Influence of Soil-Filling on Stability of The Bridge Pier

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1. Introduction
According to the structural characteristics of the bridge span, this paper analyzes the impact of different soil-filling processes, by using the pier’s data of the on-site inspection and completion. Based on “Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts” (JTG D62-2004) and “Code for Design of Ground and Foundation of Highway Bridges and Culverts” (JTG D63-2007), we calculate the horizontal force, the resistance of the pier support, the forces of the pier and pile foundation, and the deformation of the pier column, under the condition of unfavorable soil-filling.

2. Project example
We consider one bridge, of which the upper structure of the main bridge is continuous rigid frame and the approach span is a continuous rigid frame with prestressed concrete T-beam. The 15# pier is the transition pier between the main bridge and the approach bridge adopts the pile-pillar foundation, using the bored pile and the rectangular cross-section physical pier, where one cover beam is set on the pier top and square independent cap is set between the pier column and the pile foundation. The pile foundation is made of No. 25 underwater concrete, and the cover beam and the pier column are made of No. 30 concrete. The minimum filling height near the 15# pier is 1.5m. The filling heights near the 15-1# pier and 15-2# pier is 2.5m (see Figs. 1 and 2).
2.1. Analysis of bridge piers under unfavorable working conditions

The inspection results show that only the part of the 15# pier has a large slip and the inclination value of the pier is also large. Combined with the construction data, it can be seen that the surrounding soil-filling is the main factor causing the inclination of the 15# pier.

The anti-push stiffness of pier $k_i$ is

$$k_i = \frac{3EI}{l_i^3}$$  \hspace{1cm} (2.1-1)

where $i$ is serial number of the pier, $E$ is the concrete elastic modulus, $I$ is the moment of inertia of the pier body facing the mandrel, and $l_i$ is the height from the lower consolidation end to the top of the $i$th pier.

The anti-push stiffness of rubber support $z_i$ is

$$z_i = \frac{G\sum A_z}{\sum t}$$  \hspace{1cm} (2.1-2)

where $i$ is serial number of the pier, $G$ is the shear modulus of rubber material, $\sum A_z$ is the sum of the bearing area of the support, and $\sum t$ is the total thickness of rubber sheet.

The combined anti-push stiffness of pier and support $k_{zi}$ is

$$k_{zi} = 1/(1/k_i + 1/z_i)$$  \hspace{1cm} (2.1-3)

The horizontal force acting on the top of each pier $H_i$ is

$$H_i = k_{zj} T / \sum k_{zi}$$  \hspace{1cm} (2.1-4)

where $i$ is serial number of the pier and $H$ is the total horizontal force.

From Eqs. (2.1-1)—(2.1-4), it is clear that different filling methods have different effects on the inclination of each pier. Here we analyze the case that the filling is first carried out between 15# pier and 16# pier.
2.2. The force on the pier from filling
According to the site investigation, the surrounding filling of the 15# pier is mainly clay, and the filling between the 15# pier and the 16# pier is compacted. We take filling weight $\gamma=24\text{kN/m}^3$, internal friction angle $\phi=20^\circ$.

According to the as-built drawing of the bridge and the design drawings of the filling construction, the distribution of filling around the 15# pier is wide and the depth is large. Considering the filling situation, the setting of the caps, the distribution of soft soil, and the existence of temporary stacking of soil, we suppose that when the filling is first carried out between the 15# pier and the 16# pier, the distribution height $L$ of horizontal force on the 15# pier is up to 4m. The horizontal force $E_a$ is caused by active earth pressure from the following factors:

①the horizontal force $E_{a1}$ caused by the filling up to the top surface of the existing embankment. This horizontal force can be calculated according to the distribution height of the horizontal force. By the active earth pressure calculation method, we have $E_{a1}=87.1\text{kN/m}$.

②the horizontal force $E_{a2}$ caused by the soil above the top surface of the embankment, such as the backfill of the platform. The horizontal force can be calculated as the active earth pressure after the soil above the top surface of the existing embankment is converted into a uniform load, $q$, which is taken as 25 kPa.

