Failure Analysis and Reinforcement Design of Retaining Structures for a Railway Square in a Mountainous Area

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Abstract

This paper examines the failure and subsequent reinforcement design of the retaining structures under special conditions for a railway square in a mountainous area. The cause of the failure of the original design is discussed. A new scheme of keeping soils in front of retaining piles + diagonal bracing is proposed to re-design the retaining structures for railway square construction. A finite-element modelling is used to carry out detailed numerical analyses for different loading cases and verify the reliability of the reinforcement design. It is shown from the analyses that special attentions should be paid to the horizontal forces induced by diagonal braces. The construction results indicates that the proposed reinforcement scheme is effective and reliable.

Keywords: *retaining structure, reinforcement design, finite element modelling*

1. INTRODUCTION

A large number of railway stations have been built across China following the rapid growth of high-speed railway networks. For the construction of railway squares in mountainous areas, high slope and deep foundation excavation to meet the special requirements of railway station operations may cause geotechnical problems. This paper will study a reinforcement design for the retaining structures involving a deep foundation excavation under special conditions after the failure of the original design for a station square construction.

2. PROJECT OVERVIEW

The railway square to be discussed in this paper is located in south-western China. A 2-level basement would be built under the railway square (the basement would be 4-level deep at a localized area). Reinforced concrete framework was proposed for the basement supported by bored piles. The installation of bored piles for 2- level basement had not begun when the reinforcement design was introduced.

A high slope stood between the basement and existing railway station which was scheduled to open business when the railway line started commercial operations. The slope of 60 degrees was about 139m long with an elevation difference of 11.4m from top to bottom. The slope consisted of backfill (1-1), covered by a simple shotcreting without soil nails. The minimum distance between the foundation of the railway station and the retaining piles was 7.6m. (Figure 1).

According to the construction planning, the removal of the slope would result in a 11.9m pit for middle section (BC), and a 13.5m pit for outer sections (AB,CD). (Figure 2).

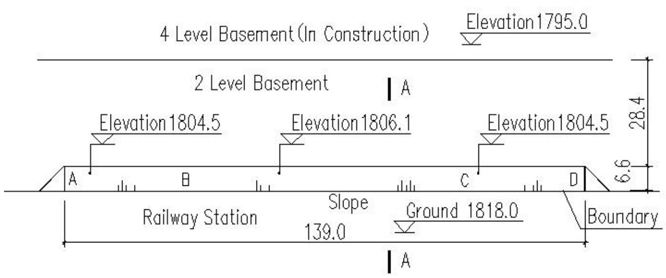

Figure 1. Construction Planning (unit:m)

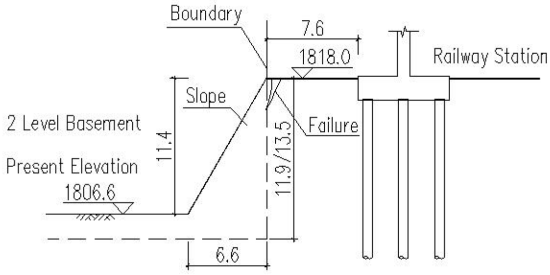

Figure 2. Cross-section A-A (unit:m)

3. GEOLOGICAL DATA

Geological survey showed soils varied from top to bottom as follows:(1-1) backfill;(2-1) Red clay, (3-1) moderately weathered limestone, (3-2) moderately-to-slightly weathered limestone, (4-1) Karst cave (unfilled), (4-2) Karst cave (filled). Table 1 shows the parameters chosen for the design of retaining structures .

Table 1. Parameters of Soil Layers

Layer No.	Soil	Natural Density γ (kN/m^3)	f_{ak}(fa) (kPa)	$E_{s(1-2)}$(E_0) (MPa)	C (kPa)	φ (°)
1-1	Misc. fill	22.0			8	20
2-1	Red clay	18.7	180	5.5	23	12
3-1	MW limestone	24.5	(2400)	Incompressible	50	20
3-2	M-to-SW limestone	24.5	(11000)	Incompressible	100	30

4. FAILURE OF ORIGINAL DESIGN

The original design was carried out by the contractor. In this design, the slope would be stabilized by using multiple rows of anchors. Engineers from our company reviewed this design and raised some concerns before this design was finalized.

