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Optimum Design of Oil Tank Foundation on Different Soil Conditions

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Abstract: Tank foundation is a base for the tank which is designed to support the weight of oil tank in order to ensure its stability. Failure of tank foundation usually occurred when the foundation system cannot support the weight of the tank or the soil bearing capacity of the area failed to resist the imposed stress from oil tank inclusive of foundation's self-weight. Failure of tank foundation can lead to pivoting effect and cracking on the foundation slab. Hence, the right choice of foundation system with reference to the bearing capacity of foundation soil is important to ensure the stability of tank foundation. Thus, this study was carried out in order to determine the deformation characteristics of foundation slab of oil tank foundation on different soil conditions with the aim to determine optimum design of oil tank foundation. The dimensions and design of the models were based on a published case study. Series of analyses with finite element models were conducted using STAAD Foundation CONNECT Edition V9. The models were aimed to analyze the stability of foundation structure, and deformation characteristics of the foundation slabs on different soil conditions. Three types of foundation system (raft, pile raft and pile foundation) were modelled in STAAD Foundation CONNECT Edition V9. The findings showed that the most optimum design for foundation structure on stiff residual soil is raft foundation. Whereas pile raft foundation structure is the most appropriate to construct on unconsolidated marine sediment deposit while pile foundation structure is highly recommended on soft peaty soil.

Keywords: Oil tank foundation, STAAD foundation, raft foundation, pile raft foundation, pile foundation

1. Introduction

Tank foundation is a base for the tank which is designed to support the weight of oil tanks and contain spillage. A tank foundation is required to provide total support for the tank bottom and the tank foundation should be designed to safely support the tank and its loads. Generally, three different foundation systems are widely utilized namely raft foundation, pile-raft foundation, and pile foundation. The soil condition needs to be considered in designing the oil tank foundation because not all types of foundation are suitable for certain soil conditions. Besides that, when the soil is initially too weak to support the weight of a full tank, it may need to be consolidated or strengthened by a surcharge of random fill before the tank is built, or by the weight of the tank itself during initial controlled loading. However, the sensitivity of the soil-bearing capacity may affect the settlement characteristics of the foundation. Hence, the tank foundation failure usually occurred when the foundation system cannot support the weight of the tank, or the settlement is too excessive.

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The deformation characteristic of the foundation slab must be observed in order to make sure the stability of foundation system. Failure of tank foundation can lead to pivoting effect and cracking on the foundation slab. Thus, the purpose of this study is to determine the deformation characteristics of the foundation slab of oil tank foundation and evaluate the performance of oil tank foundation with three different presumed soil bearing capacity that represent three different types of soil that are commonly encountered in Malaysia. The study was conducted by using commercial finite element software which is STAAD Foundation Advanced CONNECT Edition V9.

2. Literature Review

2.1 Oil Tank Foundation

There are three types of oil tank foundation system namely raft foundation, pile raft foundation and pile foundation. Three main criteria for selection of tank foundation are the bearing capacity of soil, settlement characteristics of soil and material properties of the tank. The bearing capacity is the bearing power of the soil, and the bearing capacity may become critical with large height over area's ratio which results in high imposed loads on the soil. As for the settlement characteristics, stiffness of soil and its deformation characteristics on load need to be considered in order to minimize differential settlement and total settlement when the oil tank is in service. Settlements to be considered are the long-term consolidation settlements and the degree of soil deformation related to shear/or punching shear failure [1]. In practice, concrete and steel are the most popular materials utilized for constructing oil storage tanks. However, the popularity of polyethylene, thermoplastic, and glass-reinforced plastic (fiberglass) is also increasing. The connection in between the tank and foundation slab needs to be considered as well during the design stage of the foundation system.

2.2 Soil Bearing Capacity

Soil bearing capacity is the capacity of the soil that supports the load applied to the ground and it depends on the type of soil, shear strength and density. It also depends on the depth of embedment of the load where the deeper it is found the greater the bearing capacity of soil. When there is insufficient bearing capacity, the ground can be improved or alternatively the load can be spread over a larger area such that the applied stress to the soil is reduced to an acceptable value less than the bearing capacity [2]. There are two levels of soil bearing capacity that should be considered which are ultimate bearing capacity and allowable bearing capacity [2]. The ultimate bearing capacity is the maximum possible vertical pressure that can be applied on the ground surface without causing failure. Whereas the allowable bearing capacity is the ultimate bearing capacity divided by the appropriate factor of safety. In order words, the allowable bearing capacity of soil is the amount of load the soil can take without experiencing shear failure or exceeding the allowable amount of settlement.

2.3 Settlement

Foundation settlement is caused by deformation of soil under the load of foundation structure and the factors that cause the settlement of a foundation is the type of soil and foundation structure itself. Detrimental settlement patterns that a tank foundation may develop under the effect of variable soil thickness and soil's compressibility over the plan area of the tank foundation are the major causes of foundation failures [3]. Foundation failure can lead to cracks in the foundation structure and affect the safety or serviceability of superstructure.

