Jordan Journal of Civil Engineering, Volume **12**, No. **4**, **2018**

Effect of Sand-Pile Interaction on the Response of Battered Piles Subjected to Lateral Loads

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ABSTRACT

This paper presents a parametric study on the effect of pile batter angles and soil/pile properties on the response of laterally loaded battered piles in sand using the Strain Wedge (SW) formulation. The SW model determines the lateral behavior of battered piles and the corresponding p-y curves based on soil-pile interaction. The methodology employed is validated using battered piles in sand by centrifuge model tests. The results showed that change of soil and pile properties has a significant influence on the response of laterally loaded battered piles. The lateral capacity of battered piles is highly affected by the batter angle and sand relative density. Negatively battered piles maintain a significantly higher bearing capacity than vertical piles in the range from zero to minus seven degrees of pile battering, followed by a less rate of increase in the lateral capacity with larger angels of battering. However, the bearing capacity of positively battered piles is generally less than that of vertical piles. In addition, the calculated response of laterally loaded piles was significantly affected by the pile flexure rigidity and the shape of the pile cross-section.

KEYWORDS: Battered piles, Lateral load, Sand.

INTRODUCTION

Battered piles are considered a substitute to vertical piles subjected to high lateral loads, especially in structures like off-shore and retaining structures. Classification of battered piles depending on the direction of inclination with lateral loads is either positively or negatively battered piles (Fig. 1). Several researchers have experimented to understand the behavior of battered piles under lateral loads. Kim et al. (1976) performed full-scale tests on single steel battered piles and pile groups with battered piles derived in cohesive soil. The results indicated that the pile group with battered piles was deflected laterally 50% to 70% less than the pile group with vertical piles.

Received on 11/4/2018.
Accepted for Publication on 9/8/2018.

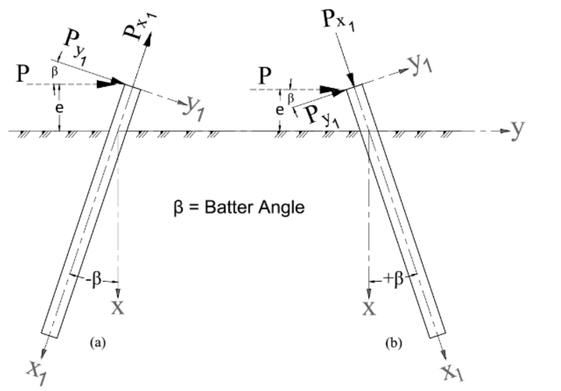

Figure (1): Types of battered piles (a) negatively battered pile (b) positively battered piles

Alizadeh and Davisson (1970) and Nimityongskul et al. (2012) performed full-scale lateral load tests on vertical and battered piles in sandy soil and found out that negatively battered piles have greater resistance than that of vertical and positively battered piles. Manoppo (2010) performed experimental tests on single aluminum, acrylic, hard rubber and steel pipe flexible batter piles ($\beta = 0^o, \pm 15^o, \pm 30^o$) in loose, medium dense and dense sandy soils, where β is the pile battering angle. The models showed that the batter angle and the soil unit weight, γ, significantly influence the ultimate horizontal capacity of the piles. Hazzar et al. (2017) investigated the response of battered piles subjected to lateral loads and the influence of vertical loads on the lateral performance. FLAC^{3D} (Itasca 2009) – finite difference computer software – was used by Hazzar et al. (2017) to study sandy soils, where the results showed that vertical load, pile batter angle and soil relative density influence the lateral response of battered piles in sandy soils. Hazzar et al. (2017) showed that negatively battered piles have a lateral response which is significantly dependent on the batter angle and sand relative density, while positively battered piles do not appear to vary considerably with batter angle and soil density. Chen and Hsu (2017) modeled a single battered pile, a 3×3 group of vertical piles and a 3×3 group (consisting of three positively battered, three negatively battered piles with β = +20° and -20°, respectively and three vertical piles) in sandy soils using a FLAC^{3D} (Itasca 2009) numerical model. Chen and Hsu (2017) used this model to study the effect of lateral soil movement on piles. The analysis showed that the maximum moment calculated on the vertical piles with pile spacing of two times the pile diameter subjected to soil movement was approximately two times that for the group of inclined batter piles with the same spacing. These results show the importance of soil properties and batter angle on the behavior of battered piles. However, the effects of the pile flexural stiffness and pile cross-section shape on the batter pile response loaded laterally were not thoroughly investigated in the literature. The Strain Wedge (SW) formulation provides a theoretical means to account for pile-soil interaction (Ashour and Norris, 2000).

