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Type selection, structural calculation and construction of anchorage in Sichuan bank of Sichuan Kahalo Jinsha River Bridge

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Abstract

Sichuan kahalo Jinsha River Bridge is a suspension bridge with a main span of 1030 m, and the anchorages on both sides are gravity anchorages. In order to adapt to special terrain and geological conditions, anchorage of Sichuan bank pioneered the use of frame structure as the anchorage foundation. The soil and the frame structure jointly bear the vertical load and resist the horizontal component of the main cable to form a "frame soil" community and fully mobilize the role of the undisturbed soil. In order to ensure the integrity of the frame structure, the indirect head of the slot section adopts a rigid joint. At the same time, the distributed grouting technology is used to strengthen the soil around the frame structure, so as to further improve the safety factor.

This paper introduces the topography and geology of the anchorage position, compares and selects different anchorage foundation schemes, and explains in detail the design concept, structure size and construction technology of the frame foundation.

The research shows that using frame structure as anchor foundation is not only reasonable, safe, good economy, but also environmentally friendly. It has solved the difficult problem of anchorage design under poor terrain and geological conditions, and will provide a good reference for the design of mountainous suspension bridges in similar condition.

Keywords: Sichuan Kahalo Jinsha River Bridge, Gravity anchorage with frame structure foundation, Frame-soil community, Finite element calculation, Theoretical calculation model of six springs, Rigid joint, Grouting reinforcement

1 Introduction

1.1 Brief introduction of the bridge

Sichuan Kahalo Jinsha River Bridge is located in the Yongshan Branch of The Expressway along the Jinsha River. It is designed to cross the Jinsha River and connect Sichuan and Yunnan. The main span is 1030 m (Fig. 1). The main girder of the bridge adopts composite structural steel truss girder, the main tower adopts concrete-filled steel tubular

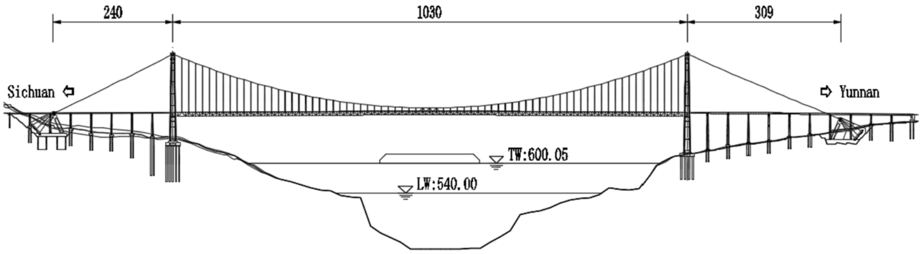


Fig. 1 Elevation layout of Sichuan Kahalo Jinsha River Bridge (unit: metre)

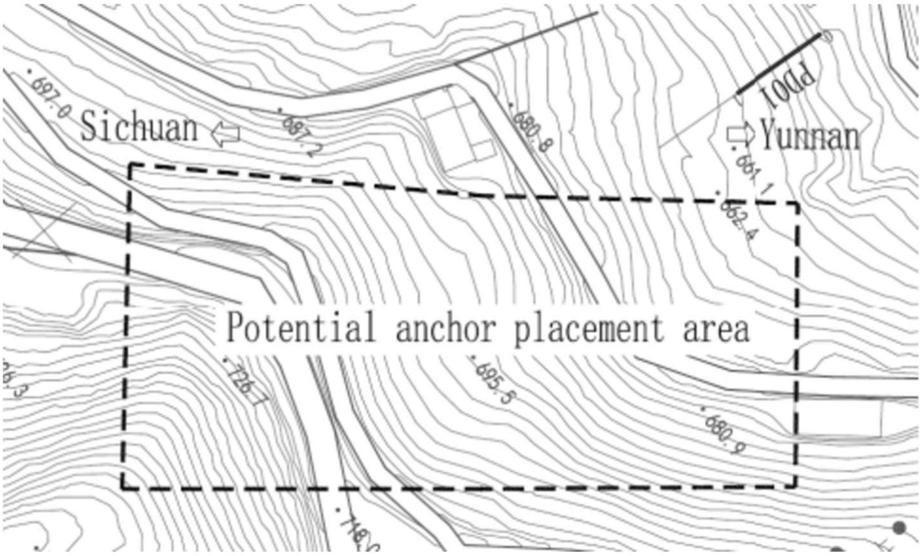


Fig. 2 Topographical plan of the anchorage of Sichuan bank

composite bridge tower, anchors on both banks are gravity anchors, and the main cable adopts high-strength galvanized steel wire.

The traditional gravity anchorage mostly adopts the enlarged foundation, which has better adaptability under the condition of good terrain and geological conditions (Ya et al. 2017; Li et al. 2007; Lai et al. 2010), and the construction is relatively simple. However, the anchorage of Sichuan bank is located in the middle and lower part of the left slope of the Jinsha River convex bank, on the front edge of the strip ridge, where the slopes on both sides of the ridge and the front edge gently slope down and then steeply up (Fig. 2), mostly between 15° and 25°. The localised shape is steep. The terrain condition is poor, and it is a typical "Elephant nose terrain", and the geological conditions at the anchorage position are poor (Fig. 3).

If the traditional enlarged foundation is used as the anchor foundation scheme, in order to meet the bearing capacity requirements, a large foundation depth is required (Ya et al. 2017; Li et al. 2007; Lai et al. 2010). In the case of large horizontal and vertical slopes, it will inevitably lead to a large amount of foundation excavation and a steep excavation slope, which is not only uneconomical, affects the ecological environment, but also brings greater risks to construction and operation. Therefore, it is necessary to explore a new type of anchor foundation (Zhao et al. 2021).

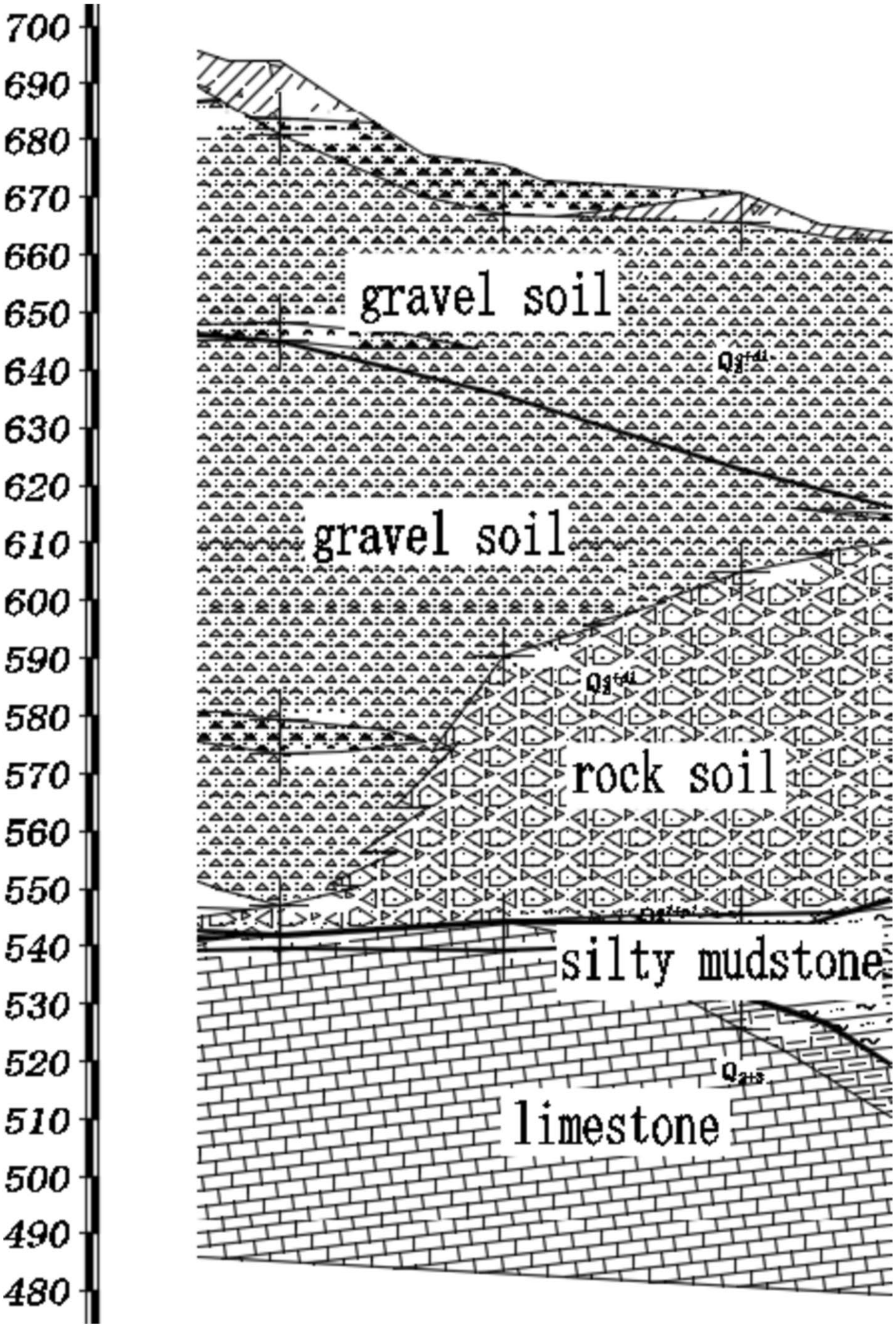


Fig. 3 Longitudinal section of engineering geology at the anchorage of Sichuan bank

