Application of Steel Sheet Pile in Deep Foundation Pit Support of Collapsible Loess Regions

Yang Yang1,2*, Wanfeng Liu1,2, Aiping Hu1,2, Fei Li1,2 and Zhaqian Yang1,2

1 School of Civil Engineering, Longdong University, Qingyang, Gansu, 745000, China
2 Provincial Key Laboratory of Loess Engineering Properties and Application in Gansu Province Universities, Qingyang, Gansu, 745000, China

*Corresponding author’s e-mail: yy2513655687@163.com

Abstract. Due to its high quality, simple construction, good durability and interchangeability, steel sheet pile can reduce the requirements of space for construction tasks and other advantages. In recent years, it has been widely used in support engineering. Taking a deep foundation pit in a collapsible loess area as an example, this paper analyzes the application and calculation of steel sheet pile support under the complex operation conditions, which is composed of many adverse factors such as the limitation of the construction work area’s narrow influence on the construction, and expounds the feasibility of steel sheet pile in the deep foundation pit support in collapsible loess area, which adds precious steel sheet pile support to the deep foundation pit in collapsible loess area. The experience has a good reference and guiding significance for the use and promotion of steel sheet pile support in similar projects.

1. Introduction
Collapsible loess is a special kind of soil, which has engineering characteristics such as relatively even distributed soil, loose structure, and pore abundance [1,2]. Therefore, the construction of deep foundation pits in collapsible loess areas requires effective and stable support to ensure the safety of construction projects and the normal service performance of existing projects [2,3,4]. In view of the high strength, light weight, good water barrier, simple construction, short construction period, good durability, and significant environmental protection effects during construction, the steel sheet piles are not restricted by weather conditions, have strong timeliness, greatly reduce the amount of soil and concrete used, and effectively protect land resources. For construction tasks, it can reduce the requirements for space and has other advantages. It is necessary to evaluate the stability of the support structure through theoretical analysis and calculation in combination with the actual project of deep foundation pit in collapsible loess area, so as to provide experience and reference for the support design of similar projects [5,6,7].

2. Project Overview
In the reconstruction project of a sponge city in a city, a gravity sewage pipeline is planned to be constructed, which needs to excavate a foundation pit in the non-motorized lane of 1.5 meters away from the stone along the east side of the pedestrian road. The maximum depth of the foundation pit is 11m, and the plane size is 5m × 5m. There are no slope conditions around. The maximum exploring depth in this survey is 55m. According to the results of this survey drilling exposure, within the scope
of the exploration depth, except for the structure layer of the road surface of the road, the top-down solid layers are mainly composed of newly accumulated fill solid, Late-Pleistocene loess-like silty clay and silt (Malan loess) and Meso-Pleistocene silt clay and silt (Lishi loess), and there is no groundwater in the survey depth of 55m.

3. Steel sheet pile support design

In view of the fact that the project was located on the non-motorized road of the main road, there was no closed traffic and sloping conditions, and the depth of the foundation pit reached 11m, it was decided to use SP-IV Larson steel sheet pile for supporting.

3.1. Related design parameters of steel sheet piles

3.1.1. Steel sheet pile parameters

SP-IV steel sheet pile is 400mm wide, 170mm high, 15.5mm thick, cross-sectional area is 96.9cm², and theoretical weight is 76.1kg/m. The steel sheet piles are inserted and connected to each other with locks.

3.1.2. Support parameters of steel sheet piles

The steel sheet piles are connected by enclosing purlin of 25b waist beam, and inclined internal support is made by steel pipes with a size of DN180mm×12mm.

3.2. Steel sheet pile design

The total design depth of the foundation pit was 11m. According to the design calculation of the second-level foundation pit, the surrounding load of the foundation pit was considered as the ground overload of 20kPa. The soil layer parameters were shown in Table 1, and the steel sheet pile layout was shown in Figure 1. The steel sheet piles were supported by 24m long SP-IV Mori steel sheet piles and 4 internal supports. The steel sheet piles were connected by enclosing purlin of 25b waist beam, and steel tubes with diameters of DN180mm×12mm were used as inclined internal supports at 1.5m distance of the end of each side. The first support was 1m from the ground, the second support was 2m from the first support, the third support was 2.5m from the second support, and the fourth support was 2.5m from the third support. Earthwork excavation should be carried out continuously in layers. When the excavation reaches 1.5m below the top of the sheet pile, the first support construction was carried out. When the excavation reaches 3.5m below the top of the sheet pile, the second support construction was carried out. When the excavation was 6m below the top of the sheet pile, the third support construction was carried out. When excavation reaches 8.5m below the top of the sheet pile, the fourth support construction was carried out.

| Layer | Soil layer type | Thickness (m) | Volumetric weight (kN/m³) | Cohesion (kPa) | Internal friction angle (°) | Side friction resistance of pile (kPa) |
|-------|----------------|--------------|--------------------------|---------------|-----------------------------|--------------------------------------|
| 1     | Fill           | 2            | 17                       | 25.3          | 21.5                        | 55                                   |
| 2     | Ma Lan loess   | 11.5         | 17.5                     | 28            | 22                          | 60                                   |
| 3     | Lishi loess    | 40           | 17.2                     | 22.3          | 19.7                        | 60                                   |
3.3. Structural internal force calculation

The elastic force earth pressure model and the classical law earth pressure model were used to calculate the internal force of the structure. The bending moment reduction coefficient was 0.85, the shear reduction coefficient was 1.00, and the load partial coefficient was 1.25. The internal force envelope diagram of the structure was calculated, as shown in Figure 2, and the surface settlement diagram was shown in Figure 3.

