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Research on mechanical characteristics of pile column pier in bedding rock slope based on MIDAS GTS

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Abstract: *bedding rock slope is the most common slope type in highway and bridge construction in mountainous areas in Southwest China. Taking the bedding rock slope section of zhangyoufang bridge as the research object, this paper uses Mida GTS finite element software to establish a three-dimensional geological model, and discusses the influence of pier characteristics on pier stress and deformation. The calculation shows that the increase of rock socketed depth, pile diameter and pier stiffness within a certain range can effectively improve the vertical bearing capacity of pile foundation and reduce the displacement of pier top. Hollow thin-walled pier has the highest safety factor. Compared with single pier and double column pier, the stress of pile column double row pier is more reasonable and reliable. Finally, the results of orthogonal test calculation show that the pier structure and pile diameter are the biggest influencing factors of horizontal displacement and vertical displacement respectively.*

Keywords: *bedding rock slope, pile pier, Midas GTS, orthogonal test*

1. Introduction

With the rapid development of basic traffic engineering in China, a large number of bridges in mountainous areas have been constructed. Bedding rock slope is the most common type of slope in bridge construction and has the most instability and failure. For the research of pile column pier on bedding rock slope, many scholars in China have made many achievements in the aspects of pier anti slide, pier anti landslide impact and slope pier structure stress. Zhongcaiping [1]

The landslide deformation mechanism and stability of a bridge pier are studied and analyzed. Yang Yan [2] and others analyzed and put forward the design concept and scheme of anti-slide pier by investigating the landslide in liujiapo village. Zhang Jinbao [3] analyzed the slope under the condition of large area of loose overburden surcharge on the slope and proposed treatment measures according to the field actual detection data. Yangwenqi [4] analyzed the influence of rock slope on pier pile foundation. Ji Tongxu and lichanglong [5] conducted numerical simulation analysis on the pier of a super large highway bridge with high and steep slope, and proposed that the main factor causing the deformation and failure of the pier was the sliding thrust of the slope on the pier.

At present, researchers' research on the application of piers in slope treatment mainly focuses on the interaction between slopes and piers, but there is less research on the resistance of piers to slope sliding thrust, which fails to reflect the reasonable structural form and mechanical properties of anti-sliding piers. Therefore, this paper takes the bedding rock slope section of zhangyoufang bridge as the research object, uses midasgts software to establish a model and carry out calculation and analysis, and compares the influence of various pier factors on horizontal displacement and vertical displacement. Finally, the influence degree of each factor was calculated by orthogonal test.

2. Project overview

The site of zhangyoufang bridge is located in section A1 of Mabian Zhaojue section of Le Xi Expressway in Mabian County, on the right bank of Mabian River and across Yangjiagou. It is located at the junction of Sichuan Basin, Eastern Hengduan Mountains and Yunnan Guizhou Plateau, with large elevation difference. The elevation of the bridge site is between 574.20 and 634.04, and the lowest **poi**nt is located in the Yangjiagou Valley in the middle of the bridge site, which belongs to the hilly landform of erosive structure, and the geological process is mainly weathering and erosion. The strata are mainly Quaternary and Jurassic.Shown in table 1. From top to bottom, the strata are: Quaternary eluvial and

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Deluvial deposits, quaternary colluvial and Deluvial deposits, and the upper member of the Middle Jurassic Shaximiao formation. There is no obvious structural trace in the bridge site. The upper overburden is mainly silty clay, with a thickness of about 0 ~ 1m and discontinuous distribution. The underlying bedrock is interbedded with strongly weathered sandstone and mudstone, which are continuously distributed. Shown in table 2. There is no groundwater outcrop in the bridge site, and the hydrogeological conditions are good.

Table 1: Formation lithology of bridge site

Quaternary eluvial diluvium	Brown yellow. Gravel mixed with silty clay. The gravel block is 2 to 20cm in diameter. It is angular sub angular.
Quaternary colluvial deposit	Purplish red, block stone with silty clay. The stones are 20 to 150cm in diameter. Angular sub angular shape
Upper member of Middle Jurassic Shaximiao Formation	1. Grayish white, strongly weathered sandstone, layered structure. 2. Purplish red, strongly weathered mudstone, layered structure. 3. Grayish white, moderately weathered sandstone, layered structure. 4. Purplish red, moderately weathered mudstone, layered structure.

