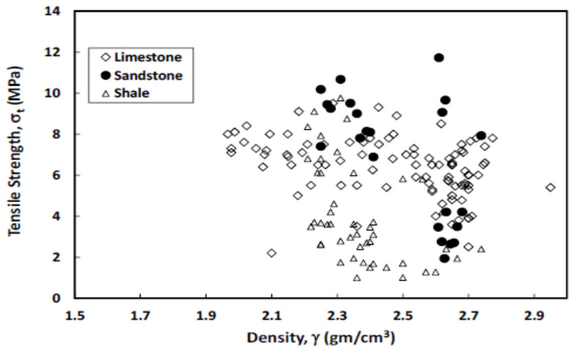

Fig. 4b. Variation of tensile strength with density for sandstone, shale and limestone

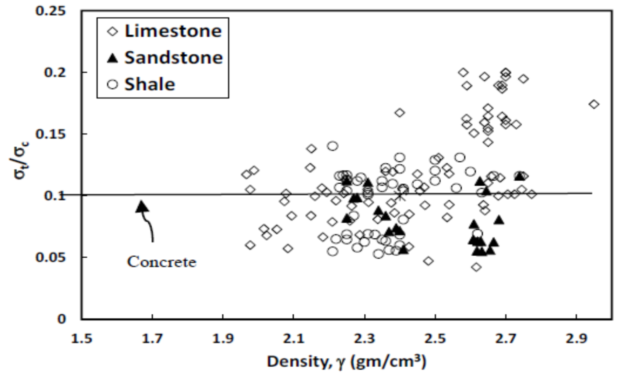

Fig. 4c. Variation of tensile/ compressive strength ratio with density for sandstone, shale and limestone