1. If the slope would be 11.9m~13.5m high and 2.6m wide with a slope ratio of 1:0.19, it would be too steep to effectively control soil movement. A high slope alone would not be able to protect the existing railway station.

2. By simply installing anchors within soft soils without connection with other rigid piles and capping beams, the capacity of the anchors to control soil movement would be limited.

Nonetheless, the contractor ignored these problems and rejected professional advice from our team and started excavation from the bottom of the slope. A crack appeared on the top of the slope soon after the excavation began, running through the whole slope with a value of 4~5cm. The excavation was immediately terminated and soils were backfilled to the bottom of the slope to contain the further spreading of the crack. The cracked part of the slope was mixed with cement.

Under the request of the owner, our team took over the responsibility to conduct the reinforcement design.

5. REINFORCEMENT DESIGN

A reinforcement scheme of keeping soils in front of the retaining piles + diagonal bracing was proposed by our team as shown in Figure 3 and Figure 4. A detailed analysis is described below.

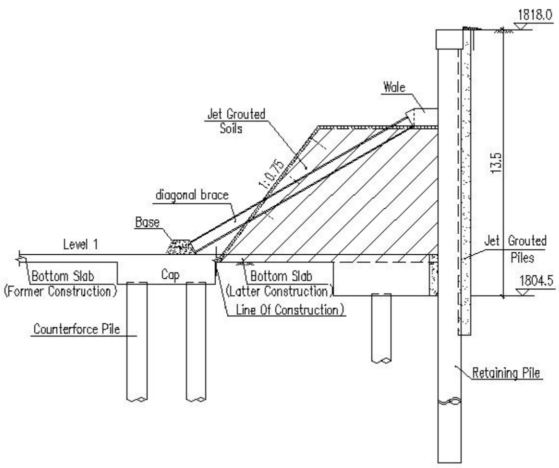

Figure 3. Cross-Section of AB and CD(unit:m)

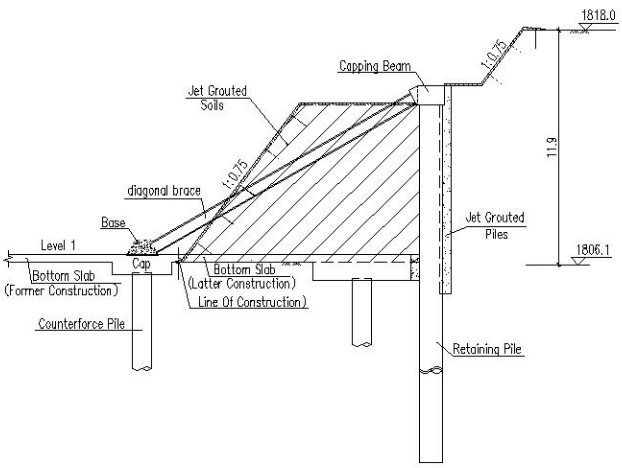

Figure 4. Cross-Section of BC(unit:m)

1. The construction of basement structures had not reached the area where excavation would take place and the basement slabs had not been built which could provide enough space for installing diagonal braces.

2. Special attentions should be paid to observing the transmission of horizontal forces under different loading cases due to installation of diagonal braces and slabs. The transmission path of horizontal forces to the retaining piles should be clear and reliable.

3. The construction of diagonal braces would leave no more room for the installation of foundation piles, so it would be necessary to install the retaining piles and foundation piles on the same soil platform at the same stage. The soil platform should be wide enough to meet the needs of foundation pile installation. As soils in front of the retaining piles kept in the passive zone possessed low strength, certain amount of soils had to be strengthened by using Φ700@550 jet grouted piles to achieve a value of C≥60 kPa for the grouted soils.