Table 2: Main physical and mechanical indexes of each soil layer

Geotechnical name	Silty clay	Pebble	Block earth rock	mudstone	sandstone	mudstone	sandstone
state	plastic	loose	loose	Intensely weathered	Intensely weathered	Moderately weathered	Moderately weathered
Cohesion	39.5	/	/	/	/	/	/
internal friction angle	18.4	/	/	/	/	/	/
Uniaxial saturated compressive strength	/	/	/	/	/	12.1	49.3
Basic allowable bearing capacity of foundation	180	280	280	300	400	600	1000
Standard value of pile side soil friction	40	55	55	60	75	/	/
Bond strength	65	190	190	220	550	270	800
Vertical subgrade coefficient	8	30	30	165	300	220	500
Natural strength	2.03	/	/	/	/	/	/

3. Model establishment

The bedding rock slope of zhangyoufang bridge is taken as the research object. In the 3D geological model of the bedding rock slope of zhangyoufang bridge, the isotropic elastic model is mainly used to simulate the bridge pier column, and the modified Moore Coulomb model is used for the rock and soil around the pile.

The stability analysis of piers with different cross-sections is mainly carried out by using the bridge buckling stability analysis, and the pier stability and critical load are calculated.

Based on the geological exploration data of the slope section of zhangyoufang bridge, CAD drawings

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were drawn, and the model was established by CAD and imported into Midas GTS.

The model is shown in Figure 1:

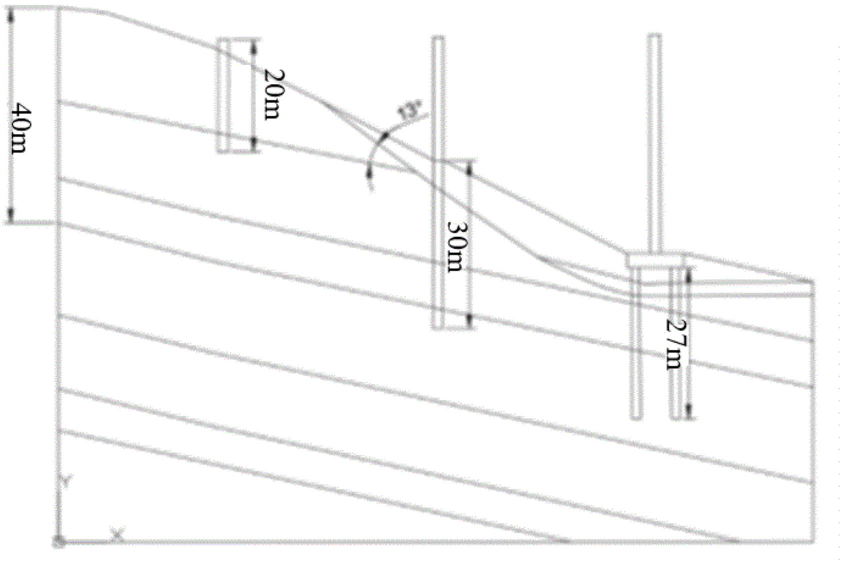

Figure 1: Calculation model of zhangyoufang Bridge

According to the left bedding rock slope and the pier 0, 1 and 2 affected by it, the overall model of the slope and bridge is established. In order to make the pile column pier in the bedding rock slope more in line with the actual stress situation, the bedding rock slope is built into a layered slope. The bridge structure and the stratum structure adopt solid elements, which are isotropic materials, but with different parameters.