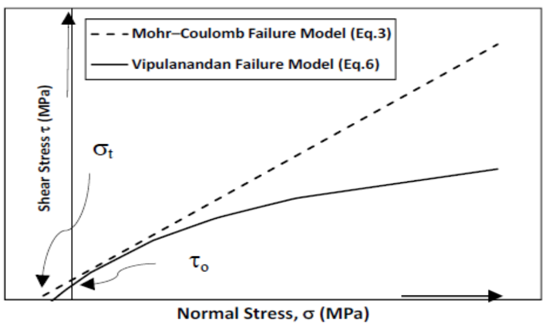

Fig. 5. Vipulanandan failure mode compared to Mohr-Coulomb model

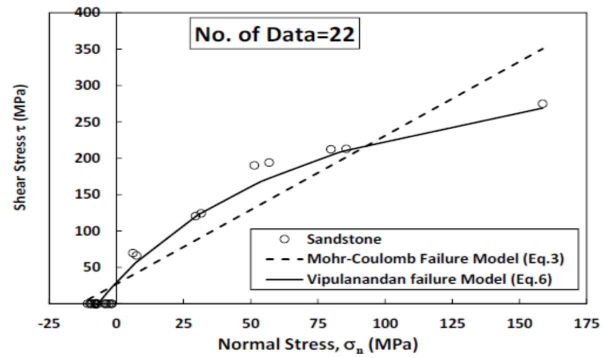

Fig. 6a. Failure shear and normal stress for sandstone

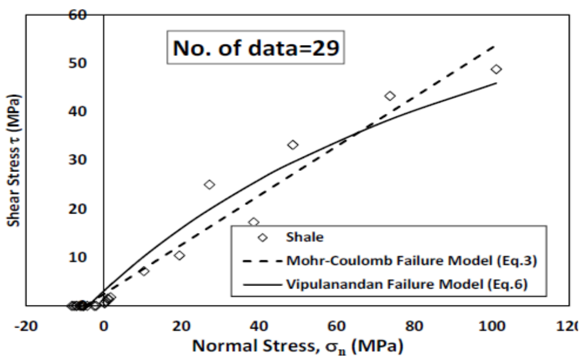

Fig. 6b. Failure shear and normal stress for shale

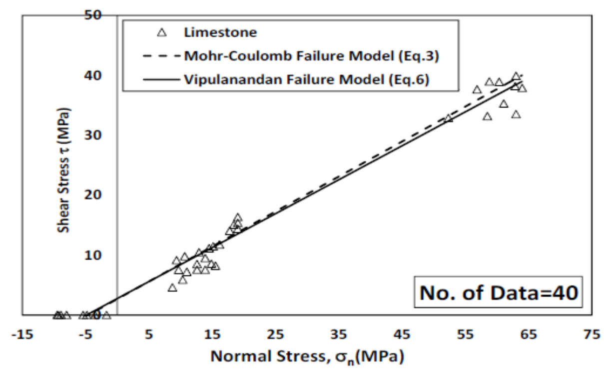

Fig. 6c. Failure shear and normal stress for limestone

The Study on Island Rock-Mass Mechanical Parameters in a Sea-Crossing Bridge

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Abstract

A sea-crossing bridge is able to shorten distance between two areas obviously, which are consequently developing rapidly in China recently. However, available bridge groups for sea-crossing bridges can be scattered in a sea-area island, which is limited by topographic settings. Construction conditions and stability of bridges are determined by the rock-mass strength of islands outcrops. Through laboratory tests of rock mass strength and large-scale field shearing tests, plus detailed analysis of special geological environment features of the islands and engineering analogy method, a method of acquiring rock-mass mechanical parameters was constructed reasonably. The suggestive value for physical and mechanics parameters for basic anchorage rock mass in a bridge case was proposed in this paper.

1 INTRODUCTION

In the field of geotechnical engineering, the value of mechanical strength of rock mass is basic parameters to carry out rock mass engineering. Determination of these parameters is the essential work to evaluate carrying capacity of rock mass and engineering stability, and to calculate rock mass engineering design and select supporting and reinforcing methods of rock mass engineering. How to obtain reliable mechanical parameters of rock mass is an important issue of designers of rock engineering. The most accurate way to obtain mechanical parameters of rock mass is to carry out large scale on-site tests, however, the tests are time consuming, and have considerable costs and many influencing factors. Thus, making acquisition of mechanical parameters of rock mass is a very difficult work.

In marine geological environment, reef rock mass has its unique characteristics, which is vulnerable to corrosion of sea breeze and sea wave, representing as sea cliff formed by gravitational collapse, cracks and faults formed from sea wave, and marine tank made by sea water growing up. In addition, flux and reflux of sea wave makes groundwater level of reef vulnerable and big fluctuation. Reef is isolated and relatively weak with long-term loose unloading, which would lead to weak stress of residual structures.

Based on indoor rock mechanics tests and outdoor in-situ tests, this paper attempts to grade quality of reef rock mass and proposed suggestive intensity parameters of anchorage foundation rock mass by using engineering geological analogy and rock mechanical property indexes of some large scale offshore engineering, according to reef rock mass quality classification system put forward by Hu Xiewen.

2. ENGINEERING GEOLOGICAL CONDITIONS OF THE SITE

The site is located in northeast of the Zhejiang southeast folding belt in the South China, which is in north of active volcanic zone of Yanshan period in the coast of Zhejiang, Fujian and Guangdong.

Trough detailed investigation, reef layers can be observed from top to bottom as follows: sludge, silty clay with break-stones, fully weathered crystal glass crumbs tuff, strong weathered crystal glass crumbs tuff, moderate weathered crystal glass crumbs tuff and weak weathered crystal glass crumbs tuff.

According to the fracture development status of reef rock mass, the whole reef mainly develop two structure planes which are inclined to six horizontal side and Ningbo side. The large fracture which is inclined to six horizontal side will control integrity of the whole reef rock mass and overall stability of anchorage slopes.

When reef exposes crystal glass crumbs tuff, its uniaxial wet compressive strength will be high, belonging to hard/extremely hard rock, and it has a strong anti-weathering ability. From the outdoor survey, it can be seen that weathering is mainly carried out along structure planes like fractures and it is featured with fracture and sandwich weathering. According to changes of rock in color, luster, mineral composition and organization structure, and integrity of rock mass, rust and corrosion degree of joint surface and physical and mechanical properties of rock, we can divide reef rock mass into 4 types: fully weathering, strong weathering, moderate weathering, and weak weathering. In view of specific topographic conditions of reef and due to scouring of sea waves, influence of unloading on relaxation of rock mass is reflected in dropping of blocks because of sea waves and less prominent unloading effects on current reef rock mass .

