Mudmat Foundation Stability on Very Soft Clay - Coupling Analytical and Numerical Analysis for a Platform in Vietnam Water

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Abstract. Mudmats are widely used in the oil and gas industry to temporarily support jacket before and during pile installation phase. This paper presents a case study on mudmat foundation stability which has taken on a geotechnical challenge when the mudmat foundation is seated on a 13.8 m thick layer of very soft clays. The mudmat stability is firstly verified using conventional procedures recommended by the industry-specific codes (ISO, API). The challenge of this analytical approach consists of consideration of mudmat stability when the degree of undrained strength heterogeneity exceeds a typical limit value of ten (10). In this case, the study of Salencon and Matar (1982) is used to extend the application range of the conventional approach. Secondarily, a numerical analysis is carried out using PLAXIS 3D Foundation. The numerical results show relative agreement in comparison with the analytical approach. Combining analytical and numerical analysis allows confirming the mudmat foundation stability. The study of Salencon and Matar (1982) seems to be a reliable reference to determine the foundation shape factor for the seabed with a high degree of undrained strength heterogeneity.

Keywords: Mudmat stability · Very soft clay · Coupling analysis

1 Introduction

In the construction of a fixed offshore platform, when pre-piling and suction buckets are not chosen, mudmats are widely used to provide temporary stability for the fixed platform during the installation phase. The design of the mudmat foundation is commonly considered as a shallow foundation. Loads acting on mudmats can be complex and tridimensional due to environmental loads, operational loads, and jacket self-weight.

The conventional design approach, as described in ISO [1], DNV [2] and API [3] focuses on the linear superposition of applied vertical, horizontal, and moment loadings. These ultimate loadings are determined based on the classical bearing capacity equation for the failure of a vertically loaded strip foundation on uniform soil. Semi-empirical factors then are introduced to account for foundation shape, load inclination and eccentricity, heterogeneity in soil strength profile, and embedment. According to

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[4], the conventional approach will under-predict the capacity for non-uniform shear strength profiles, even for simple eccentricity with no lateral load.

An alternative approach that aims to represent ultimate limit states under combined loading consists of using interaction diagrams or failure envelopes. Failure envelopes can be expressed in planes of the vertical, moment, or horizontal load (V-H, V-M, H-M) or as a three-dimensional surface (V-H-M). The failure envelope approach has been developed for shallow foundations of various geometries including strip, circular, and rectangular [5–11]. Details of various important contributions were summarized in [4, 12]. Therefore, most of the available closed-form expression of failure envelope for the undrained condition were provided for a strength heterogeneity up to 10. For a larger degree of strength heterogeneity, closed-form expressions of failure envelope were provided in [8], but the foundation was limited to a circular shape.

This paper presents a case in which mudmat lies on very soft clay with complex combined loading. Firstly, an analytical approach is used to verify the mudmat stability according to the API standard [3]. The very soft clayey layers challenge the analytical approach with a degree of strength heterogeneity larger than 10. Subsequently, a numerical study is also performed to compare with the analytical results to confirm the mudmat configuration.

2 Project Description and Geotechnical Data

The project is a moderately sized gas development, located in the gas fields offshore southern Vietnam. The platform model is shown in Fig. 1. This platform is configured as an unmanned minimum facilities wellhead platform.

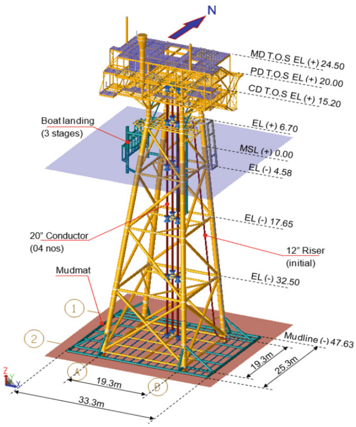

Fig. 1. Overview of the platform and timber mudmat

Due to Transportation & Installation (T&I) method constrained by the client, a mudmat foundation is chosen to support the jacket before and during the pile driving phase. The results of a preliminary design show that the necessary dimension of the mudmat is 33.3 m long and 25.3 m wide. The seastates expected at the proposed window are given in Table 1. The mudmat stability is checked with minimal and maximal water depth for all steps of the pile driving phase. The up-ending of the jacket is assisted by two buoyancy tanks. Therefore, the on-bottom stability was verified with loadings before and after the removal of two buoyancy tanks. The on-bottom stability was analyzed with 221 load combinations following [3].