The buried width between the left and right pier caps of 15# pier is 2.6m. At the left and right piers, the filling between the 15# pier and the 16# pier generates the horizontal force $H=87.1\times 2.6\times 2=453.0\text{kN}$.

2.3. Anti-sliding check of bridge pier support
On the top of the 15# pier support, the reaction force (half width) about the self-weight, caused by the 15th span T-beam, bridge deck pavement, ancillary facilities, and so on, is 1837.5kN, the reaction force (half width) about the live load is 1049kN, and the total reaction force is 2886.5kN.

The reaction force (half width) about the self-weight, caused by the deck pavement and auxiliary facilities of the main bridge, is 3360kN, the reaction force (half width) about the live load is 2064kN, and the total reaction force is 5424kN.

Based on “Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts” (JTG D62-2004) and the similar bearing test data, when the PTFE plate is in contact with the stainless-steel plate, the friction coefficient is 0.04. The maximum anti-sliding force provided by the PTFE plate rubber support under the 15# pier top T-beam is 2886.5kN×0.04=115.5kN. According to the on-site inspection, the box girder of the main bridge is equipped with a one-way basin support at the top of the 15# pier. The friction coefficient of the bearing is also taken as 0.04. The maximum anti-sliding force provided by the one-way basin support is 5424kN×0.04=217.0kN.

Therefore, the total anti-sliding capacity of the 15# pier support is $F=332.5\text{kN}$, which is less than the horizontal force. As a result, there is relative slip between the support and the stainless-steel plate, which is consistent with the fact.

2.4. Force on the bridge pier column and pile foundation

2.4.1. Braking force of support. The braking force of 15# pier top support is taken as 332.5kN (half width).

2.4.2. Calculation method about the force on the pier column and pile foundation. The force on pile foundation is calculated according to the Appendix P of “Code for Design of Ground Base and Foundation of Highway Bridges and Culverts” (JTG D63-2007). In the calculation, we take $m=5000\text{kN/m}^4$.

The horizontal force at the top of each pile foundation $H_{0j}$ is
\[ H_{0j} = (H_i - t_i) / n , \]  
\[ (2.4-1) \]

and the bending moment at the top of each pile foundation \( M_{0j} \) is

\[ M_{0j} = t_i l , \]  
\[ (2.4-2) \]

where \( H_i \) is the horizontal force, \( t_i \) is the braking force of each pier top support, \( n \) is the number of piers (pile foundations) in each pier, \( i \) is serial number of the pier, \( j \) is serial number of the pile foundations, and \( l \) is the pier height.

The bending moment of the cross section of the pile at the depth \( z \) below the top of each pile foundation \( M_{lj} \) is

\[ M_{lj} = \alpha^2 EI(x_0A + \frac{\varphi_0}{\alpha}B + \frac{M_{0j}}{\alpha^2 EI}C + \frac{H_{0j}}{\alpha^2 EI}D) , \]  
\[ (2.4-3) \]

where \( \alpha \) is the deformation coefficient, \( \alpha = \sqrt{\frac{mb}{EI}} \), \( EI \) is the bending stiffness, \( EI = 0.8E_c I \), \( E_c \) is the concrete compressive modulus of elasticity, \( I \) is the section moment of inertia, \( m \) is proportional coefficient of horizontal resistance coefficient of non-rock foundation, \( b_1 \) is the calculation width of the pile, and \( x_0, \varphi_0, A, B, C, D \) are the coefficients in calculation of the force on the top of single-row pile-column piers formulated in the Appendix P of “Code for Design of Ground Base and Foundation of Highway Bridges and Culverts” (JTG D63-2007).

The maximum normal stress of the cross section of the pile at the depth \( z \) below the top of each pile foundation \( \sigma_{zj\text{max}} \) is

\[ \sigma_{zj\text{max}} = \frac{M_{lj} \gamma_{\text{max}}}{I} + \sigma_{nj} , \]  
\[ (2.4-4) \]

where \( \gamma_{\text{max}} \) is the largest distance between the cross section of the pressure zone or tension zone and the neutral axis of the pile, \( \sigma_{nj} \) is the compressive stress on the cross section of the pile generated by the self-weight of the superstructure, pier column, cover beam or other components and the live load of the vehicle.

