Tunnelling and Underground Space Technology 83 (2019) 243–253

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Characterization of deep cement mixing wall behavior using wall-to-excavation shape factor

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ARTICLE INFO

Keywords:
Deep cement mixing
Excavation
Unbraced
Wall slenderness
Soft ground

ABSTRACT

This research proposes a novel performance-based design concept to characterize the horizontal displacement of DCM walls and the responsiveness of wall displacement to wall strength. In the study, a DCM-walled excavation project was utilized as the base case. Parametric study was then conducted to examine the wall behavior with diverse wall shapes. In addition, the responsiveness of wall to material strength and the effect of variable excavation depths on the wall behavior were determined. A downscaled field test was carried out to validate the parametric study. The wall-to-excavation shape factor was subsequently proposed as the design concept to facilitate the selection of suitable wall shape to a given excavation depth. Further validation indicated that the wall-to-excavation shape factor effectively characterized the wall horizontal displacement and the responsiveness of displacement to wall strength. In essence, the proposed concept is of use to the preliminary design of DCM walls and helps identify the cause of excavation failure.

1. Introduction

Across the globe, urbanization contributes to scarcity of land to accommodate ever-increasing populations, a phenomenon which leads to growing utilization of underground space (Hsiung et al., 2018; Qihu, 2016; Wallace and Ng, 2016). With urbanization comes the emergence of densely populated areas. In dense residential areas, regulations on noise, pollution and vibration related to building construction are particularly rigorous. The deep cement mixing (DCM) wall is thus an effective solution to underground excavation projects in the urban environment. The DCM walls were successfully implemented in many countries, such as, Sweden (Ignat et al., 2016, 2015), Belgium (Denies et al., 2012), Portugal (António et al., 2012; Gomes Correia et al., 2013), USA (Andromalos and Bahner, 2003; Bahner and Naguib, 1998; Lindquist et al., 2010; Nicholson et al., 1998), Japan (Terashi, 1997), China (Shao et al., 2005; Wang et al., 2010; Xu, 2007), and Thailand (Jamsawang et al., 2017; Tanseng, 2012).

Unlike a braced DCM wall which is suitable for deep excavation, an unbraced DCM wall is optimal for intermediate excavation depths (i.e., one- or two-story basement) (Shao et al., 2005). Moreover, no bracing installation is required, resulting in lower construction costs and shorter completion time (Bahner and Naguib, 1998; Shao et al., 2005). Specifically, the DCM retaining walls for excavation are categorized into reinforced (Andromalos and Bahner, 2003; Bahner and Naguib, 1998; O'Rourke and O'Donnell, 1997; Rutherford et al., 2007; Shao et al., 2005; Yang, 2003) and unreinforced DCM walls (Wang et al., 2010; Xu, 2007). The focus of this research is the unreinforced DCM wall.

The traditional DCM walls are massive in shape but low in stiffness. This could be attributed to the fact that most traditional DCM walls were constructed based on the gravity wall principle (Briaud et al., 2000; Mun et al., 2012; Shao et al., 2005), resulting in the massive size and low stiffness). Due to limited space for construction in urban areas, modern DCM walls are elongated and slender with deeper embedment (Jamsawang et al., 2017; Tanseng, 2012), relative to the traditional DCM wall. For intermediate excavation depths, the thicknesses of DCM walls constructed in the past varied from 5.6 m (column-wall pattern with 8.5 m high) to 2.8 m (block pattern with 15 m high). In fact, the difference in wall shapes contributes to differences in the horizontal displacement and structural response between the traditional (gravity wall-based) and modern DCM walls.

Besides, the beam theory, which is appropriate for rigid and slender conventional retaining walls, e.g., concrete diaphragm walls, is inapplicable to the DCM walls. This could be attributed to different stiffness and slenderness between the gravity wall, conventional walls, and DCM walls. The strength of DCM (wall material), which has a linear relationship with stiffness (e.g., Jamsawang et al., 2017, 2016;

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https://doi.org/10.1016/j.tust.2018.09.033
Received 10 May 2018; Received in revised form 23 August 2018; Accepted 30 September 2018
0886-7798/

Jongpradist et al., 2010, 2018; Lorenzo and Bergado, 2006; Voottipruex et al., 2011), is typically in the range of 600–1800 kPa in current practice. The strength of DCM wall is subject to the cement content and site-specific conditions (Mun et al., 2012; Rutherford et al., 2007; Shao et al., 2005) but not in direct proportion to the cement content (e.g., Jongpradist et al., 2011; Lorenzo et al., 2006; Uddin et al., 1997).

To ensure that the serviceability limit state under urban environment is satisfied, a common design criterion is to limit the maximum wall deflection. Unnecessarily strict constraints usually lead to uneconomic design. Therefore, reliable estimates of wall deflections under working conditions are essential. For the conventional non-DCM walls, several techniques were proposed to characterize the wall movement behavior, including Rowe's flexibility number (Rowe, 1952), system stiffness (Clough et al., 1989), displacement flexibility number (Addenbrooke, 1994), and relative stiffness ratio (Bryson and Zapana–Medina, 2010). All of them are used for braced excavation (e.g., Hong et al., 2015; Zhang and Goh, 2016). However, unlike the conventional walls mainly relying on the bracing system, the unbraced DCM wall is composed of only the wall and surrounding soils. Thus, the influencing factors of the movement behavior of unbraced DCM walls are the material properties, wall shape, excavation depth, and soil conditions. Fig. 1 illustrates the schematic of an unbraced DCM wall system and relevant notations.

