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Geotechnical investigation and tension-pile solution for foundation of SFT prototype at Qiandao Lake

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Abstract

Mooring foundation system is one of the key components for Submerged Floating Tunnel (SFT). In-situ geotechnical investigations have been performed at Qiandao Lake, China and the geological characteristics of the lake-bed sediments are obtained. In accordance to the geotechnical analyses and the review on various types of foundations in the offshore engineering, the rock-embedded tension-pile may be employed as the potential foundation solution for providing the required uplift resistance to the buoyancy of SFT, especially for the steep sloping terrain at the sea/lake bed. The uplift bearing capacity of the tension pile embedded in the layered sediments is further investigated numerically, with an axisymmetric finite element model for the vertical-loading condition, and with a symmetric 3-D finite element model for the oblique-loading one. Numerical results indicate that, the sediment characteristics have much effect on the shear stress along the pile-sediment interface, and the loading angle also has much influence on the ultimate tension loads.

Keywords: tension-pile group; geotechnical investigation; submerged floating tunnel; foundation solution

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1. Introduction

Submerged Floating Tunnel (SFT) is an attractive technical solution for waterway crossings, especially in the nature reserves (e.g. Qiandao Lake, China) for its negligible environmental impact [1, 2]. SFT is a type of tubular structure submerged in the water with the Archimedes buoyancy taking actions. In the offshore engineering, many types of floating structures have been utilized for oil and gas exploration, mainly including Tension Leg Platform (TLP), Jackup Platform, Spar Platform, and FPSO. The offshore floating structures are usually moored to the seabed with various kinds of foundations, including suction caisson, plate anchor, spudcan, gravity foundation, and tension pile, etc [3]. Similar to the aforementioned offshore floating structures, the tubular structure of SFT may also be

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tethered to the sea/lake bed with a foundation mooring system to obtain required stability in the filed.

Pile foundations [4] have been widely used for the structures on land and in the offshore field. Compared with the conventional compressive pile loaded downwards, the tension pile is employed for the upward loading conditions, which bring much complexity in the pipe-sediment interaction process. To properly evaluate the bearing capacity of the tension pile embedded in various sediments is one of the main concerns for the engineering design of tension piles.

In this paper, the choice of appropriate foundations for the SFT prototype at Qiandao Lake is discussed, in accordance to the engineering geological analyses of the initial geotechnical investigations. The uplift resistance of tension piles embedded in layered sediments is further investigated numerically with case study.

2. Geotechnical investigations for SFT prototype construction at Qiandao Lake

Geotechnical investigations are generally divided into three separate phases, i.e. Stage I: preliminary investigations, Stage II: initial design investigations, and Stage III: final design investigations, to minimize costs and for developing the necessary data at each stage of the approval, design, and construction of a project.

At the stage of preliminary investigations, adequate information should be obtained to justify site selection and preliminary cost estimates. After the preliminary investigations on various sites with the local government in Qiandao Lake in 2005, the SFT Prototype has been determined to be constructed at the Archimedes Bridge Bay (ABB) of Qiandao Lake. Recently, initial design investigations have been carried out along the selected route for construction of the SFT prototype at Qiandao Lake (see Fig. 1(a)). The main objectives of initial design investigations are to get in-situ information to obtain regulatory approvals, develop engineering and environmental data, and refine cost estimates, etc. In this stage of initial design geotechnical investigations, five positions were chosen for boring and sediment sampling. Based on the drill logs, the engineering geology section was obtained as shown in Fig. 1 (b).

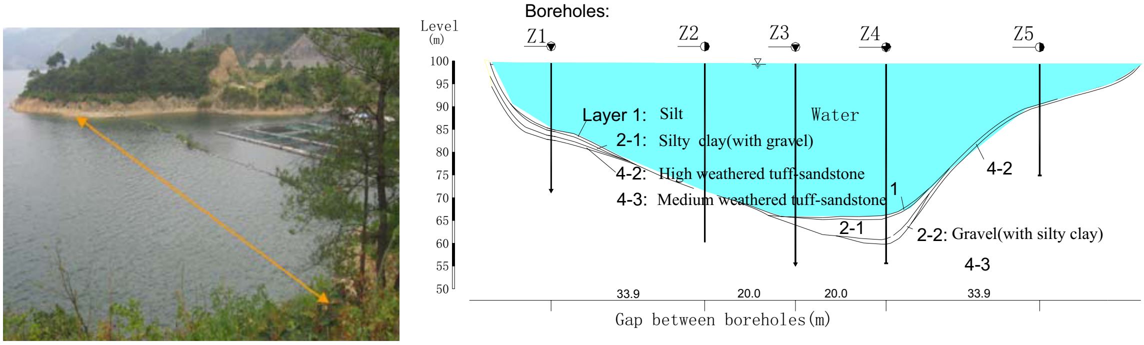


Fig. 1. (a) In-situ geotechnical investigations at Archimedes Bridge Bay, Qiandao Lake, China: Selected route for SFT prototype construction; (b) Engineering geology section

There usually exist five layers along selected route in the lakebed (see Fig. 1 (b)), i.e.

