried out a lot of monitoring on the support structure with the safety level of 1st and 2nd. Measures, for the foundation pit without abnormal conditions, these monitoring data can reflect the stress and deformation of the supporting structure. By categorizing these data, the deformation and stress law of the foundation pit in this area giving a summary. In order to prevent interference from too many factors in the analysis process and better reflect the regularity of various monitoring data during the excavation of the foundation pit, the following three criteria must be met in the statistics of the monitoring data of the foundation pit.

(1) The deformation and supporting internal force of the monitored foundation pit are mainly caused by the unbalanced force generated by the excavation of the foundation pit. The statistics of the monitoring points of nearby buildings are not counted.

(2) The monitoring data of the foundation pit contains the horizontal displacement of the soil behind the pile in the middle of the pit wall, the surface settlement of the soil behind the pile at
different distances from the side of the pit, and the axial force of the anchor cables at different vertical depths.

(3) There must be more than three sets of each monitoring data for the foundation pit for comparison, and no statistics will be made for the data affected by the sudden situation.

This paper mainly selects the foundation pits in Shaanxi, Gansu and Ningxia. As shown in Table 1, the statistical deformation and settlement data come from the literature [11-21].

| Foundation pit number | Project name                                                                 | Support method                              | Pile spacing (mm) | Pile diameter (mm) |
|-----------------------|-----------------------------------------------------------------------------|---------------------------------------------|-------------------|-------------------|
| JK1                   | Foundation pit project of Wanshou Road Station of Xi’an Metro Line 1       | Bored piles + steel pipe internal support  | 1600              | 1200              |
| JK2                   | Foundation pit project of Yongningmen Station of Xi’an Metro Line 2        | Bored piles + steel pipe internal support  | 1400              | 1200              |
| JK3                   | Foundation pit project of Youjiazhuang Station on Xi’an Metro Line 2       | Bored piles + steel pipe internal support  | 1200              | 800               |
| JK4                   | Foundation pit project of Dacha City Station, Xi’an Metro Line 4           | Bored piles + steel pipe internal support  | 1500              | 1200              |
| JK5                   | Foundation pit project of Lujiaecun Station on Xi’an Metro Line 4          | Bored piles + steel pipe internal support  | 1400              | 1000              |
| JK6                   | Shaanxi Iron and Steel Family Foundation Pit Project                       | Mixing pile + anchor cable                 | 1500              | 800               |
| JK7                   | Fengji Changan Building Foundation Pit Project                             | Bored piles + steel pipe internal support  | 1200              | 800               |
| JK8                   | Foundation Pit Project of Science and Technology Building in Eastern suburbs of Xi’an Xi’an High-tech Zone Hi-tech Shangdu Foundation Pit Project China Railway. First International Foundation Pit Project | Bored pile + anchor cable                 | 1200              | 600               |
| JK9                   | Qujiang Xiangdu Foundation Pit Project                                      | Bored pile + anchor                        | 1500              | 800               |
| JK10                  | Foundation pit engineering of Century Avenue Station of Lanzho Metro Line 1 | Bored pile + anchor                        | 1600              | 800               |
| JK11                  | Foundation pit engineering of Century Avenue Station of LanzhoMetroLine 1  | Bored pile + anchor                        | 1500              | 600               |
| JK12                  | Foundation pit project of a comprehensive building in a hospital in Lanzhou | Bored pile + anchor                        | 1800              | 1500              |
| JK13                  | Foundation pit project of Yinchuan Tianxi International Center Project      | Bored pile + anchor                        | 1500              | 1200              |
| JK14                  |                                                                               | Bored pile + anchor                        | 2300              | 1000              |
| JK15                  |                                                                               | Bored pile + anchor                        | 1500              | 800               |
3. Enclosure Lateral Shift

Table 2 shows the maximum lateral displacement of the pile and the lateral displacement of the top soil. It can be found that the horizontal displacement of the pile is closely related to the excavation depth. When the excavation depth of the foundation pit is relatively shallow, the maximum horizontal displacement of the pile occurring in the middle and upper part of the pile, the structure is inclined to the inside of the foundation pit. With the increase of the excavation depth and the application of horizontal support, the supporting structure gradually becomes an arch shape, and the position of the maximum horizontal displacement of the pile gradually moves downward. The lateral displacement of the pile body at the corner of the pit is significantly smaller than the lateral displacement of the mid-span position. This phenomenon is more obvious in the narrow and long foundation pit project.

