A method for balancing lateral pile stiffness within a large pile group under an LNG tank over uneven bedrock topography

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ABSTRACT
When LNG tanks are constructed at sites underlain by shallow and undulating bedrock, pile groups must be designed with variable pile lengths and rock-socketed lengths. This poses a challenge to the design and construction of consistent horizontal stiffness of piles. The drastic difference in pile lateral stiffness can result in major damage to LNG tanks subjected to strong earthquakes. This paper presents a solution for this challenge called reduced horizontal restraint (RHR) piles, which serve to reduce the lateral stiffness of piles in shallow bedrock to match that of piles in deep bedrock. The RHR pile is unique in that it introduces an annular cushion consisting of sand/gravel between pile and bedrock. A case of a large, bored pile group supporting an LNG tank is presented to demonstrate the feasibility of this technique.

RÉSUMÉ
Lorsque des réservoirs de GNL sont construits sur des sites reposant sur un substrat rocheux peu profond et ondulé, les groupes de pieux doivent être conçus avec des longueurs de pieux et des longeurs d'ancrage dans la roche variables. Cette conception pose un défi pour obtenir une rigidité horizontale uniforme des pieux. La différence drastique de rigidité latérale des pieux peut avoir de graves conséquences pour les réservoirs de GNL soumis à de forts tremblements de terre. Cet article présente une solution à ce défi appelée pieux à retenue horizontale réduite (RHR), qui servent à réduire la rigidité latérale des pieux dans le substrat rocheux peu profond pour correspondre à celle des pieux dans le substrat rocheux profond. Le pieu RHR est unique en ce qu'il introduit un cousin annulaire constitué de sable/gravier entre le pieu et le substratum rocheux. Un cas d'un grand groupe de pieux forés supportant un réservoir de GNL est présenté pour démontrer la faisabilité de cette technique.

1 PREFACE

According to Saeid et al. (2013) and a report of the China National Energy Administration (2019), liquefied natural gas (LNG) has become an intermediate green and clean energy (between fossil and fully renewable energies) favored by countries all over the world due to its advantages of low pollution, high efficiency and complete combustion. At present, the construction of LNG infrastructure is in full swing. As of March 2019, China has built 21 LNG terminals with a total of 69 LNG tanks (Wu, et al. 2019). According to Code for Design of Liquefied Natural Gas Port and Jetty (2021), the selection of the LNG terminal site should first consider the port and jetty with superior natural conditions which are generally located on mountainous coastal regions and characterized by marked variations of bedrock depths. These conditions create many geotechnical engineering problems when constructing large LNG tanks.

LNG tanks are commonly used to store LNG. One of the important design considerations is the ability to withstand natural disasters such as hurricanes, earthquakes, etc. When a tank (160,000 m^3 LNG capacity) is full, the energy it contains is about 70 times that of the Hiroshima atomic bomb. If the tank structure experiences rupture, the consequences can be disastrous (Zheng et al. 2014). Therefore, a seismic-resistant design for an LNG tanks is a key issue for design engineers.

The foundation of an LNG tank is typically larger than a common building foundation. Taking a 220,000m^3 storage tank as an example, the foundation supporting the tank can be up to 92m in diameter. Most of tanks are supported by piled foundations, except in some conditions where shallow bedrock is present and shallow foundations are preferable. According to Code for Design of Liquefied Natural Gas Receiving Terminal (2015) and EN14620 (2006), when performing foundation seismic calculations under operational base earthquake (OBE) and safe shutdown earthquake (SSE) conditions, the piles need to resist large horizontal loads. Therefore, the piled foundation of an LNG tank generally has the characteristics of large number of piles and/or large pile diameter (Wang et al. 2021). When LNG tanks are constructed in mountainous coastal regions, piles are usually bottomed in the bedrock to ensure the vertical bearing capacity of the piles. However, due to the undulating bedrock surface, piles must be designed with variable pile lengths and rock-socketed lengths, which leads to a large difference in the horizontal stiffness of piles. Under the same horizontal load, the deformation between piles is inconsistent. In the seismic design of a large-scale and heavy-loaded tank structure, the designer must ensure the relative uniformity of horizontal deformation of piles with variable pile lengths and rock-socketed lengths to avoid stress concentrations. This paper introduces a new concept, termed reduced horizontal restrain (RHR) piles, into an LNG tank project for achieving consistent horizontal stiffness of piles within a group. A field test was performed, and the experimental results were used to guide the design of RHR piles. Discussions were made of the design and construction of RHR piles.