1.2 Current practice and research

As the major stress member of suspension bridge, anchorage plays an important role in transferring the tension of main cable to the foundation. The construction scale is usually huge and the cost is high. Therefore, it is necessary to conduct special research on the anchorage scheme according to the specific construction conditions, so as to achieve the technical and economic optimization. There are two common foundation forms of anchorage: gravity anchorage and tunnel anchorage (Zhao et al. 2021; Wang et al. 2019). Generally, gravity anchorage relies on its own weight to resist the vertical component of the main cable, and relies on the friction between the anchor foundation and the base to resist the horizontal component of the main cable. Tunnel anchorage directly transfers the main cable tension to the surrounding rock (Wang et al. 2019; Dzceer et al. 2018). Gravity anchorage has low dependence on construction conditions and wide application range, so it is the first choice for long-span suspension bridge anchorage usually (Zhao et al. 2021).

The common foundation forms of gravity anchorage include expanding foundation, underground diaphragm wall foundation and caisson foundation. The suspension bridges built before the middle of the twentieth century usually adopt an enlarged foundation, and the base is placed on hard rock to ensure the safety of the structure. After the middle of the twentieth century, with the increase of the span, the construction conditions became more and more complicated. If the anchorage foundation was placed in hard rock, the project scale was large and the cost was high. Therefore, with the construction of Verrazano Bridge in the United States as a symbol, the construction of anchorage on the soil foundation began to explore (Wen et al. 2009; Cheng et al. 2009; Seitz et al. 2019; Zhou et al. 2014).

Most of the anchors of suspension Bridges in China place the base in the rock layer. When the geological conditions are good, shallow buried expanded foundation is often chosen. When the geological condition is poor, the deep foundation is chosen. In order to save the engineering amount, the underground diaphragm wall foundation is used in the deep foundation (Qin et al. 2018; Yang and Niu (2010)). When the construction of diaphragm wall is difficult, caisson foundation is used. Whether it is underground diaphragm wall or caisson, it is mainly used as construction means to provide temporary support for soil excavation, and does not participate in the force of the main structure.

It is a waste to only use large underground diaphragm wall and caisson as temporary structure. In order to make full use of the structure, during the construction of the Aomori Bridge (main span 240 m cable-stayed bridge) in Japan, engineers used the underground diaphragm wall as the base of the main tower, permanently. In this case, the underground diaphragm wall is not as a temporary structure but as a permanent structure, the vertical force transmitted by the main tower depends on the underground diaphragm wall structure itself and the friction between the wall and the soil for support (Hu et al. 2006; Han and Chen 2016; Satoshi et al. 1992). Therefore, the reinforcement of wall sections and the connection between wall sections are very important.

Different from the main tower of cable-stayed bridge, the anchorage foundation of suspension bridge should bear not only vertical force, but also large horizontal component force. Therefore, although the underground diaphragm wall as a permanent structure has a good economy, but it needs to solve a series of problems such as structural calculation and rigid joint construction. So far, no long-span suspension bridge has adopted the underground diaphragm wall as the permanent foundation of the anchoring structure (Luo et al. 2023a; Liu et al. 2019; Li et al. 2021).

During the design of this bridge, based on the construction technology of the underground diaphragm wall, we solve the problem of rigid joints between the wall sections and the structural calculation problem, makes the underground diaphragm wall form a frame structure, and becomes the anchoring foundation of the kilometer-level suspension bridge, which is the first time in the world.

2 Anchorage foundation scheme research

The geological conditions at the location of the anchorage of Sichuan bank are poor, and the overlying soil layer is 130 m thick, mainly composed of gravel soil and block soil. The anchorage foundation bearing layer is located in the gravel soil, the physical and mechanical parameters of the gravel soil layer are as follows (Table 1).

The tunnel-type anchorage has high requirements on geological conditions (Yang et al. 2022; Zhang et al. 2019; Luo et al. 2023b), which cannot adapt to the geological conditions here. Therefore, in the comparison study of the scheme, the tunnel-type anchorage is not considered.

2.1 Enlarged foundation gravity anchorage

Through the calculation of the main structure, the rise-span ratio of the main cable is selected to be 1/9.5. The angle between the main cable and the horizontal line of the mid-span at the bridge tower is 23°. The side span of the main cable has 3 more back wire bundles than the middle span, and the angle between the side span of the main cable and the horizontal line is between 23° and 26.5°. The topography of the Sichuan bank is gentle down and steep up (Fig. 2). In order to reduce the amount of soil excavation, the anchorage should be placed in a place where the terrain is gentler, that is, close to the Yunnan bank. Therefore, the angle between the side span of the main cable and the horizontal line on the Sichuan bank should be as large as possible, so the angle between the side span of the main cable and the horizontal line is selected as 26.5°.

During the service stage, the side span main cable pulling force (left and right together) is 5.3×10^5kN. In order to meet the requirements of main structure stress and cable strand anchoring arrangement, the topographic and geological conditions are considered carefully, the anchorage size is selected as follows (Figs. 4 and 5).

Using the structural dimensions shown in the figure above, the overall calculation of the anchorage construction and operation stages were carried out, and the results are shown as follows.

During the construction stage, tensile stress at the front end of the anchorage were discovered, and the maximum foundation compressive stress at the rear end of the

Table 1 Physical and mechanical parameters table of natural state of gravel soil

Degree of weathering	Intense ~ moderate	Moderate
natural density (g/cm^3)	2.3	2.3
allowable bearing capacity [σ_0] (kPa)	550	600
standard value of friction resistance [q_{ik}] (kPa)	180	200
friction coefficient	0.45	0.45
cohesion (kPa)	15 ~ 20	15 ~ 20
internal friction angle (°)	32 ~ 35	32 ~ 35

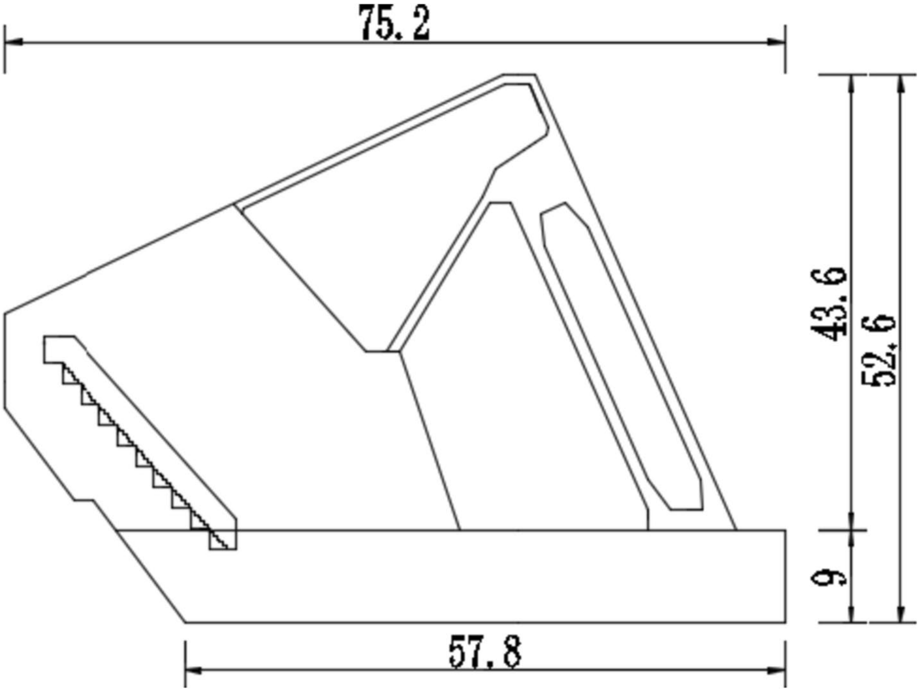


Fig. 4 Elevation view of enlarged foundation gravity anchorage (unit: metre)

