About the uplift resistance of subsea structures

La résistance à l'arrachement des structures sous-marines

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ABSTRACT: The decommissioning of subsea foundations on soft soils is a critical issue for the offshore industry. This requires uplifting subsea structures from the seabed, overcoming the self-weight of the structure, but more importantly the potential suction forces developing at the soil foundation interface. Reduced scale model tests in a geotechnical centrifuge and coupled finite element analysis are presented to reveal the mechanism governing the increase in uplift resistance generated by the development of suction. The predominance of uplift rate in the development of suction, and foundation geometry in the magnitude of suction generated is demonstrated. Effects of loading history and changes in strength through softening and by consolidation are also presented. Mitigation strategies to facilitate the retrieval of subsea structures are discussed, notably with respect to mechanisms generating breakout at the foundation invert and release of suction forces.

RÉSUMÉ : Le décommissionement des structures sous-marines est récemment devenue un problème important pour l'industrie pétrolière. Il implique de pourvoir retirer du sol marin les structures qui y sont posées, en exerçant un force d'arrachement supérieur au poids propre de la structure, potentiellement augmenter des forces de succion qui peuvent se développer à l'interface sol structure. Des essais sur modèles réduits en centrifugeuse, ainsi que des analyses éléments finis sont présentées afin d'identifier les mécanismes gouvernant le développement de ces forces de succion. Ils démontrent l'importance de la vitesse d'arrachement de la fondation, en fonction de sa géométrie et des caractéristiques du sol. La conséquence de l'histoire du chargement de la fondation et des changements de cohésion du sol est également discutée. Des stratégies pour limiter le développement des forces de succion et ainsi faciliter l'arrachement des structures sous-marines sont proposées.

KEYWORDS: Decommissioning, subsea structures, foundation, uplift resistance, consolidation, centrifuge, numerical modelling.

1 INTRODUCTION

Subsea structures include shallow foundations that support deep water pipeline and manifold. Due to high horizontal loads from thermal expansion of deep water pipelines and jumpers, mudmats are often designed with skirts around their perimeters to increase their capacity. The ability to remove subsea structures from deep water is of increasing concern for the offshore industry. Their removal is required for maintenance of aging infrastructure, to abide by environmental regulations during decommissioning and for future re-use. Subsea structures are removed by simply attaching them to cables and pulling them with a crane barge, which barge capacity is a limiting factor. Unexpected uplift resistance can cause significant cost overrun due to the high expense of operating deep water barges.

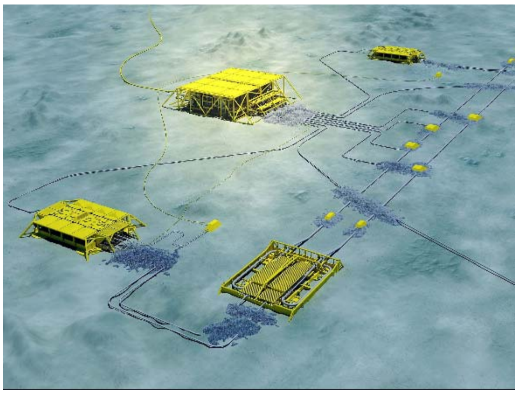

Figure 1. Example of subsea structures.

In the fine grained soils of deep water seabeds, the uplift force required to remove a subsea structure may be amplified by the development of suction at the interface between the foundation and the underlying seabed. Relatively few studies have attempted to examine the development of suction and its influence on uplift resistance. Most of the existing literature has focused on validating mitigation measures to reduce the uplift resistance and facilitate their retrieval and decommissioning (see notably Lieng et al., 1995, and Bhattacharya et al. 2005).

This paper presents a summary of a four year research programme undertaken at the Centre for Offshore Foundation Systems to systematically investigate the mechanisms governing the development of suction during uplift through combined centrifuge and numerical modelling. Prediction methods are developed to estimate the uplift resistance and mitigation measures are proposed based on the suction mechanisms.

2 MECHANISMS GOVERNING UPLIFT RESISTANCE

2 .1 *Uplift undrained mechanism*

A key aspect of the uplift resistance of shallow foundations on soft sediments relates to the potential development of suction forces at the foundation invert and whether a full reverse end bearing mechanism is generated. Knowledge of the failure mechanism as a function of the parameters governing the development of suction is essential for the estimation of the uplift resistance.