4. Factors affecting pier characteristics

According to the actual situation of zhangyoufang bridge, the influence of rock socketed depth, pier shaft stiffness, pile diameter and pier form on pier characteristics is mainly considered. According to the slope stability calculation, the potential sliding surface is located 12m from the top of 0 pier, so the rock socketed depth is 15m, 20m, 25m and 30m; Pier shaft stiffness selection and $\frac{1}{2}EI, EI, 2EI, 4EI$

Single pier, double column pier and pile column double row pier are selected for comparative analysis; Hollow thin-wall pier, rectangular pier with equal section and circular pier with equal section are adopted for Pier 2, and double column circular pier is adopted for Pier 0 and Pier 1; The pile diameters of foundation piles are 1m, 1.5m, 1.8m and 2m. By changing the characteristic factors of each pier, the influence on the deformation and internal force of the pier of bedding rock slope is analyzed. The specific values of pier characteristic factors are shown in table 3 below;

Table 3: Values of pier characteristic factors

influence factor	Value 1	Value 2	Value 3	Value 4
Embedding depth	15m	20m	25m	30m
Pier shaft stiffness	$1/2EI$	$E\ I$	$2\ E$	$4\ E$
Section form	Hollow thin wall single pier	Rectangular pier with constant section	Circular pier with constant section	/
structural style	Single pier	Double column pier	Pile column double row pier	/
Diameter of foundation pile	1m	1.5m	1.8m	2m

5. Analysis on the influence of pier characteristics on pier stress of bedding rock slope

5.1 Rock socketed depth

Midas GTS is used to establish the pier model of bedding rock slope under the action of the last level of combined load. With pier 0#, the rock socketed depth is 15m, 20m, 25m and 30m respectively. The pile diameter of the foundation pile is 2m, the stiffness of the pier shaft is EI, and the double column pier.

According to the model analysis and calculation, the stability results of bedding rock slope under each working condition under the last level of combined load are as follows.

Shown in table 4.

Table 4: Stability coefficient results of bedding rock slope under various working conditions

working condition	Initial slope	Socketed depth			
		15m	20m	25m	30m
Slope stability coefficient	1.38	1.52	1.65	1.85	1.8504

It can be seen from the table that the appropriate embedded depth of pier pile foundation can effectively ensure the stability of the slope. When the engineering properties of rock and soil around the pile are poor, the embedded depth of pier pile foundation can be appropriately increased. The embedded depth must reach the stable bearing layer below the potential sliding surface of slope deformation and failure.

The rock socketed depth not only affects the exertion of the lateral resistance of the rock socketed section, but also directly affects the bearing capacity of the pier foundation pile. It has a great influence on the load sharing of pile tip.

The following Figure 2 shows the distribution of vertical bearing capacity composition with rock socketed depth.

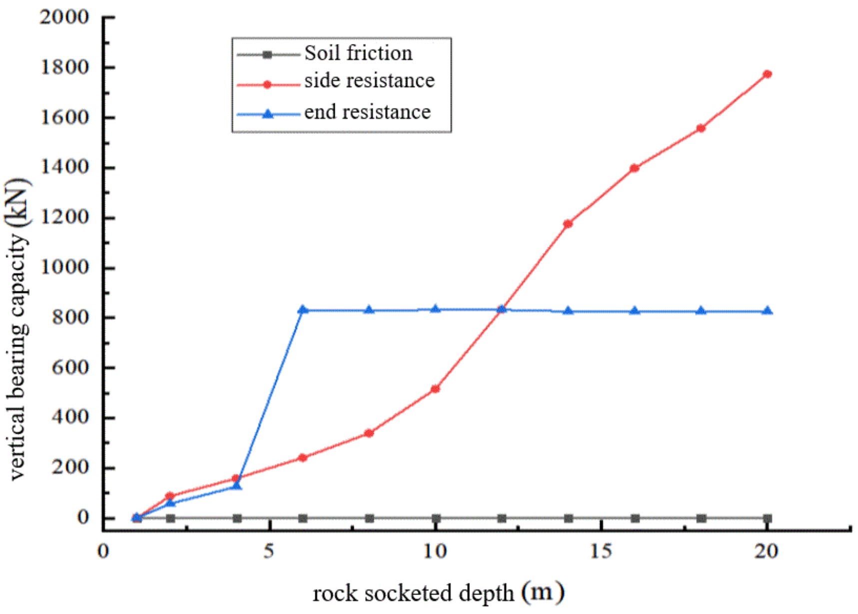

Figure 2: Distribution of vertical bearing capacity composition with rock socketed depth

It can be seen from Figure 2 that with the increase of rock socketed depth, the end resistance and side resistance increase rapidly, but the end resistance will not change when it increases to a certain extent, and the side resistance will always increase. When the depth reaches 12.5 m, the lateral resistance exceeds the end resistance, and still increases with the increase of rock socketed depth, indicating that the main influence of rock socketed depth is the lateral resistance.