- Layer 1: Silt

Main characteristics: grey color, saturated, slight plasticity; sediments include settled soil particles suspended in water, organic silts etc.

- Layer 2-1: Silty Clay

Main characteristics: grey-yellow color, saturated, good plasticity; gravel contents: 15-35%, soil particle diameter: 2-20mm, particle shape: subangular, composition: tuff- sandstone, high dry strength and tenacity.

- Layer 2-2: Gravel mixed with silty clay

Main characteristics: grey yellow or grey green color, medium dense to dense; gravel contents: 50-75%, particle size: 20-40mm, maximum grain up to 80mm; particle shape: subangular; component: tuff-sandstone with some medium coarse sand; moderate dry strength and tenacity. Distributed randomly (usually exists at flat zones).

- Layer 4-2: Highly Weathered Tuff-Sandstone

Main characteristics: perplish brown or grey green color; core sample: shiver or gravel shape, eroded locally, crack filled with manganese mineral. Distributed randomly (missing at some locations).

- Layer 4-3: Medium Weathered Tuff-Sandstone

Main characteristics: perplish brown, grey green color, good hardness; core sample: shiver shape, column shape (length: 5-30cm), eroded locally, grey-green color, weathered crack filled with manganese mineral, block structure.

The thickness of the stratum along the selected route for SFT construction is shown in the Table 1. As illustrated in Table 1 and Fig.1 (b), the lakebed is mainly composed of tuff-sandstone randomly covered with thin soils. The test results on compressive strength of rock specimens show that, the medium weathered tuff-sandstone has excellent bearing capacity, and no faults or crash zones exist in this stratum. The medium-weathered tuff-sandstone could be employed for supporting the structures, and the shallow overburden soil would have slight influence on the foundation design.

Table 1. Stratum thickness along the selected route at the lakebed of ABB

Stratum No.	Stratum Name	Stratum Thickness (m)				
		Z1	Z2	Z3	Z4	Z5
1	Silt	0.30	/	0.30	0.70	/
2-1	Silty clay	1.10	/	2.70	4.50	/
2-2	Gravel (mixed with silty clay)	/	/	/	1.20	/
4-2	Highly-weathered tuff sandstone	0.90	/	/	/	0.30
4-3	Medium-weathered tuff sandstone	>11.60	>11.00	>7.60	>4.20	>15.40

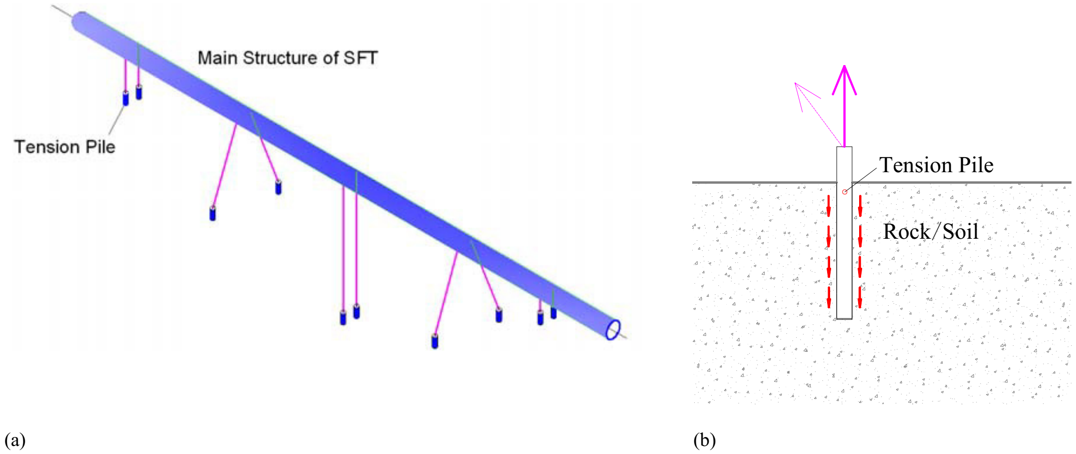
3. Choice of appropriate foundations for the SFT prototype: Discussion

In the offshore engineering, with the increase of water depth, floating structures have been successfully utilized for oil and gas exploration, such as Tension Leg Platform (TLP), Jackup Platform, Spar Platform, FPSO, etc. Floating structures are usually moored to the seabed with various foundations. Quite a few types of foundations, such as suction caissons, plate anchor, spudcan, gravity foundation etc, have been invented and employed efficiently in the field [3].