The SW method was developed orginally by Norris (1986) for laterally loaded vertical flexible piles in uniform sandy soil and then upgraded for multi-layered soils by Ashour et al. (1998). The SW model formulation has shown very good agreement with actual field results for vertical piles subjected to lateral loads (Ashour et al., 1998; Ashour and Norris, 2000). Over the past two decades, the SW formulation has been also extended to analyze laterally loaded pile groups and large-diameter drilled shafts in layered soils (Ashour et al., 2004; Ashour and Ardalan, 2012). Full details on the SW formulations of battered piles in sandy soils are presented in Ashour et al. (2018). The SW model correlates the traditional one-dimensional BEF (Eq. 1 and Fig. 2c) to envisioned three-dimensional soil-pile interaction (Fig. 2a and b). Young's modulus of the soil (E) is related to the corresponding horizontal subgrade modulus (E_s). Also, the deflection pattern of the pile along its depth (i.e., y *versus* depth x) is related to the soil strain (γ) that exists in the developing passive wedge in front of the pile. Furthermore, the BEF line load (p) for a given deflection is related to the horizontal stress change ($\Delta\sigma_h$) acting along the face of the developing passive wedge (Fig. 2). More details on the basics of the SW model are presented in Ashour et al. (1996, 1998).

$$EI\frac{d^4 y_1}{dx_1^{\ 4}} + P_{x1}\frac{d^2 y_1}{dx_1^{\ 2}} + E_s(x_1)y_1 = 0 \qquad (1)$$

where EI is the pile flexural rigidity and P_{x1} denotes the axial load at the pile segment. The purpose of this analysis is to study the influence of soil-pile interaction on the pile lateral response using the modified SW formulation suggested by Ashour et al. (2018).

MODIFIED SW FORMULATION

The SW formulation was modified in different studies to account for pile inclination (Ashour et al., 2018). This modified formulation was coded in FORTRAN code. A summary of this modification is presented in this section. The applied lateral load is divided into its components P_{y1} and P_{x1} (perpendicular and axial components, respectively, see Fig. 1). When the pile starts to move laterally, a wedge starts to grow depending on the location and the state of loading. The size of the wedge changes with the variation of soil properties (friction angle, φ, effective unit weight, γ, strain at 50% of stress, ε_{50}) and pile properties (width/diameter, D, bending stiffness, EI, and pile-head condition). The basic SW model concepts (i.e., Ashour et al., 1996, 1998) are applied in the x_1 - y_1 plane under lateral load P_{y1} (P_{y1} = P cos (β)) and the pile head displacement in y_1-direction is obtained as y_1. The lateral displacement at the pile head in the y-direction is calculated as:

$$y = y_1 \cos\beta \tag{2}$$

VALIDATION (CENTRIFUGE PILE MODEL TESTS)

Zhang et al. (1999) performed centrifuge model tests in dry medium dense sand. The sandy soil had a relative density (D_r) of 36%, a dry unit weight of 14.50 kN/m^3 and an internal friction angle of 33.3°. The model was tested at 45g. The prototype model used was a 0.43m square pile, 13.7m long, with a flexural stiffness (EI) of 206MN-m^2.The point of loading was 2.14m above the ground surface. A series of tests were performed at different values of batter angles (β = ±14° and β = ±7°). A comparison between the results of the prototype model of the centrifuge test and the proposed SW model is presented in Fig. 3. As shown in Fig. 3, there is generally good agreement between the measured and calculated pile-head lateral response for both positively and negatively battered piles with β of -7° and -14°. It was however noted that the computed results of positively battered piles with β of +7° and +14° are stiffer than the measured ones at the early stage of loading. Generally, the modified version of SW method is applicable to handle the problem of laterally loaded battered piles.