3. Methodology

Three types of foundation system namely raft pile-raft and pile foundation were modeled numerically via STAAD Foundation Advanced CONNECT EDITION V9. Presumed soil bearing capacities of 100 kPa, 200 kPa and 300 kPa which represent three different types of soils (peat soil, marine sediment soil and residual soil) were applied for the foundation structures. Optimum design of foundation systems on different types of soils were determined by referring to the deformation of the foundation slab. In addition, the moment distribution and vertical stress distribution were also determined via STAAD Foundation Advanced.

A series of finite element models for three types of foundation design were numerically modeled. A dead load of 2000kN was assigned on the surface of the foundation slab to simulate the dead weight of the oil tank. Secondly, some other design parameters namely slab thickness, soil bearing capacity, concrete property, and modulus of elasticity for the concrete were imputed in the model.

The elasticity modulus of concrete was calculated by referring to the formula from Eurocode 2 (CEN 2004) which is shown in Equation (1) below. Whereas the slab thickness, pile cap self-weight, pile spacing, pile capacity and the

$$E_{cm} = 22000\ (0.1.\ f_{cm})0.3 \qquad (1)$$

Where, $f_{cm} = f_{ck} + 8$

number of piles required were calculated manually. Thickness slabs of 1100 mm were taken for raft foundation, pile-raft foundation, and pile foundation. Before analyzing the foundation system, the subgrade modulus for the soil needs to be calculated. The subgrade modulus was calculated from soil bearing capacity which is known as presumed bearing capacity. Input the data for allowable bearing capacity and for this study bearing capacity of 100 kPa, 200 kPa and 300 kPa represent different types of soil which are peat soil, marine sediment soil and residual soil. The factor of safety chosen is 3 for designing the foundation structure because the maximum value was chosen to obtain the most critical result so the foundation structure will be safer.

Then, the analyses were executed and the calculation sheets for each of the foundation structures were obtained. The deformation and vertical stress distribution were obtained from the calculation sheet. The slab was then designed by assuming the strength of steel and concrete which are 500 N/mm2 and 30 N/mm2 based on Eurocode 2. After designing the slab, the slab cut option was chosen by drawing a virtual line on the slab to obtain the cross-sectional view of the slab for the moment distribution.

4. Result and Discussion

Three foundation structures were modeled in STAAD Foundation advanced CONNECT Edition V9 which were raft foundation, pile raft foundation and pile foundation. The structures for the foundation were designed in 3D as shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3, respectively. The triangular mesh for the foundation structures needed to be generated before the analyses were started.

