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Experimental and Analytical Studies on Pull-out Resistance of Suction Foundation

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ABSTRACT
The purpose of this study is to clarify the mechanism of pull-out resistance for shallow suction foundation in clay layer and to propose a method estimating the pull-out resistance. The effects of penetration depth, open ratio, cohesion of clay layer and pull-out velocity on suction and pull-out resistance are investigated through a series of laboratory experiment and a finite element analysis which is introduced to look deep into the failure mode of suction foundation. The theoretical pull-out resistance is compared with the measured one in order to investigate the validity of proposed equations on the pull-out resistance. The following main conclusions are obtained from the study; 1) three different failure modes are experimentally and analytically confirmed to exist, 2) suction and pull-out resistance are affected by the penetration depth, open ratio, cohesion of clay layer and pull-out velocity, 3) the pull-out resistance becomes larger respectively as the cohesion of clay layer, depth ratio of foundation and pull-out velocity increase, and 4) the theoretically estimated pull-out resistance compares fairly well with the experimental one.

KEY WORDS: analysis; clay; experiment; offshore; pull-out resistance; shallow foundation; suction

INTRODUCTION

Suction foundations have been widely applied to many varieties of offshore structures and facilities such as gravity based structure, tension leg platform, anchor pile, semi-submersible production system and so on (Randolph et al., 2005). In Japan, suction foundations were used for breakwaters (Ohshima, 1962, Takahashi, 2001, Zen et al., 1998 and 2003) and fender caisson (Masui et al., 2001). Studies on suction anchor are reported as well (Inoue et al., 1976 among others).

Taking advantage of suction, two different applications of suction forces are considered; one is the suction artificially applied to foundations during the installation by pumping water from inside foundations. The other is the suction generated by the motion of foundations due to ocean wave action after the installation. Design issues for the suction foundation, therefore, can be divided into those concerned with installation and those associated with operations. This paper focuses on the suction caused during operations in relation to the pull-out resistance of suction foundation.

Suction caissons for anchoring system comprise generally with a length to diameter ratio (called the depth ratio herein) in the range 3 to 6. The ratio more than 1 is generally considered as the deep foundation. Many interesting studies have been made on the pull-out resistance of deep foundation (Andersen et al., 1999 among others). On the other hand, quite few studies on the pull-out resistance of shallow foundation have been reported. Furthermore, studies on the suction during pulling out of foundation are very limited. Inoue et al. (1976) reported the vacuum force caused by pull-out of cylindrical solid suction anchor from sandy seabed. The pull-out resistance of shallow suction foundation in clay layer is, however, not well known. Therefore, the purpose of this study is to make clear of the mechanism of pull-out resistance of shallow suction foundation in clay layer in terms of suction, and to propose a method to estimate the pull-out resistance.

PULL-OUT RESISTANCE OF SUCTION FOUNDATION

When shallow suction foundation is pulled out from clay seabed, three types of failure modes can be considered as shown in Figs.1 to 3. First one in Fig.1 called “Failure mode A” herein is the mode where only suction caisson is slipped out of seabed. Second in Fig.2 is called “Failure mode B” where the soil inside caisson moves together with caisson. “Failure mode C” in Fig.3 represents the mode where soil wedge is formed at the bottom edge of caisson. Taking account of equilibrium of forces in these three failure modes, the following equations (1) to (3) are obtained;

<u>Failure mode A</u>

$$F_{RA} = p_{su} \cdot A_u + p_{sd} \cdot A_t + c_u \cdot 2\pi \cdot r_{out} \cdot D + c_u \cdot 2\pi \cdot r_{in} \cdot D + W' \qquad (1)$$

<u>Failure mode B</u>

$$F_{RB} = p_{sd} \cdot \left(\pi \cdot r_{out}^{\ 2}\right) + c_u \cdot 2\pi \cdot r_{out} \cdot D + W' + W_s' \qquad (2)$$

<u>Failure mode C</u>

$$F_{RC} = p_{sd} \cdot \left(\pi \cdot r_{out}^{\ 2}\right) + c_u \cdot 2\pi \cdot r_{out} \cdot D + W' + W_s + W_s' + \left(\gamma \cdot D - 6c_u\right) \cdot \pi \cdot r_{out}^{\ 2} \qquad (3)$$