Figure 1. The layout of steel sheet piles

Figure 2. Structural internal force envelope
It can be known from Figure 2: The standard value of the maximum bending moment inside the foundation pit is 114.37kN·m by using the elastic pressure earth pressure model. The standard value of the maximum bending moment outside the foundation pit is 66.52kN·m, and the standard value of the maximum shear force is 82.02kN. The maximum displacement of the steel sheet pile is 13.89mm, and the standard value of the maximum support reaction force of the internal support is 120.52kN. The classic method of earth pressure model is used to calculate the maximum value of the maximum bending moment inside the foundation pit, which is 61.38kN·m, the standard value of the maximum bending moment outside the foundation pit is 78.20kN·m, and the standard value of the maximum shear force is 82.16kN. The maximum displacement of the steel sheet pile is 0mm, and the standard value of the maximum supporting reaction force of the internal support is 130.41kN.

It can be known from Figure 3 that, calculated by the triangle method, the maximum settlement amount of the foundation pit surface is 13 mm; calculated by the parabolic method, the maximum settlement amount of the foundation pit surface is 20 mm; and calculated by the index method; the maximum settlement amount of the foundation pit surface is 10 mm.

3.4. Steel sheet section calculation

The internal forces of the structure were calculated using the elastic method and the classical method, respectively, and the standard value of the maximum bending moment of the foundation pit was 114.37kN·m. It can be obtained through calculation that, the design value of the maximum bending moment of the foundation pit is 121.52kN·m, the bending modulus is 2270cm³ per meter, the allowable bending stress is 215MPa, and the bending stress of the steel sheet pile is 53.532MPa, which is less than the allowable bending stress. Therefore, the steel sheet pile section meets the specification requirements.

3.5. Overall stability calculation

The overall stability calculation method adopted the Swedish slice method, and the stress state was calculated according to the effective stress method. The strip width in the stripe method was 0.40m. The specific slip surface data was: the arc radius was 25.020m, and the center coordinate was (-2.606, 11.839). When excavation depth is 11m, it was calculated that the overall stability safety factor Ks = 2.202 > 1.30 is calculated, which meets the specification requirements.

3.6. Anti-overturning stability calculation

3.6.1. Anti-overturning (moment of support bottom) stability check calculation

\[ K_{ov} = \frac{M_p}{M_a} \]

- \( M_p \)—the anti-overturning bending moment of the passive earth pressure and the fulcrum force on the pile bottom. For the internal support, fulcrum force is determined by the internal support pressure resistance; for the anchor rod or anchor cable, the anchor point force is the smaller one between the anchorage force and resistance force of anchor rod or cable.
• $M_a$—refers to the overturning moment of active earth pressure on the bottom of the pile. The minimum safety factor in each working condition is $K_{ov} = 1.974 > 1.200$, which meets the requirements of the specification.

3.6.2. Stability check of overturning (kick destruction)

• Checking of the overturning stability around the lowermost support or anchor pulling point, and multiple fulcrum points were referred to Appendix V of the Design Specifications for Building Foundations (GB50007-2011) [8], JGJ 120-2012) [9], Section 4.2.2.

$$K_t = \frac{\sum M_{Ep}}{\sum M_{Ea}}$$

• $\sum M_{Ep}$—the sum of anti-overturning moments in the passive zone (kN·m / m);
• $\sum M_{Ea}$—the sum of overturning moments in the active zone (kN·m / m);
• $K_t$—the overturning stability safety factor with support piles and wall support, taking $K_t \geq 1.200$.

The minimum safety factor is $K_t = 2.415 > 1.200$ under each working condition, which meets the anti-overturning specification requirements.

3.7. Internal support calculation

Take the maximum support reaction force calculated under the above working conditions in Figure 2 as the basis for the internal support design. The maximum reaction force of the internal support is 130.41kN / m, and the overall support is modeled using midas as shown in Figure 4 (the brace is welded below the intersection of the supporting steel pipe and the ring beam as a vertical constraint). The internal force calculation results are shown in Figures 5, 6, and 7, respectively.

![Figure 4. Internal support model](image1)
![Figure 5. Deformation of internal support](image2)
![Figure 6. Moment diagram of internal support](image3)
![Figure 7. Composite stress of internal support](image4)
From Figure 5, Figure 6 and Figure 7, we can know that the maximum deformation of the long side of the cofferdam is 0.473mm < [L/400] = 12.5mm, the maximum combined stress of the ring beam 25b I-beam is 126.7MPa < [170] MPa, and the diagonal brace DN180mm×12mm maximum combined stress is 42.8MPa < [170] MPa, so the internal support forces meet the requirements [10].

4. Conclusion
Collapsible loess is a special kind of soil, which has engineering characteristics such as relatively even distributed soil, loose structure, and pore abundance. Therefore, the construction of deep foundation pits in collapsible loess areas has many constraints, high risks and high construction costs. In the formulation of the construction plan, it is necessary to consider both the design plan and the landform, hydrogeology, construction period, season, and cost. In the past, the application of steel sheet pile support in deep foundation pit construction in collapsible loess area was less. In this paper, under the premise of determining the geological conditions and determining the piling position, the engineering practice proved that, for the underground engineering construction with higher requirements for environment, more restrictions in engineering period, various kinds of obstacles above ground and underground leading to narrow construction area, the application of steel sheet pile can effectively shorten the construction period of support, save engineering cost, and save the land for construction. Moreover, reasonable arrangement of time limit for a project process can meet the construction requirements of deep foundation pit in collapsible loess area, which can also provide certain reference for the application and popularization of using steel sheet pile in deep foundation pit for supporting in the collapsible loess area.

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