| Foundation pit number | Maximum lateral displacement of pile body in the middle of foundation pit (mm) | Lateral displacement of pile top in the middle of foundation pit (mm) | Excavation depth (m) | Maximum lateral displacement of pit corner pile (mm) | Side shift of pit corner pile (mm) | Excavation depth (m) |
|-----------------------|--------------------------------------------------------------------------------|-----------------------------------------------------------------|---------------------|-------------------------------------------------|-------------------------------|---------------------|
| JK1                   | 26.8                                                                          | 5.0                                                             | 28.20               | 10.5                                             | 2.6                           | 28.20               |
| JK2                   | 14.2                                                                          | 3.5                                                             | 18.50               | 7.2                                             | 1.4                           | 18.50               |
| JK3                   | 22.1                                                                          | 5.1                                                             | 17.19               | 8.5                                             | 1.0                           | 16.98               |
| JK4                   | 27.4                                                                          | 3.6                                                             | 18.24               | 7.4                                             | 2.4                           | 16.02               |
| JK5                   | 33.8                                                                          | 9.3                                                             | 17.80               | 10.9                                            | 2.5                           | 17.63               |
| JK6                   | 7.6                                                                           | 2.9                                                             | 8.00                | 4.0                                             | 0.7                           | 8.00                |
| JK7                   | 12.8                                                                          | 8.5                                                             | 16.00               | 8.2                                             | 1.9                           | 16.00               |
| JK8                   | 24.2                                                                          | 7.5                                                             | 15.20               | 8.5                                             | 2.0                           | 14.20               |
| JK9                   | 15.0                                                                          | 11.3                                                            | 18.80               | 11.7                                            | 2.6                           | 18.80               |
| JK10                  | 15.6                                                                          | 3.3                                                             | 13.00               | 6.5                                             | 1.2                           | 13.00               |
| JK11                  | 27.0                                                                          | 8.1                                                             | 18.86               | 8.8                                             | 3.8                           | 17.86               |
| JK12                  | 15.2                                                                          | 4.0                                                             | 17.10               | 7.1                                             | 1.4                           | 17.34               |
| JK13                  | 28.8                                                                          | 8.6                                                             | 24.00               | 14.2                                            | 2.6                           | 24.00               |
| JK14                  | 36.3                                                                          | 10.5                                                            | 20.20               | 13.9                                            | 3.5                           | 20.20               |
| JK15                  | 20.4                                                                          | 9.9                                                             | 17.00               | 15.8                                            | 1.7                           | 17.00               |

Respectively to foundation pit excavation is completed maximum lateral soil and pile top lateral soil as the ordinate, H as the abscissa, and the excavation depth will be 15 different excavation depth of foundation pit painting and coordinates, respectively, as shown in figure 2, it can be seen that with the increase of excavation depth H, on top of the pile soil lateral and maximum lateral are increasing, maximum lateral of the foundation pit in the middle of the pile body excavation depth of 0.8 %o ~ 2.0 %o, pile top lateral for foundation pit excavation depth of 0.2 %o ~ 0.6 %o, the Angle of the pit maximum lateral pile for foundation pit excavation depth of 0.3 %o ~ 0.7 %o, The lateral movement of pile top is 0.05%~0.15% of the excavation depth of foundation pit. It can be seen from figure 3 that the spatial effect of the foundation pit has little influence on the position of the maximum displacement of the pile body, and the maximum lateral displacement occurs between 0.4 and 0.8 h. For structural loess strata using multiple fulcrum pile supporting control deformation of foundation pit.
is a kind of effective method, but the deformation will be subjected to many elements, such as the vibration of the foundation pit of the surrounding environment, construction machinery, foundation pit near the vehicle load, the existing around the foundation pit construction structure, the effect of time and space, etc., the current many researchers used the method of numerical simulation to predict the settlement deformation of foundation pit, often in the process of establishing the model of simplifying the foundation to do a lot of, can't consider accidental factors of the outside world, many parameters is obtained according to experience, this approach can not accurately predict the deformation of the foundation pit. To be familiar with the software in a variety of mechanical characteristics of the structure unit and calculation principle of personnel can also simulate the foundation pit deformation trend, for construction personnel and field it is difficult to accept the software, the foundation pit monitoring is simple and clear, and can reflect the real-time change of foundation pit under the effect of various factors, the data should be taken seriously by the researchers, by various factors under the influence of the deformation law of consolidation, could help researchers better to improve the shortage of the software to calculate, also can provide some guidance for construction personnel.