3. PHYSICAL MECHANICS TESTS OF ROCK/ ROCK MASS

3.1 Indoor rock tests

Exposed rock mass of reef is mainly strong weathered rock with highly weathered and developed joint fissures. It is not easy to take samples from the site. The rock samples are relatively integrated and moderate weathered with weak weathered rock cores. Four sets of moderate weathered reef borehole cores have been taken as samples plus 12 sets of weak weathered sections，and the 16 sets of rock samples have received indoor physical mechanics tests like soil natural density, proportion, water absorption, saturated percent sorption and compression resistance, and strength of extension. The results show in the table 1, from which we can see that reef rock mass generally belongs to hard rock with a high strength, weak softening degree and good shear resistance capability.

Table 1 Physico-mechanical parameters of rock in the reef

Natural drying density (g/cm^3)		2.52～2.64	Specific gravity	2.63～2.69
Water absorption (%)		0.43～1.78	Coefficient of water saturation (%)	0.50～2.04
Saturated compressive strength (MPa)		>60	Softening index	0.72～0.78
Poisson ratio		0.20～0.25	Elastic modulus (GPa)	>30
Ultimate tensile strength (MPa)		>3.0		
Triaxial test	Peak angle of internal friction (°)	50～59	Residual angle of internal friction (°)	44～48
	Peak cohesive stress (MPa)	9.5～19.6	Residual cohesion (MPa)	1.0～2.65

3.2 On-site deformation tests of rock mass

Complete deformation test of rock mass of reef includes two locations, and the test points are mainly arranged in weak weathered rock mass and they are both vertical deformation points (see Figure1-2).

Figure 1 Deformation test point E_0D_1-1

Figure 2 Deformation test point E_0D_1-2

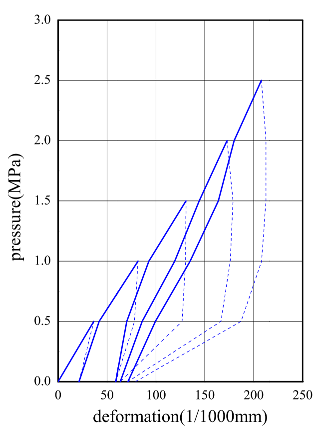

Figure 3 On-site deformation test curve of Lilaitou reef rock mass (E_0-1(V))

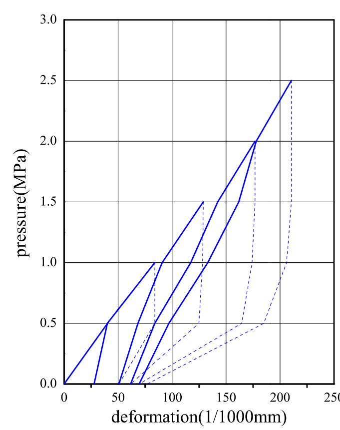

Figure 4 On-site deformation test curve of Lilaitou reef rock mass (E_0-2(V))

Deformation of reef rock mass mainly includes quasi linear type and elastic-plastic type, and although constitutive relation of the structure plane belongs to the elastic-plastic type, other parts below grade 4 load approximate to straight lines except for parts of low load. Therefore, all the following deformation modulus adopted tangential slope of P-W0 envelope lines. The deformation test results of the two points in the reef can be seen in table 2, and the test curve is as shown in Figure 3-4.

From the test results, we can see that mosaic ~ submassive rock mass in the weak weathering area has better deformation resistance and its stress-strain curve is close to the linear type, which indicates that plastic deformation of rock mass fractures is not big and under a pressure below 2.5MPa, it is mainly featured with elastic deformation with the deformation modulus of 3.59～3.68Gpa.

