การวิเคราะห์การตอบสนองของเสาเข็มเดี่ยวต่อแรงกระทำด้านข้างสองทิศทาง โดยใช้แบบจำลองย่อส่วน

Analysis of Single Pile Response to Bi-directional Lateral Loading Using Scaled-Down Model

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บทคัดย่อ

p)
y)
p-y
, , , , p-y

Abstract

Pile analysis typically considers lateral loads in a single direction, while in reality, piles must resist both lateral loads in multiple directions and axial forces, where the loading sequence may affect pile deformation behavior. This research investigated the behavior of a single pile in dense sand subjected to lateral loads in two perpendicular directions using a scaled-down model. The results showed that (1) soil resistance in one direction decreased when the load in the other direction increased, (2) applying load in the second direction caused pile head movement in both directions, with deflection in the first direction being initially high and gradually decreasing, (3) soil resistance in the first direction varied with depth, decreasing near the ground surface but increasing at greater depths, and (4) the relationship between soil reaction (p) and deflection (y) in each direction depended on the load magnitude in the other direction, and the relationship in the first direction also varied with loading history. The findings demonstrate that using p-y curves from single-direction analysis is not suitable for predicting pile behavior under bi-directional lateral loading

Keywords: Pile, Lateral loading, Bi-directional loading, Internal reaction, p-y curve

1. บทนำ

[1]

2
p) y)

Static loading

[2]

p-y

Load-control x
Displacement-control y

2. การดำเนินการ

2.1 วัสดุอุปกรณ์

2.1.1 ทรายแห้ง

0.896

2.1.2 เสาเข็มจำลอง

T

mm 0.9 m

cm m [

Scaling factor, n

Strain gauge

			Scaling factor	Scaling factor
, L (m)	18	0.9		0
, D (m)	1	$5x10^{-2}$		
, E (GPa)	20		-	-
, I (m^4)	$6.80x10^{-3}$	$2.54x10^{-8}$	-	-
, EI (Nm^2)	$1.36x10^{8}$	$1.40x10^{3}$	20^4	17.7^4

ตารางที่ 2

2.2 การเตรียมการทดสอบ

100 cm 98 cm

1.5 g/cc

y 2 ( )

x 2 ( ) load cell

LVDT) 3

No.	MLR	Fx application	Fy application	Fy Displacement Limit (mm)
1	0	Load-control	Displacement-control	10
2	0.25	Load-control	Displacement-control	10
3	0.5	Load-control	Displacement-control	10
4	0.75	Load-control	Displacement-control	10
5	1	Load-control	Displacement-control	10

2.3 แผนการทดสอบ

x Load-control Monotonic load ratio (MLR)

MLR 0.25, 0.50, 0.75 1.00

y

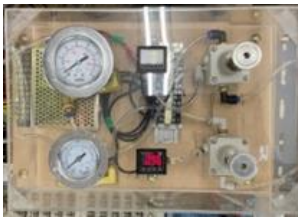
Displacement-control 0. mm/min

10 mm MLR

2



( )

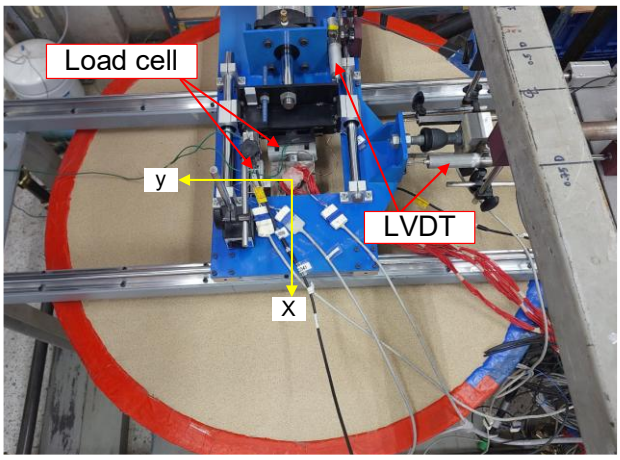


( )

รูปที่ 2 y x

รูปที่ 1 Strain gauge

ตารางที่ 1



รูปที่ 3

State Load history
x y
Su ([8]
Multi-direction)