Table 1. On-bottom stability seastates

Parameter	Value	Unity
Maximum wave height	3.0	m
Wave period	6.0	s
Current velocity	0.5	m/s
Number of load combinations due to environmental loadings and T&I sequence	221	[-]

The geotechnical survey was carried out by a qualified contractor. The investigation comprised of one 150-m sampling borehole and one 150-m continuous Piezocone Penetration Test (PCPT) borehole. The clayey soil is classified as very soft to soft from the seafloor to 13.80 m below the seafloor, overlaying firm to stiff clays to 27.10 m. For depths greater than 27.10 m, the clays are generally very stiff. The undrained shear strength, S_u increases respectively from 2 kPa at the seafloor to 25 kPa at 13.80 m below the seafloor (Table 2).

Table 2. Geotechnical data

Stratum	Depth [m]		Soil type	Unit weight [kN/m^3]	Sensitivity, S_t [-]	S_u [kPa]	E_u kPa
1	Top	Bottom					
	0.00	3.00	Clay	15.60	3.0	2 to 8	160 to 640
	3.00	13.00	Clay	15.60	3.0	8 to 22	640 to 1760
2	13.00	13.80	Clay	19.00	3.0	25	2000
3	13.80	16.00	Clay	18.80	2.0	45 to 75	7200 to 12000
	16.00	20.00	Clay	18.80	2.0	75	12000
	20.00	24.50	Clay	18.80	2.0	75 to 80	12000 to 12800

(*continued*)

Table 2. (*continued*)

Stratum	Depth [m]		Soil type	Unit weight [kN/m^3]	Sensitivity, S_t [-]	S_u [kPa]	E_u kPa
	24.50	27.10	Clay	18.80	2.0	80 to 85	12800 to 13600
4	27.10	40.60	Clay	18.30 to 17.30	4.0	110	17600
5	40.60	42.50	Clay	19.50	2.0	110 to 225	17600 to 36000

To perform numerical analysis, undrained Young's modulus is necessary as an input parameter. This parameter was not provided in the geotechnical data and was derived from correlations available in the literature. Among various correlations, the one proposed by Duncan and Buchignani (1976) reported in [13] was used to estimate undrained Young's modulus of soils. Stiffness ratio E_u/S_u was described as a function of over-consolidation ratio (OCR) and plasticity index (I_P). For a conservative assumption, the lower bound of the stiffness ratio was used such as $E_u/S_u = 80$ for the three first layers below the seafloor and $E_u/S_u = 160$ for other layers. Adopted values of the undrained Young's modulus are given in Table 2.

3 Analytical Approach

The mudmat stability was firstly verified according to the industry-specific codes API 2GEO [3] and API RP 2A-WSD [14]. Following the soil data provided in Sect. 2, the seabed was classified as a saturated clayey profile. Mudmat was checked with the undrained bearing capacity-linearly increasing shear strength. The vertical allowable load under undrained conditions is given as follows:

$$Q_d = F\left(s_{u0}N_c + \frac{\kappa B'}{4}\right)K_c A'$$

where Q_d is the vertical allowable load, F is the correction factor given as a function of $\kappa B'/s_{u0}$, κ is the rate of increase of undrained shear strength with depth, S_{u0} is the undrained shear strength of cohesive soil, N_C is a dimensionless constant equal to 5.14, B' is the minimum effective lateral mudmat dimension, A' is the effective area of the foundation, K_C is the correction factor that accounts for load inclination (i_C), footing shape (s_C), depth of embedment (d_C), inclination of the base (b_C), and inclination of the seafloor surface (g_C).