2 PROJECT OVERVIEW

2.1 Project Introduction

The project was to construct an LNG storage and transportation project mainly consisting of two LNG tanks (160,000 m^3 LNG capacity) and related supporting facilities. The site included an excavated mountain area, backfill area and a dike, with a total land area of about 180,000 m^2. In the detailed soil investigation stage, the ground elevation was 6.09-6.85m above sea level, and the design ground elevation was 6.7m. Fig.1 shows an aerial image of the site.

Figure 1. Aerial site image

2.2 Subsurface Soil Condition

Based on the borehole data， the upper soil layers consisted of artificial fill soil, marine clay, alluvial silty clay–rock mixtures, underlain by bedrock that was composed mainly of strongly weathered granite and moderately weathered granite.

The depth of the moderately weathered granite was 2.80 ~ 52.40m below ground. The RQD value was 45 ~ 50%, and the standard value of saturated compressive strength of rock was 74.9MPa. According to the Chinese rock classifications, the basic quality grade of rock mass was Class Ⅲ, which could be used as a toe bearing stratum of piles.

2.3 Hydrogeologic Condition

Groundwater was found in pore space in the upper soil layer or in bedrock fissure. Elevation of groundwater was closely related to sea water level, and greatly affected by tidal variations, seasonal changes, and atmospheric precipitation. The depth of the typical water level was from 4.30-4.70m below ground. The bedrock fissure water existed in the joints and fissures of strongly weathered granite and moderately weathered granite layers, with poor permeability, low water quantity and great variation of the water level.

The Chinese environmental classification type for this site was Class II. Based on the water chemical analysis, groundwater had weak corrosiveness to concrete structures, weak corrosiveness to steel in reinforced concrete structures under a long-term water immersion environment, and strong corrosiveness to steel bars of reinforced concrete structures in a dry-wet alternating environment. The artificial fill soil was slightly corrosive to steel structures. Clay layers were highly corrosive to steel structures, and seawater was corrosive to the steel racks.

2.4 Earthquake Effect

According to Code for Seismic Design of Buildings (2010), the seismic hazard analysis indicated that the earthquake resistance at the site was class 7, the site environmental classification was Class II, the design earthquake fell in the second group, the basic seismic acceleration value was 0.10g, and the characteristic period was 0.40s.

3 DESIGN REQUIREMENTS AND CHALLENGES

3.1 Design Requirements

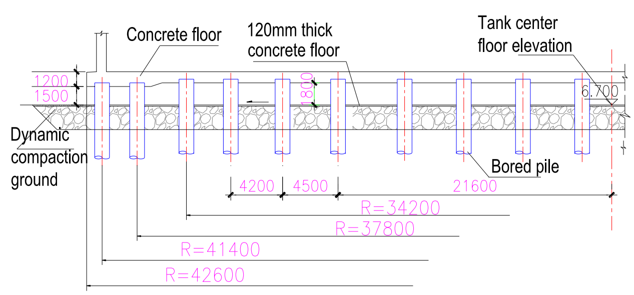

Figure 2. The design of pile foundation (part of drawing)

Piles supporting this LNG tank were rock-socketed bored piles. The diameter of each pile was 1200mm, and the pile cap was elevated 1700mm or 2000mm above grade, as shown in Fig.2. The bearing layer of the pile was the moderately weathered granite, and the rock-socketed length was not less than 1200mm. The 28-day strength of concrete for piles was 40MPa, the reinforcement was made of HRB400 steel rebar, and the thickness of the concrete cover to the reinforcement was 70mm. The ultimate compressive and lateral load capacity of single pile shall not be less than 12000kN and 1000kN, respectively.