N Uni-direction
Cross loading
y x
x N
y

y, F_y (N) x, F_x (N)
x y 9

State 2
x y
y x
y
x 10 State 2
x y
10 y (State 2)
x (Δx_h)
y (Δy_h) 0
Passive zone
x
(A B 11)
(B C 11)
Interaction
State 1

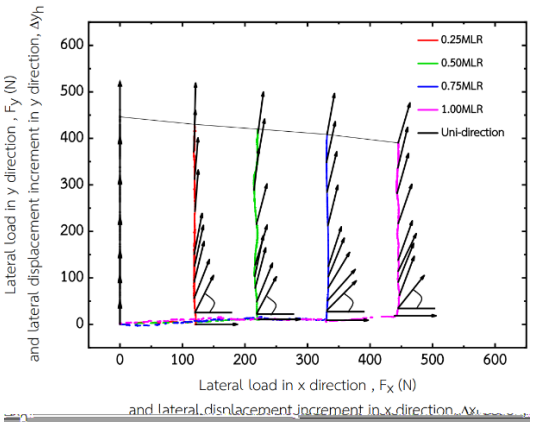
3.4 ปฏิกิริยาภายในเมื่อให้แรงกระทำกับเสาเข็มสองทิศทาง

y), M), V),
p) y
State y
mm 12

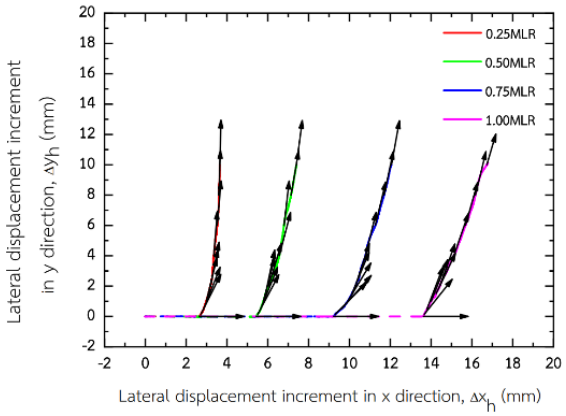
x y
y
3 x State

2 mm
Strain gauge

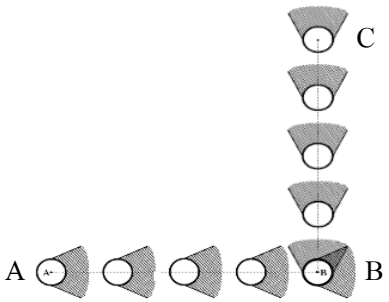
4 y x 2
3 Georgiadis, et
al. ( ) [9] Strain gauge
x y)
Strain



รูปที่ 9 x, F_x (N)
y, F_y (N) Displacement vector
F_x F_y



รูปที่ 10 x, Δx_h
(mm) y, Δy_h (mm)



รูปที่ 11
[8]