The correction factor (K_C) and foundation shape factor (s_C) are determined by the following equations in [3]:

$$K_C = 1 + s_C + d_C - i_C - b_C - g_C$$

$$s_C = s_{CV}(1 - 2i_C)\left(B'/L'\right)$$

While other components of K_C (except s_C) can be calculated by the formulas given in [3], the foundation shape correction factor, s_C is only given as a function of $\kappa B'/s_{u0}$ for the range $0 \leq \kappa B'/s_{u0} \leq 10$. However, the degree of strength heterogeneity for the present project, $\kappa B'/s_{u0}$ varies between 10.73 and 19.47, is larger than the range proposed by API 2GEO [3]. Therefore, the shape factor cannot be directly determined with this code. This shape factor can be determined for large soil strength heterogeneity basing on the study of Salencon and Matar [15]. Figure 2 shows the diagram reproduced from [15], which was used to determine the circular foundation shape factor.

The sliding stability was checked following API 2GEO code [3] for the undrained condition in the following equation:

$$H_d = s_{u0}A$$

where A is the surface area of the mudmat. The overturning stability was also verified by calculating the ratio between the restoring moment and the overturning one around x-direction (long edge of the mudmat) and y-direction (short edge of the mudmat).

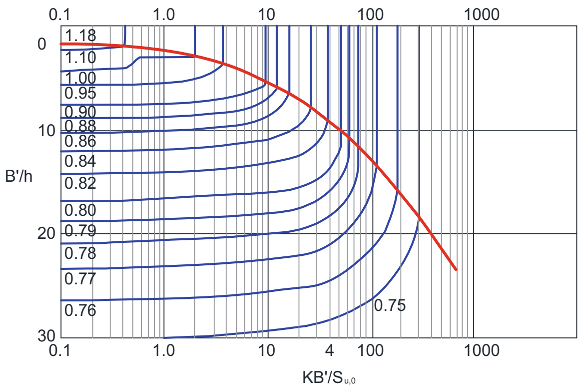

Fig. 2. Diagram for determination of s_{CV} reproduced from [15]

For each load case summarized in Table 1, a pair of the upper-bound and the lower-bound cases was considered. The lower-bound corresponds to the lower value of the correction factor F (for fully smooth interface condition) and the upper one corresponds to the higher value of the correction factor F (for fully rough interface condition) [3]. The most critical cases in terms of factor of safety for both the lower and upper-bound conditions are shown in Table 3.

Table 3 shows that the factors of safety (FoS) determined by the analytical study satisfy the requirements of industry-specific codes [3, 14]. However, due to the high degree of undrained strength heterogeneity, the foundation shape factor cannot be directly determined by the industry-specific codes. Consequently, the analytical results may have some uncertainties. Therefore, these results need to be confirmed by other approaches such as numerical analysis. The most critical cases 1013, 2006, and 2122 are chosen for the numerical analysis.

Table 3. Factor of safety (FoS) of the on-bottom check following API [3]

Load case	Minimal FoS					
	Lower bound			Upper bound		
	Vertical	Sliding	Overturning	Vertical	Sliding	Overturning
1013	2.02	2.37	2.23	2.41	2.37	2.23
2006	3.48	2.17	8.21	4.18	2.17	8.21
2122	1.79	2.28	2.71	2.15	2.28	2.71

4 Numerical Approach

The numerical model was carried out using PLAXIS 3D Foundation. This finite element model is shown in Fig. 3. The mudmat was modeled in the following manner: (i) beams represent the mudmat horizontal bracings and (ii) floors (shells) represent the mudmat timber. The structural element unit weight was set as zero to eliminate additional weights to the mudmat. In this finite element model, 23496 of 15-noded tetrahedral elements with 62281 nodes were generated. The Poisson's ratio was taken as 0.49 for all clayey soil layers as common practice in total stress analyses.

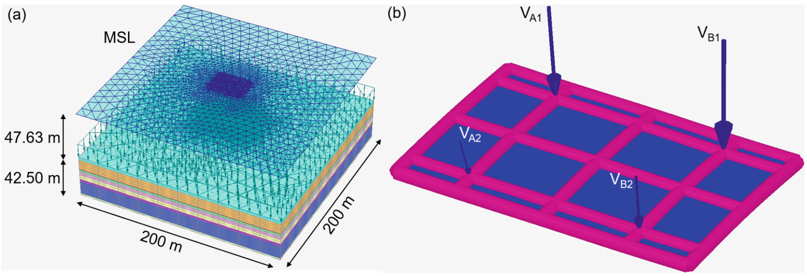

Fig. 3. Mudmat model in PLAXIS 3D Foundation

The loading at four legs of the mudmat was derived from the three selected load cases (2122, 2006 and 1013) and summarized in Table 4. These forces were then converted to the system coordinates of PLAXIS 3D Foundation.