To that purpose, Chen et al (2012) performed a series of centrifuge tests on a model foundation with prototype length L of 10 m, width B of 50 m, and skirt length d varying from 0 to 2 m. The foundation, sitting on slightly over consolidated kaolin clay with a strength gradient k of about 1.2 kPa/m, was uplifted from its centre at normalised velocities vB/c_v (with v the uplift rate and c_v the coefficient of consolidation of the soil estimated at 1.5 m/y) ranging from 0.4 to 2000. The modelling enabled the measure of the uplift resistance and of the pore pressures at the three locations of the foundation invert. A brief overview of the results is presented in Figure 2, which plots the evolution of uplift resistance and average excess pore pressure (or suction) at the foundation invert with uplift velocity.

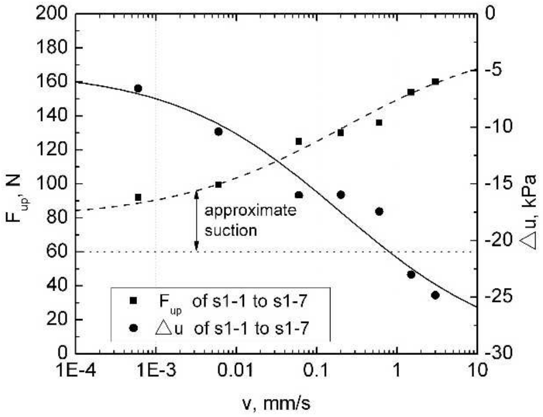

Figure 2. Uplift resistance and suction at the foundation invert during centrifuge test as a function of the uplift rate. The dotted line represents the self-weight of the foundation (i.e. the minimum uplift resistance).

As evident from Figure 2, an increase in uplift rate results in an increase in uplift resistance, associated with increasing negative excess pore pressures, i.e. suction. More interestingly, the shape of the suction development resembles the shape of typical consolidation curves implying that the soil transitions from a drained to an undrained behaviour with increasing uplift rate, with suction being capped when fully undrained conditions are reached. This indicates that the maximum uplift capacity could potentially be predicted using undrained bearing factors, providing that the undrained failure mechanism is identical between compression and uplift.

This particular point was investigated by Li et al. (2015a) who performed coupled numerical analysis using the modified Cam Clay soil model. Figure 3 presents a comparison of the normalised principal in-plane shear strain contours between undrained compression and undrained uplift. The contours demonstrated that the failure mechanism is identical in size and shape, and reversed in direction, warranting the use of a unique bearing factor for both compression and uplift.

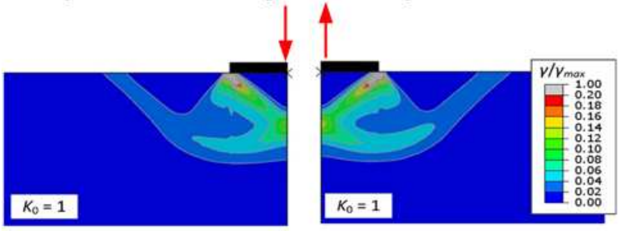

Figure 3. Comparison of undrained failure mechanism between compression (left) and uplift (right).

Further examination of the pore pressure field indicated differences between the two loading cases. Only positive excess pore pressures are generated in compression, whereas both positive and negative pore pressures are generated during undrained uplift, because of the balancing contribution of the change in mean total stresses and deviatoric stresses. This results in the compression resistance increasing, but the uplift resistance decreasing with a reduced loading velocity (i.e. towards partially drained conditions). Both are related to the pore pressure dissipations in the soil as the effective stress path moves towards their corresponding total stress paths.

2.2 *From undrained to drained uplift*

From the discussion in the previous section, it becomes evident that a solution to reduce the uplift resistance of subsea structure is to reduce the uplift velocity to achieve fully drained behaviour of the soil such as the only resistance to overcome is the submerged weight of the foundation. In soft sediments and considering the typical range of coefficient of consolidation, this would typically result in uplift time in the order of weeks, which is not economically viable. Most likely, partially drained conditions might be achieved at best, imposing the necessity to evaluate the uplift rate delimiting partially drained and fully undrained conditions. This was established by Li et al. (2014a) through a comprehensive series of centrifuge tests on square and circular skirted foundation on kaolin clay, uplifted at increasing velocities, exploring maximum normalised velocities three times larger than Chen et al. (2012).