3.5 เส้นโค้ง py-y และเส้นโค้ง px-x

3.5.1 Critical Depth ของเส้นโค้ง p_y-y และ p_x-x

p_y-y p_x-x

Passive resistance

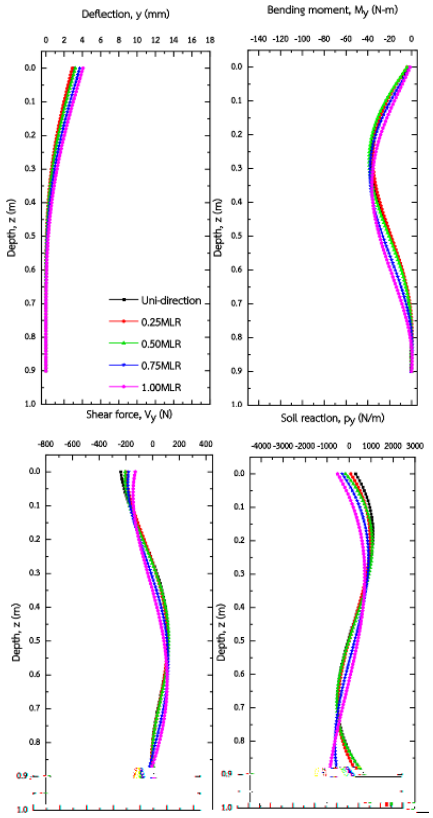
p_y-y p_x-x

m m

p-y

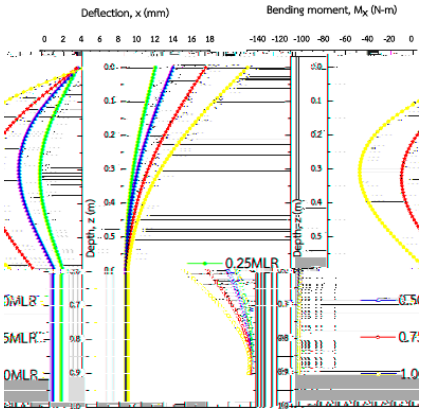
Critical depth D NAVFAC DM

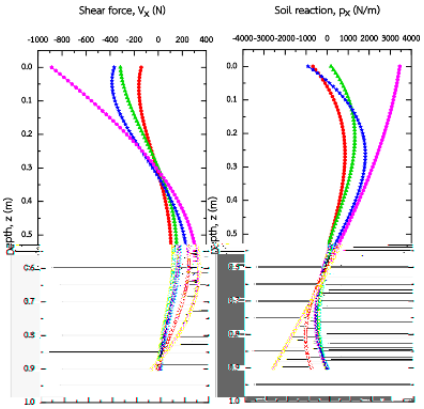
7.2 [10] cm



รูปที่ 12 y x

y mm





รูปที่ 13 x x

y mm

3.5.2 เส้นโค้ง py-y และเส้นโค้ง px-x ที่ระดับความลึกต่างๆ ของเสาเข็ม

p_y-y y

m, m, m m 4

p_y-y p_y)

y) y)

p_y)

p_y-y p_y-y

Soil modulus, E_s)

p_y-y

m p_y-y

m 4

Verdure, et al. ([11] p-y

Georgiadis, et al. ([9] p-y

p_y-y Uni-direction

p_y-y Bi-direction

p_x-x x

m, m, m m

Bi-direction) p_x-x

p_x) x)

m

x) p_x)

m m

x) p_x)

E_s) p_x-x

m

m

p_x)

x [15] p_x-x

y x y 1) p_x x

x x 2) p_x x

x p_x x

p_y-y p_x-x x

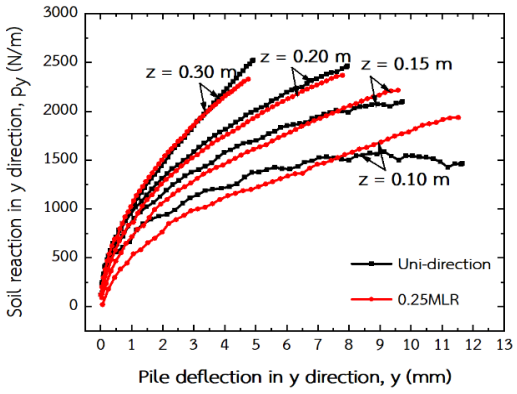
p-y

E_s)

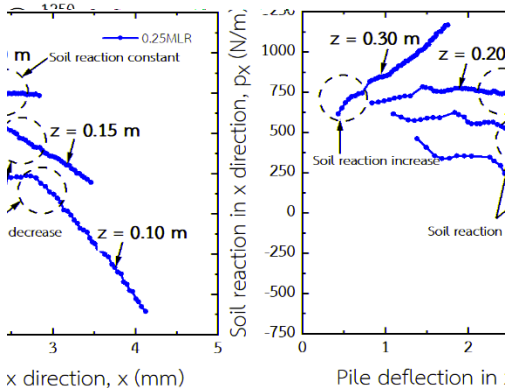
x State

Matlock ([12]

Reese, et al. ([13] [14]



รูปที่ 14 p_y-y



รูปที่ 15 p_x-x

3.5.3 เส้นโค้ง py-y และเส้นโค้ง px-x ที่ระดับความลึกต่างๆ ของเสาเข็ม

p_y-y y m

Uni-direction)