Table 2 On-site rock mass deformation test results of Lilaitou reef

No.	Test number	Test position	Lithology	The E_0 and E values (GPa) of rock mass under pressure P(MPa)						Envelope modulus E_0(GPa)	Secant modulus E_0(GPa)
				P	0.5	1.0	1.5	2.0	2.5		
1	E_0-1(V)	The upper part of the reef	Tuff	E_0	4.10	3.66	3.43	3.46	3.60	3.68	3.60
				E	9.81	13.2	6.67	5.91	5.81		
2	E_0-2(V)	The lower part of the reef	Tuff	E_0	3.72	3.56	3.48	3.38	3.55	3.59	3.55
				E	12.0	9.00	6.67	5.58	5.60		

3.3 On-site rock mass shear test

The test arranged 1 set of shear in the rock mass and the structure plane to grasp shear resistance capability of reef rock mass and controlling structural planes, and meanwhile, concrete/ bedrock shear tests were conducted in rock mass in weak weathering area (see Figure5-12). The results are shown in table 3.

Figure 5 Sample preparations before shearing in the shear test point

Figure 6 Characteristics of shearing surface after shearing in the shear test point

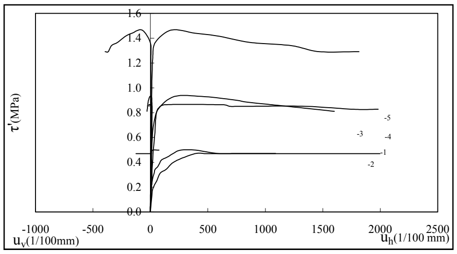

Figure 7 Stress-strain curve of shear test of structure plane (shear resistance cutting/peak strength)

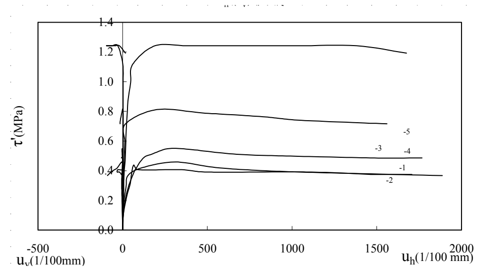

Figure 8 Stress-strain curve of shear test of structure plane (shear resistance/ residual strength)

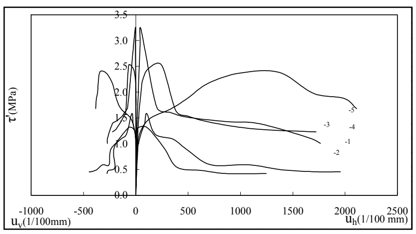

Figure 9 Stress-strain curve of on-site concrete / rock mass shear test (shear resistance cutting/peak strength)

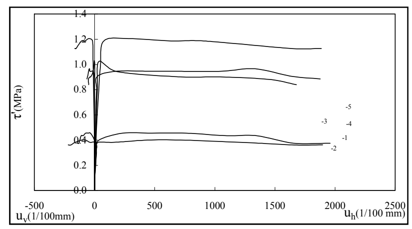

Figure 10 Stress-strain curve of on-site concrete / rock mass shear test (shear resistance/ residual strength)

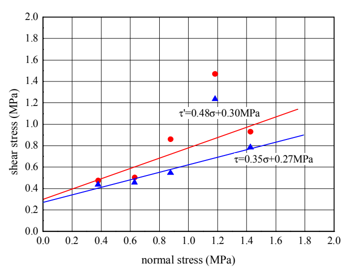

Figure 11 Shear resistance strength curve of shear test of controlling structural plane