- **Suction caisson**, also named as ‘suction pile’, ‘bucket foundation’, ‘caisson anchor’, and ‘skirt foundation’, is usually installed by applying under-pressure (‘suction’) to its interior after it is allowed to penetrate under its own weight. The difference between the hydrostatic water pressure outside the cylinder and the reduced water pressure inside provides a differential pressure that acts as a penetration force in addition to the weight. After installation, the caisson’s interior is sealed off and vertical loading creates an internal underpressure which in turn mobilizes the end bearing resistance of the soil at the caisson tip.
- **Plate anchor** is commonly driven vertically or inclined to the desired depth and then rotated to its optimal position by applying a vertical tension on the mooring line. The bearing capacity of a drag anchor depends strongly on its final orientation and depth below the seabed.
- **Spudcan** is widely used as the footing of the mobile jackup rigs (platform) for installing new platforms, maintenance work and drilling and even for production for fields of limited life. Spudcans are typically circular or polygonal in plan, with a shallow conical underside and a central spigot to provide improved sliding resistance.
- **Gravity foundation** employs its own weight to balance the buoyancy of floating structures, such as a one-point mooring system.
- **Tension Pile** (to be discussed in detail, see below)

In sum, suction caisson, plate anchor and spudcan are generally installed on sands or clays, so they may not be appropriate for the foundation on the lakebed at ABB, which is mainly composed of tuff-sandstone. Generally speaking, the gravity foundation is less economical in material cost than tension pile. However, in the practical application of gravity foundation to be installed upon the steep slope, the bottom preparations are required to avoid bottom sliding.

As shown in Fig.1 (a), the lakebed terrain at ABB of Qiandao Lake has the feature of steep bed-surface. Thus, tension pile embedded in the sediments mainly consisting of medium-weathered sandstones may be employed in the optional mooring system to provide the required uplift resistance (see Fig. 2(a) and (b)), in case that overburden shallow soil is insufficient to develop enough skin frictions along the pile shaft. As well-known, a drilled and grouted pile is a type of pile for the foundation of offshore platforms. The piles are usually installed by drilling a hole below the seafloor, removing the drilling tool, lowering a steel/reinforced-concrete pipe into the open hole, and grouting the annulus between the pipe and the sediments. In the following section, the uplift resistance of a tension pile in the layered sediments will be analysed.



(a) (b)

Fig. 2. (a) An optional mooring systems for the SFT prototype at Qiandao Lake, China; (b) Schematic map of a tension pile in the sediment

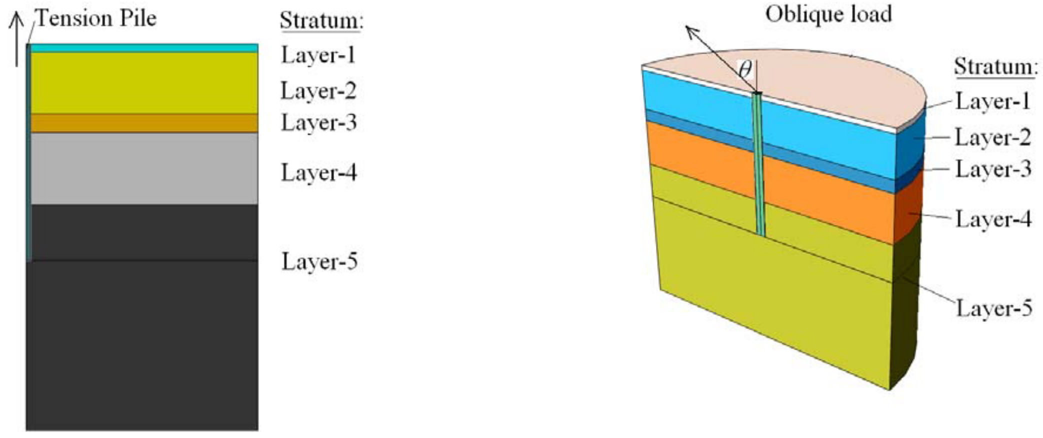
4. FEM analysis on uplift resistance of tension piles: A case study

4.1. FEM model for simulating tension pile-rock/soil interaction

An axisymmetric finite element model (FEM) for the interaction of a single tension pile with layered sediments under the action of vertical loading (see Fig. 3(a)), and a symmetric three-dimensional (3-D) finite element model for oblique loading.