2.4.3. Force on the pier column. The calculation results show that the bending moment and tensile stress of the 15# pier are the largest at the ground surface, where the bending moment is 3285kN·m and the tensile stress is 1.6MPa.

The 15# pier column is made of No. 30 concrete. The design value and standard value of axial tensile strength for No. 30 concrete are taken with reference to that for the C30 concrete. That is, the design value of axial tensile strength is 1.39 MPa and the standard value is 2.01 MPa.

According to the calculation results, the maximum tensile stress of the 15# pier pile (from the cover beam to the filling surface) does not exceed the design value and standard value of axial tensile strength for No. 30 concrete.
2.4.4. Force on the pile foundation. The 15-1# pier and 15-2# pier have the same structure. The calculation results of the bending moment and stress of 15-1# pier and 15-2# pier pile are shown in Table 2.4-1 and Figures 3 and 4.

15-3# pier and 15-4# pier is connected with the sidewalk stairs. Thus, comparing with 15-1# pier and 15-2# pier, the anti-push stiffness of 15-3# pier and 15-4# pier is improved. The calculation results of the bending moment and stress of 15-3# pier and 15-4# pier pile are shown in Table 2.4-1 and Figures 5 and 6.

The 15# pier foundation is made of No. 25 concrete. The design value and standard value of axial tensile strength for No. 25 concrete are taken with reference to that for the C25 concrete. That is, the design value of axial tensile strength is 1.23MPa and the standard value is 1.78MPa.

According to the calculation results, the stress of the 15-1# pier and 15-2# pier pile exceeds the design value and standard value of axial tensile strength for No. 25 concrete. The stress of the 15-3# pier and 15-4# pier pile exceeds the design value, but does not exceed the standard value.

According to the Appendix P of “Code for Design of Ground Base and Foundation of Highway Bridges and Culverts” (JTG D63-2007), the displacements of 15-1# pier top and 15-2# pier top are 9.50cm, less than the slip between the support and the beam. While the results for 15-3# pier and 15-4# pier are 8.74cm, close to the slip between the support and the beam.

That the displacements of the 15-1# pier and 15-2# piers are smaller than the slip between the support and the beam is attributed to the following reason. (i) Due to the lack of concrete elastic modulus test data, the standard value is used in the calculation. The difference between the actual elastic modulus of 15# pier and the standard value has a great influence on the results about the displacement of the pier top. (ii) During the long-term loading process of the 15# pier support, the actual friction performance of the PTFE plate and the stainless-steel plate changes, which will influence the calculation results.
Fig. 5 The distribution of pile bending moment of 15-3# pier and 15-4# pier pile.

Fig. 6 The distribution of stress of 15-3# pier and 15-4# pier pile.

Table 2.4-1 Pile foundation bending moment and pile body stress.