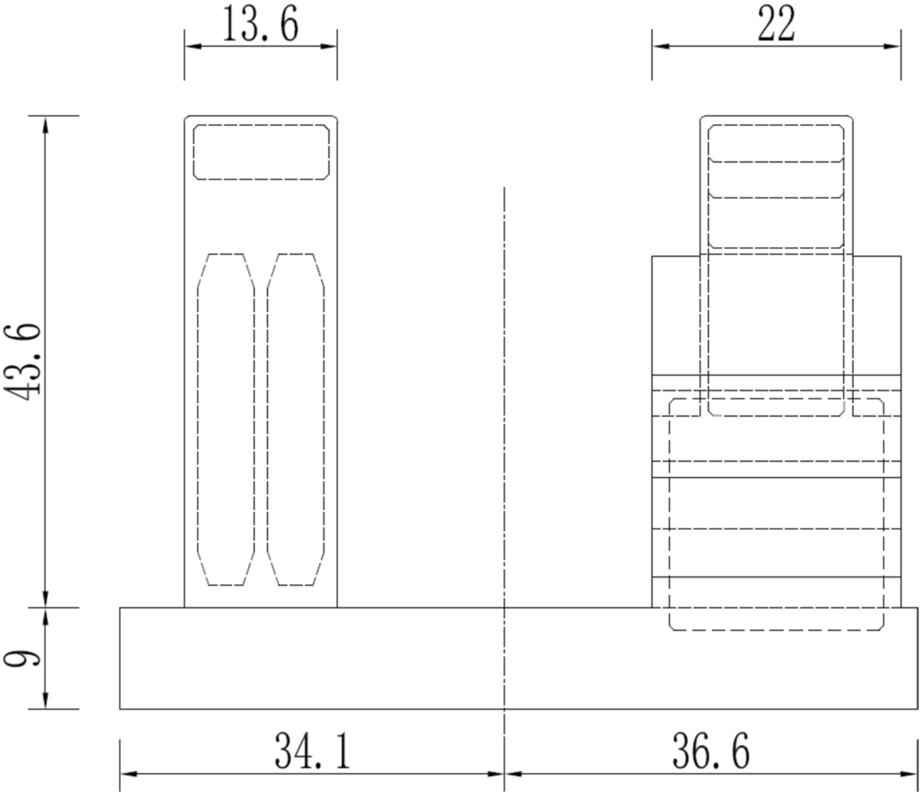


Fig. 5 Cross-sectional view of enlarged foundation gravity anchorage (unit: metre)

anchorage is 1270kpa, which does not meet the specification requirements (Industry Standard Editorial Committee of the People's Republic of China 2019). In the service stage, the anti-slip safety factor is 1.42, which does not meet the requirement that the anti-slip stability factor is not less than 2.0 (Industry Standard Editorial Committee of the People's Republic of China 2015).

It can be seen that using the enlarged foundation gravity anchor, the anti-slip stability and the bearing capacity of the foundation does not meet the requirements. In order to meet the requirements of the bearing capacity, it is necessary to increase the buried depth of the foundation to 20 m below the Q3 gravel soil layer. A 3D model (Fig. 6) is created, and calculations show that the excavation volume reaches 1.52 million m^3, and the maximum excavation depth reaches 162 m, which requires huge amount of construction and generates potential operational risks.

2.2 Gravity anchorage with frame structure foundation

The bearing capacity of the anchorage position is about 550kpa, which does not meet the specification requirements. But the standard value of friction resistance is about 200kpa, which should be fully utilized to reduce the requirement of the foundation bearing capacity. In order to make full use of the soil, a closed frame structure was considered as the anchorage foundation, which does not require excavation of the surrounding soil. Not only the friction between the side wall of the frame and the soil is used to provide a certain vertical force, thereby reducing the stress of the foundation, but also, the internal soil within the frame is mobilized to form a "frame soil" community, which resists the horizontal component of the main cable.

On the basis of enlarged foundation gravity anchorage, keeping the structure size above the cushion cap unchanged, the anchorage foundation adopts the frame structure as shown in the figures below (Figs. 7 and 8). According to the structural stress characteristics and requirements, the frame foundation is divided into front leg and rear leg, both of the same size. Through calculation, the foundation size is as follows: the distance between the front and rear leg is 21 m, the longitudinal size is 18 m, the transverse size is 64.8 m, and it is equally divided into 6 boxes, and all the wall thicknesses are 1.2 m.

The calculation result shows that the bearing capacity and deformation of the structure meet the requirements of the specifications (See under 3.2). The maximum soil pressure

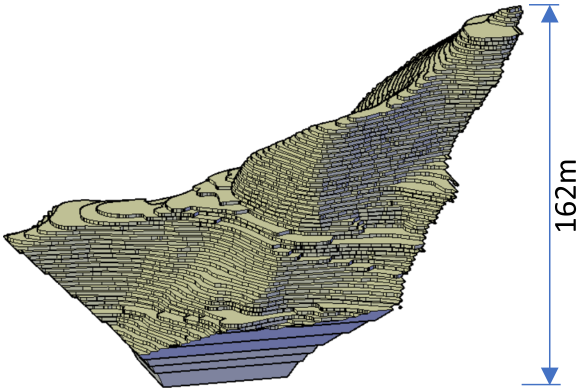


Fig. 6 3D model of soil excavation (enlarged foundation gravity anchorage)

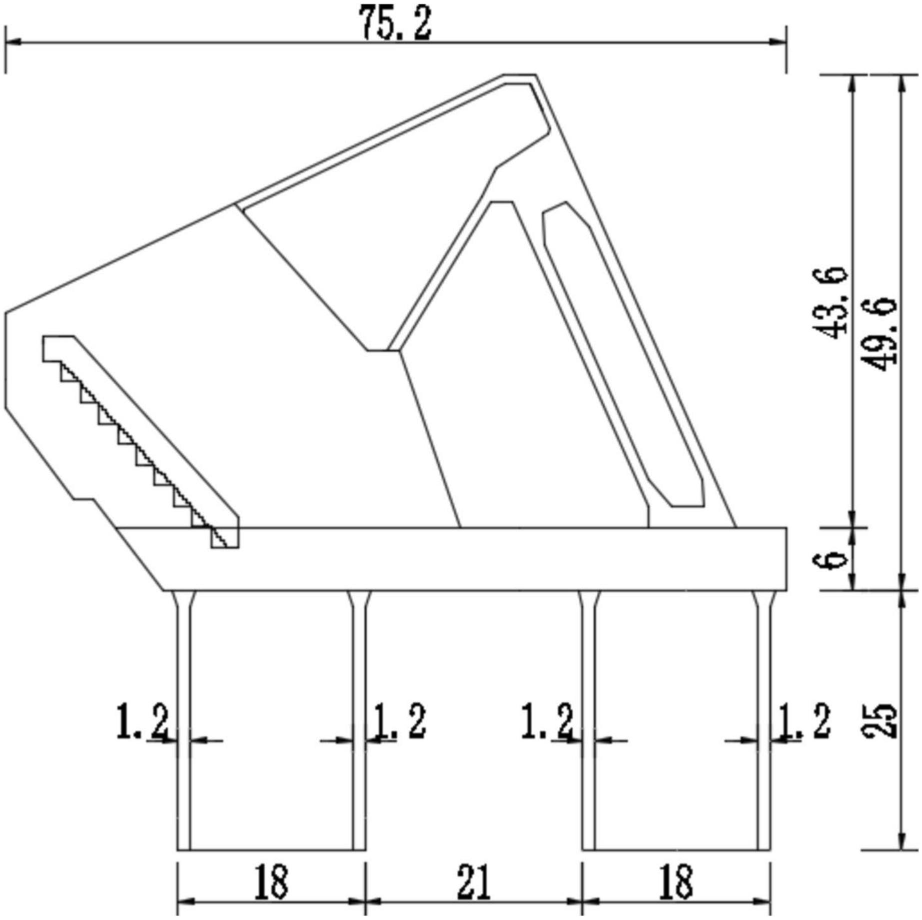


Fig. 7 Elevation view of gravity anchorage with frame structure foundation (unit: metre)

at the bottom of the cushion cap is 400kpa, and the surface gravel soil meets the structural bearing requirement. The depth of the foundation is shallow, which can reduce the amount of foundation excavation. Based on the 3D model for calculation (Fig. 9), the excavation volume is 0.48 million m^3, and the maximum excavation height is 87 m. Compared with the enlarged foundation gravity anchorage, the excavation is reduced by about 1.04 million m^3, and the slope height is reduced by about 65 m, which greatly reduces the amount of excavation works and reduces the construction and operational risks. Therefore, the gravity anchorage with frame structure foundation was selected as the final anchorage scheme, and a detailed force analysis was carried out.

3 Force analysis of gravity anchorage with frame structure foundation

3.1 Force mechanism

Drawing on the construction technology of the underground diaphragm wall, in the process of constructing the frame foundation, the soil around the frame and the surrounding area is not excavated, which not only reduces the amount of excavation and post-protection works, but is also conducive to full use of undisturbed soil (Liu et al. 2022).