INFLUENCE OF SOIL-PILE INTERACTION

A parametric study was conducted on battered piles subjected to lateral loads and embedded into sandy soils. The main objective of this analysis is to study the influence of soil-pile interaction on the lateral response of battered piles. This study focuses on the influence of the following parameters on the response of laterally loaded battered piles; 1) pile batter angle (β), 2) sand relative density (D_r), 3) pile cross-section shape and 4) pile flexure rigidity EI. Tables 1 and 2 present the properties of soils and piles used in this study. The battered piles are investigated for several batter angles β which range from -26.5˚ to +26.5˚. In this study, the piles are loaded laterally with zero vertical load. The pile is loaded laterally until reaching a lateral defection of 100 mm at about 0.3D, where D is the pile diameter/width.

Influence of Pile Batter Angle (β) and Sand Relative Density (D_r)

Figures 4 through 6 show the influence of pile batter angle on the lateral response of battered piles embedded in different states of sandy soils ranging from very loose to dense sands as presented in Table 2. In all the analyses, steel pile with pipe cross-section (no. 1) presented in Table 1 was used to compute pile response in this section. As expected, negatively battered piles calculated response (pile head movement *versus* lateral load magnitude) is higher than that of vertical and positively battered ones. Negatively battered piles have capacities 24% to 46% greater than that of vertical ones for β = -7˚ to -26.5˚, respectively. Positively battered piles have 19% to 43% softer response than that of vertical piles for β = +7˚ to +26.5˚.