The study revealed two fundamental aspects of the foundation uplift behaviour. Firstly, the transition between partially drained and undrained behaviour occurs at normalised velocity of about 200 (see the transition point in Figure 4), i.e. about one order of magnitude higher than the threshold commonly accepted for foundation in compression (see notably Randolph et al., 2005 among others). This is essentially due to the change in boundary conditions and the associated change in the length of the drainage paths. In compression, the foundation embeds deeper into the soil, increasing the length water has to travel to reach zones of hydrostatic conditions. In contrast, under uplift, the drainage paths are shortened as the foundation is pulled out of the soil. The shortening is further enhanced by the downward movement of the soils associated with the reverse end bearing mechanism and consequently, undrained conditions for uplift are achieved under a higher displacement rate than for compression.

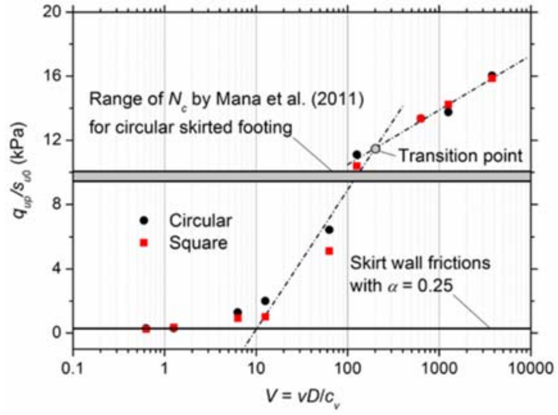

Figure 4. Evolution of uplift resistance (normalised by the initial shear strength s_{u0} at the foundation invert) with normalised uplift velocity. The centrifuge tests explore normalised velocity beyond that achieved by Chen et al. (2012) in Figure 2.

The second finding relates to the evolution of the uplift resistance in the undrained region. As evident in Figure 4, the uplift resistance keeps increasing once fully undrained condition has been reached. The rate of increase is compatible with strength increase due to viscous enhancements (+10-15%, see Einav and Randolph, 2005), such that it can be captured by standard logarithmic formulations based on a reference strain rate at which the undrained shear strength is estimated and a strain rate parameter in the range 0.1-0.2. Accordingly, while undrained conditions cap the magnitude of suction that is developed at the foundation invert, further increase in uplift resistance might be observed if the uplift rate is sufficient to generate viscous effects and increase the undrained shear strength of the soil.

3 EFFECT OF PRELOADING

3 .1 *Experimental evidences*

The previous sections identified the fundamental mechanisms governing the uplift resistance of subsea foundations. However they ignore an important aspect of the foundation behaviour, which is related to its loading history. During installation and operation, subsea foundations experience preloading due to self-weight and potential ballasting or active suction installation. This preloading results in excess pore pressures generated around the foundation, which subsequently dissipate to increase the operative shear strength of the soil and enhance the uplift capacity of the foundation.

The phenomenon of strength increase from consolidation is well characterised and has been recently investigated to predict increase in foundation bearing capacity as a function of the level of preloading applied (defined as the ratio to the un-preloaded ultimate undrained bearing capacity), and the degree of consolidation achieved. Considering the similarity between compression and uplift as illustrated in section 2.1, it may be reasonably assumed that the uplift resistance is also affected by loading history and preloading. Li et al. (2015b) performed a series of uplift centrifuge tests on a skirted circular foundation embedded on slightly overconsolidated kaolin clay, exploring preloading levels ranging from 20 to 80% of the ultimate undrained bearing capacity and degrees of consolidation ranging from 0 to 93%.