4. Separate designs could be carried out for outer sections (AB, CD) and middle section (BC). The excavation for the middle section was smaller with a larger distance of 14.7m to the railway station, certain amount of soils could be removed from the top of the retaining piles to make the implementation of design easier and more economical. The reliability and cost reduction should be considered at the same time.

5. The construction procedure could be easily illustrated step by step.

Our team began the design based on the above mentioned scheme. Taking sections AB and CD as example, the excavation would be 11.9m deep and the retaining piles be Φ1200@1500 with an effective length of 29m. The maximum horizontal displacement was calculated to be 28.8mm. Figure 5 shows the construction procedure.

Step 1: 1. Backfilling the slope in two stages until reaching an elevation of 1818m to form a soil platform for retaining pile installation.

2. Installing retaining piles, jet grouted piles, and capping beams with concrete being cured to

100% designed strength.
Step 2: 3. Removing 2nd-stage backfill to the designed elevation of 1813m.
4. Installing counterforce piles and foundation piles.

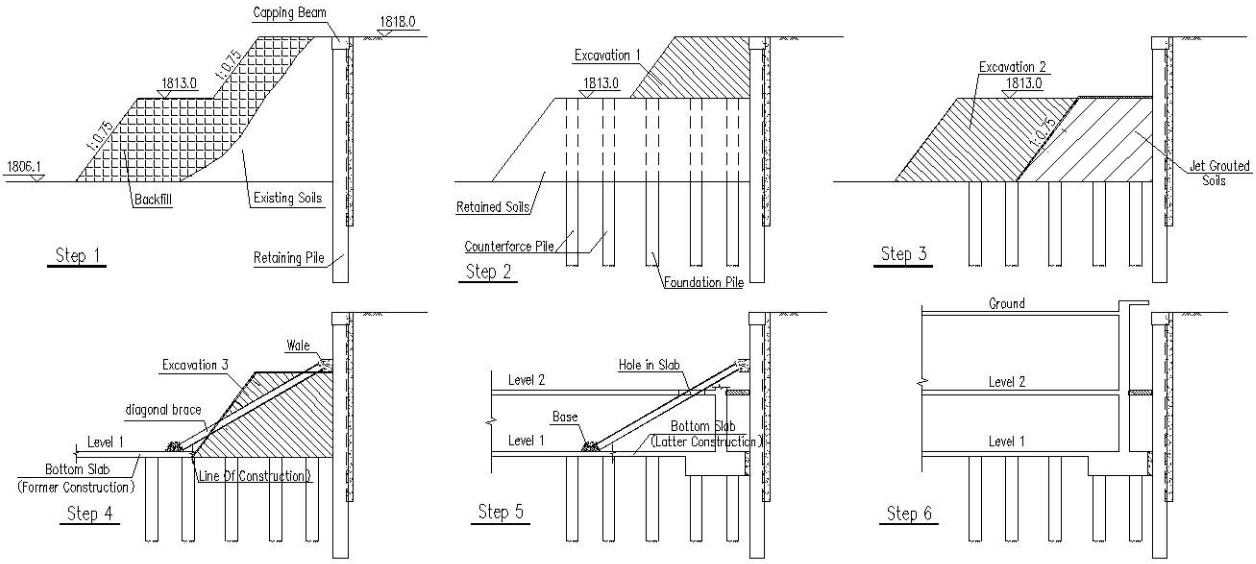

Figure5. Construction Procedure for AB and CD(unit:m)

Step 3: 5. Grouting the remaining soils according to the design requirement.
6. Removing the unneeded soils.
Step 4:7. Installing bottom slab of the basement, base and wales of diagonal braces, bearing plates; casting concrete for these objects at the same time; curing concrete to 100% designed strength.
8. Digging a trench in the remaining soils for installation of diagonal braces.
9. Removing the remaining soils.
Step 5: 10. Setting up the basement structures to 2nd level of slab.
11. Transferring supports to the slabs.
Step 6:12. Removing diagonal braces and completing the construction of the remaining basement structures.
13. Backfilling the gap between the basement and the retaining piles with plain concrete .