In these two proposed FEMs, The lakebed sediment is simulated with the well-known Drucker-Prager (D-P) elastoplasticity constitutive model which is provided in the ABAQUS software [5], and the pile is treated as an elastic cylindrical material. The proposed numerical model has been verified with the existing test results [6]. In this case study, the parameters of the pile and the layered sediments are chosen as listed in Table 2, referencing to the properties of the sediments at Qiandao Lake.

In the numerical simulation of the tension pile-sediment interaction, it is crucial to properly describe the contact conditions between the pile and the neighbouring layered sediments. At the pile-sediment interface, the contact-pair algorithm provided in the ABAQUS software [5] is adopted to simulate the moving tension pile along the deformable sediment. The pile-sediment friction is defined by the Penalty Function with the advantage that it guarantees the positive definiteness of sparse matrix in the calculation. Both the frictional mechanism and the bonding mechanism can be simulated with the proposed finite element model. The pile-sediment frictional coefficient is set as $\mu=0.4$; the maximum pile-sediment bonding strength is set as 300kPa for the vertical loading condition. On the outer circumferential boundary, no displacement in the radial direction takes place; meanwhile the bottom boundary is fixed, i.e. the displacement and rotation are not permitted. The non-contact sediment surface is treated as a free boundary.



(a) (b)

Fig.3. Finite element models for the interaction of a single tension pile with layered sediments: (a) Axisymmetric model for vertical loading; (b) Symmetric three-dimensional (3-D) model for oblique loading

Table 2. Properties of the pile and the layered sediments (for case study)

Stratum No.	Material/ Stratum	Thickness (m)	Pile length L (m)	Pile diameter D (m)	Mass density ρ (kg/m^3)	Elastic modulus E (Pa)	Poisson's ratio ν	Cohesion strength C (Pa)	Angle of internal friction ϕ (^{0})
	Pile	/	6.0~14.0	0.6~1.0	2.3×10^3	28.0×10^9	0.17	/	/
Layer-1	Silt	0.5	/	/	1.9×10^3	0.50×10^6	0.45	0.10×10^3	5.00
Layer-2	Clay	4	/	/	2.1×10^3	6.00×10^6	0.30	35.0×10^3	29.3
Layer-3	Gravel-clay mixture	1.2	/	/	2.3×10^3	8.50×10^6	0.30	56.0×10^3	33.1
Layer-4	Highly-weathered tuff sandstone	4.0	/	/	2.4×10^3	15.0×10^6	0.20	84.0×10^3	40.6
Layer-5	Medium-weathered tuff sandstone	12.0	/	/	2.4×10^3	50.0×10^6	0.20	210×10^3	44.5

4.2. Numerical results and discussions

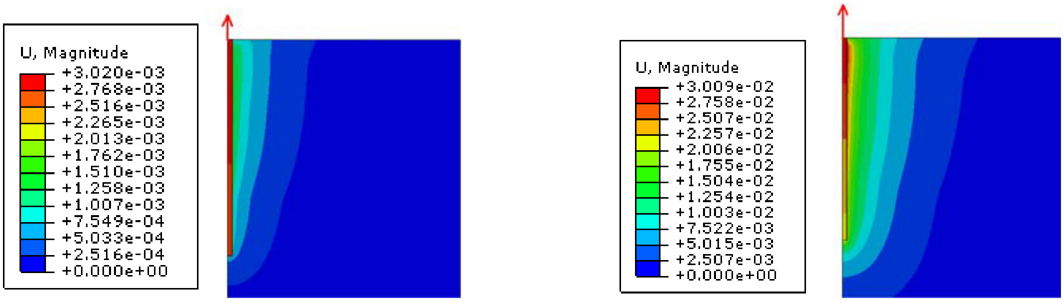
The uplift bearing capacity of the tension pile is investigated numerically for the two cases of loading conditions, i.e. Case I: vertical loading, and Case II: oblique loading.