Fig.3 presents the layout of piles under a quarter tank, including 316 piles. The piles were arranged in a square shape surrounding by three rows of ring piles. The interior piles consisted of a total of 148 piles (dubbed as Pc piles) with a pile spacing of 4800mm. Due to the space constraints, 48 of them were arranged slightly out of alignment in the square grid. Three rows of ring piles (dubbed as Pa piles) consisted of 168 piles each in the two outmost rows and 48 piles in the most inner row.

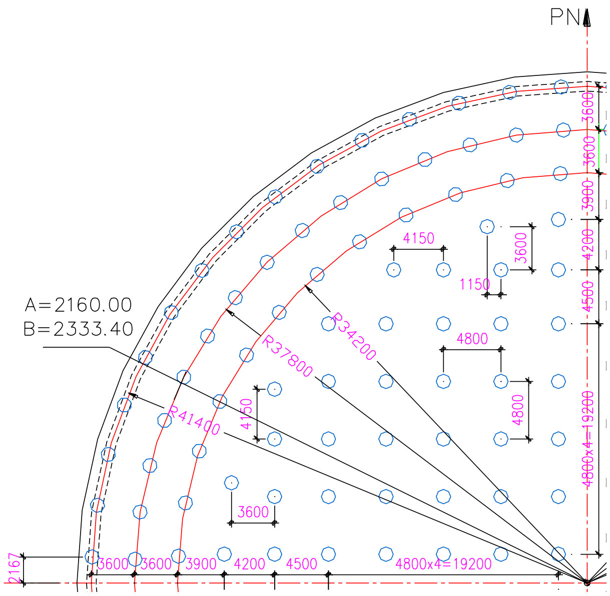

Figure 3. The partial pile layout plan

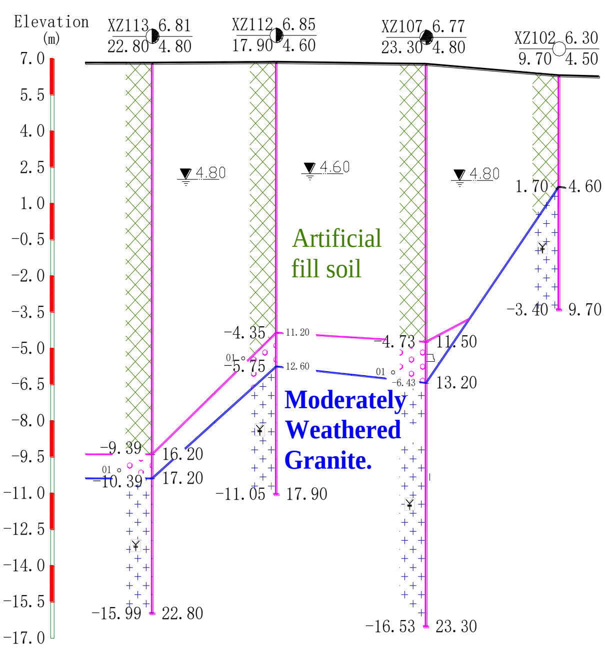

Figure 4. Typical engineering geological profile of the TK02 tank area

3.2 Engineering Challenges

Fig.4 shows the typical subsurface soil profile below the TK02 tank area. Fig.5 is the elevation contour map of the top of the moderately weathered granite layer. Based on the site investigation data and LNG tank design requirements, moderately weathered granite was selected as the pile toe bearing stratum. As can be seen from the Fig.4 and 5, the top of the moderately weathered granite layer in the TK02 tank area varied drastically in terms of elevations, with the shallowest depth of 2.8m and the deepest depth of 26.5m. This led to the design of difference in the pile lengths supporting tank TK02. Although the varying pile lengths helped to achieve the relatively uniform axial stiffness between piles in this large pile group, it poses a challenge to attaining consistent horizontal pile stiffness.