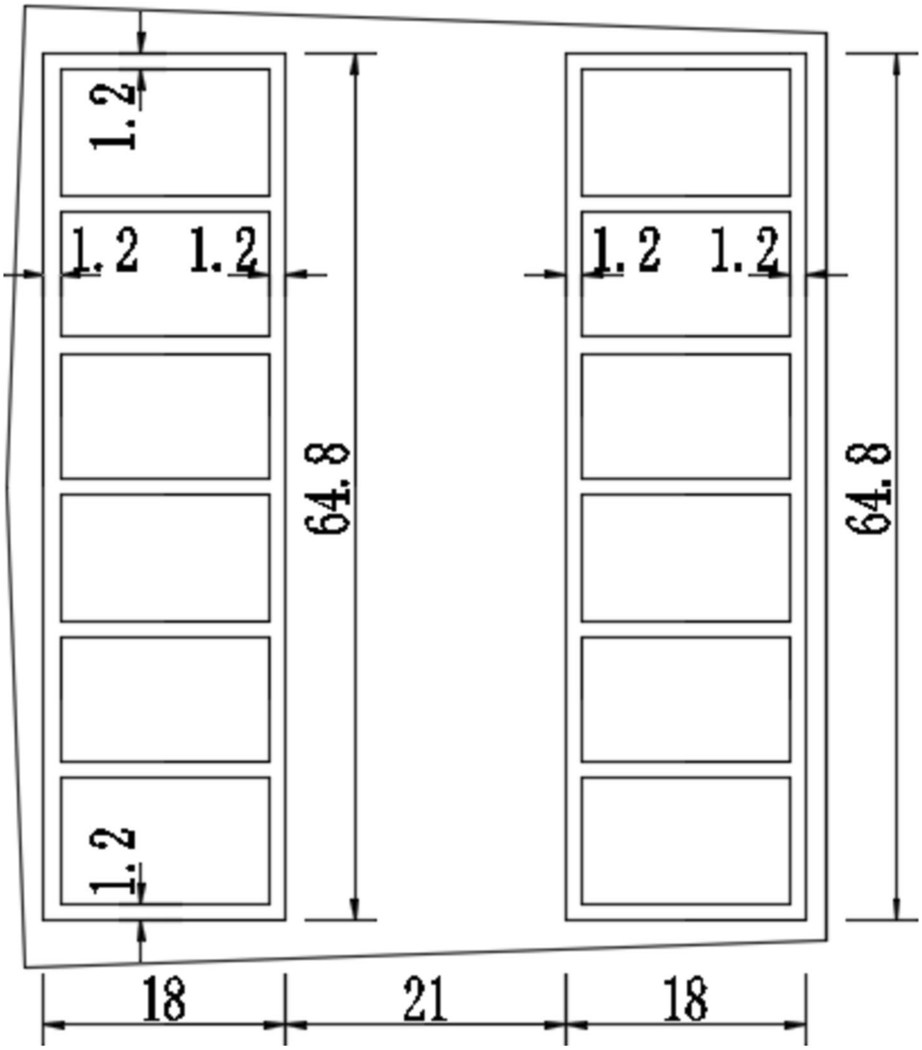


Fig. 8 Plan of gravity anchorage with frame structure foundation (unit: metre)

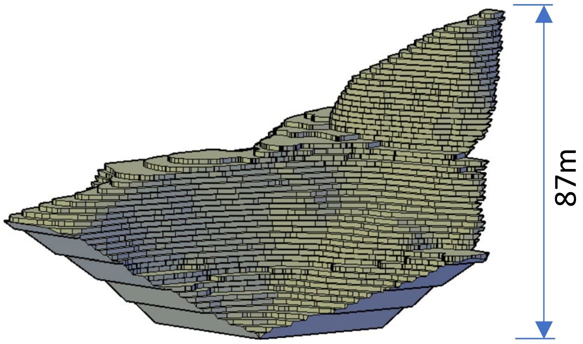


Fig. 9 3D-model of soil excavation (frame structure foundation gravity anchorage)

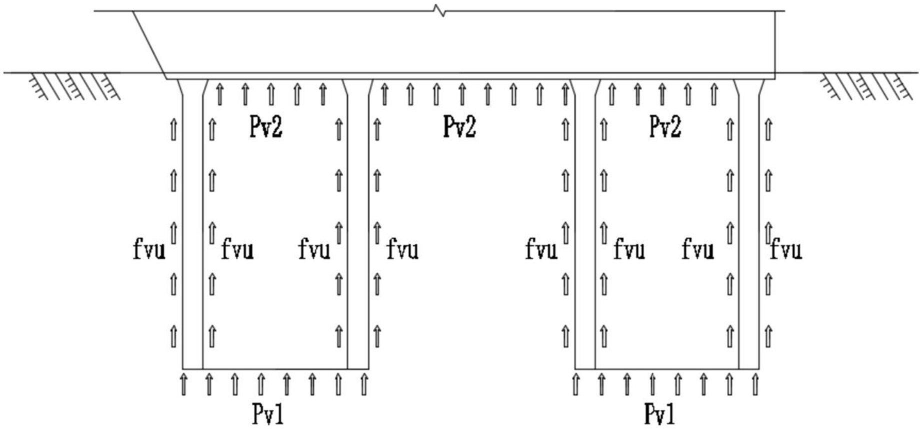


Fig. 10 Schematic diagram of vertical bearing of frame foundation

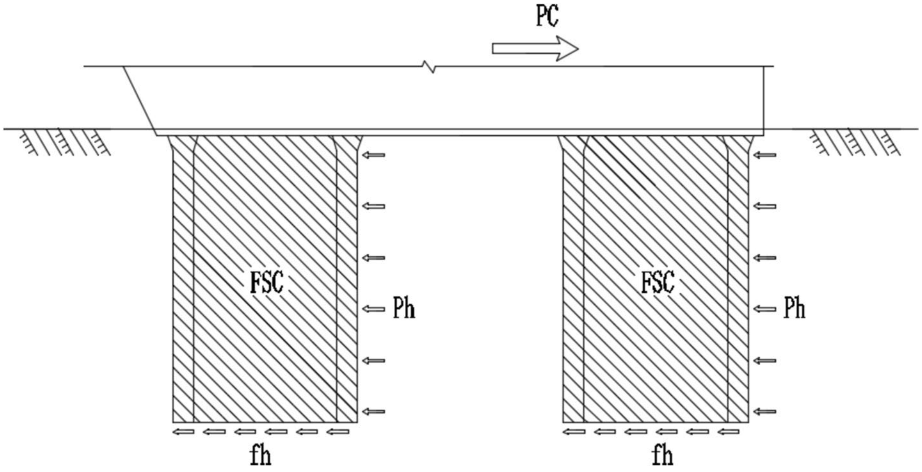


Fig. 11 Schematic diagram of horizontal load bearing of frame foundation

In the vertical direction (Fig. 10), the friction resistance between soil and walls of the frame foundation (both inner and outer) is used to resist the vertical load together with the support force of the bottom of the cushion cap and the bottom of the frame foundation, so as to reduce the requirement of the foundation bearing capacity of the anchorage (Wu et al. 2015).

In the horizontal direction (Fig. 11), the frame foundation and the adjacent soil form a "frame-soil" community to resist the horizontal component force of the main cable, enhance the resistance of the anchorage in the horizontal direction (Cui et al. 2018; Cheng et al. 2012).

3.2 Structure calculation

By experiment, we get the physical and mechanical parameters of the bearing layer shown in Table 2. The elastic modulus is 886.58 MPa at the buried depth of 15 m and below, and it changes linearly from the buried depth of 15 m to the surface to 338.15Mpa. The standard tension value of the single main cable under dead load is 241051kN, and the standard tension value under dead load and live load is 265974kN. According to the above material

Table 2 Mechanical parameters of the soil layer where the frame foundation is located

Soil layer	Gravelly soil
elasticity modulus (MPa)	338.2 ~ 886.6
volume weight (KN/m^3)	24.2
Poisson's ratio	0.27
internal friction angle (°)	25.2
cohesion (kPa)	128

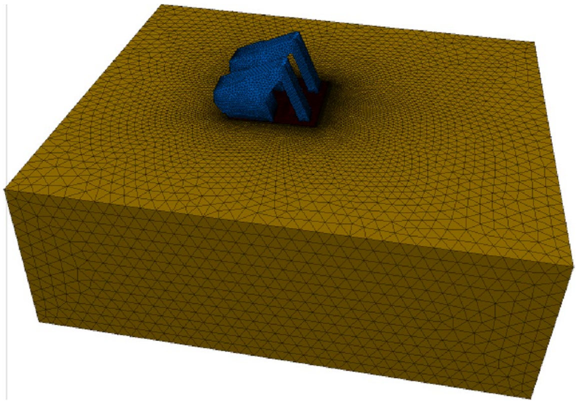


Fig. 12 FLAC3D computing model

and load information, through FLAC3D, ABAQUS finite element model and theoretical calculation, the structure analysis is carried out for three working conditions. Working condition 1: When the construction is completed, the state of anchorage weight is only considered. Working condition 2: The operating state after the dead-load cable force is applied. Working condition 3: The operating state after the dead load and live load cable forces are applied.