In this numerical analysis, the mudmat settlement was first considered. The mudmat settlement for load case 2122 is shown for row 1 in the x-direction (Fig. 4a) and row B in the y-direction (Fig. 4b). The maximal settlement of the mudmat was about 116.29 mm for this load case. According to the difference of vertical loading acting on 4 legs, differential settlements were correspondingly observed for the mudmat base. The maximal differential settlement for three selected cases along mudmat diagonals was about 88 mm, equivalent to an inclination of 0.12° of the mudmat. The differential settlements of the mudmat seem small and shall be accounted for in the T&I analysis.

To compare with the analytical analysis, the factor of safety (FoS) was determined for the load cases 1013, 2006, and 2122 using the phi/c reduction procedure in PLAXIS

Table 4. Loading on four jacket legs

Load case	Leg point	Loading (kN)		
		Vx	Vy	Vz
1013	A1	0.7		−1716.4
	A2	0.7	177.9	−511.1
	B1			−1536.5
	B2		177.9	−331.1
2006	A1		−135.8	−1340.7
	A2			−1504.6
	B1	−139.0	−135.8	−846.7
	B2	−139.0		−1010.7
2122	A1	129.6		−2010.2
	A2	129.6	131.6	−837.1
	B1			−2487.2
	B2		131.6	−1314.1

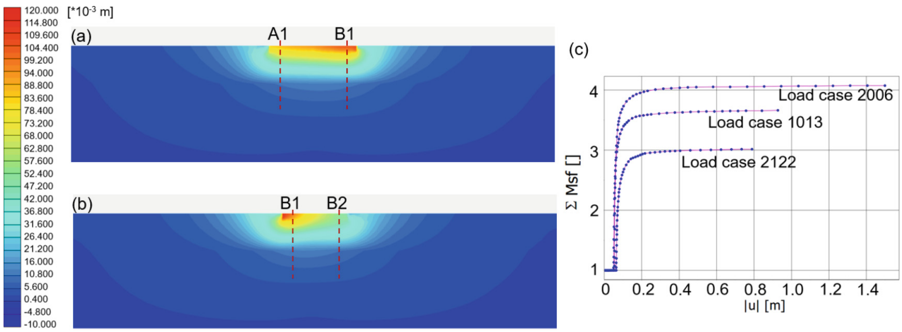

Fig. 4. Mudmat settlement for the load case 2122 (a) Row 1 in x-direction; (b) Row B in y-direction; (c) FoS determined for the three load cases 1013, 2006 and 2122

3D Foundation. The results were shown in Fig. 4c. In these numerical analyses, the FoS was the combined FoS for simultaneous vertical, horizontal, and moment loading. In contrast, the FoS determined in the analytical approach was separately determined for vertical loading, horizontal sliding, and moment overturning. Therefore, the comparison in terms of FoS between the analytical and numerical analysis is relative and essentially in the aspect of the FoS magnitude.

In some cases, the analytical approach gives smaller values of FoS than the numerical method. These discrepancies of the FoS may be explained by the difference in terms of the FoS calculation method and by the under-prediction of the bearing capacity in the analytical approach [4]. In general, a relative agreement between the analytical and numerical analysis was obtained. The numerical results have helped to confirm that the given mudmat satisfies the requirements mentioned in [3, 14].

5 Conclusions

In this work, the presence of very soft clayey layers under the mudmat leads to a high degree of undrained strength heterogeneity that challenges the conventional design procedure basing on the industry-specific codes. To confirm the mudmat foundation stability, a coupled study including an analytical and a numerical study was carried out. The factors of safety determined by the two approaches were in relatively good agreement, essentially in terms of magnitude. The results of these two approaches confirmed the satisfaction of the proposed mudmat according to the requirements specified in the standard API 2GEO. When the degree of undrained strength heterogeneity of the seabed is high, the study of Salencon and Matar (1982) seems to be a helpful reference to determine the foundation shape factor and the undrained bearing capacity.

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