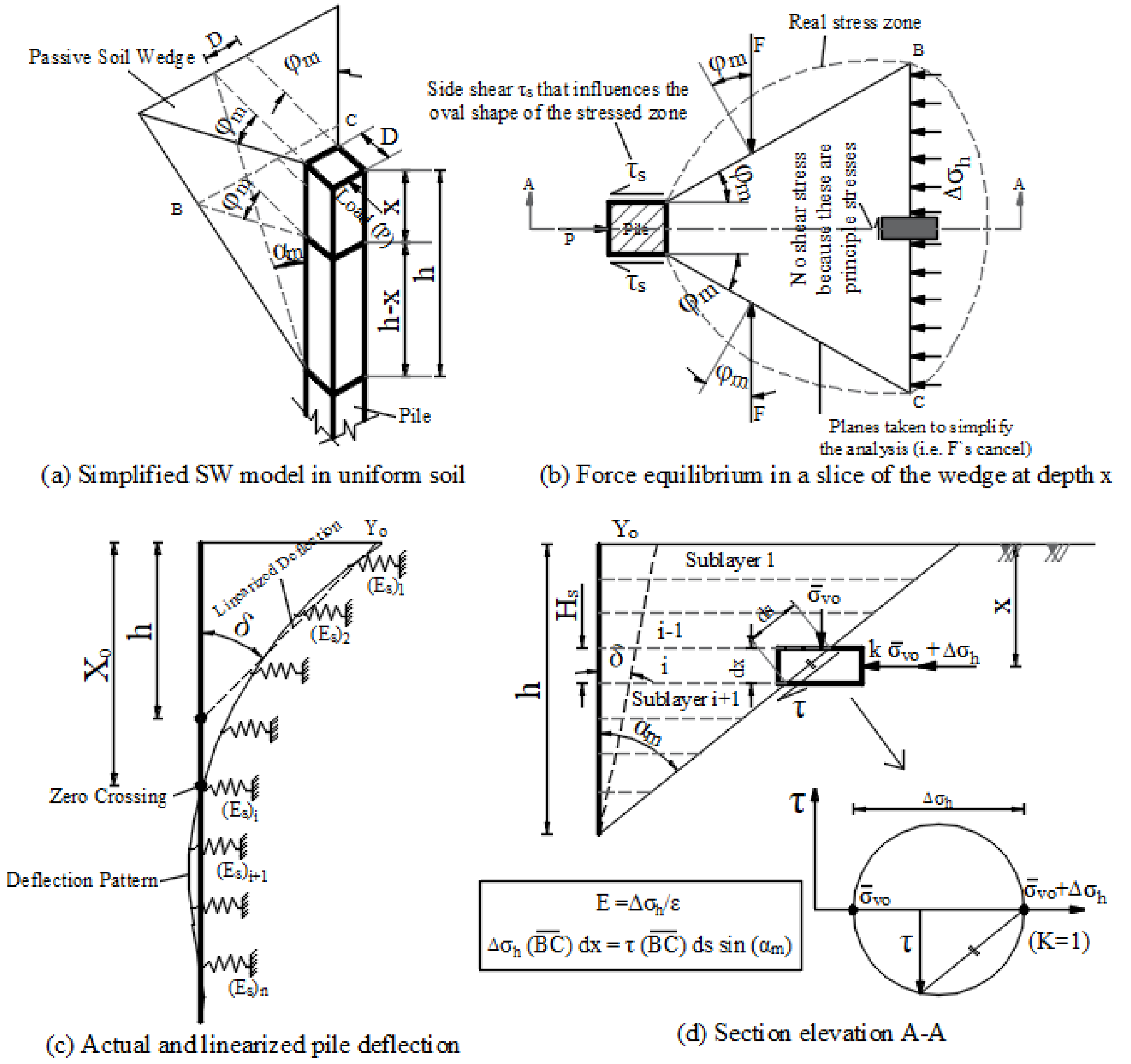

Figure (2): Strain wedge model basic concept (Ashour et al., 2018)

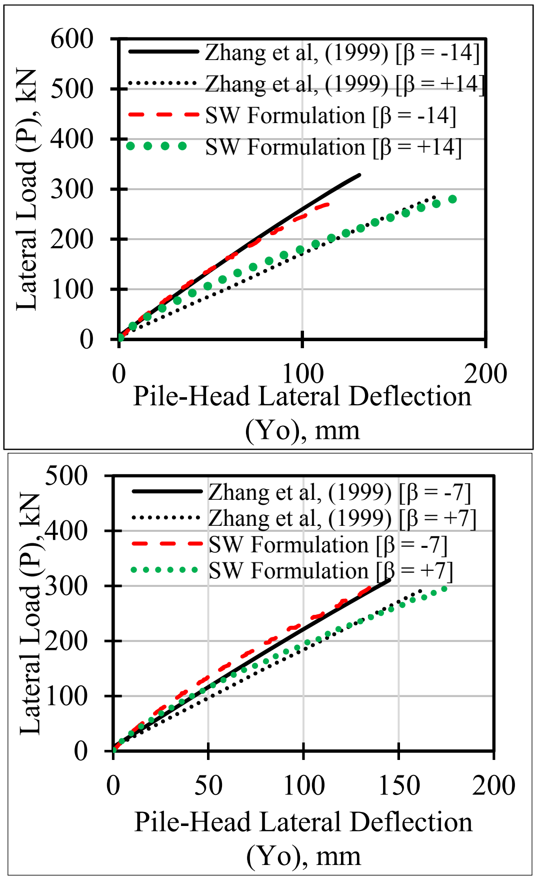

Figure (3): Calculated and measured response of laterally loaded battered piles in centrifuge tests

Table 1. Properties of piles used in the parametric study

No.	**Type**	**D (mm)**		**t (mm)**		**L (m)**	**EI (kN-m²)**
		B_f	**H_w**	**t_f**	**t_w**		
1	Steel Pipe	324		9.525		20	23261
2	Steel Pipe	324		40		20	73308
3	Steel Pipe	324		100		20	105750
4	Steel H-Section	327	324	5.9	5.9	20	23468

B_f Flange width *t Pipe thickness t_f Flange thickness
H_w Web height t_w Web thickness

Table 2. Properties of sand used in the parametric study

Sand State	Dr (%)	γ(kN/m³)	φ (degree)	ε_{50}
Very Loose	15	16	28	0.0065
Loose	30	17	30	0.0052
Medium	60	19	35	0.0037
Dense	80	21	40	0.0028

Figures 5 and 6 present the effect of changing sand state (from very loose to dense) on the batter pile response. Negatively battered piles (i.e., β = -20°) are found to have capacities greater than these of vertical piles, increasing by 30%, 34%, 39% and 42% for very loose, loose, medium dense and dense sands, respectively (Fig. 5). However, the capacities of positively battered piles are found to be softer than those of vertical ones by 27%, 32%, 38% and 41% for very loose, loose, medium dense and dense sands, respectively (Fig. 6).