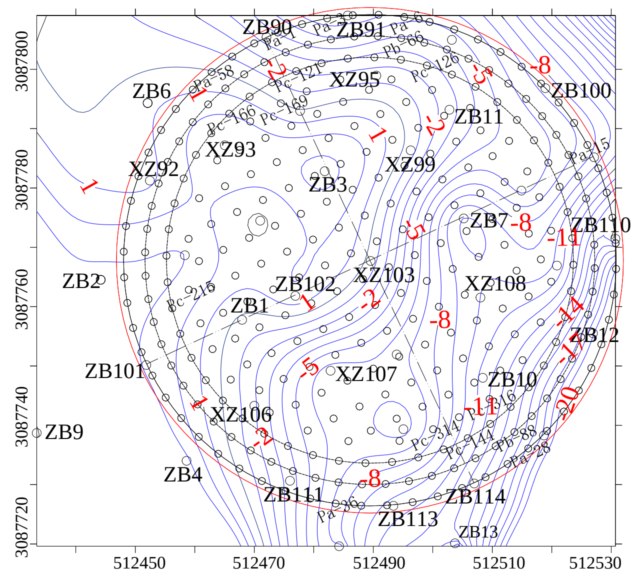

Figure 5. The elevation contour map of moderately weathered granite roof

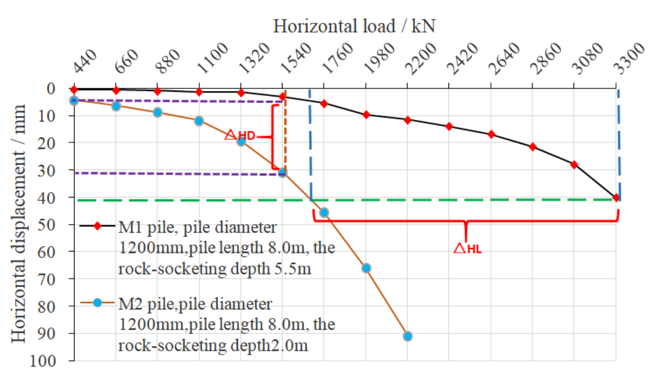

Figure 6. Horizontal load-displacement curves of rock-socketed piles

Fig. 6 shows two horizontal load-displacement curves obtained from the lateral loading tests at the same site. The two test piles were of the same total length but different in rock-socketed length. The figure clearly indicates that under the same horizontal load, the two piles developed considerably different horizontal responses. An increase in the rock-socketed length corresponded to an increase in lateral stiffness. This means that a deeper rock-socketed pile would undergo a smaller horizontal head movement given a lateral load or would attain a higher horizontal resistance of pile given the same lateral movement. Therefore, pile group with variable pile lengths of rock-socketed lengths would result in the significant difference in horizontal stiffness of piles.

A drastic difference of lateral pile stiffness within the LNG tank foundation can result in major damage for this type of large-scale structures subjected to extreme hazard events such as hurricanes, earthquakes, etc. According to the requirements of Code for Design of Liquefied Natural Gas Receiving Terminal (2015) and EN14620 (2006), the foundation designer of the tank needs to carry out seismic calculations under OBE and SSE. Due to the different horizontal stiffness between piles, there is a probability of premature failure of rock-socketed short piles under earthquake, particularly the large earthquake such as SSE. Therefore, special technical measures should be taken during the design and construction.

