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Long-term settlement analysis of partially improved thick clay deposit

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ABSTRACT

Prefabricated vertical drains (PVDs) were partially or fully penetrated into thick clay deposits at a reclamation project in Busan City, Korea. Elasto-viscoplastic finite element analysis is conducted to predict the long-term behaviors using a macro-element technique. Settlements predicted using laboratory-based and back-analyzed soil parameters are in good agreement with monitored data. The relationships of time versus volumetric strain and excess pore pressure at each element are effective in investigating the overall behaviors; that is, the settlements in the improved zone degrade from steep to gentle slopes, whereas those in the unimproved zone change with a relatively gentle slope. The effect of partially penetrated PVD on u_e dissipation appears to be in relatively good agreement with results obtained by Ong et al.'s (2012) method.

1. Introduction

Ground improvement with vertical drains (largely, prefabricated vertical drains, known as PVDs) has been extensively performed in many parts of the world (Chai et al., 2010; Indraratna et al., 2012; Liu and Chu, 2009; Lo et al., 2008; Rowe and Taechakumthorn, 2008; Saowapakpiboon et al., 2011). Advanced rigs allow the installation of PVDs into depths of 50 m or more. However, the installation depth is generally determined by locally available rigs, variations in clay thickness and consistency, and economy, among others. Hence, the vertical drains are often partially or fully penetrated into the clay deposits. In cases of fully penetrated vertical drains, primary consolidation may be largely completed within a relatively short time and thereafter secondary compression occurs over an extended period. In the case of partially penetrated drains, primary consolidation may first occur and then be completed within a shorter time in the PVD-improved zone. However, primary consolidation continues to occur in the unimproved zone, relying on its thickness for a longer time. Several rigorous and approximate consolidation solutions have been developed for fully penetrated drains (Barron, 1948; Carillo, 1942; Hansbo, 1981; Lo, 1991; Onoue, 1988; Yoshikuni and Nakanodo, 1974; Xie, 1987). However, no analytical solution is available for the partially penetrated drains. The solutions have to be determined using numerical techniques (Hart et al., 1958; Dames and Moore, 1982; Ong et al., 2012; Runesson et al., 1985; Xie, 1987; Zeng and Xie, 1989). Unfortunately, consolidation behaviors predicted by the solutions show a different trend from that of measured records (Chung et al., 2009). Likewise, the reliable prediction of such behaviors with laboratory or field test results is difficult to achieve. For instance, the prediction of several reclamation projects in Singapore was determined to have an accuracy of at most ±20% (Bo et al., 2003). The final settlement and consolidation time of large-scale reclamation projects in the Nakdong River Delta area, Busan City of Korea were underestimated by 120–200% and 200–600%, respectively (Chung, 1999). Decisive differential settlement problems occasionally occur in the reclaimed area where PVDs have been partially or fully penetrated.

Two hypotheses (hypotheses A and B) that vary from traditional concept have been formulated: i.e., time-dependent or creep settlement occurs during or after the primary consolidation (Leroueil et al., 1990). However, proving any of the hypotheses using long-term field monitoring data is difficult (Bertok, 1987; Lo et al., 2008; Mimura et al., 2003; Mimura and Jang, 2005b). A typical example is found in several man-made reclaimed islands including Kansai International Airport in Osaka Bay, where an extremely large long-term settlement has occurred in quasi-overconsolidated Pleistocene clays (Mimura et al., 2003; Mimura and Jang, 2005b). To predict a time-dependent behavior, numerous approaches have been conducted with strain-rate dependent models (Kim and Leroueil, 2001; Leroueil et al., 1983) and elasto-viscoplastic (or rheological) models (Adachi and Okano, 1974; Adachi and Oka,

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1982; Karim et al., 2010; Kutter and Sathialingam, 1992; Mirjalili et al., 2012; Sekiguchi, 1977; Yin, 2001; Yin and Graham, 1989; Yin et al., 2002). A time-dependent behavior during recompression of the Osaka Pleistocene clays was also considered (Mimura and Jang, 2004, 2005a).

This study focuses on the long-term settlement prediction of thick clay deposit where PVD has been partially penetrated for a reclamation project (Noksan Industrial Land Development Project). The project area is located in the east of Busan New Port (BNP), Busan City of Korea. For this purpose, two monitored results are typically considered in the area in which PVD was partially and fully penetrated. An elasto-viscoplastic finite element analysis (FEA) is performed for both cases in accordance with soil investigation data or back-analyzed results. The analyzed settlement is validated through comparison with the monitored data. Variations in excess pore pressures are then investigated. The effect of partial improvement in the thick clay deposit is observed during the monitored and the subsequent, long-term durations. Moreover, the effect of PVD on the vertical drainage, which occurred in the unimproved zone, is discussed.