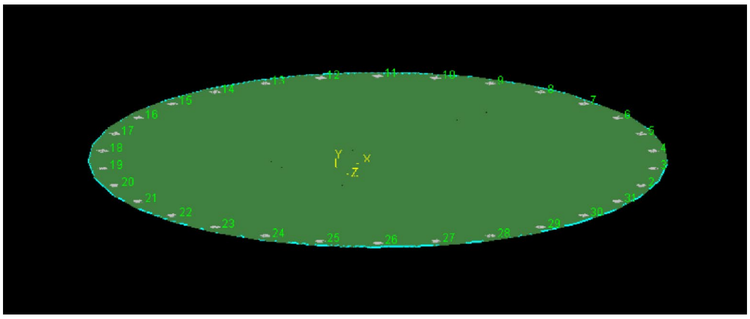

Fig. 4.1 - Raft foundation structure in STAAD foundation advanced

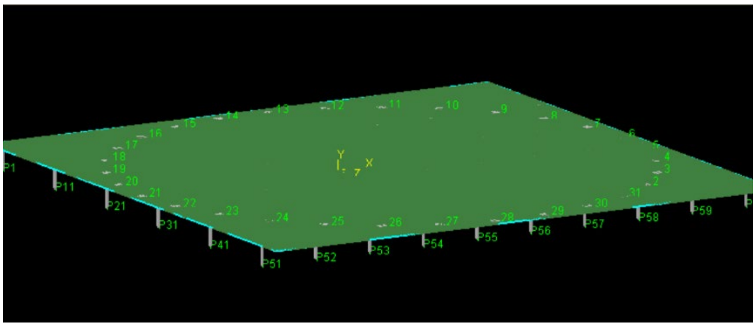

Fig. 4.2 - Pile raft foundation structure in STAAD foundation advanced

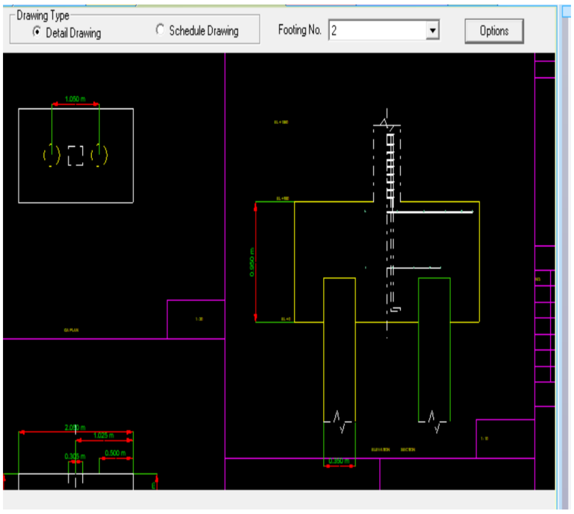

Fig. 4.3 - Pile cap in STAAD foundation advanced

4.1 Foundation Structure with Different Presumed Soil Bearing Capacity

The foundation structures were modeled with different soil bearing capacities that represent different types of soil namely peat soil, marine sediment deposit and residual soil with presumed soil bearing capacity of 100 kPa, 200 kPa and 300 kPa each. The presumed soil bearing capacity was obtained from Building by Laws. The results of analyses are shown in Table 4.1.

Table 4.1 - Analysis result obtained from STAAD foundation advanced

Case	Type of Foundation	Type of Soil	Soil Bearing Capacity (kPa)	Moment distribution (kNm/m)	Vertical stress distribution (kN)	Deformation/ Displacement (mm)
I-a	Raft	Peat soil	100	1899.63	2940.21	19.91
I-b	Raft	Marine soil	200	1596.29	3163.17	10.30
I-c	Raft	Residual soil	300	1575.92	4137.63	7.30
II-a	Pile Raft	Peat soil	100	43.96	59.16	1.14
II-b	Pile Raft	Marine soil	200	52.85	35.49	1.11
II-c	Pile Raft	Residual soil	300	77.818	41.50	2.10
III-a	Pile	Peat soil	100	1563.41	2162.74	21.27
III-b	Pile	Marine soil	200	1561.41	2093.44	25.17
III-c	Pile	Residual soil	300	1056.86	1852.55	31.91

From the analysis, the sensitivity of the soil bearing capacity affects the foundation structure. Other than that, even the foundation structures are the same but the different soil bearing capacity can obtain different results in terms of the moment distribution, vertical stress distribution and deformation that have occurred.

4.2 Foundation Structure with The Same Type of Soil

For peat soil, based on Table 4.1 raft foundation structure shows the highest moment distribution value, vertical stress distribution value and deformation value with 1899.63 kNm/m, 2940.21 kN and 19.91 mm. Based on the previous research from Rahman (2020) [5] the allowable settlement of a structure depends on the structure itself, the foundation, and the type of soil so, different types of structure have varied degree of tolerance to the settlements. The allowable settlement for the foundation structure is 25 mm, therefore the deformation occurred for the foundation system is acceptable.

For marine sediment deposit, (Table 4.1) raft foundation structure shows the highest moment distribution value, vertical stress distribution value but lower deformation value than pile with 1596.29 kNm/m, 3163.17 kN and 10.30 mm.

As for residual soil deposit, raft foundation structure shows the highest moment distribution value, vertical stress distribution value but lower deformation value compared to pile foundation with 1575.92 kNm/m, 4137.63 kN and 7.30 mm. Meanwhile for pile raft foundation structure, the data obtained are the lowest among the three foundation structures with 77.82 kNm/m, 41.50 kN and 1.12 mm. As for pile foundation structure, the data acquired for moment distribution is 1056.86 kNm/m, for vertical stress distribution is 1852.55 kN and for deformation is 31.91 mm. However, the allowable settlement for the foundation structure is 25 mm therefore the deformation occurred for pile foundation structure is not acceptable for this type of soil. The high deformation for pile foundation slab could be due to high punching shear resulting from high bearing capacity of foundation soil. The findings suggested that the thickness of pile foundation should be increased when dealing with stiff soil underneath. Anyway, it is important to note that the findings are purely analytical as practically the length of piles are designed based on the soil bearing capacity and not possible to be set constants for all the cases.

5. Conclusion

The study was conducted to analyze the deformation characteristics of foundation structures on different soil conditions and to evaluate the performance of oil tank foundation with three different soil bearing capacities that represent three different types of soils. The objectives of this study have been outlined as the guideline for fulfilling the fundamentals of the study. To analyze the deformation characteristics of foundation structure, three different types of foundation structures were modeled for this study which are raft, pile raft and pile foundation. The foundation structures were supported by different soil bearing capacities that represent three different types of soils (peat soil, marine sediment deposit and residual soil) to distinguish the sensitivity of the soil bearing capacity toward the foundation structure. The analysis result obtained shows that the soil bearing capacity affects the moment distribution, vertical stress distribution and deformation of the foundation structure. Besides that, the optimum design for the foundation structures was determined by referring to the minimum value of deformation that happened because the least deformation might have less reinforcement needed to construct the foundation structures.

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