4 FIELD TESTS AND DESIGN OPTIMIZATION

4.1 Reduced Horizontal Restraint (RHR) Piles

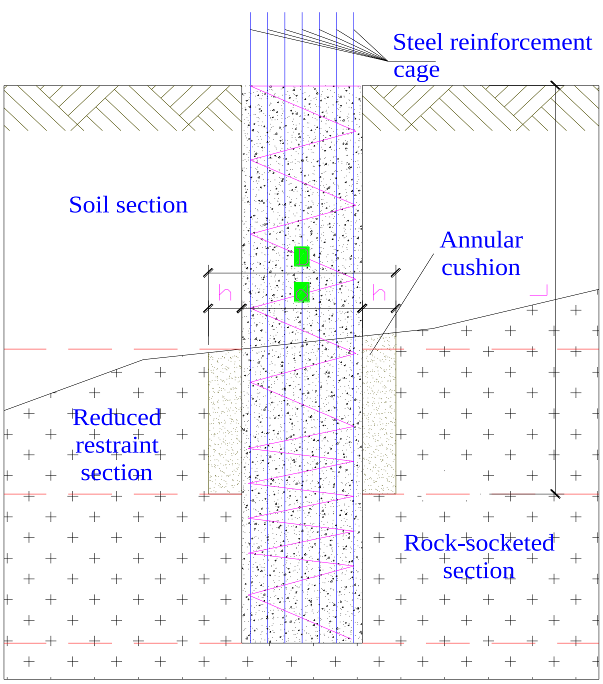

Figure 7. The construction diagram of RHR pile

To solve the problem of unequal horizontal stiffness of piles within the foundation in areas underlain by shallow and undulating bedrock, this paper presents a solution called reduced horizontal restraint (RHR) piles. As can be seen from Fig. 7, RHR piles consist of five parts, namely, soil layer section, the reduced restraint section, the annular cushion, the rock-socketed section and steel reinforcement cage.

The design of rock-socketed piles must consider the depth of bedrock. When the depth of bedrock is less than or equal to *L*, which is the critical bedrock depth, the horizontal restraint of bedrock on piles is significant, and the shallower the bedrock, the greater the lateral restraining force from the bedrock. However, when the depth of bedrock is greater than *L*, the horizontal restraint of bedrock becomes smaller. Therefore, when the depth of bedrock is less than *L*, an annular cushion consisting of sand/gravel between the pile and the bedrock is placed in order to reduce the lateral stiffness of piles to stiffness level of piles bottom on deep bedrock. The thickness of the annular cushion is shown below.

Thickness of annular cushion = (D–d) /2 [1]

where D is diameter of reaming tool, and d is design diameter of pile.

4.2 Field Test

Before the implementation of the RHR pile concept in this project, two test piles consisting of RHR pile and reference pile (no RHR) were constructed at the project site and laterally loaded. The data from horizontal load tests were analyzed and compared. Specifically, the RHR pile (S1) and reference pile (S2) were identical in geometry and material properties, except that the former included the cushion section but the latter did not.

According to the field test results (Xu et al. 1982), which showed that the depth of the maximum bending moment point was 3.3-5.0 times the pile diameter, and the depth of the zero moment point was 10.5-13.3 times the pile diameter, it was decided that the critical bedrock depth, *L*, was 6m. Considering the feasibility of the construction, the annular cushion thickness was 300mm, which was composed of well-graded gravel and medium-coarse sand, and the maximum diameter of gravel should be less than or equal to 25mm. Table 1 summarizes the structural information of the test piles.

Table1 The parameters of test piles

	Items	RHR pile (S1)	The rock-socketed pile (S2)
	Diameter (mm)	1200	1200
Pile length (m)	Above ground	1.0	1.0
	Soil section	2.5	2.5
	Reduced restraint section	3.5	0
	Rock-socketed section	2.0	5.5
	Annular cushion thickness (cm)	30	0
	Steel rebar	HRB400，24Φ20mm，Φ14mm@100mm/60mm，Φ22mm@2000mm	
	The theoretical amount of concrete (m^3)	10.18	
	Actual amount of concrete (m^3)	12	12
	Concrete filling coefficient	1.18	1.18
	Concrete strength (MPa)	40	