| Depth z/m | h=α | Bending moment /kN·m | Stress /MPa (positive if tensile) | Depth z/m | h=α | Bending moment /kN·m | Stress /MPa (positive if tensile) |
|-----------|-----|-----------------------|----------------------------------|-----------|-----|-----------------------|----------------------------------|
| 0.00      | 0   | 3823                  | 2.12                             | 0         | 0   | 3823                  | 1.37                             |
| -0.43     | 0.1 | 3838                  | 2.13                             | -0.45     | 0.1 | 3839                  | 1.38                             |
| -0.87     | 0.2 | 3867                  | 2.16                             | -0.91     | 0.2 | 3870                  | 1.41                             |
| -1.30     | 0.3 | 3815                  | 2.17                             | -1.36     | 0.3 | 3879                  | 1.42                             |
| -1.73     | 0.4 | 3869                  | 2.16                             | -1.81     | 0.4 | 3873                  | 1.41                             |
| -2.17     | 0.5 | 3845                  | 2.14                             | -2.27     | 0.5 | 3851                  | 1.39                             |
| -2.60     | 0.6 | 3803                  | 2.10                             | -2.72     | 0.6 | 3809                  | 1.36                             |
| -3.04     | 0.7 | 3741                  | 2.04                             | -3.17     | 0.7 | 3748                  | 1.31                             |
| -3.47     | 0.8 | 3660                  | 1.96                             | -3.63     | 0.8 | 3667                  | 1.25                             |
| -3.90     | 0.9 | 3560                  | 1.86                             | -4.08     | 0.9 | 3568                  | 1.17                             |
| -4.34     | 1   | 3441                  | 1.15                             | -4.53     | 1   | 3450                  | 1.08                             |
| -4.77     | 1.1 | 3307                  | 1.61                             | -4.99     | 1.1 | 3316                  | 0.98                             |
| -5.20     | 1.2 | 3158                  | 1.47                             | -5.44     | 1.2 | 3167                  | 0.86                             |
| -5.64     | 1.3 | 2997                  | 1.31                             | -5.89     | 1.3 | 3006                  | 0.73                             |
| -6.07     | 1.4 | 2825                  | 1.14                             | -6.35     | 1.4 | 2834                  | 0.60                             |
| -6.50     | 1.5 | 2645                  | 0.97                             | -6.80     | 1.5 | 2654                  | 0.46                             |
| -6.94     | 1.6 | 2460                  | 0.79                             | -7.25     | 1.6 | 2469                  | 0.32                             |
| -7.37     | 1.7 | 2272                  | 0.61                             | -7.71     | 1.7 | 2281                  | 0.17                             |
| -7.81     | 1.8 | 2083                  | 0.42                             | -8.16     | 1.8 | 2091                  | 0.02                             |
| -8.24     | 1.9 | 1895                  | 0.24                             | -8.61     | 1.9 | 1903                  | -0.13                            |
| -8.67     | 2   | 1710                  | 0.06                             | -9.07     | 2   | 1717                  | -0.27                            |
| -9.54     | 2.2 | 1356                  | -0.29                            | -9.97     | 2.2 | 1363                  | -0.55                            |
| -10.41    | 2.4 | 1034                  | -0.60                            | -10.88    | 2.4 | 1039                  | -0.80                            |
| -11.27    | 2.6 | 150                   | -0.88                            | -11.79    | 2.6 | 155                   | -1.02                            |
| -12.14    | 2.8 | 512                   | -1.11                            | -12.70    | 2.8 | 515                   | -1.21                            |
| -13.01    | 3   | 319                   | -1.30                            | -13.60    | 3   | 322                   | -1.36                            |
| -15.18    | 3.5 | 32                    | -1.58                            | -15.87    | 3.5 | 32                    | -1.58                            |
| -17.34    | 4   | 3                     | -1.61                            | -18.14    | 4   | 3                     | -1.61                            |
| -42.00    | 3   | -1.61                 | -42.00                           | 3         | -1.61 |
2.5. Results and discussion

Combined with the on-site inspection, the calculation shows that when the surrounding filling of the 15# pier is first carried out between the 15# pier and the 16# pier, the stress of the 15-1# pier and 15-2# pier pile will exceed concrete axial tensile strength, while the stress of the 15-3# pier and 15-4# pier pile will exceed the design value but be less than the standard value of concrete axial tensile strength.

For the lower structure of the 15# pier, the anti-push stiffness of 15-3# pier and 15-4# pier is larger than 15-1# pier and 15-2# pier, because of the connection with the sidewalk stairs. Therefore, under the same horizontal force, the slip between the beam and the top support of the 15-3# pier and 15-4# pier will be less than that of 15-1# pier and 15-2# pier.

3. Conclusion

Before carrying out the soil-filling construction, the impact on the pier should be fully considered, and the protection measures and construction plan should be formulated. If possible, the stress relief holes should be placed near the pier foundation to reduce the filling pressure on the pier.

During the construction, the state of the space under the bridge should be surveyed in time. Once the pier column is abnormally displaced or deformed, the construction should stop to ensure the safety of the bridge.

In order to ensure the safety of the bridge, for the bridges with soil-filling around the piers, the impact of soil-filling must be analyzed based on the span structure combined with the site investigation and completion data, and furthermore the appropriate treatment measures should be taken for the affected pier foundation and superstructure.

References

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