3.2.1 FLAC3D finite difference model

Flac3D finite difference software was used to simulate and analyze the anchorage. The model has a total of 8,284,535 elements and 2,049,250 nodes. Model range: 350 m in longitudinal direction, 300 m in transverse direction and about 120 m in vertical (Fig. 12). The soil is gravel soil.

The Mohr–Coulomb model is used for the soil. The linear elastic model is used for the anchorage foundation. The contact surface element is set between the soil and the anchorage foundation, and its cohesion and internal friction angle of the contact surface element are 0.5 times that of the gravel soil. Normal and tangential stiffness is calculated according to the following formula.

$$k_n = k_s = 10 \times max(\frac{K + 4G/3}{\Delta z_{min}}) \tag{1}$$

$$K = \frac{E}{3 \times (1 - 2\gamma)} \tag{2}$$

$$G = \frac{E}{2 \times (1 + \gamma)} \tag{3}$$

In formula (1) ~ (3), kn is the normal spring stiffness of the frame-soil interface, ks is the tangential spring stiffness of the frame-soil interface, K is the volume modulus of soil around the frame, G is the shear modulus of soil around the frame, Δz_{min} is the minimum element size of soil grid partition around frame, and γ is the Poisson ratio of soil.

3.2.2 ABAQUS finite element model

The ABAQUS finite element software was used to simulate and analyze the anchorage, the model has a total of 144,860 elements (Fig. 13), the element type is C3D8R, and the size of the soil model is the same as that of the Flac3D model.

The Mohr–Coulomb model is used for the soil. The linear elastic model is used for the anchorage foundation. The contact conditions between the soil and the anchorage foundation are set as normal hard contact and tangential as the penalty parameter of 0.45.

3.2.3 Theoretical computational model

The soil is simulated with distributed soil springs, and a six-spring theoretical analysis model is established (Fig. 14). K_V: vertical foundation counter-force coefficient of foundation bottom; K_S: horizontal foundation counter-force coefficient on foundation bottom; K_H: horizontal foundation counter-force coefficient in front of foundation; K_{SVB}: vertical foundation counter-force coefficient in front of foundation; K_{SVD}: vertical foundation counter-force coefficient on foundation side; K_{SHD}: horizontal foundation counter-force coefficient on foundation side. The vertical and horizontal displacements of the anchorage foundation are relatively small, and they did not reach the plastic stage. Therefore, only the elastic behaviour of the soil is considered in the theoretical calculation.

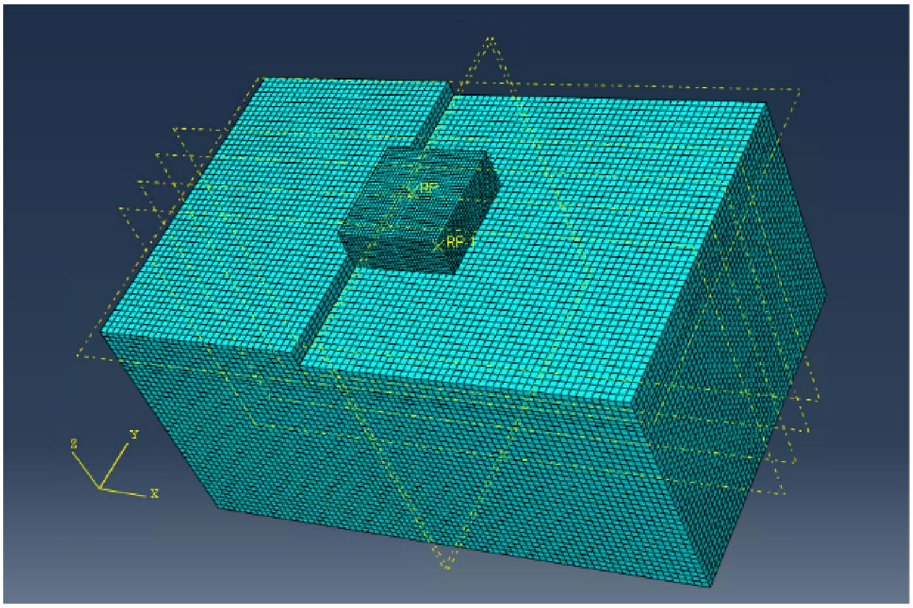


Fig. 13 ABAQUS computing model

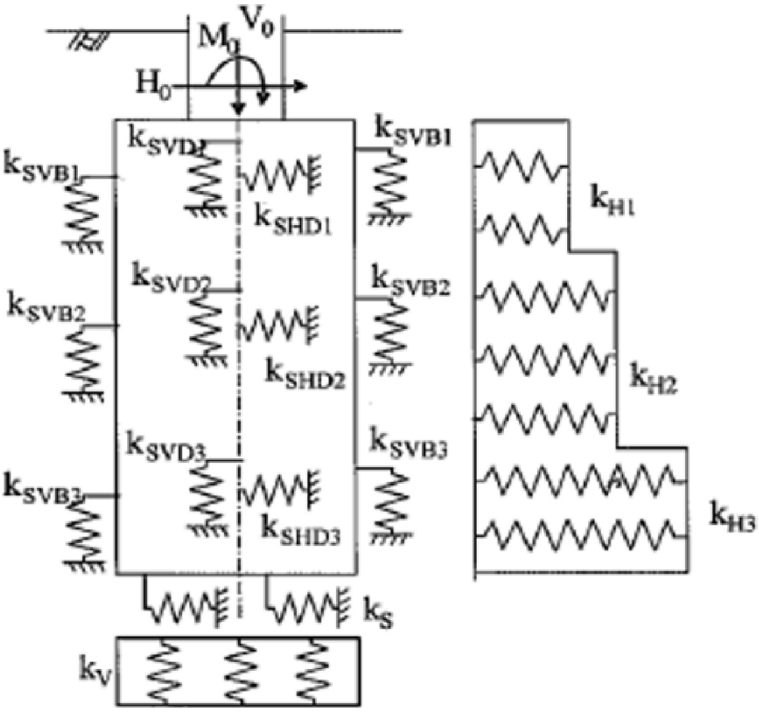


Fig. 14 Six-spring theoretical analysis model

Table 3 Stress and displacement comparison (work condition 1)

Model	Horizontal displacement of the cushion cap (mm)	Vertical displacement of the cushion cap (mm)	Horizontal displacement of the vice cable saddle (mm)	Stress of front leg (kPa)	Stress of rear leg (kPa)
ABAQUS	-2.1	-11.3	-6.7	970	1430
FLAC3D	-1.7	-8.5	-9.5	860	1730
theoretical calculation	-2.3	-5.3	-7.4	330	1410

3.2.4 Calculation results

From the calculation results of stress and displacement, the results of the three calculation methods are relatively close, and the theoretical calculation results are slightly smaller than the calculation results of FLAC3D and ABAQUS. Based on the three calculation results, the maximum horizontal displacement of the anchor in the operation stage (Table 5) is 21.4 mm, which is far less than the specification limit (Industry Standard Editorial Committee of the People's Republic of China 2015): 0.0001 $L_0 = 0.0001 \times 1030m = 103mm$. The maximum vertical displacement is 5.3 mm, which is much smaller than the specification limit (Industry Standard Editorial Committee of the People's Republic of China 2015):$0.0002L_0 = 0.0002 \times 1030m = 206mm$. During construction, the stress at the base of the rear leg is greater than that of the front leg (Table 3), and the maximum value is 1730 kPa. During the operation phase, the stress levels of the front and rear leg are equivalent (Tables 4 and 5), and

Table 4 Stress and displacement comparison (work condition 2)

Model	**Horizontal displacement of the cushion cap (mm)**	**Vertical displacement of the cushion cap (mm)**	**Horizontal displacement of the vice cable saddle (mm)**	**Stress of front leg (kPa)**	**Stress of rear leg (kPa)**
ABAQUS	8.7	2.2	18.9	1070	1240
flac3D	6.6	0.5	17.8	1140	1260
theoretical calculation	2.9	4.8	3.6	710	870

Table 5 Stress and displacement comparison (work condition 3)

Model	**Horizontal displacement of the cushion cap (mm)**	**Vertical displacement of the cushion cap (mm)**	**Horizontal displacement of the vice cable saddle (mm)**	**Stress of front leg (kPa)**	**Stress of rear leg (kPa)**
ABAQUS	9.8	2.5	21.4	1130	1180
flac3D	6.6	0.5	17.9	1210	1190
theoretical calculation	3.4	5.3	4.7	1010	730

Table 6 Vertical force distribution ratio (%) (work condition 2)

Model	Vertical resistance at the bottom of front leg	Outer friction of front leg		Inner friction of front leg	Total of front leg	Vertical resistance at the bottom of rear leg
flac3D	16.0	8.4		3.7	28.1	18.8
Theoretical calculation	9.1	11.5		2.3	22.8	7.3
Model	Outer friction of rear leg	Inner friction of rear leg	Total of rear leg	Resistance of the bottom of cushion cap	Resistance of cushion cap side	Total
flac3D	7.4	3.8	30.0	37.1	4.9	42.0
theoretical calculation	9.3	1.8	18.4	57.2	3.9	61.1

the maximum value is 1260 kPa, which is less than the foundation bearing capacity at the bottom of the frame foundation after depth and width modification, which is 3057 kPa. It can be seen that the frame foundation used as the foundation of gravity anchorage is safe and reliable.

