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Influence of Surcharge Strip Loads on the Behaviour of Cantilever Sheet Pile Walls: A Numerical Study by ABAQUS

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Abstract. Cantilever sheet pile walls are the ancient earth retaining systems extensively used in a deep excavation in congested urban areas adjacent to existing structures. In the present investigation, the two-dimensional finite element method has been implemented to study the behavior of sheet piles under a uniform surcharge strip foundation load placed at different positions from the wall top edge in dense sand. Sequential excavation of front-fill soil is done in four layers to incorporate the construction effects during wall installation. The present study has found that a foundation of 2 m width has been the critical one based on maximum wall deformation criteria under surcharge loading irrespective of the foundation's position. A parametric study is performed by varying the wall embedded depth and the foundations position above and below the backfill surface to determine the wall deformation, bending moment, and ground settlement behavior. The wall deformation, bending moment, and ground settlement are maximum when the surcharge load is positioned near the wall's top edge. As the surcharge distance increases both above and below the backfill surface, its effect decreases. The present numerical model validation has been done with available literature.

Keywords: Cantilever Sheet Pile Wall (CSPW), Surcharge Strip Load, Finite Element (FE) Method, Wall Deformation, Bending Moment (BM), Ground Settlement (GS).

1 Introduction

CSPWs are generally used to retain temporary and permanent excavations of limited heights, usually less than 5 m [1]. However, a surcharge may also exist on the field at any distance from the CSPW, for example, vehicles, buildings, and storage areas [2]. Those additional surcharge loads on the ground surface create additional stress on the wall, causing additional wall deflection, BM, and backfill GS [3]. Over the years, the study of the CSPW has been carried out by several researchers. A laboratory model test and numerical analysis have been conducted using the computer code PLAXIS on a CSPW under surcharge strip loads in the sand [4]. Numerical analysis by the computer program FLAC2D has been performed for a braced excavation to calculate the different design parameters that considerably affect the excavation behavior [5]. Numerical analysis of CSPWs with strip load on backfill soil has been performed using a finite difference-based method by FLAC2D [6]. A numerical study has been performed using ABAQUS 2D to determine the behavior of cantilever concrete diaphragm walls under sequential excavation of frontfill soil [7]. Laboratory experimental study has been performed to evaluate the behavior of a CSPW adjacent to a strip footing in the sand [8].

However, the literature shows a considerable research gap in the influence of surcharge strip load on CSPWs placed at varying vertical and horizontal distances from the wall top edge. The present study fills this existing research gap. Hence to achieve the goal, a two-dimensional FE method has been implemented to study the behavior of CSPWs under a uniform surcharge strip foundation load placed at different positions from the wall top in dense sand.

2 Wall and Soil Profiles

In the present numerical study, two-dimensional FE modeling is done by ABAQUS. The SKZ 38 is chosen as CSPW from Skyline Steel technical product manual [9]. The overall height of the CSPW selected in the present study is 10 m, where the height (H) in the excavation zone is 4 m and an embedded depth (D) of 6 m. The properties of the CSPW are shown in Table 1. Dense sand is used in the present numerical analysis. The soil parameters used are shown in Table 2.

Table 1. Description of sheet pile used in the present study (adopted from Skyline Steel 2017).

Section provided	Cross-sectional area (cm^2/m)	Section modulus (cm^3/m)	Moment of inertia (cm^4/m)
SKZ 38	234.40	3350	76588

Table 2. Soil parameters used in the present study (after Singh and Chatterjee 2020).

Soil type	Unit weight [γ] (kN/m^3)	Friction angle [φ] (degree)	Poisson's ratio [μ]	Young's modulus [E] (MPa)
Dense sand	18.4	39	0.30	90

3 Numerical Modeling

The ABAQUS software package has been chosen to perform two-dimensional FE modeling of the CSPW and soil. Several researchers have successfully used the Mohr-Coulomb constitutive model for sandy soils in FE modeling of retaining structures [1-3, 5-7]. Hence, the present study uses an elastic-perfectly plastic Mohr-Coulomb model with a non-associated flow rule to model the soil. To represent the elastic strain component of the soil behavior, the parameters required for the Mohr-Coulomb model are the Modulus of elasticity, E, and Poisson's ratio, μ. To represent the plastic strain component of the soil behavior, the effective strength parameters are cohesion, c', and angle of friction, φ', along with the dilation angle, ψ, which are required. The soil and sheet pile is modeled by an 8-nodded biquadratic plane strain quadrilateral element with reduced integration (CPE8R). The vertical boundary of the model is free in the vertical direction, and the bottom boundary is kept fixed.