Fig. 4 (a) and (b) give the contour of total displacement of the layered sediments around the vertically loaded tension pile (L = 14 m, D = 0.6m) for the two given values of the pile-top displacement w = 3mm, and 30mm, respectively. These figures show that, for the tension pile embedded in the layered sediments with different properties, the sediment displacement is continuous along the tension pile, and the displacement zone gets enlarged with increasing the pile-top displacement from 3mm to 30mm.

Nevertheless, the sediment characteristics have much influence on the shear stress along the pile-sediment interface, as shown in Fig. 5. The total tension load (Q) on the tension pipe embedded in N layers of sediments can be obtained with Eq. (1):

$$Q = \sum_{i=1}^{N} \int_{L_{i-1}}^{L_i} q_i(z) \pi D \mathrm{d}z \tag{1}$$

where L_i is the embedment thickness of the pile in the ith layer of the sediments. As shown in this figure, the profiles of the pile-sediment interfacial stress along the pile surface embedded in the layered sediments are quite similar. As the pile-top displacement increases up to a certain value (e.g. w = 30mm, see Fig. 6), the pile-sediment interfacial shear stress at the Layer-5 (medium-weathered tuff sandstone) gets nearly five time larger than that at the Layer-2 (clay). With the increase of the strength and the rigidity while the sediments get deeper, the shear stress at the pile-sediment interface gets much higher, indicating the layer of medium-weathered tuff sandstone contributes much larger to the resultant uplift capacity of the tension pile than the upper soft sediment covers.



(a) (b)

Fig. 4. Displacement contour of the layered sediment around the vertically loaded tension pile (L = 14 m, D = 0.6m) for two given values of the pile-top displacement (w): (a) w=3 mm; (b) w = 30 mm

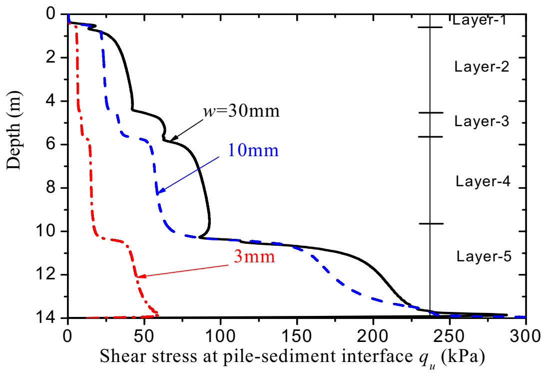
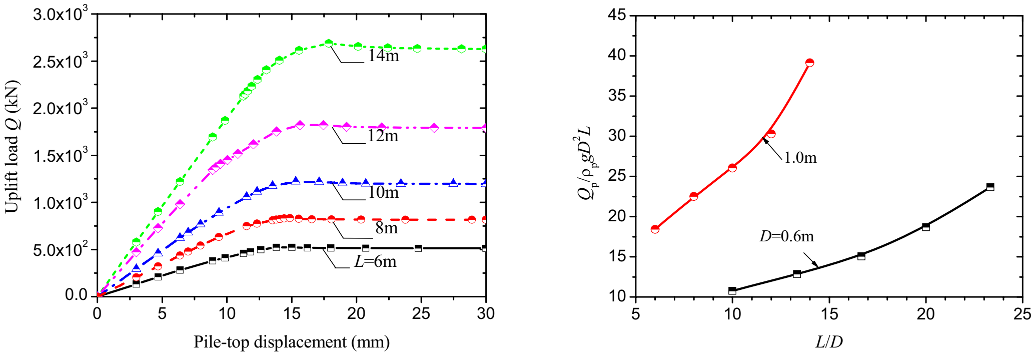


Fig. 5. Development of the shear stress along the pile-sediment interface for various values of pile-top displacement (L = 14m, D = 0.6m)

Fig. 6(a) shows the variation of the uplift load with the pile-top displacement of single tension piles for various values of pile length. For a certain pile length, with the increase of pipe-top displacement, the uplift load increases gradually to its maximum value, named as the ultimate tension load (Q_p). For this examined layered sediment, the values of the dimensionless ultimate tension load increases with the increase of the pile length, as shown in Fig. 6(b). The dimensionless ultimate tension load q_p is expressed as

$$q_p = \frac{Q_p}{\rho_p g D^2 L} \tag{2}$$

whose physical meaning is the ratio of ultimate tension load to the weight of the pile structure, where ρ_p is the mass density of the pile. Note that, a critical length of the tension piles exists under most of pile/sediment conditions. That is, the ultimate tension load would stop increasing while the pile length reaches its critical value. The interfacial shear degradation effects on axial uplift capacity of a tension pile have been further investigated by Yan and Gao [6].