From the calculation results of FLAC3D, the vertical forces borne by the front leg, the rear leg and the cushion cap are almost the same (Table 6), and the cushion cap is slightly larger, which is 42%. From the theoretical calculation results, the vertical force is mainly provided by the resistance of the bottom of the cushion cap, accounting for 61.1%. The distribution of the horizontal force among the various parts of the foundation (Table 7), the FLAC3D calculation results are basically consistent with the theoretical calculation data. The horizontal force shared by the front leg is about 40%, the horizontal force shared by the rear leg is about 22%, and the rest of the horizontal

Table 7 Horizontal force distribution ratio(%) (work condition 3)

Model	Frontal resistance of front leg	Friction at the bottom of front leg		Friction at the outside of front leg	Friction at the inside of front leg	Total of front leg	Frontal resistance of rear leg
flac3D	25.8	4.1		6.6	4.2	40.7	16.8
theoretical calculation	25.5	5.4		5.1	2.2	38.2	6.9
Model	Friction at the bottom of rear leg	Friction at the outside of rear leg	Friction at the inside of rear leg	Total of rear leg	Friction of cushion cap	Resistance of the front of cushion cap	Total
flac3D	0.2	3.8	1.6	22.3	29.4	7.7	37.1
theoretical calculation	6.1	8.0	2.1	23.2	29.7	8.9	38.6

resistance is provided by the cushion cap. Most of the horizontal resistance borne by the frame comes from passive earth pressure provided by the soil in front of the front wall of the frame.

3.2.5 Preliminary summary

1. Using the frame structure as the gravity anchorage foundation, during construction and operation stage, the soil stress is less than the bearing capacity of the foundation, the horizontal and vertical displacement of the structure are far less than the standard limit, so the structure is safe and reliable.
2. The vertical load of the anchorage is jointly borne by the bottom of the cap, the front and rear legs of the frame structure. The vertical load shared by the front and rear leg is almost equal, shared by the cap is slightly larger.
3. The horizontal load of the anchorage is shared by the bottom of the cap, the front and rear legs of the frame structure. The horizontal load shared by the front leg and the cap is almost equal, shared by the rear leg is slightly smaller. The horizontal resistance from the front and rear legs is mainly provided by the pressure between the front wall of the frame and the soil.
4. In the construction process, the disturbance to the original soil should be minimized, so that all parts of the soil can be efficiently used.
5. After the construction of the frame structure is completed, grouting should be carried out to strengthen the soil at important positions, such as the soil at the bottom of the frame structure, the soil at the bottom of the cap, and the soil at the front of the frame structure, to further ensure the safety of the structure.

4 Frame foundation construction

The frame structure is used as the anchorage foundation. The core design concept is to make full use of the undisturbed soil. Therefore, during the construction process, it is very important to reduce the disturbance to the undisturbed soil. For this reason, the construction technology of the underground diaphragm wall is used for reference, and the groove milling machine is used to dig the soil into the groove, without excavating the

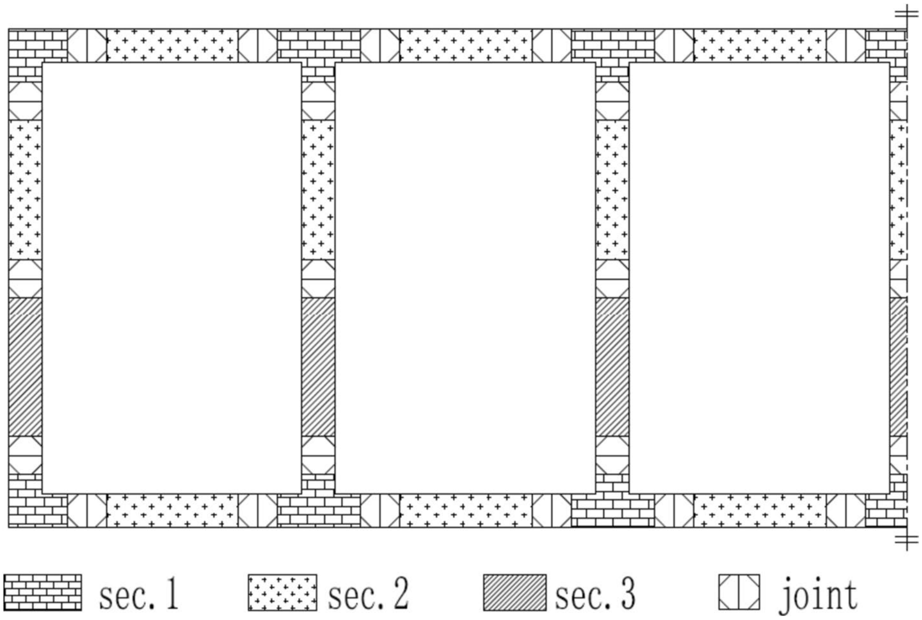


Fig. 15 Schematic diagram of the division of the groove section of the frame foundation

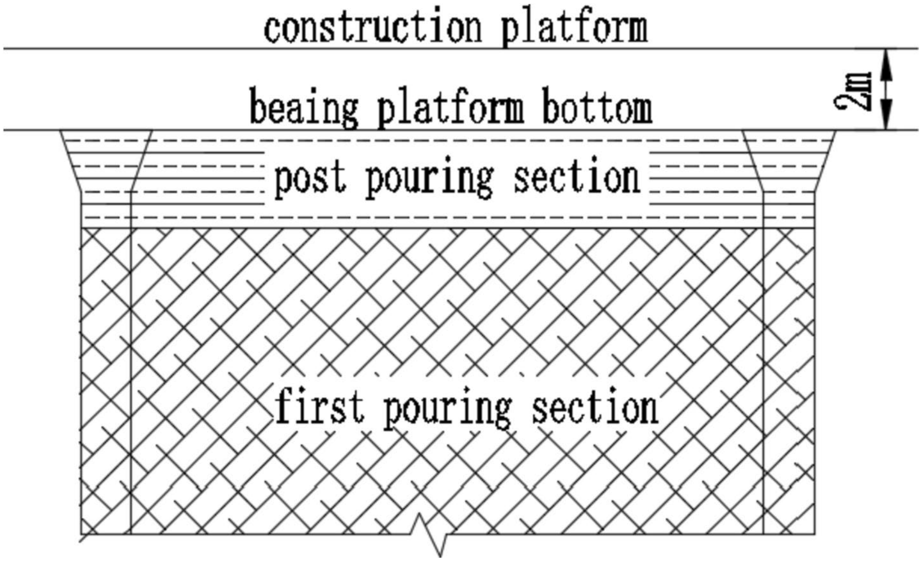


Fig. 16 Location map of frame foundation construction platform

surrounding soil. And grouting reinforcement is carried out on the soil in the relevant range to further ensure the safety of the structure. The specific method is as follows.

4.1 Division of construction segments

The 25 m frame foundation is vertically divided into a 22.6 m first pouring section at the bottom and a 2.4 m post-cast section at the top for construction (Fig. 16). The wall of the first pouring section is of equal thickness (1.2 m). Divide the groove section (Fig. 15) and use the groove milling machine to excavate, and use the mud protection wall during the excavation process. After the excavation is completed, the reinforcement cage is lifted and the underwater concrete is poured. After the concrete in the grooves on both sides reaches the designed strength, the rigid joints are constructed to form the overall frame (Cheng et al. 2012). After the concrete of the first pouring section at the bottom reaches the design strength, the post-cast section at the top is constructed. In order to protect the soil on the bottom of the cushion cap, the frame foundation construction platform is selected at a position 2 m above the bottom of the cushion cap (Fig. 16). After the construction of the frame foundation is completed, and before the construction of the cushion cap, the soil shall be excavated to the elevation of the bottom of the cushion cap to maximize the protection of the undisturbed soil.

4.2 Joint construction

In order to ensure the overall force of the frame structure, the rigid joints are used between the slots. The joint position is set near the zero point of the bending moment (Japan Association of Diaphragm Wall 1993), and the size is 1.4 m × 1.2 m ((Fig. 17), so as to meet the requirements of the construction operation in the joint. The transverse steel bars in the first pouring groove section on both sides are mechanically connected with the transverse steel bars arranged in the joint to achieve rigid connection.