The load is applied in four steps: the geostatic step is used by taking an earth pressure coefficient at rest condition (k_0) calculated by Jaky's equation (1-sin φ) to generate the initial conditions to keep the model in equilibrium. In the second step, self-weight is applied to the entire model, and in the third step, the surcharge load (q) of 30 kPa is applied on the backfill soil using a model footing, and in the last step, the excavation is done sequentially in layers each having 1 m thick. A schematic diagram of the soil-wall model with dimensions is shown in Fig. 1.

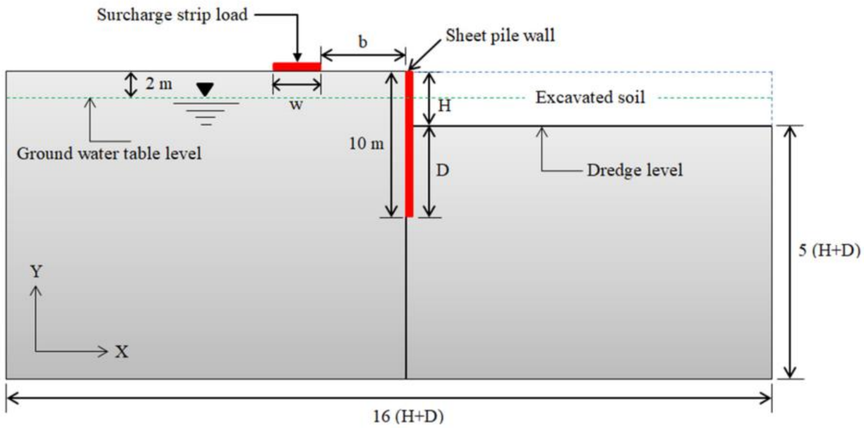

Fig. 1. Schematic diagram of the soil-wall model used in the present study.

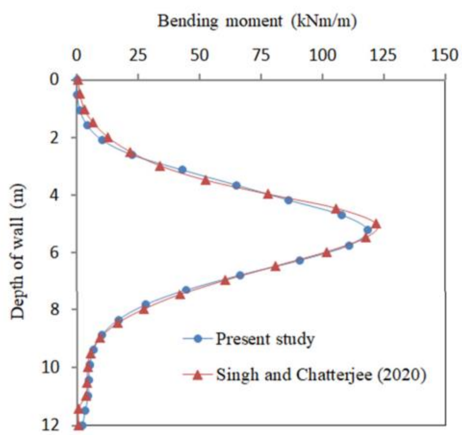

Fig. 2. A comparison of BM along the wall depth is found in the present analysis and that of Singh and Chatterjee (2020).

4 Numerical Model Validation

To verify the present numerical model, the result obtained from the model test is compared with the results (based on the numerical model study) reported by Singh and Chatterjee (2020). The numerical analysis performed by Singh and Chatterjee (2020) is based on the finite difference-based method by FLAC2D. For the validation purpose, a uniform surcharge load of magnitude 20 kPa is imposed on the backfill ground surface for infinite length as applied by Singh and Chatterjee (2020). Similar soil and wall profiles and similar boundary conditions are maintained for the present numerical model as considered by Singh and Chatterjee (2020). Fig. 2 represents the BM variation curve with wall depth for the present study and the study reported by Singh and Chatterjee (2020). The comparison curves show good agreement between the present study and the study of Singh and Chatterjee (2020).