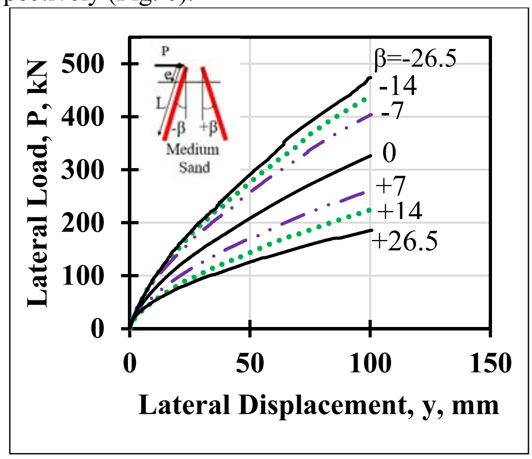

Figure (4): Influence of pile batter angle on the pile lateral response in medium dense sand

Figure 7 displays the relationship between the ratio of ultimate capacity (Ω) ($\Omega = P_b / P_v$, where P_b and P_v are the ultimate pile capacities for battered and equivalent vertical piles, respectively) *versus* batter angle for different sand packing states. As shown in Fig. 7, sand relative density has an influence on the value of Ω. The effect of sand relative density is not very significant for batter angles in the range of (±7 °). The effect of soil relative density is more pronounced in higher batter angles. Moreover, the influence of batter angle is significant in the same range.

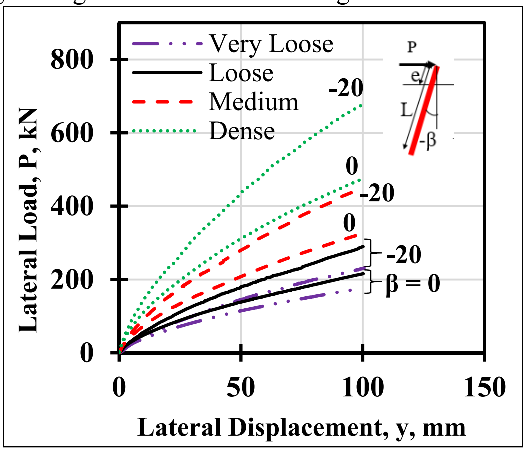

Figure (5): Influence of soil relative density for negatively battered piles

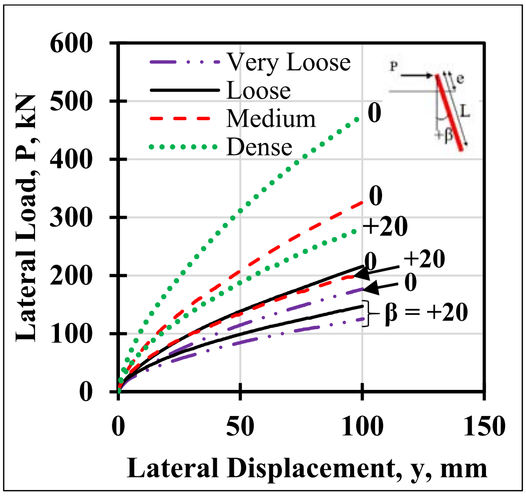

Figure (6): Influence of soil relative density for positively battered piles

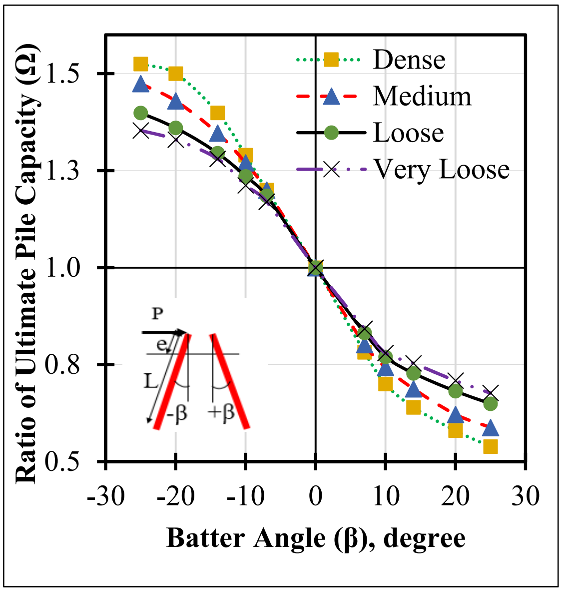

Figure (7): Ratio of ultimate bearing capacity

Influence of Pile Flexural Rigidity (EI)

Three piles (no. 1 through 3 in Table 1) are used to calculate the response of laterally loaded battered piles embedded in medium dense sandy soil for different values of pile flexural rigidity (EI). The influence of EI on the lateral response of battered piles is presented in Fig. 8. By increasing the thickness of the steel pipe pile to be 40mm and 100mm, the pile flexural rigidity of the pile increased by 3 and 4.5 times its value while the pile width stayed constant as shown in Table 1. The response of piles (negatively battered and positively battered) increases with the increase in flexure rigidity (EI) as shown in Fig. 8. The capacity of the piles increased by 69% and 76% for negatively battered and positively battered piles, respectively, when pile flexural rigidity increased three times (pile no. 1 and pile no. 2). Moreover, it was found that by increasing the flexural rigidity four and a half times, the pile bearing capacity increased by 97% and 117% for negatively battered and positively battered piles, respectively (pile no. 1 and pile no. 3).