Specific construction steps are as follows:

Step 1 Put down the steel cage of the previous groove section with the joint steel plate, pour the concrete (Fig. 18 a).
Step 2 Put down the steel cage of the adjacent groove section with the joint steel plate, pour the concrete (Fig. 18 b).
Step 3 After the concrete in the initial slot reaches the designed strength, weld the connecting angle steel and steel plate to form a whole joint box (Fig. 18 c).
Step 4 Mechanically connect horizontal steel bars (Fig. 18 d).
Step 5 Put down the vertical reinforcement and bind it to the horizontal reinforcement, pour the self-compacting and micro-expanding concrete in the joint (Fig. 18 e).

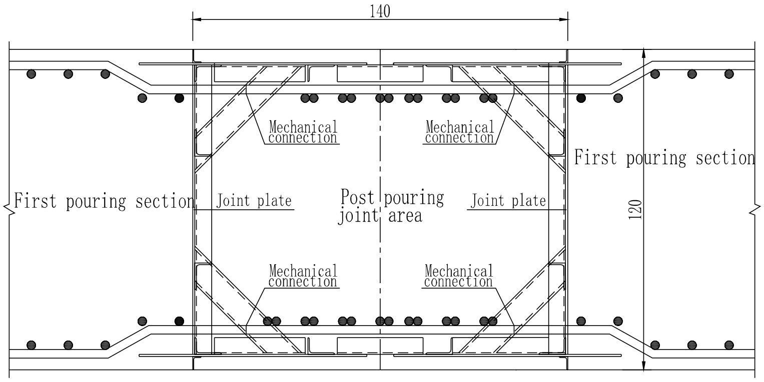
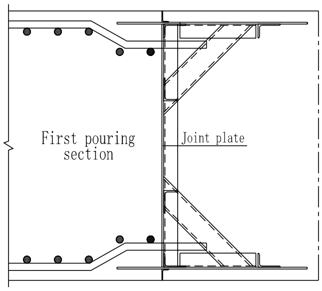
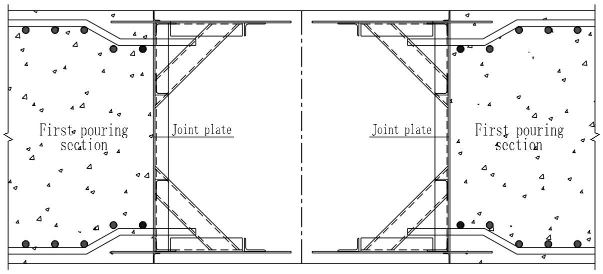


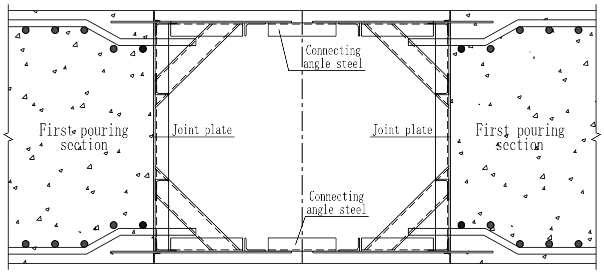
Fig. 17 Ichnography of rigid joint



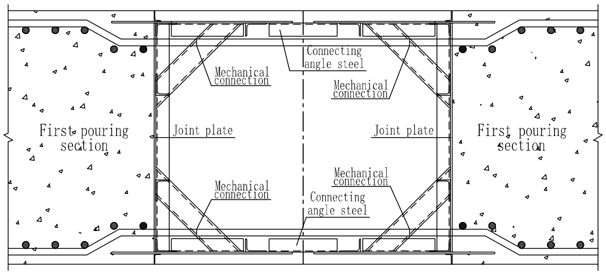
a diagram of step1



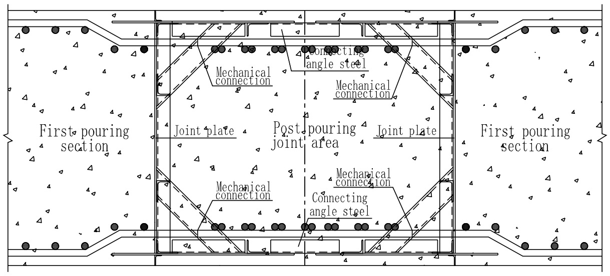
b diagram of step2



c diagram of step3



d diagram of step4



e diagram of step4

Fig. 18 **a** Diagram of step1. **b** Diagram of step2. **c** Diagram of step3. **d** Diagram of step4. **e** Diagram of step4

Post-grouting reinforcement

In the construction process, distributed grouting technology is used to grouting the bottom of the frame, the side wall of the frame, the front soil of the front wall, the internal soil of the frame and the backfill soil in batches to improve the soil performance, reduce the creep of the soil in the later stage, and make the structure safe and durable.

(1) Frame bottom grouting

In order to eliminate the influence of construction adverse factors such as sediment at the bottom of the frame and ensure the vertical bearing capacity of the structure, after the completion of the frame structure construction, the bottom of the frame foundation is grouting by the straight pipe grouting technology. Using the acoustic measuring pipe as grouting pipe, at the bottom of the wall is set up a T shaped grouting device arranged as the measuring pipe, not only to ensure no leakage, but also to ensure that the check valve can be open in 2 ~ 5 MPa pressure after the concrete final set. The grouting pipe is bound to the inner side of the reinforcement cage and put down with the reinforcement cage. The steel pipe joint is welded firmly one by one with a special collar. The top of the grouting pipe is 0.2 m ~ 0.3 m above the ground, and it is forbidden for mud and cement mud to enter the grouting pipe.

(2) Frame side wall distributed grouting

In order to strengthen the connection between the underground frame foundation and the soil, eliminate the weak layer produced in the construction process, the post-grouting technology is used on the side wall of the frame structure to improve the compressive and shear strength between the wall and the soil. The grouting pipe is tied on the reinforcement cage and the grouting pump is used to realize the reinforcement of the foundation.

The grouting outlet is preset at a vertical interval of 2 m, and the grouting pipe is fixed on the reinforcement cage before the wall is formed. In the process of grouting, the grouting core tube is lowered to the designated grouting outlet by lifting the positioning device. First, the high-pressure rubber in the stop grouting plug is expanded to form a sealed space between the grouting tube through the water pressure. And then, the grouting core tube is pressed to achieve the layered grouting. After the grouting of the same section is finished, the grouting core tube is moved to the next preset position of the grouting outlet by lifting the positioning device until the grouting of the whole wall is completed. The distributed post-grouting device can make the grouting liquid completely cover the outer surface of the frame foundation, and realize effective bonding and load transfer between the frame and soil.

(3) Foundation soil grouting

The horizontal resistance of soil plays an important role in the stress process of anchorage foundation, it should be fully used to improve the bearing performance of anchorage foundation. To achieve this purpose, the sleeve valve tube grouting method was used to strengthen the foundation soil (grouting depth of 25 m) of the front and rear walls and the enclosing area of the frame foundation (grouting depth of 5 m).

The vertical and horizontal spacing of grouting holes in front toe foundation soil is 4 m (Fig. 19), and the average depth of grouting holes is 25 m. The reinforcement area of foundation soil for the front limb of the front wall is preliminarily set at 16 m, for the back limb 21 m. The longitudinal and transverse spacing of the grouting holes in the enclosing area of the frame structure is 3.0 m (Fig. 16), and the average hole depth of the grouting holes is 5 m.

(4) Backfill soil grouting

The backfill soil in front and left side of anchorage (lower side) is reinforced by grouting to further enhance the horizontal carrying capacity of anchorage. The spacing of grouting pipes is 3 m. The grouting depth is 1 m below the bottom surface of the cap, that is 1 m vertical overlap with the foundation soil grouting (Fig. 20).

After grouting, the reinforced soil at each site should be sampled to test the grouting effect and ensure the safety of the structure.