The following Figure 3 shows the influence of the change of rock socketed depth calculated by the model on the horizontal displacement of the pier.

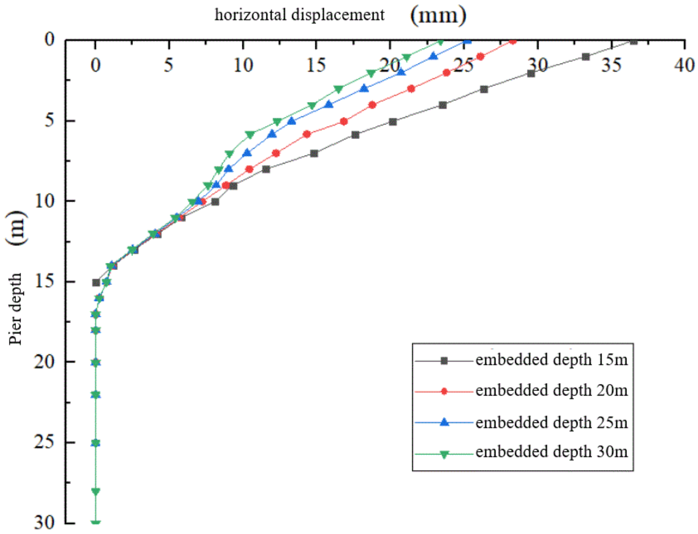

Figure 3: Influence of rock socketed depth change on horizontal displacement of pier

According to Figure 3, the change of embedded depth has a certain impact on the lateral deformation and stress of pier. At 25m rock socketed depth, the horizontal displacement of pier top is 25.517mm. After 30m rock socketed depth, the horizontal displacement of pier top is 23.752mm. Therefore, it can be seen that the pier top will have a large horizontal displacement when the rock socketed depth is small, and increasing the rock socketed depth appropriately can improve the horizontal bearing capacity, but when the lower part of the rock socketed depth reaches a certain length, it can no longer significantly improve the bearing capacity of the pier pile foundation.

5.2 Pier shaft stiffness

Midas GTS is used to establish the pier model of bedding rock slope under the action of the last level of combined load. The 0 #pier is a double column pier with a pier length of 20m, a pile diameter of 2m, and a pier shaft stiffness of $\frac{1}{2}EI, EI, 2EI, 4EI$. The influence of pier shaft stiffness change on pier horizontal displacement calculated by the model is shown in the following figure 4.

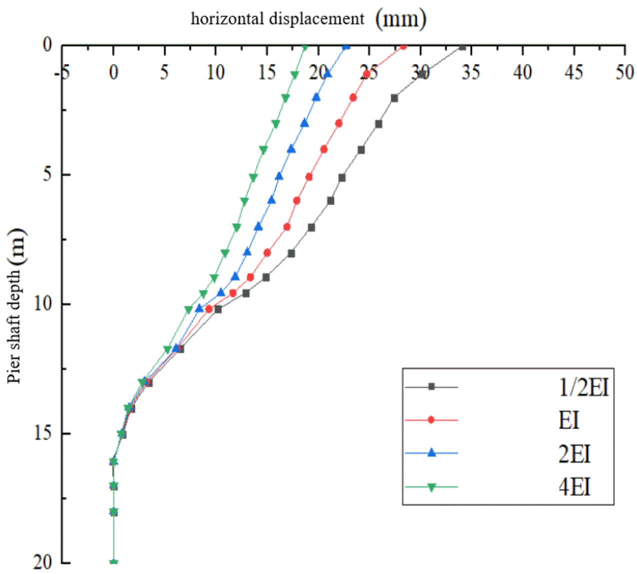

Figure 4: Effect of pier shaft stiffness on pier horizontal displacement

According to the above figure, the change of pier shaft stiffness has a certain impact on the horizontal displacement of pier. When the stiffness of the pier shaft is$\frac{1}{2}EI$, the horizontal displacement of the pier top is the largest. With the increase of pier shaft stiffness, the horizontal displacement of pier top

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decreases. With the increase of pier shaft depth, the horizontal displacement decreases slowly and linearly. When it reaches about 15m, the horizontal displacement is 0.