5 Results and Discussions

Wall deflection, BM, and GSs are studied for a surcharge strip load of 30 kPa positioned horizontally at a distance of b = 0.0 m, 2.0 m, 4.0 m, and 6.0 m (b = horizontal distance of surcharge load along the backfill soil from the wall top edge) and vertically along the wall depth at a distance of u = 0.0 m, 1.0 m, 2.0 m, 3.0 m, and 4.0 m (u = vertical distance of surcharge load along the wall depth from the wall top edge).

5.1 Determination of the Critical Width of Surcharge Load

The critical width of a surcharge load is the optimum width which gives the maximum value of wall deformation and BM for any surcharge load magnitude. The present study determines the critical surcharge width based on maximum wall deflection criteria. To determine the critical width, a 30 kPa surcharge load of varying widths positioned at horizontal distances, b = 0.0 m, 2.0 m, 4.0 m, and 6.0 m. The variable width of the surcharge is taken as w = 1 m, 2 m, 3 m, 4 m, and 6 m. The maximum wall deflection with a 30 kPa surcharge magnitude of variable width positioned at various horizontal locations is shown in Fig. 3. Fig. 3 indicates that a surcharge width of 2 m produces maximum wall deformations in all horizontal surcharge positions. Hence, 2 m width is considered critical in the present study. Fig. 4 displays the wall deflection profile with a 30 kPa surcharge placed at b = 0.0 m and u = 0.0 m for varying surcharge width.

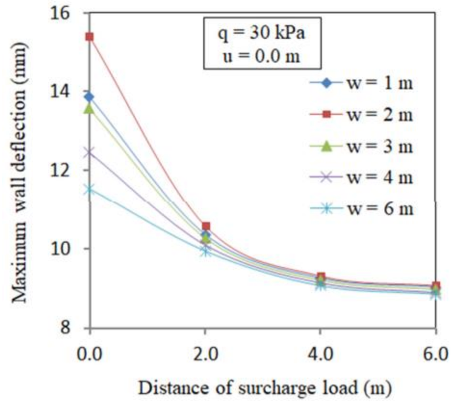

Fig. 3. Variation of maximum wall deflection with a horizontal distance of surcharge load for variable surcharge width.

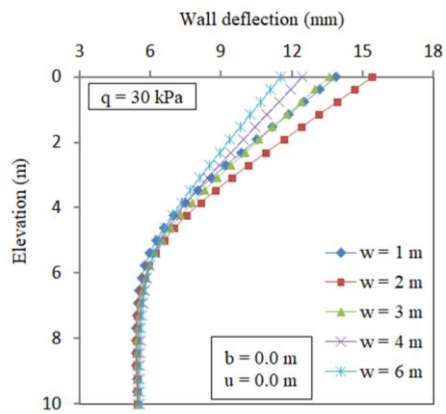

Fig. 4. Variation of wall deflection with elevation for variable surcharge width.

5.2 Effect of Surcharge Position in the Horizontal Direction on Wall Deflection, BM and GS

To determine the effect of surcharge strip load on wall deflection, BM, and maximum GS, a surcharge load of width 2 m with a magnitude of 30 kPa, is placed at various horizontal positions of b = 0.0 m, 2.0 m, 4.0 m, and 6.0 m over the backfill soil. Figs. 5 (a) and 5 (b) show the wall deflection and BM profile respectively, along the wall depth for a 30 kPa surcharge load placed at various horizontal positions. Both the figures indicate that with the increase in surcharge distance along the backfill surface, the deflection and BM significantly reduce. After a distance of 4 m, the effect of surcharge on wall deflection and BM profile is insignificant. An increase in surcharge distance over the backfill soil results in a 1.49, 1.62, and 1.68 times decrease in maximum wall deflection for surcharge positions 2.0 m, 4.0 m, and 6.0 m respectively, compared to surcharge position of b = 0.0 m. The increase in surcharge distance over the backfill soil results in a 2.04, 2.55, and 2.7 times decrease in maximum BMs for surcharge positions 2.0 m, 4.0 m, and 6.0 m respectively, compared to surcharge position of b = 0.0 m.