5 Conclusion

Sichuan Kahalo Jinsha River Bridge adopts frame structure as the anchorage foundation. Compared with the traditional enlarged foundation, it has lower requirements on the bearing capacity of the foundation, less excavation, and lower risk, which is beneficial to ecological environment protection and has good economy. Frame structure is used to mobilize the soil in the enclosed area, forming a "frame-soil" structure to resist vertical and horizontal forces together. Calculations show: the structure is safe and reliable, and the force is reasonable. The groove milling machine is used to excavate the slot sections, and the construction platform is set 2 m above the bottom of the bearing platform, which reduces the

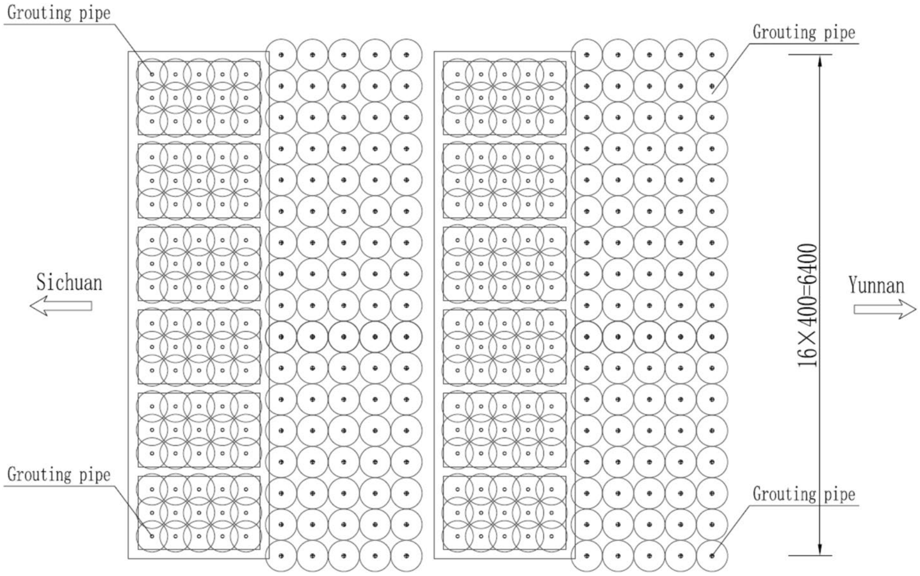


Fig. 19 Plan of foundation grouting (unit: cm)

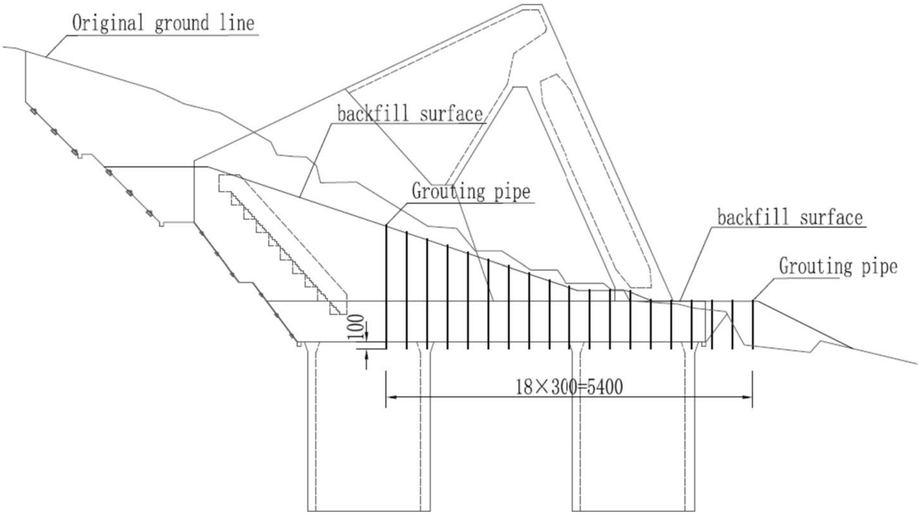


Fig. 20 Elevation view of backfill grouting (unit: cm)

disturbance to the undisturbed soil during the construction process. At the same time, the distributed grouting technology is used to reinforce the soil around the frame (including backfill), which further ensures the safety of the structure.

This is the first time that frame structure has been used as the gravity anchorage foundation. It has solved the difficult problem of anchorage design under poor terrain and geological conditions, and will provide a good reference for the design of mountainous suspension bridges in similar condition.

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Authors' contributions
Qiyu Tao planned overall research design and reviewed the manuscript. Qigang XU collected and analyzed data, and prepared the manuscript. Li Chen carried out structural force analysis and provided the analysis data. Rui Gu reviewed structural calculations and related data. All authors read and approved the final manuscript.

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Declarations

Competing interests
All authors declare that there are no competing interests.

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References

Cheng Q-G, Wen H, Song Z (2009) State of art in research on rectangular closed diaphragm wall as bridge foundation. Architect Technol 40(3):198–203

Cheng QG, Wu J-J, Song Z et al (2012) The behaviour of a rectangular closed diaphragm wall when used as a bridge foundation [J]. Front Struct Civ Eng 4:398–420

Cui L-C, Luo L-G, Yi S-P et al (2018) Bearing performance of split shaft diaphragm wall anchor foundation of bridge. Highway 6:78–84

Dzceer R, Gkalp A, Adatepe E (2018). Design, construction and performance of single bore multiple anchored diaphragm wall in Turkey. ce/papers 2(2–3):433–438.

Han SL, Chen GX (2016) Construction technology of diaphragm wall under special geological anchorage. Construct Technol 45(01):42–45

Hu YSH, Zhao YM, Du HC (2006) Construction Techniques for Diaphragm Wall of Anchorage Foundation of Huangpu Bridge over Zhujiang River. Bridge Construct 05:59–61+67

Industry Standard Editorial Committee of the People's Republic of China (2015) Design specification for highway suspension bridge (JTG/ T D65–05–2015) [S]. China Communication Press, Beijing

Industry Standard Editorial Committee of the People's Republic of China (2019) Specifications for Design of Foundation of Highway Bridges and Culverts (JTG 3363–2019) [S]. China Communication Press, Beijing

Japan Association of Diaphragm Wall (1993) Underground continuous wall foundation engineering (Design method) [M]. The Japan Research Public Works Research Institute, Tokyo

Lai Y-J, Wu C-J, Zhang Z-X (2010) Test and numerical analysis of effect of notched sill of gravity anchorage on soft rock ground of suspension bridge. Chin J Rock Mech Eng 29(3):593–602

Li JP, Li YS, Wang R-L et al (2007) Research on displacement of anchorage of suspension bridge. Rock Soil Mech 28(1):145–150

Li W, Yang H, Yin X-T et al (2021) Study on limit bearing feature of gravity anchorage based on model test. J Highway Transport Res Dev 38(6):97–103

Liu XR, Han YF, Jing R et al (2019) Bearing characteristics, deformation failure characteristics and typical case studies of tunnel-type anchorage. Chin J Underground Space Eng 15(6):1781–1791

Liu Y, Feng J, Li X-G et al (2022) Bearing mechanism of new type combined gravity anchor of suspension bridge. Chin J Underground Space Eng 18(1):187–193

Luo Y, Jiang W, Yi L et al (2023a) Foundation selection for south-bank gravity anchorage of Yidu Changjiang river bridge. Bridge Construction 53(S1):127–133

Luo W-B, Liang N-H, Liu X-R et al (2023b) Application and research status of tunnel type anchorage based on literature statistics. Chin J Underground Space Eng 19(1):207–219

Qin S-G, Luo F-Y, Ou-yang P (2018) Study on mechanical performance of ground anchor structure of wellbore underground diaphragm wall. Western Commun Sci Technol 02:92–96

Satoshi KY et al (1992) Design and construction of ultra thick underground wall for an anchorage of Akashi-Kaikyo bridge. Doboku Gakkai Ronbunshu 1992(444):87–96

Seitz J, Penguy B, Gang W (2019) Diaphragm wall and piles set record in africa: foundation for Africa's largest suspension bridge in Mozambique. Afr J Sci Technol Innov Dev 11(4):449–455

Wang D-Y, Tang H, Ge X et al (2019) Study on the bearing characteristic and failure pattern of tunnel-type anchorage. Chin J Rock Mech Eng 38(2):3374–3383

Wen H, Cheng Q-G, Meng F-C et al (2009) Diaphragm wall-soil-cap interaction in rectangular-closed diaphragm wall bridge foundations. Front Architect Civil Eng China 3:93–100

Wu J-J, Cheng Q-G, Wen H et al (2015) Model study of the vertical bearing behaviours of lattice shaped diaphragm walls as bridge foundations in soft soil. Chin J Rock Mech Eng 34(12):2580–2592

Ya G, Wang XD, Xian R et al (2017) Numerical simulation of the bearing mechanism of underground diaphragm wall-anchor combined foundation. Highway 1:106–111

Yang FJ, Niu XL (2010) Construction of underground diaphragm wall for south anchorage foundation of the 4th Nanjing Changjiang River Bridge. Bridge Construct 06:7–79+83

Yang G-J, Tian Q-W, Lyu M-H et al (2022) Review of mechanic characteristics of tunnel-type anchorage of long-span suspension bridge. J Jilin Univ (Engineering and Technology Edition) 52(6):1245–1263

Zhang Y-H, Wu A-Q, Zhou H-M et al (2019) Review of bearing capacity and deformation characteristics of tunnel type anchorage for suspension bridge. Rock Soil Mech 9:3573–3584

Zhao X-Q, Zhan W, Yan X et al (2021) Research status and future development prospect of suspension bridge anchorage. Chin J Geotech Eng 43(2):150–153

Zhou J, Zhou E-J, Li Y-B et al (2014) Scheme comparison and selection for anchor foundation of Maputo bridge in Mozambique. World Bridges 42(06):7–11

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