The results show that properly increasing the stiffness of pier shaft can reduce the horizontal displacement and improve the structural stability.

5.3 Pile diameter

Midasgts is used to establish the pier model of bedding rock slope under combined load. The pier is 20m long, the pier shaft stiffness is EI, 0 # pier is a double column pier, and the pile diameters of foundation piles are 1.0m, 1.5m, 1.8m and 2m. The influence of the change of pile diameter of foundation piles on the horizontal displacement of piers is obtained through model calculation. Shown in the Figure 5 and Figure 6.

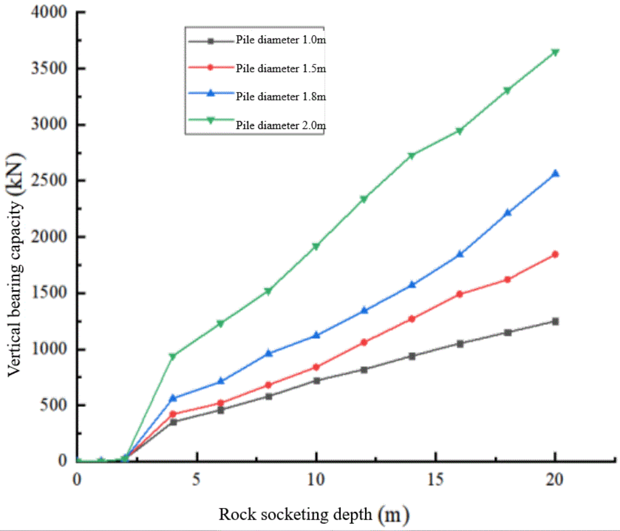

Figure 5: Distribution of vertical bearing capacity of different pile diameters

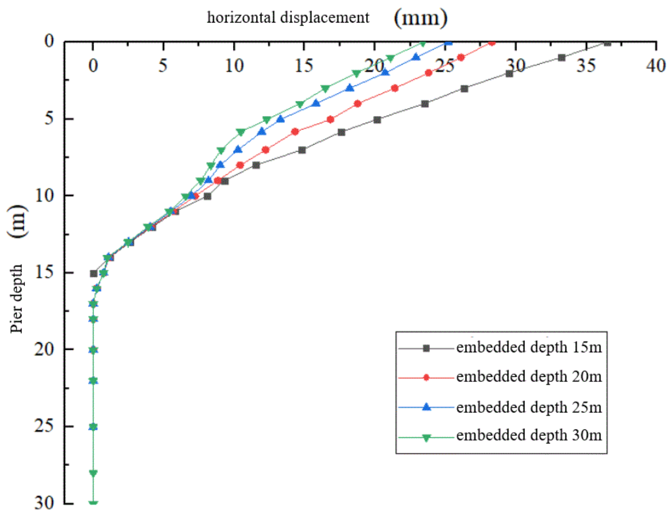

Figure 6: Distribution of side resistance and end resistance of different pile diameters

According to Figure 5 and Figure 6, the pile diameter has a great impact on the vertical bearing capacity of the pier. The change of pile diameter directly changes the vertical bearing area of the pier pile foundation. With the same rock socketed depth, the vertical bearing capacity increases rapidly with the increase of pile diameter.

The horizontal and vertical displacement results of each pile diameter of Pier 0 are shown in the following figure. Shown in Figure 7 and Figure 8.

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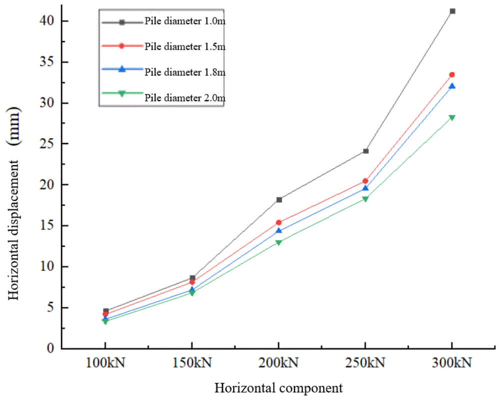