Despite the widespread use of DCM walls, there exists no established analysis and design method for reinforced and unreinforced DCM walls. Therefore, a performance-based design concept is essential to understanding the characteristics of the deformation and behavior of DCM walls. Specifically, according to Wang et al. (2010), the deformation behavior of unreinforced DCM walls lay between that of flexible and rigid walls. Furthermore, databases of DCM-walled excavations showed variations in the maximum horizontal displacement location, dispersing along the wall length (Fig. 2). The dispersion suggests multiple horizontal displacement patterns in the unbraced-unreinforced DCM-walled excavation, giving rise to various mechanical wall behaviors.

Thus, this research proposes a novel performance-based design concept (i.e., the wall-to-excavation shape factor) to characterize the horizontal displacement of unbraced-unreinforced DCM walls and reveal the responsiveness of displacement behavior to wall compressive strength. In the concept development, a finite element model was generated as the base case and verified. Parametric study was then carried out, given various wall shapes; and three displacement patterns

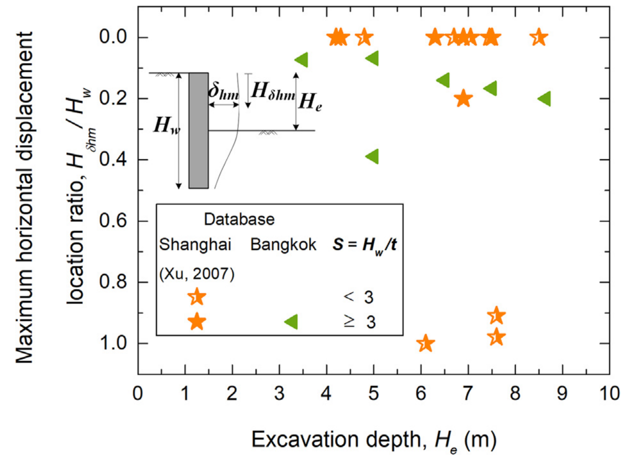

Fig. 2. Database of unbraced-unreinforced DCM walls of excavation projects in Shanghai, China; and Bangkok, Thailand.

determined: modes A, B, and C. Furthermore, the responsiveness of displacement behavior to wall strength was examined, given variable slenderness ratios and compressive strengths. The effect of different excavation depth ratios and wall strength improvement on the displacement was also determined. A downscaled field test was subsequently carried out to validate the parametric study. Together with the database of field measurements in previous works, the effectiveness of the proposed concept is verified.

2. Preliminary investigation

2.1. Base case

Fig. 3(a) and (b) illustrate a 27 m × 40 m × 5 m (W × L × H) excavation for the DCM-walled basement of a high-rise building and the cross-sectional view of the wall, respectively. The construction project (the base case) location is in a densely-populated area in Thailand's capital Bangkok, which is surrounded by residential buildings. The noise and vibration regulations must be strictly observed, necessitating the implementation of unreinforced DCM walls without bracing. The wall was of three rows of 1 m-diameter DCM columns for 15 m in depth,

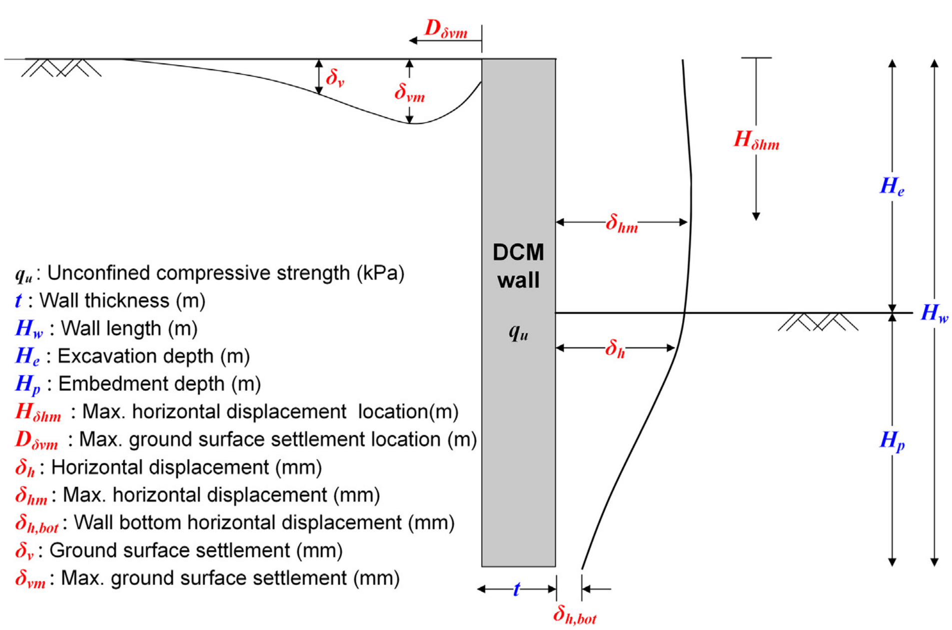

Fig. 1. Schematic of an unbraced-unreinforced DCM wall system and notations.