**Figure 2.** Relationship curve between pile lateral displacement and excavation depth.  
**Figure 3.** Relationship curve between the position of maximum movement and excavation depth.

### 4. Ground Settlement outside the Pit

Table 3 gives the maximum surface settlement values of 15 foundation pit projects and their specific locations. According to the monitoring data of surface settlement at different positions from the pit wall at different excavation depths, it can be seen that when the excavation depth is relatively shallow. The settlement of the foundation pit is also relatively small. As the excavation depth of the foundation pit increases, the settlement of the foundation pit gradually increases, and the distance from the maximum settlement to the pit wall gradually increases with the increase of the excavation depth.

Respectively by the location of the pit wall surface maximum subsidence value and distance L as ordinate, H as abscissa to foundation pit excavation depth, will be 15 foundation pit monitoring data from within the coordinate system, from figure 4 can be found in the central is bigger than the maximum surface subsidence of foundation pit excavation pit maximum ground surface settlement of the Angle, the ground settlement in the middle of the value of the excavation depth of 0.35‰ ~ 1.2‰, the surface subsidence value of the Angle of the pit foundation pit excavation depth of 0.1‰ ~ 0.5‰, which is due to the Angle of the pit restraint stiffness of foundation pit is large, and the foundation pit have played an important role in mutual support between the pit wall, limits the deformation of foundation pit. It can be seen from figure 5 that the spatial effect of the foundation pit has little influence on the position of the maximum ground settlement, and its value is between 0.5 and 1.0H.
Table 3. Settlement movement of soil behind the pile.

| Foundation pit number | Maximum surface settlement in the middle of foundation pit (mm) | Distance of maximum surface settlement from pit wall (m) | Excavation depth (m) | Maximum surface settlement at pit corner (mm) | Distance of maximum surface settlement from pit wall (m) | Excavation depth (m) |
|-----------------------|---------------------------------------------------------------|-----------------------------------------------------|----------------------|---------------------------------------------|-----------------------------------------------------|----------------------|
| JK1                   | 26.8                                                          | 13.0                                               | 28.20                | 10.5                                        | 9                                                    | 28.20                |
| JK 2                  | 14.2                                                          | 12.0                                               | 18.50                | 7.2                                         | 10                                                  | 18.50                |
| JK 3                  | 22.1                                                          | 9.0                                                | 17.19                | 8.5                                         | 9                                                    | 16.98                |
| JK 4                  | 27.4                                                          | 15.0                                               | 18.24                | 7.4                                         | 12                                                  | 16.02                |
| JK 5                  | 33.8                                                          | 14.0                                               | 17.80                | 10.9                                        | 12                                                  | 17.63                |
| JK 6                  | 7.6                                                           | 7.0                                                | 8.00                 | 4.0                                         | 7                                                    | 8.00                 |
| JK 7                  | 12.8                                                          | 22.0                                               | 16.00                | 8.2                                         | 16                                                  | 16.00                |
| JK 8                  | 24.2                                                          | 13.0                                               | 15.20                | 8.5                                         | 9                                                    | 14.20                |
| JK 9                  | 15.0                                                          | 11.0                                               | 18.80                | 11.7                                        | 8                                                    | 18.80                |
| JK10                 | 15.6                                                          | 10.0                                               | 13.00                | 6.5                                         | 7                                                    | 13.00                |
| JK11                 | 27.0                                                          | 16.0                                               | 18.86                | 8.8                                         | 13                                                  | 17.86                |
| JK12                 | 15.2                                                          | 13.0                                               | 17.10                | 7.1                                         | 13                                                  | 17.34                |
| JK13                 | 28.8                                                          | 16.0                                               | 24.00                | 14.2                                        | 14                                                  | 24.00                |
| JK14                 | 36.3                                                          | 17.0                                               | 20.20                | 13.9                                        | 15                                                  | 20.20                |
| JK15                 | 20.4                                                          | 21.0                                               | 17.00                | 15.8                                        | 21                                                  | 17.00                |