Figure 7: Horizontal displacement of each pile diameter of pier 0

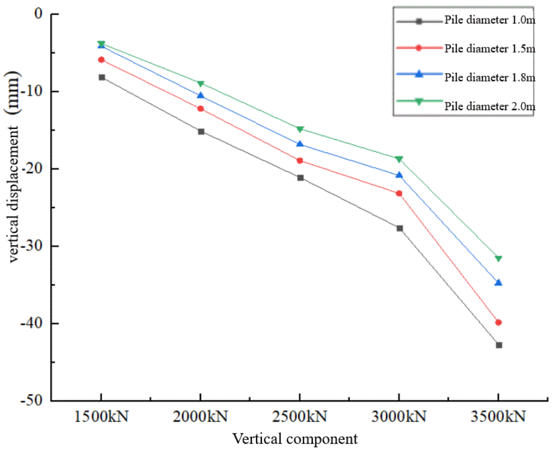

Figure 8: Vertical displacement of each pile diameter of pier 0

The results of analyzing the horizontal displacement and vertical displacement of each pile diameter of 0 #; pier show that: (1) with the increase of pile diameter, the horizontal displacement and vertical displacement of the pier top are significantly reduced. From the displacement change curve, it can be seen that the horizontal bearing capacity and vertical bearing capacity of the foundation pile have been significantly improved. (2) With the increase of pile diameter, the displacement increases first and then decreases. When the pile diameter increases to a certain value, the bearing capacity of pile foundation tends to slow down.

5.4 Pier form

5.4.1 Stability analysis of piers with different section forms

In order to verify the influence of the section form on the stability of the pier, the buckling stability of the pier is analyzed. In the simulation scheme, hollow thin-walled pier, equal section double column circular pier and equal section double column rectangular pier are adopted for Pier 2 #, 4 # respectively. Model 1 is equal section circular pier model, model 2 is equal section rectangular pier model, and model 3 is hollow thin wall pier.

The following table shows the stability analysis results under the combined force of piers. Shown in table 5.

Under the combined load, the 2# pier of the three cross-section forms is the third-order mode instability, and the hollow thin-walled pier has the largest stability safety factor, followed by the rectangular pier with equal cross-section, and the circular pier with equal cross-section is the smallest. The stability safety factor of hollow thin-walled pier top is the largest, followed by constant cross-section rectangular pier, and constant cross-section circular pier is the smallest.

Table 5: Eigenvalue stability analysis results under combined action

Pier No	Section form	Instability mode	Stability safety factor
2	Double column round pier	Third order mode	306
	Double column rectangular pier	Third order mode	308
	Hollow thin wall pier	Third order mode	343
4	Double column round pier	Fifth order mode	354
	Double column rectangular pier	Fifth order mode	360
	Hollow thin wall pier	Fifth order mode	383

The results show that the hollow thin-walled pier with equal cross-section has higher stability safety factor than the rectangular pier with equal cross-section or the circular pier with equal cross-section under combined load. Capable of withstanding high critical loads.

5.4.2 Stress analysis of piers with different structural forms

Midas GTS is used to establish the pier model of bedding rock slope under combined loads at all levels. The pier is 20m long, the stiffness of the pier body is EI, and the pile diameter of the foundation pile is 2m. 0 #pier adopts single pier, double column pier and pile column double row pier respectively. Through model calculation, the influence of different structural forms on the horizontal displacement of the pier is shown in the following Figure 9 and Figure 10:

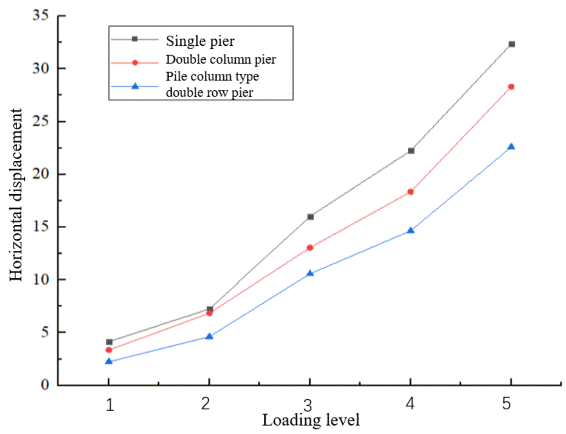

Figure 9: Horizontal displacement of various structural forms of pier 0

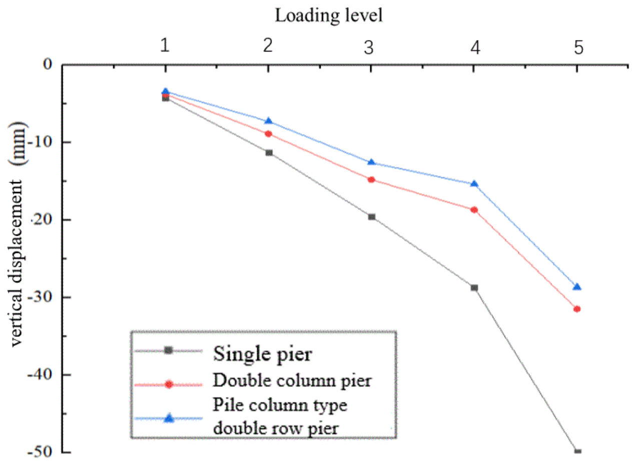

Figure 10: Vertical displacement of each structural form of 0 pier

According to the figure, under the last level of combined load, the horizontal displacement and

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vertical displacement of double row pile structure of pile column pier are smaller than those of single pier and double column pier top. The reason is that the pile column pier can work together through the cross beam to reasonably distribute the internal force and bending moment of the front and rear rows of piles, and the cross beam at the top of the pile also has a certain constraint on the displacement at the top of the pile. This kind of structure requires lower strength of pile body material.

6. Orthogonal test analysis

In order to fully reflect the influence of the characteristics of each pier on the stress and deformation of the pile foundation of the pile column pier, the orthogonal test method is used for calculation and analysis.

Range analysis was used to analyze the influence degree of each influencing factor. The parameter for evaluating the significance of factors is the range R. by calculating the average of the test values of each factor at different levels, and then calculating the range of the average, the large range of each factor has a great impact on the test results, which can be determined as the main influencing factor.

The calculation formula is:$R_j = Max\{K_{1j}K_{2j}K_{3j}K_{ij}\} - Min\{K_{1j}K_{2j}K_{3j}K_{ij}\}$

$$K_{ij} = \sum_{i=1}^{n} Y_{jk}$$

Where K_{ij} is the statistical parameter of the factor j at the level i; n is the test parameter of the factor j at the level i; Y_{jk} is the k-th test result of the factor j at the level i.

The parameter values and factors are listed in the table 6 below:

Table 6: Values of influencing factors on pier characteristics

factor	Pier shaft stiffness	Diameter of foundation pile	structural style	Socketed depth
Level 1	1/2EI	1	Single pier	15
Level 2	EI	1.5	Double column pier	20
Level 3	2ei	1.8	Double row pier	25
Level 4	4ei	2	Double column pier	30

The four factors are analyzed by orthogonal test, and the four factors are installed horizontally with L16 (4^5) for orthogonal test. Therefore, the L16 (4^5) orthogonal test table is selected to study the influence of four factors on the stress and deformation of pile pier foundation pile.

The table 7 below is the orthogonal test table of pier characteristics:

Table 7: Orthogonal test table of pier characteristics

factor	Pier shaft stiffness	Diameter of foundation pile	structural style	Socketed depth
Test 1	1/2EI	1.5	Double row pier	20
Test 2	EI	2	Single pier	20
Test 3	2ei	2	Double row pier	25
Test 4	4ei	1.5	Single pier	25
Test 5	1/2EI	1.8	Single pier	30
Test 6	EI	1	Double pier	30
Test 7	2ei	1	Single pier	15
Test 8	4ei	1.8	Double pier	15
Test 9	1/2EI	2	Double column pier	25
Test 10	EI	1.5	Double column pier	25
Test 11	2ei	2	Double column pier	20
Test 12	4ei	1.5	Double column pier	20
Test 13	1/2EI	1.5	Double column pier	15
Test 14	EI	2	Double column pier	15
Test 15	2ei	1.5	Double column pier	30
Test 16	4ei	2	Double Column Pier 2	30

The 16 test schemes in L16 (4^5) orthogonal test table were analyzed and calculated by midagts software. The last level of combined load was applied during the test to obtain the horizontal and vertical

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displacement of pier top. The calculation results are as follows.Shown in table8.