Fig. 8 shows the head load-displacement curves of the test piles under lateral loading. Both S1 and S2 piles were loaded to the horizontal displacement in excess of 7% of the pile diameter. Fig. 8 shows that at horizontal displacement of 6mm, 10mm and 40mm, the head load of S1 pile was 590kN, 644kN and 907kN respectively, and the corresponding load for S2 pile was 1208kN, 1252kN and 1613kN respectively. This result indicates that the inclusion of 3.5 m RHR section reduced lateral stiffness or resistance of pile by approximately 50% under the same displacement. After the loading tests, the integrity of the piles was measured using low strain test and visually inspected after excavating soils around the piles. Fig. 9 shows that S1 pile remained sound, but S2 pile was damaged. This result approved that the RHR pile was able to achieve the decreased lateral resistance in the wide range of lateral displacement or loading, while maintaining the good quality of the pile.

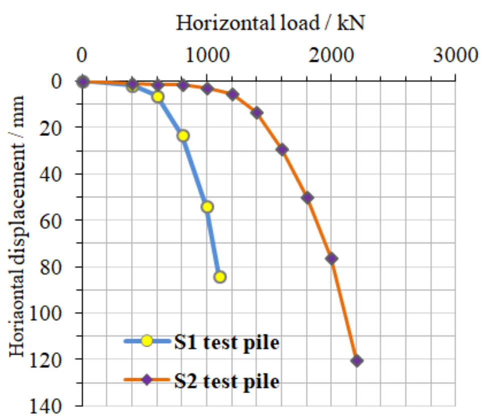

Figure 8. Load-displacement curves of the test piles

Figure 9. Test results of pile integrity

Fig.10 and 11 plot lateral displacement distributions along pile length for S1 (RHR pile) and S2 piles (reference pile). The displacement profiles were obtained from the inclinometers embedded in the test piles. It can be observed that the point of zero horizontal displacement was deeper in S1 pile than in S2 pile. This indicates that S1 pile engaged a longer portion of pile to respond to the lateral loading while S2 pile was easily overstressed as it

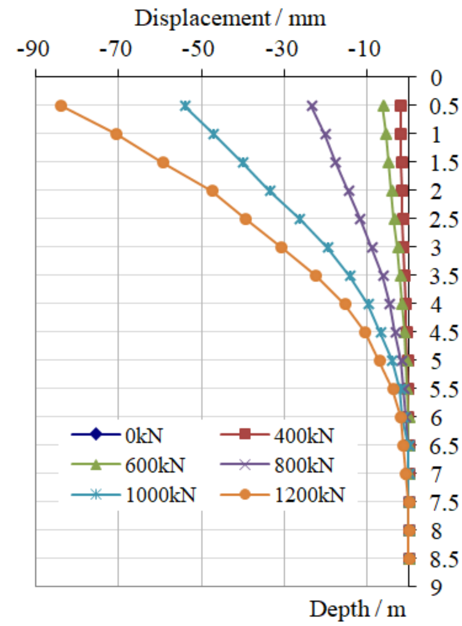

Figure 10.The horizontal displacement of the S1 pile (RHR pile) under each load

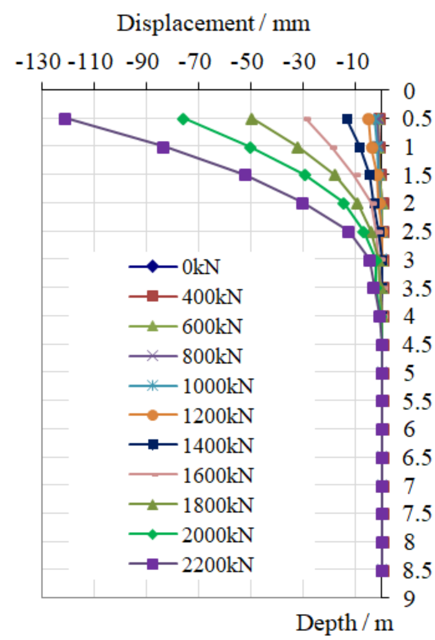

Figure 11.The horizontal displacement of the S2 pile (reference pile) under each load

engaged a shorter pile section. That explained why S2 pile underwent damage during the loading test. Furthermore, the figures also indicate that with the increase in the lateral loads, the zero-displacement point tended to move downward for both test piles.