6. FINITE ELEMENT ANALYSIS

Finite element modelling could more accurately analyse the working conditions of the retaining structures and the soil movement which could then be used to evaluate the effect of the construction of railway square on the railway station. Soils were treated as small strain elements (HS small) and the diagonal braces were modelled as anchor rods which only provided horizontal forces. 4 loading cases were analysed for the first 5 steps. The railway station was not treated as a structural element to simplify the modelling. The results are shown from Figure 6 to Figure 13.

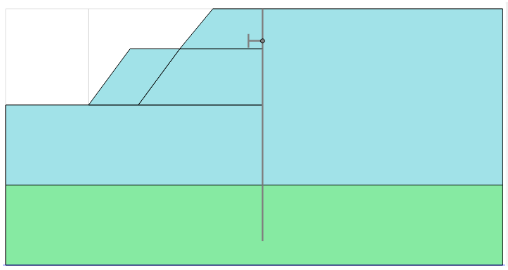

Figure 6. Case 1: Backfilling Soils; Installing Retaining Piles

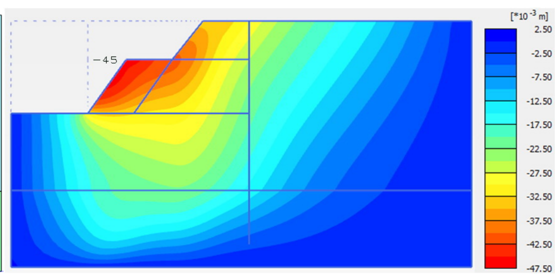

Figure 7. Horizontal Displacement for Case 1

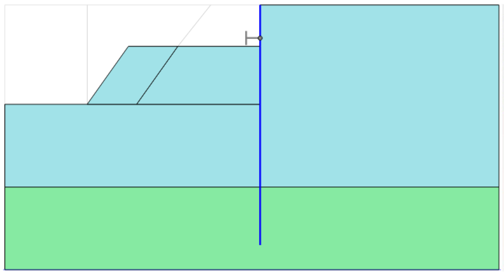

Figure 8. Case 2: Removing 2-Stage Backfill

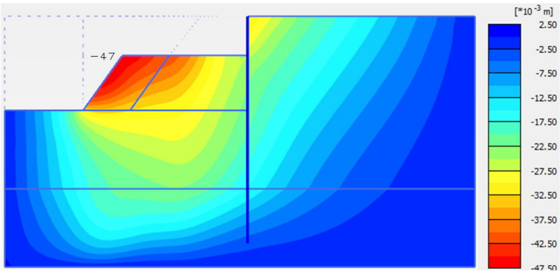

Figure 9. Horizontal Displacement for Case 2

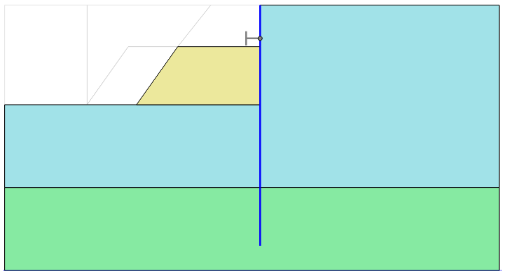

Figure 10. Case 3: Strengthening the Remaining Soils; Removing the Unneeded Soils