Table 8: Calculation results of orthogonal test

factor	Pier shaft stiffness	Diameter of foundation pile	structural style	Socketed depth	Horizontal displacement (mm)	vertical displacement (mm)
Test 1	1/2EI	1.5	Double row pier	20	23.35	-35.34
Test 2	EI	2	Single pier	20	31.22	-32.85
Test 3	2ei	2	Double row pier	25	22.43	-31.99
Test 4	4ei	1.5	Single pier	25	32.25	-34.22
Test 5	1/2EI	1.8	Single pier	30	31.67	-32.25
Test 6	EI	1	Double row pier	30	23.78	-35.22
Test 7	2ei	1	Single pier	15	33.64	-38.44
Test 8	4ei	1.8	Double row pier	15	22.88	-35.44
Test 9	1/2EI	1	Double Column Pier 2	25	28.34	-36.37
Test 10	EI	1.8	Double column pier	25	26.88	-33.07
Test 11	2ei	1.8	Double Column Pier 2	20	26.58	-34.12
Test 12	4ei	1	Double column pier	20	27.78	-37.48
Test 13	1/2EI	2	Double column pier	15	26.43	-34.27
Test 14	EI	1.5	Double Column Pier 2	15	27.54	-36.62
Test 15	2ei	1.5	Double column pier	30	27.33	-33.32
Test 16	4ei	2	Double Column Pier 2	30	26.17	-31.17

The results of orthogonal test are calculated and analyzed, and the calculated displacement data of each column of the same level test group are accumulated to obtain the accumulated valuesK_1, K_2, K_3, K_4, and range R = $K_{max}-K_{min}$ at different levels. The variance and range R of displacement under various influencing factors are obtained, and the specific results are shown in Figure 11 below.

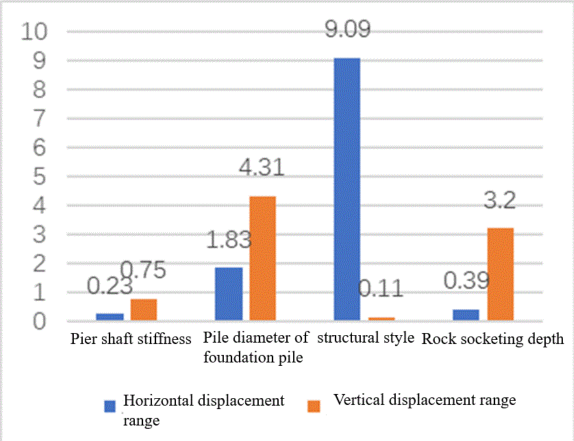

Figure 11: Analysis results of horizontal and vertical displacement of pier top

The size of range R represents the influence of factors on the results. The greater the range, the greater the influence. According to the above figure, the influence order of horizontal displacement is: pier structure > pile diameter > rock socketed depth > pier shaft stiffness. The influence order of vertical displacement: pile diameter > rock socketed depth > pier shaft stiffness > pier structure.

7. Conclusion

The influence of the characteristics of each pier on the stress of the pier under the condition of bedding rock slope is analyzed, and the main conclusions are as follows:

(1) The influence of rock socketed depth on the vertical bearing capacity of pier pile foundation is obvious. The lateral resistance increases faster with the increase of pile depth. The change of pier shaft stiffness has a certain impact on the horizontal displacement of pier, and the horizontal displacement of pier top will develop greatly when the pier shaft stiffness is small. The change of pile diameter can directly affect the pile side stress area and pile end stress area, and also affect the pile side friction.

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(2) Under combined load, the stability safety factor of hollow thin-walled pier is about 10% higher than that of rectangular pier and circular pier. Compared with single pier and double column pier, the double row pile structure of pile column pier can produce smaller displacement and deformation, and has lower requirements for the strength of pile body material.

(3) According to the calculation and analysis of orthogonal test, it is shown that. The influence order of horizontal displacement is: pier structure > pile diameter > rock socketed depth > pier shaft stiffness. The influence order of vertical displacement: pile diameter > rock socketed depth > pier shaft stiffness > pier structure.

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