4.3 Design Optimization

Based on the field test results and design requirements, RHR piles were used for the area with the depth of bedrock less than *L*=6m; otherwise, traditional rock-socketed piles were used. Table 2 presents the design of piles under the LNG tank in terms of the rock-socketed length.

The thickness of the annular cushion between pile and bedrock should not be less than 300mm, which was composed of well-graded gravel and medium-coarse sand. The maximum diameter of gravel should be less than or equal to 25mm, and the relative compaction should not be less than 80%. Meanwhile, the portion of pile shaft above and below the surface of bedrock needed to be enhanced in reinforcement as shown in Fig.12 to prevent potential damage due to the stress concentration.

Based on the soil investigation and geological conditions revealed by pile drilling, a total of 58 RHR piles were implemented during the construction of the foundation.

Table 2 The embedded depth of pile into rock

Tank no.	Pile type	Top of bedrock depth（m）	Rock-socketed length（m）	Number of piles
		L≤7	3.6	
		7＜L≤9	3.3	
	Pa	9＜L≤12	3	60
		12＜L＜18	2.4-2.7	
		L≥18	1.8-2.1	
TK02		L≤7	1.8	
	Pb	7＜L≤12	1.5	60
		L＞12	1.2	
		L≤7	1.8	
	Pc	7＜L≤12	1.5	196
		L＞12	1.2	
	Pa	25.5＜L≤55.5	1.2	60
TK03	Pb	25.5＜L≤55.5	1.2	60
	Pc	25.5＜L≤55.5	1.2	196

5 CONCLUSIONS

When LNG tanks are constructed at sites underlain by shallow and undulating bedrock, it is common to design pile groups with variable pile lengths and rock-socketed lengths, which results in significant differences in horizontal stiffness of piles. When subjected to extreme hazard events such as hurricanes, earthquakes, etc., the drastic difference in pile horizontal stiffness may cause the failure of rock-socketed piles in shallow bedrock. The localized ruptures can be cascading to the gross failure of the pile group. This phenomenon requires the special care during the design, especially for large-scale and heavy-loaded structures.

This study indicated that the reduced horizontal restraint (RHR) piles were effective in achieving uniform

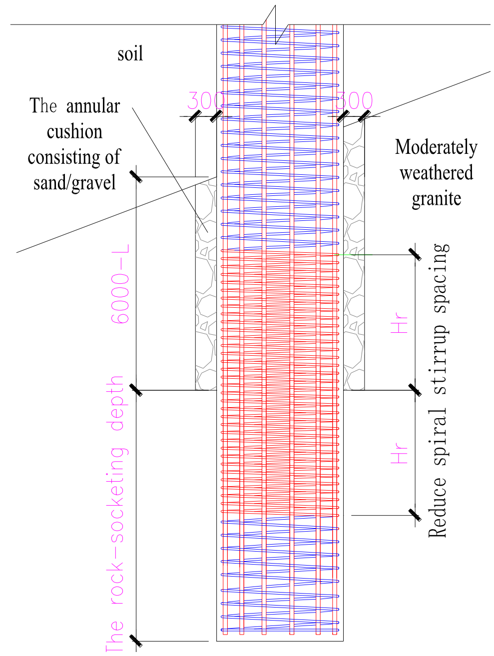

Figure 12.The detailed structure drawing of RHR pile

lateral stiffness/resistance of piles in a piled group while maintaining the uniform axial stiffness. It is recommended that the annular cushion be composed of well-graded gravel and medium-coarse sand and the thickness should not be less than 300mm. The maximum diameter of gravels should not be more than 25mm, and the relative compaction should not be less than 80%.

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