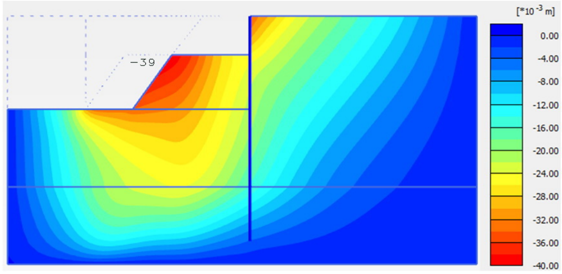

Figure 11. Horizontal Displacement for Case 3

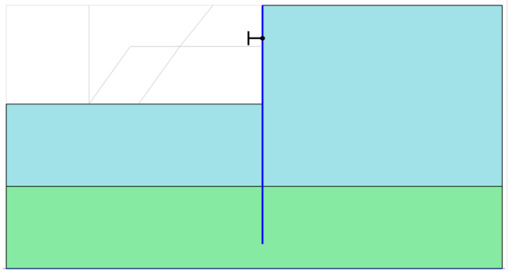

Figure 12. Case 4: Installing Braces; Removing Remaining Soils

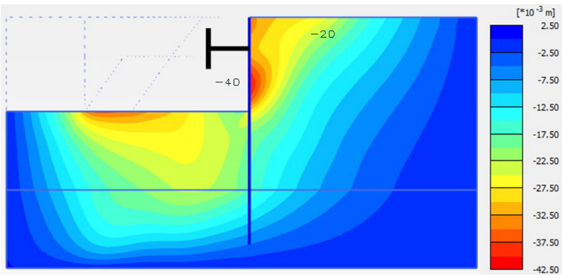

Figure 13. Horizontal Displacement for Case 4

These results describe the deformations of the retaining piles and soils for all stages of the basement construction. Despite a maximum horizontal displacement of 47mm may occur for the soils in front of the retaining piles, the effect on the retaining structures is small. Because of the support of the soils in front of the retaining piles, the displacement of the retaining piles and the soils behind them is calculated to be within a smaller value which will reduce the influence on the railway station. The maximum displacement of the retaining piles is approximately 40mm for Case 4 which meets the requirements specified by the design standards.

It can also be seen that the horizontal displacement of the soils on the top of the slope (behind the retaining piles) becomes smaller and smaller with the increase of distance between a calculated point and the retaining piles which means the railway station is not located within the area where larger soil movement occurs. Although the horizontal displacement of the soils right under the railway station is about 20mm, the superstructure and foundation of the railway station have formed a combined structure after the completion of the construction of the railway station which possesses adequate rigidity to resist the horizontal soil movement. The effect of the basement construction on the railway station is acceptable and controllable.

7. DESIGN OF STRUCTURE MEMBERS

Sections AB,CD and section BC are shown in Figure 3 and 4 respectively.

The retaining system can be divided into the following elements:

1. Retaining piles and capping beams：Φ1200@1500 bored piles were chosen as the retaining piles with an effective length of 29m in sections AB, CD, and 25m in section BC. All piles were embedded into soil layer (3-2) for no less than 2m.

2. Diagonal braces：Φ609×14 steel tubes were chosen as diagonal braces. Each steel brace has a total length of 12.7m with an inclination angle of 30 degrees and a spacing of 9m. The braces were treated as compressive-flexural members.

3. Wales ：Since the retaining piles were higher for sections AB，CD, additional wales were designed to connect retaining piles and braces.

4. Counterforce piles and their bearing platforms：Since the bottom slab sat on (1-1) backfill, counterforce piles below the brace base were designed to carry the self-weight of braces and to resist the vertical forces.

8. CONSTRUCTION RESULTS

During the construction, the soils behind the retaining piles were stable; no lateral movement was recorded for the foundation of the railway station; the structures of the railway station remained intact. These results show this reinforcement scheme can effectively protect the safety of the railway station.

9. CONCLUSIONS

The following conclusions can be drawn from this reinforcement design:

1. The priority of reinforcement design to deal with foundation failure is to fully understand the objectives and clearly identify the structural members to protect and the measures to take.

2. The reinforcement scheme must take the site condition into consideration in order to meet the needs of site condition and to ensure the constructability.

3. The reinforcement scheme of keeping soils in front of the retaining piles + diagonal bracing is completely suitable for the protection of the existing structures during construction involving high slope and deep foundation. Similar projects in the future may take this example as reference.

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