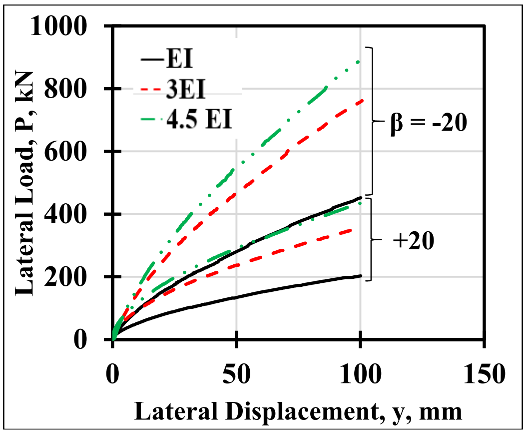

Figure (8): Influence of pile flexural rigidity

Influence of Pile Cross-Section

Pile cross-section was changed from pipe section to H-section keeping flexural rigidity the same. As illustrated in Fig. 9, the capacity of the piles increased by 18% and 24% for negatively battered and positively battered piles, respectively by changing pile cross-section from pipe to H-section.

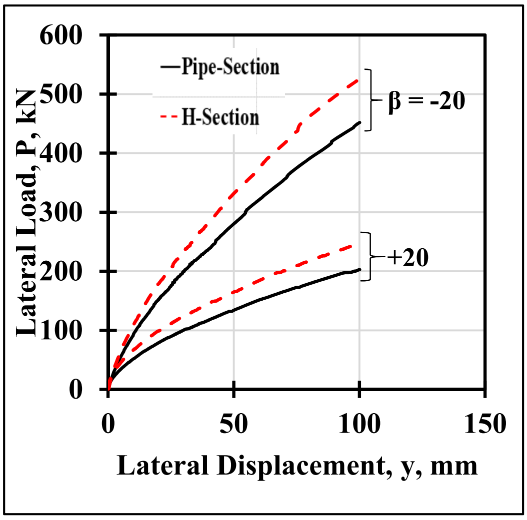

Figure (9): Influence of pile cross-section shape

CONCLUSIONS

The influence of soil/pile interaction on the lateral response of battered piles is investigated by using a modified version of Strain Wedge model formulation. The modified model is validated using centrifuge tests on battered piles presented in the literature. The developed formulation inherited SW advantages of calculating the effect of pile/soil interaction. Based on the parametric study conducted on the pile/soil interaction, the following conclusions can be derived:

1) According to the modified strain wedge formulation presented herein, the response of the battered piles in sandy soils was influenced by both pile batter angle and sand density. For negatively battered piles in the range of β up to -7 degrees, the lateral response of battered soil is significantly affected by the batter angle, where the effect of the batter angle β decreases in the range from -7 to -26.5 degrees. For positively battered piles, the effect of the batter angle is significant up to +14 degrees and insignificant in the range of +14 to +26.5 degrees.
2) The presented modified SW formulation predicted a general increase of the battered pile response under lateral load with increasing sand density.
3) The battered pile response shows a significant change with flexural stiffness change while keeping other pile and sand soil properties the same. In this study, the capacity of the pile increased by 68% and 76% for negatively battered and positively battered piles, respectively, by increasing the pile flexural rigidity three times without changing the other pile and sand properties.
4) The presented SW formulation can predict the change of batter pile response due to change in pile cross-section. In the current study, change in pile cross-section (from circular pipe section to H-section) while keeping the rest pile and sand properties unchanged showed an increase of the capacity of the piles by 18% and 24% for negatively and positively battered piles, respectively.
5) The presented results show that the SW formulation is capable of taking into account the effect of change in sand soil and pile properties on the response of battered piles under lateral loads.

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