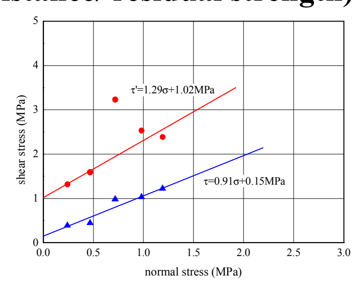

Figure 12 Shear strength curve of On-site concrete/rock mass shear test

Table 3 Shear test results of on-site rock mass and structure surface

Test number	Type	Shear test results (σ、τ)						Shear resistance cutting		Shear resistance	
		Number	1	2	3	4	5	f'	c'(MPa)	f	c(MPa)
τ-1	Tuff	σ	1.55	0.35	1.29	0.99	0.54	1.82	1.41	0.82	1.23
		τ′	4.15	2.35	3.95	2.00	1.98				
		τ	2.33	1.47	2.29	1.45	1.48				
τ-2	Structure plane	σ	0.38	0.63	0.88	1.19	1.43	0.48	0.30	0.35	0.27
		τ′	0.47	0.50	0.86	1.47	0.93				
		τ	0.44	0.46	0.55	1.24	0.79				
τ-3	Concrete /tuff	σ	0.24	0.72	0.47	1.19	0.98	1.29	1.02	0.91	0.15
		τ′	1.31	3.22	1.58	2.38	2.52				
		τ	0.40	0.97	0.45	1.21	1.02				

The remarks of τ-1, τ-2, and τ-3 are as follows: moderate weathering/ submassive structure, controlling structural planes/ strong weathering, moderate weathering.

4. QUALITY GRADING AND MECHANICAL PARAMETERS OF REEF ROCK MASS

4.1 Basis of quality grading of reef rock mass

The project is located in a reef in Zhoushan Islands and its engineering geological conditions are similar to that of Zhoushan Xihoumen Bridge, thus the essay conducted the quality grading according to sea reef rock mass quality classification expression put forward by Hu Xiewen. Thus rock mass quality comprehensive index

$$Z = R_s \times RBI \times K_v \times K_Y$$

The index Z is the comprehensive index of sea reef rock mass quality grading and Z of rock masses of different grades can be obtained according to quantification limits of rock mass of different grades in view of their different controlling factors. Values of comprehensive index Z of rock mass of different grades can be seen in table 4, and reef rock mass can be divided into five grades. By evaluating sea reef rock mass quality of the bridge and anchorage foundation, the essay provided quantitative limits and mechanical parameters to sea-crossing bridge sea reef rock mass foundation and slope stability and provided basis to rational design and corresponding measures of embedded depth of the bridge and anchorage.

Table 4 quality grading of sea reef rock mass and corresponding grading quantization parameters (based on RBI classification)

Rock mass quality grading	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ
Compression strength: R_s (MPa)	Hard rock	Rather hard rock	Rather soft rock	Soft rock	Extremely soft rock
	＞60	60～30	30～15	15～5	＜5
Rock mass block index :RBI	Blocky structure	Massive structure	Submassive structure～mosaic structure	Cataclastic structure	Granular structure
	100～50	50～20	20～5	5～1	＜1
Rock integrity coefficient :K_v	Complete	Relatively complete	Relatively vulnerable rocks	Vulnerable rocks	Extremely vulnerable rocks
	＞0.75	0.75～0.55	0.55～0.35	0.35～0.15	＜0.15
Weathered degree coefficient :K_Y	Unweathered	Weak weathering	Moderate weathering	Strong weathering	Fully weathering
	1.0～0.9	0.9～0.8	0.8～0.4	0.4～0.2	＜0.2
Comprehensive index :Z	$Z = R_s \times RBI \times K_v \times K_Y$				
	＞2025	2025～264	264～10.5	10.5～0.15	＜0.15

The basic characteristics of each grade of rock mass quality are as follows: Ⅰ: The rock mass is hard and complete, fresh, undeveloped structure surface, and >100cm fracture space. Ⅱ:

The rock mass is hard and complete, weak weathered, fresh, unloading, 1-2 sets of fractures, fresh fractures, mild rusted in part, and 50～100cm space. Ⅲ: The rock mass is relatively complete, moderate weathered, weak weathered in part, 2-3 sets of fractures, mild rusted fractures, and 30～50cm space. Ⅳ: The rock mass is broken, weak weathered, strong weathered in part, secondary mud filling in parts of fractures, strong water permeability, <30cm fracture space. Ⅴ: In the fault fracture zone, the rock mass is vulnerable and it is in form of dust and rock fragments. Dusts are tight in certain circumstances of confining pressure and they will be in granular when they are exposed.

When there is underground water in rock mass which is not benefit to its stability, the grading results should be modified by taking consideration of influence of underground water, and the comprehensive index after modification should be calculated according to the following formula:

$$[Z] = Z + K$$

In the formula, K is the modified coefficient due to influence of underground water and it will be determined according to table 5.