5. Support Shaft Force
During the excavation of the foundation pit, the supporting axial force gradually increased and eventually stabilized. Due to the influence of external factors, the axial force occasionally fluctuated. Since the angle braces are often applied at the corners of the pits, the axial force fluctuations there are large, and the law cannot be summarized. Therefore, this article only counts the axial forces near the middle of the foundation pit. Table 4 gives 15 steel pipes in the middle of the foundation pit. The axial force of the anchor cable and the anchor rod, it can be seen that the position of the maximum axial force of the foundation pit is basically the same as the position of the maximum lateral displacement of the pile, between 0.4 - 0.8H, as can be seen from figure 6, the supported The maximum measured axial force N_f is 35% to 80% of the designed axial force N_t, indicating that the design of some foundation pits is conservative.
Table 4. Axial force of the strut.

| Foundation pit number | Maximum supporting axial force in the middle of the foundation pit (kN) | Number of support channels | Total support channels | Preload (kN) | Design axial force (kN) | Excavation depth (m) |
|-----------------------|--------------------------------------------------|-----------------------|------------------------|-------------|------------------------|---------------------|
| JK1                   | 1286.0                                           | 4                     | 5                      | 750.0       | 2254.0                 | 28.20               |
| JK 2                  | 1102.0                                           | 2                     | 3                      | 400.0       | 1620.0                 | 18.50               |
| JK 3                  | 250.0                                            | 2                     | 3                      | 180.0       | 1210.0                 | 17.19               |
| JK 4                  | 709.0                                            | 2                     | 3                      | 453.0       | 1590.0                 | 18.24               |
| JK 5                  | 410.0                                            | 1                     | 3                      | 600.0       | 1050.0                 | 17.80               |
| JK 6                  | 150.0                                            | 1                     | 1                      | /           | 540.0                  | 8.00                |
| JK 7                  | 240.0                                            | 2                     | 3                      | 300.0       | 754.0                  | 16.00               |
| JK 8                  | 544.0                                            | 2                     | 3                      | 350.0       | 1240.0                 | 15.20               |
| JK 9                  | 450.0                                            | 3                     | 4                      | 360.0       | 1420.0                 | 18.80               |
| JK10                  | 530.0                                            | 2                     | 2                      | 670.0       | 1302.0                 | 13.00               |
| JK11                  | 652.0                                            | 2                     | 3                      | 450.0       | 1208.0                 | 18.86               |
| JK12                  | 900.0                                            | 2                     | 3                      | 552.0       | 1380.0                 | 17.10               |
| JK13                  | 1345.4                                           | 3                     | 4                      | 700.0       | 2841.0                 | 24.00               |
| JK14                  | 692.4                                            | 2                     | 3                      | 330.0       | 1131.7                 | 20.20               |
| JK15                  | 469.6                                            | 2                     | 3                      | 300.0       | 1060.0                 | 17.00               |

Figure 6. Relationship curve of the monitor-design axial force.

6. Conclusion

(1) For the foundation pit with shallow excavation depth, the maximum lateral displacement of the pile is located in the middle and upper part, and gradually moves downward with the increase of the excavation depth. It reaches 0.8‰ ~ 2.0‰ H, and the lateral displacement of the pile top is 0.2‰ ~ 0.6‰ H. Due to the influence of space effects, the maximum lateral displacement at the corner of the pit and the lateral displacement of the pile top are significantly smaller than the middle of the foundation pit, which are 0.3‰ ~ 0.7‰ H and 0.05‰ ~ 0.15‰ H, respectively.

(2) The maximum surface settlement of the foundation pit in the structural loess area generally occurs at 0.5 ~ 1.0H, the surface settlement in the middle of the foundation pit is 0.35‰ ~ 1.2‰ H, and the surface settlement at the pit corner is 0.1‰ ~ 0.5‰ H.
(3) The maximum value of the axial force of the foundation pit occurs near the maximum lateral displacement of the pile, that is, 0.4 ~ 0.8H. The maximum measured axial force Nf of the support is 35% ~ 80% of the designed axial force Nt. The design is conservative and has a large degree of redundancy, which is also the common status quo in China's foundation pit engineering.

(4) At present, we can start from two aspects to improve the status quo of China's foundation pits. During the construction of the foundation pit project, the monitoring frequency is dynamically adjusted according to the corresponding stage of the foundation pit, and some key positions are monitored, analyzed, and processed in real time. Find hidden safety hazards in time; pay attention to the monitoring data of the previous foundation pits, sort out the internal force and deformation laws of the foundation pit support structure in each area, and optimize the design of the foundation pit support.

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