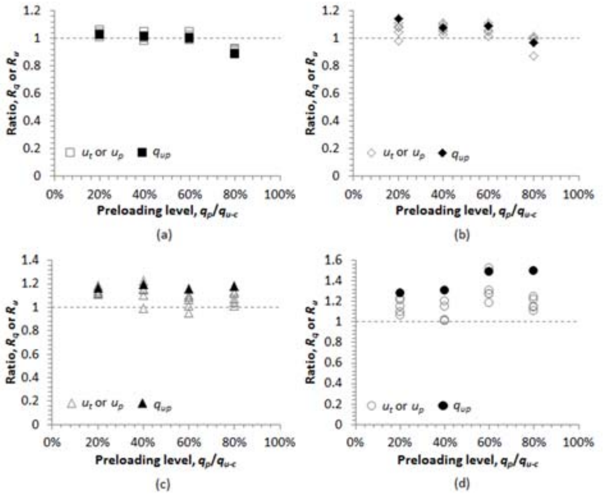

Figure 5. Effect of preloading on uplift resistance. The evolution of normalised uplift resistance (q_{up}) and pore pressure (u_t and u_p) is plotted as a ratio of that without preloading for increasing levels of preloading for degrees of consolidation of <1% (a), 15-31% (b), 45-53%, (c) and 91-93% (d).

Figure 5 presents the centrifuge test results as a function of the evolution of uplift resistance and suction with level of preloading and degree of consolidation. In these plots, results are normalised by values without preloading. It demonstrates significant linear increase in uplift resistance with degree of consolidation. The rate of increase is proportional to the level of preloading, with greater levels of preloading resulting in greater rates of increase in uplift resistance for a given degree of consolidation. However, for the highest level of preloading (e.g. 80%), a reduction in the uplift resistance is evident for degrees of consolidation lower than 30%. This reduction results from the immediate softening of the clay generated by the application of preloading and the associated shearing of the soil, whose magnitude increases with the level of preloading. With consolidation, the strength of the clay increases from the softened value to values greater than the intact shear strength. For low levels of preloading, the reduction in shear strength due to the application of preloading is either marginal or immediately compensated by the increase due to consolidation. For levels of preloading equal to or higher than 80%, when the foundation nearly mobilises a full failure mechanism, the reduction in strength is such that 30% of the consolidation is required for the strength to regain its initial value. This requirement does not prevent higher levels of preloading to exhibit the higher increase in capacity at full consolidation.

3.2 *Modelling preloading effects*

Figure 5 illustrates the importance of foundation load history when predicting the uplift resistance. This is particularly relevant for offshore subsea structures, which are expected to remain in operation over 20-30 years, a time frame sufficiently long for consolidation phenomenon to occur.

The load history can be adequately captured by adjusting the operative shear strength that represents the average strength of the soil mobilised during uplift, as a function of the softening and hardening resulting from preloading and consolidation. This has been achieved by Li et al. (2015b) who developed a framework based on critical state theory, where the changes in undrained shear strength during preloading and consolidation are correlated to the changes in vertical effective stress level of the soil. The framework is based on the well-established relationship between the specific volume and the vertical effective stress, which was used for interpreting the behaviour of risers under episodic cyclic loading (Hodder et al., 2013). The softening is assimilated to that caused by cyclic disturbances (Einav & Randolph, 2005) by relating the damage parameters to the level of preloading and by introducing a factor that accounts for the partial remoulding resulting from one cycle of shearing. The hardening due to consolidation is accounted for by relating the operative shear stress to the pore pressure dissipation in the soil, which is assumed to be linearly related to the degree of consolidation.

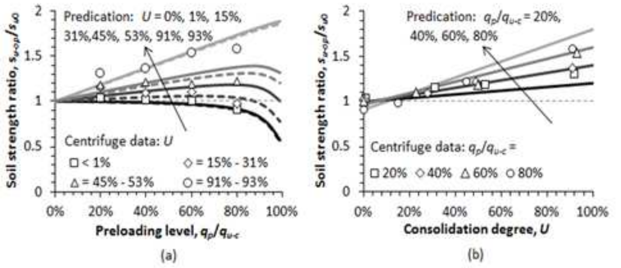

Figure 6. Effect of preloading on uplift resistance. Comparison of analytical modelling with centrifuge tests results.