Engineering rock mass grading of the modified comprehensive index [Z] will be conducted according to table 4.

Table 5 Underground water influences modified value

Status of underground water \ Rock mass quality grading		I	II	III	IV	V
Wet of water drops		0	0	-1	-2～-3	-4～-6
Rain or flashy flow	Hydraulic pressure ＜0.1 MPa or unit water yield < 10 L/(min·m)	0	-1	-2～-3	-4～-6	-7～-9
	Hydraulic pressure ＞0.1 MPa or unit water yield ＞10 L/(min•m)	0	-2	-4～-6	-7～-9	-10

4.2 Quality grading of reef rock mass

Table 6 Statistics of RQD and RBI of various reef drill holes in different weathered areas

Drilling number	Sludge	Fully weathering		Strong weathering		Moderate weathering		Weak weathering	
		RQD	RBI	RQD	RBI	RQD	RBI	RQD	RBI
MDZK05	0 (0～1.7m)	/	/	/	/	34.2(1.7～23.2m)	4.2	44.8(23.2～40.6m)	5.0
MDZK06	/	/	/	/	/	67.9(0~27.2m)	9.5	72.1(27.2~60.0m)	16.8
MDZK07	/	/	/	/	/	58.7(0~31.2m)	10.6	70.6(31.2~60.7m)	26.1
MDZK08	/	0(0~4.0m)	0	14.0(4.0~16.4m)	1.5	14.1(16.4~28.0m)	1.6	61.1(28.0~44.1m)	22.4
MDZK09	0(0~2.1m)	/	/	29.7(2.1~9.0m)	3.4	57.7(9.0~23.4m)	6.2	70.6(23.4~42.5m)	8.2
MDZK10	0(0~8.3m)	0(8.3~14.0m)	0	11.6(14.0~15.8m)	1.3	5.0(15.8~17.9m)	0.3	74.8(17.9~50.3m)	11.1
MDZK11	/	/	/	22.9(0~9.6m)	4.6	15.7(9.6~17.5m)	1.7	71.2(17.5~42.7m)	20.5
MDZK12	/	/	/	13.9(0~13.2m)	1.5	18.9(13.2~18.6m)	2.1	58.3(18.6~47.0m)	11.6
MDZK13	0(0~3.0m)	/	/	/	/	28.7(3.0~28.0m)	3.3	23.6(28.0~40.8m)	2.6
MDZK14	/	/	/	25.6(0~12.5m)	3.9	22.3(12.5~22.4m)	2.7	56.8(22.4~45.3m)	6.6
Average value	**0**	**0**	**0**	**19.6**	**2.7**	**32.3**	**4.2**	**60.4**	**13.1**

According to the above grading methods and system, the 6 representative drill holes in the vertical 1-1′ section which runs through the whole reef (along the line direction) , namely, MDZK6, MDZK7, MDZK13, MDZK8, MDZK14 and MDZK11, were selected to have detailed rock mass quality grading evaluation. Based on this, the engineering geological longitudinal section in the site and sliced figure of different elevation could reveal quality grading results of rock mass vividly. Quality index RQD of rocks in different weathered areas and their corresponding rock mass block index RBI can be seen in table 6.

According to the RQD and RBI of various holes in different weathered areas, the average value of strong weathered rock mass is 19.6% and the integrity is unfavorable; the average value of RQD of weak weathered rock mass is 32.3% and the integrity is relative bad; and the average value of RQD weak weathered areas is 60.4% and the integrity is mediate. Therefore, the integrity of the whole reef rock mass is generally mediate ~ general, and it is especially unfavorable within 20m. The essay only introduced the representative drill hole MDZK6.

Drill hole MDZK6: the elevation of the hole is 0.80 m and the depth is 60.0m. According to the geological record, the hole can be divided into moderate weathered layer and the weak weathered layer according to weathering characteristics.