Fig. 6 shows the variation of maximum GS with surcharge distance in the horizontal direction for 30 kPa surcharge load. Increase in surcharge distance results in a significant reduction in the maximum GS. After a surcharge distance of 4 m, the maximum GS shows a linear trend, which indicates that the effect of surcharge on GS after 4 m is insignificant. An increase in surcharge distance over the backfill soil results in a 2.08, 2.76, and 3.17 times decrease in maximum wall deflection for surcharge positions 2.0 m, 4.0 m, and 6.0 m respectively, compared to surcharge position of b = 0.0 m.

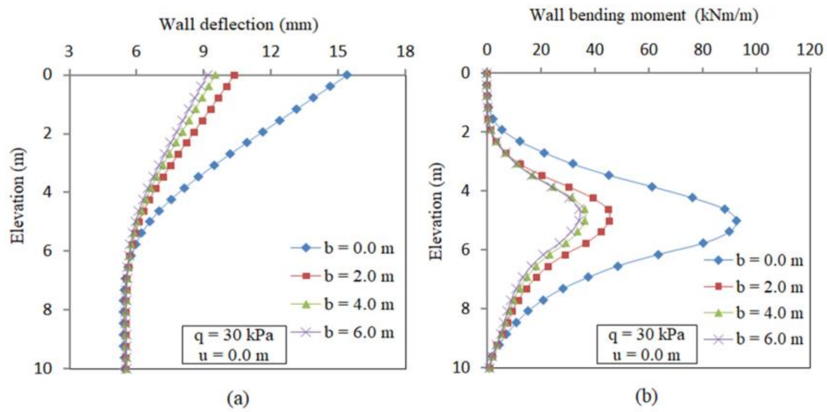

Fig. 5. Variation of (a) wall deflection, and (b) BM along the wall depth for surcharge load placed at different horizontal positions.

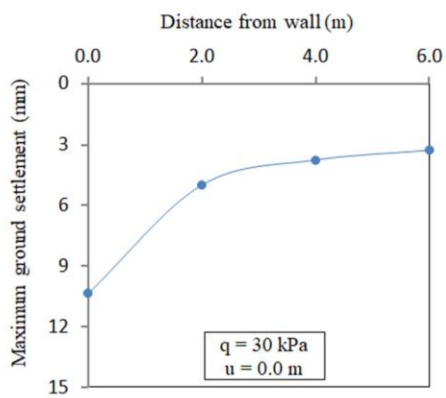

Fig. 6. Variation of maximum GS for surcharge load placed at different horizontal positions.

5.3 Effect of Surcharge Position in the Vertical Direction on Wall Deflection and BM

To determine the influence of surcharge strip load on wall deflection and BM, a surcharge load of width 2 m with a magnitude of 30 kPa is placed at various vertical positions of u = 0.0 m, 1.0 m, 2.0 m, 3.0 m, and 4.0 m along the wall depth. Figs. 7 (a) and 7 (b) shows the wall deflection and BM profile respectively, along the wall depth for a 30 kPa surcharge load placed at different vertical positions. Both the figures indicate that with the increase in surcharge distance vertically along the wall depth, the deflection and BM significantly reduce. However, after a vertical distance of 2 m, the effect of surcharge on wall deflection and BM profile is insignificant. An increase in surcharge distance along the wall depth results in 1.26, 1.51, 1.58, and 1.59 times decrease in maximum wall deflection for surcharge positions 1.0 m, 2.0 m, 3.0 m, and 4.0 m respectively, compared to surcharge position of u = 0.0 m. An increase in surcharge distance along the wall depth results in 1.42, 2.12, 2.49, and 2.50 times decrease in maximum BMs for surcharge positions 1.0 m, 2.0 m, 3.0 m, and 4.0 m respectively, compared to surcharge position of u = 0.0 m.