The framework is compared with the centrifuge results in Figure 6, which shows the evolution of the operative shear strength with level of preloading and degree of consolidation. The framework captures the key aspects of the soil behaviour for a wide range of preloading level and degrees of consolidation, and notably the reduction in uplift resistance at high level of preloading and low degree of consolidation.

It is important to acknowledge that the framework only accounts for preloading effects. During operation, susbsea foundations may experience various loading (such has horizontal cyclic loading on foundations for pipeline end termination, see Cocjin et al., 2014), which complicates the load history and result in varying degrees of softening and hardening. The framework presented above, and that developed by Cocjin et al., (2014) maybe be used to predict operative shear strength changes under these specific loading histories.

4 APPLICATIONS

4 .1 *Predicting uplift resistance*

Findings presented so far provide a rigorous basis to estimate the uplift resistance of subsea structures. This is undertaken as follows:

1. Establish the expected drainage conditions as a function of the uplift rate, geometry of the foundation and coefficient of consolidation of the soil. Undrained conditions are achieved for normalised velocities greater than 200.
2. Under undrained conditions (the most likely case), the maximum uplift capacity q_u can be estimated as:

$$q_u = N_c s_{u0} \tag{1}$$

Where N_c is a bearing factor and s_{u0} the operative shear strength. As discussed, the bearing factor in uplift is identical to the bearing factor in compression and can be evaluated as a function of the skirt embedment and soil shear strength heterogeneity ratio using standard charts or formulations (see Randolph et al., 2004 for details). Such a chart is presented in Figure 7, which shows the comparison of back calculated uplift bearing factors from the centrifuge tests by Chen et al. (2012) with upper bound solutions.

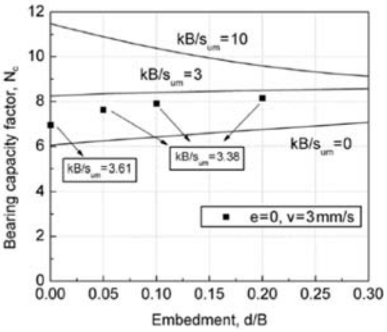

Figure 7. Bearing factors for uplift resistance

The operative shear strength can be evaluated from standard soil characterisation tests (e.g. T-bar tests) and when required adjusted to account for load history as discussed in section 3.2.

3. For partially drained conditions, the bearing factor has to be reduced. The exact value can be estimated from model testing, as presented in Figure 4.

4 .2 *Reducing the uplift resistance*

To facilitate the retrieval and decommissioning of subsea structures, it appears necessary to limit the suction generated at the foundation invert. This can be achieved either by reducing the drainage length, and as such reducing the rate resulting in partially drained conditions and by facilitating the suction breakaway at the soil foundation interface.

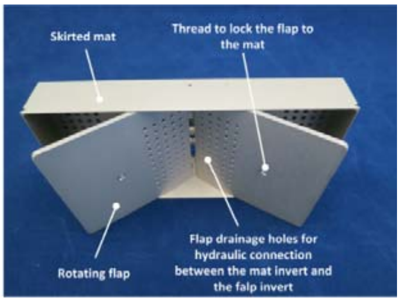

Figure 8. Foundation model with suction flap to reduce uplift resistance

Various options have been explored. Chen et al. (2012) applied eccentric uplift to generate early suction breakaway, observing a reduction in uplift of up to 45%. Li et al. (2014b) introduced perforation into the foundation and observed uplift resistance reduction of up to 75%, with a high number of small perforations being more efficient than a small number of large perforations. More recently, a concept combining perforations and suction flaps, as presented in Figure 8, was explored. Results indicated reduction in uplift resistance of up to 85%. However further work is necessary to assess the practical use of such solutions.

5 CONCLUSIONS

The paper summarises the main outcomes of research undertaken recently to estimate the uplift resistance of subsea structures. It is demonstrated that the uplift resistance can be significantly augmented by the development of suction at the foundation invert. Under undrained conditions, most likely to be relevant for offshore operations, the uplift resistance can be estimated based on bearing factors identical to those in compression and an operative shear strength that can be adjusted to account for load history. The uplift resistance can be reduced by using a suction flap, perforated foundation or eccentric uplift to limit the suction generated, although their practicability needs to be further assessed.

3 ACKNOWLEDGEMENTS

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