The first layer (0～27.2 m) is the moderate weathered crystal glass crumbs tuff which is mainly dominated by mosaic structure (there are submassive structures in part), and integrity of sections with a depth of 6.8～6.9m, 7.2～7.6m, 12.0～13.6m, 17.2～19.0m, 20.0～20.4m and 24.4～25.0m are unfavorable due to fracture development and cataclastic structures of rock mass. The rock uniaxial compression and saturation strength within the sections R_s = 75.75 MPa; the rock quality designation (average value of the layer) RQD = 67.90% and the rock block index RBI = 9.47; the rock integrity coefficient (average value of the layer) K_v = 0.73; the weathered degree coefficient K_Y = 0.6; and according to exposure of the drill hole, status of underground water is wet ~ water seepage, and the modified value K = -1 in view of table 4.

The second layer (27.2～60.0 m)is the weak weathered crystal glass crumbs tuff which is in submassive structure ~ blocky structure. And the integrity of sections in the depth of 33.2～33.6m and 34.0～34.5m is unfavorable due to fracture development and cataclastic structures of rock mass. The rock uniaxial compression and saturation strength within the sections R_s = 78.73 MPa; the rock quality designation (average value of the layer) RQD = 72.13% and the rock block index RBI = 16.80; the rock integrity coefficient (average value of the layer) K_v = 0.59; the weathered degree coefficient K_Y = 0.8; and according to exposure of the drill hole, status of underground water is water seepage, and the modified value K = 0 in view of table 4.

According to the above grading system, the rock mass quality grading results of the drill hole are shown in table 7.

Table 7 Rock mass quality grading results of the drill hole MDZK6

Classification parameter		Parameter value	
		The first layer (0-27.2 m)	The second layer (27.2-60.0 m)
1	Uniaxial compression strength: R_s (MPa)	75.75	78.73
2	Rock mass block index :RBI	9.47	16.80
3	Rock integrity coefficient :K_v	0.72	0.58
4	Weathered degree coefficient :K_Y	0.4	0.8
Rock mass quality comprehensive index :Z		$Z = R_s \times RBI \times K_v \times K_Y$	
		191.76	591.07
Rock mass quality grading (basic)		Ⅲ	Ⅱ
5	Status of underground water	Wet ~ water seepage	Water seepage
	Correction coefficient of underground water: K	-1	0
Modified rock mass quality comprehensive index [Z]		190.76	591.07
Rock mass quality grading		Ⅲ	Ⅱ

As what mentioned before, the rock mass quality grading results of the drill hole was classified according to weathered areas. But in fact, there are fracture development intensive belts within various sections, which will give rise to variations of quality among rocks in the same grade. Thus the overall average values of various sections in the table will be graded independently when thickness of fracture development intensive belts exceeds 0.5m. in view of this, by combining the above grading results and considering defects of the whole reef rock mass due to development of regional structures, the essay divided two sub-grades in the Ⅲ grade and Ⅳ grade rock mass, and the detailed grading results can be seen in table 8 and the representative profile map.

The Rock mass structure type, the weathering features, and the basic characteristics of rock mass are as follows: Ⅱ: massive structure, weak weathering, Weak weathered, unloading and hard and complete rock mass. Fractures generally generate 1-2 sets. The fractures are fresh with slight rust in part. And the space is 50-100cm. $Ⅲ_1$: submassive structure,Partial massive structure, lower part of weak weathering, The lower sections in the weak weathered areas have no load and the rock is relatively complete. The fractures generally generate 2-3 sets with slight color fading in part. Along large fractures, there are weathered secondary minerals with mediate or slight rust, and the space is 30-50cm.$Ⅲ_2$: mosaic structure, upper part of weak weathering, The upper sections in the weak weathered areas have no load and the rock has an unfavorable integrity. There are fractures with mediate rust. And the space is 10-30cm. IV_1: cataclastic structure, moderate weathering, Weak weathered and unloading, the rock is vulnerable. There are fractures with a space of <10cm, which mainly refer to fracture intensive areas with moderate and weak weathered areas. IV_2: cataclastic structure, strong weathering, Strong weathered, Strong weathered, weak load, vulnerable rocks and developed fractures. The fractures are seriously rusted with a space of <10cm.V: granular structure, fully weathering, Fully weathered