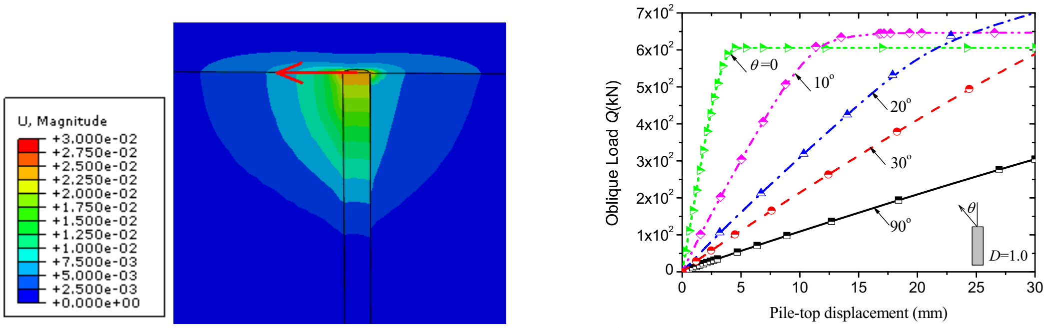


(a) (b)

Fig. 6. (a) Uplift load-displacement curves of the single tension pile for various values of pile length (L=6 ~ 14m; D = 0.6m); (b) Variation of dimensionless ultimate uplift load with dimensionless pile length

As illustrated in the aforementioned optional mooring systems for the SFT prototype (see Fig. 2(a)), the tension piles may be either vertically loaded or obliquely loaded. Thus it is interesting to examine the effects of loading angle on the uplift resistance of the tension pile by employing the symmetric three-dimensional (3-D) finite element model for oblique loading (see Fig. 3(b)). Note that in the 3-D simulation for the obliquely-loaded pile-sediment interaction, the bonding mechanism at the pile-sediment interface was neglected, i.e. only the friction mechanism was taken into account.

Fig. 7(a) gives the displacement contour of the layered sediment around the horizontally loaded tension pile at the pipe-top displacement w = 30 mm. The sediment displacement is not axisymmetric for the obliquely loaded tension pile. The displacement discontinuity is observed between the pile and the neighbouring sediment, especially at the back of the bending pile. The variation of the total tension load with pile-top displacement of an obliquely-loaded single tension pile is shown in Fig. 7(b). It is indicated in this figure that, the loading angle has much influence on the ultimate tension load. For a certain value of pile-top displacement before the tension pile reaches its critical bearing state, the oblique loads get smaller with increasing loading angle. The ultimate values of the tension load tend to become larger for the bigger loading angles. Nevertheless, the pile-top displacement would become the more prevailing influential factor while increasing the loading angle.



(a) (b)

Fig. 7. (a) Displacement contour of the layered sediment around the horizontally loaded tension pile (L = 14 m, D = 1.0 m; θ=90^0, w = 30 mm); (b) Effects of loading angle: Variation of the total tension load with pile-top displacement of an obliquely-loaded single tension pile

5. Concluding remarks

In-situ geotechnical investigations including the preliminary and initial design investigations have been performed at Qiandao Lake, China. By means of boring and sampling, the engineering geology section along the selected route in the lakebed has been obtained, which indicates that the lakebed is layered sediments mainly composed of tuff-sandstone and randomly covered with thin clay soil or gravels. Note that the final design geotechnical investigations are needed for the formal construction design of the foundations.

The brief review of the foundations commonly used in offshore engineering is made. Considering the properties of in-situ sediments, tension piles or gravity foundations may be chosen as the foundations for the SFT prototype. As the lakebed terrain at the chosen site in Qiandao Lake has the feature of fluctuant surface with steep slope, the tension pile is more preferential than the gravity foundation.

The uplift resistance of tension pile embedded in the layered sediments is further investigated numerically. An axisymmetric finite element model (FEM) is proposed for simulating the behavior of a single tension pile under the action of vertical loading, and a symmetric three-dimensional (3-D) finite element model for the oblique loading. Numerical results indicate that, the sediment characteristics have much influence on the shear stress along the pile-sediment interface. The layer of medium-weathered tuff sandstone contributes much larger to the resultant uplift capacity of the tension pile than the upper soft sediment covers. The loading angle also has much influence on the ultimate tension loads. In the engineering practice, the pile-group may be considered for a safer design for the SFT foundation. Specific attentions should also be paid to the long-term bearing degradation of tension piles especially due to the cyclic loading.

Acknowledgements

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