2. Site description

2.1. Overview of the reclamation project

The Noksan reclamation site is located southwest of the Nakdong River Delta, as shown in Fig. 1. The area had a total of 6,956,000 m^2. The sea bed was approximately 2–3 m below the mean sea level. The reclamation work was initiated in the early 1990s and continued for 10 years or more. A geotextile sheet was placed, and crushed rocks that were equal to or smaller than 10 cm in diameter were largely placed (typically, 5 m in height). A type of PVD (100 mm × 3 mm; known as Kolon drain board) was installed at a designated depth. A triangular drain spacing of 1.5 m was largely applied based on soil condition. A vibratory rig, extensively used in the epoch and with a maximum installation depth of approximately 30 m was adopted. Hence, PVD was partially or fully penetrated into the clay deposit. Various monitoring instruments, including surface settlement gauge (plate type), extensometer (spider magnetic type), piezometer (vibrating wire type), and inclinometer (multi-stepped type), were installed. Unfortunately, the installation was set up at the early stage of or immediately after the fill placement. Information regarding the two monitored

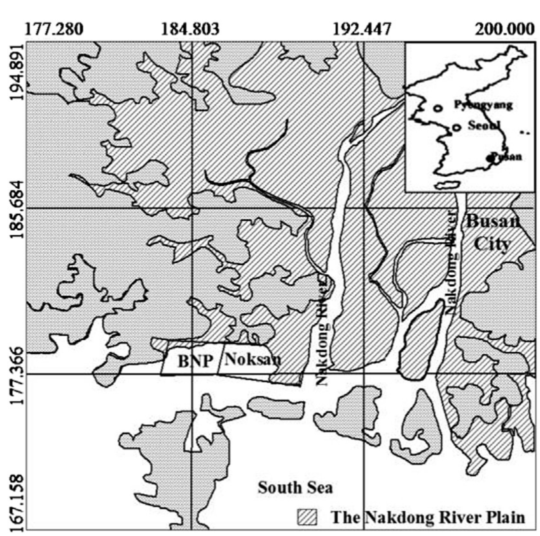

Fig. 1. Reclaimed sites in the Nakdong deltaic area.

locations, typically selected for full (SP-21) and partial (SP-15) penetration of PVD, is shown in Table 1. At each location, a surface settlement gauge and an extensometer were installed (Fig. 2).

2.2. Geology and geotechnical properties

The deposit at the construction site generally consisted of a sand/silt soil, soft to firm silty clay, sand and gravel layers overlying bed rocks (Chung et al., 2002, 2003a,b). The deposit appeared to vary from one site to another, ranging from 30 m to 70 m in thickness. The clay deposit was divided into upper clay (0–30 m), described as soft and normally consolidated, and lower clay (30–60 m), described as firm to hard and slightly overconsolidated. A detailed and comprehensive investigation was carried out at the BNP site close to the Noksan site (Chung et al., 2002, 2003b). On the basis of this result, the age of the clay varied from 5000 years at the top to 10,000 years at the depth of 30 m. The depositional environment of the upper clay showed a continuity (near sea, inner shelf, and near sea environment), whereas that of the lower clay exhibited a discontinuity (mixed by tidal-flat, inner shelf, near sea, estuarine channel, and coast). A sand layer between the two clay layers occasionally appeared.

A typical soil profile of the Noksan area is presented in Fig. 3.The unit weight of the clay varied from 1.5 Mg/m^3 to 1.75 Mg/m^3. The water content ranged from 45% to 60%. The plasticity index of the upper clay varied from 25% to 35%, and that for the lower clay ranged from 15% to 30%. The liquid limit was equal to or higher than the water content. The undrained shear strength from field vane, $s_{u,FV}$ linearly increased with increasing depth, as determined from various normally consolidated clays. The compression index C_c obtained using a conventional oedometer test increased from 0.3 to 1.2 at depths of 0–30 m. This index slightly decreased to 0.3 at the depth of 50 m. The consolidation yield stress σ'_p was estimated to be less than the effective overburden stresses at depths below 15 m, which may result from the adopted sampling and consolidation test methods (Chung et al., 2003a). The soil properties of each layer are summarized in Table 2.

3. Elasto-viscoplastic FEA

3.1. Constitutive model and formulation

A modified plane strain version of elasto-viscoplastic finite element analysis (Sekiguchi et al., 1982) was implemented. The constitutive model adopted in the version includes a viscoplastic flow rule, generally expressed as follows:

$$\dot{\varepsilon}^{p}_{ij} = \Lambda \frac{\partial F}{\partial \sigma'_{ij}} \quad (1)$$

where F is the viscoplastic potential, and Λ is the proportional constant. The viscoplastic potential F is defined as follows:

$$F = \alpha \cdot \ln\left[1 + \frac{\dot{v}_0 \cdot t}{\alpha}\exp\left(\frac{f}{\alpha}\right)\right] = v^{p} \quad (2)$$

Table 1
Conditions of partially and fully penetrated PVD.

Location no.	Clay thickness (m)	Length of PVD (m)	Spacing of PVD (m)	Drainage condition
SP-21	18.0	18.0	1.5	Fully improved, two-way
SP-15	48.5	23.0	1.5	Partially improved, one-way