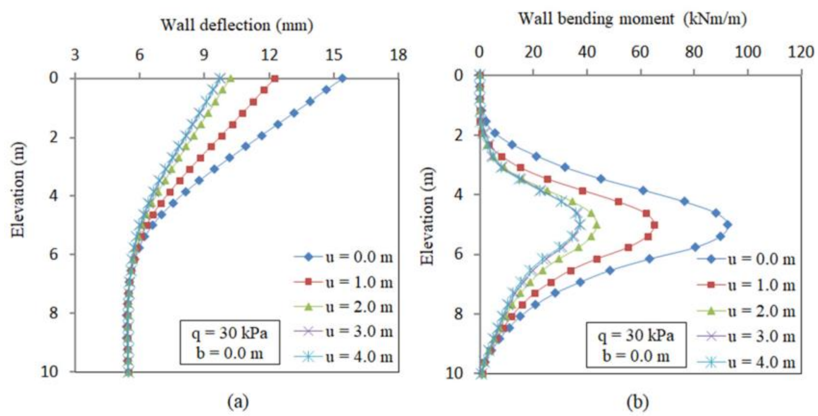

Fig. 7. (a) Wall deflection, and (b) BM profile along the wall depth for surcharge load placed at different vertical positions.

5.4 Effect of Wall Embedded Depth on Wall Deflection and BM

To determine the influence of embedded depth on wall deflection and BM, a surcharge load of width 2 m with a magnitude of 30 kPa is positioned at b = 0.0 m and u = 0.0 m. The embedded depths chosen in the present study are D = 4 m, 6 m, and 8 m. Figs. 8 (a) and 8 (b) show the wall deflection and BM profile respectively, with varying embedded depths. Fig. 8 (a) indicates that an increase in the embedded depth results in a decrease in the wall deflection profile because higher the embedded depth provides higher passive restraint, which provides more lateral stability of the ASPW. But the opposite trend is displayed as per Fig. 8 (b), where an increase in embedded depth results in an increase in BM because of higher passive restraint below the dredge level and lateral fixity of ASPW.

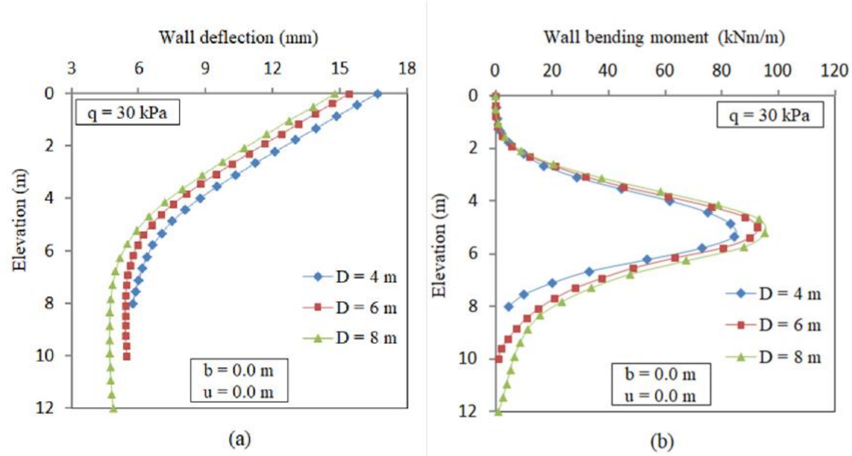

Fig. 8. (a) Wall deflection, and (b) BM profile along the wall depth for varying embedded depths with 30 kPa surcharge load.

6 Conclusions

A numerical study has been performed to investigate the influence of surcharge strip loads on the behavior of CSPW in dense sand. From the present study, the following conclusions are made:

- The critical width of the surcharge strip footing is 2 m based on maximum wall deflection criteria irrespective of its position from the wall top edge on the backfill soil.
- An increase in the surcharge distance along the backfill surface (horizontal direction) from the wall top edge reduces the wall deflection, BM, and maximum GS significantly. However, after a distance of 4 m, the effect of surcharge on wall deflection, BM, and maximum GS is insignificant.
- An increased surcharge distance along the wall depth (vertical direction) from the wall top edge reduces the wall deflection and BM significantly. However, after a distance of 2 m, the effect of surcharge on wall deflection and BM is insignificant.
- An increase in the embedded depth decreases the wall deflection profile because the higher embedded depth provides higher passive restraint, which provides more lateral stability to the ASPW.
- An increase in embedded depth increases in BM because of the development of higher passive restraint below the dredge level and lateral fixity of ASPW.

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