MLR, MLR, MLR MLR)

16 m p_y-y

x

(y) p_y-y

x

3.6 การใช้เส้นโค้ง p-y สำหรับเสาเข็มที่รับแรงกระทำด้านข้างสองทิศทาง

Uni-direction x_h

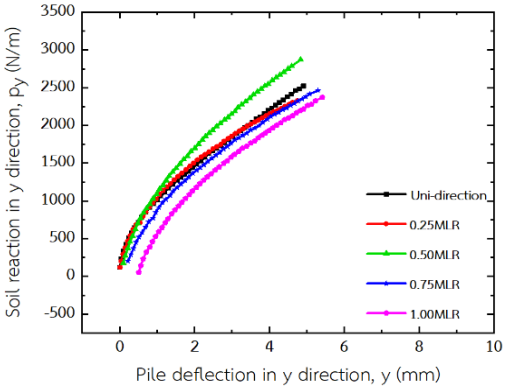
F_x = , 0.50, 0.75 1.00MLR F_y = 250

N y_h mm

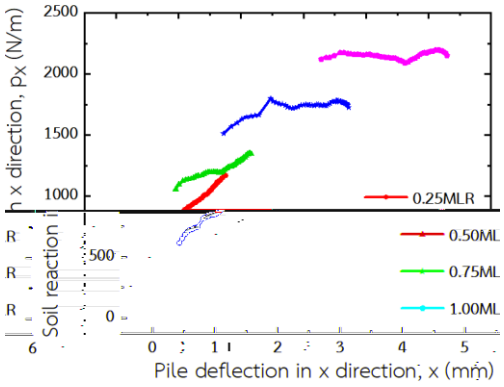
(d_h) F_x

d_h = √(x_h y_h

d_h Unidirectional test result



รูปที่ 16 p_y-y 0.30 m



รูปที่ 17 p_x-x 0.30 m

underestimate d =

√(x y m

x $P_{x,max}$ x

MLR, MLR, MLR MLR y

P_y = N/m x y p-y

d Unidirectional

test result underestimate

p_x-x p_y-y

p_x-x

Fit p_x-x P_x = x

p-y API ([16]

Reese, et al. ([17]

Wesselink, et al. ([18] Calcareous sand) Dyson and Randolph ([19]

Reese ([20] Weak rock

$P(y) = ky^m$ m [21]

p_y-y p_y-y F_x = MLR

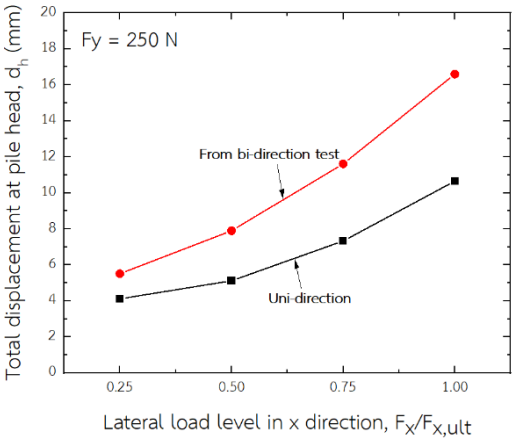
1

p_x-x p_y-y p-y

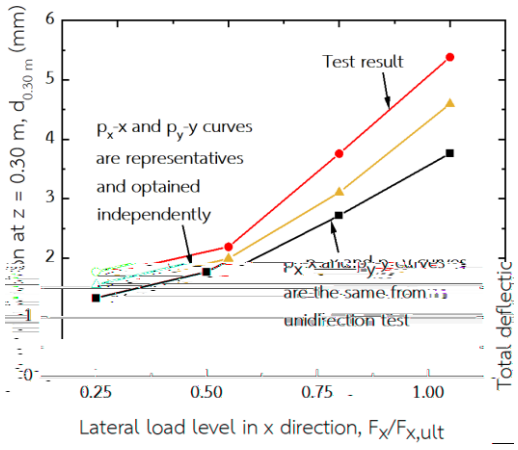
p_x-x p_y-y

p-y

p-y



รูปที่ 18



รูปที่ 19 m

p-y

p-y

4. บทสรุป

x

y) Load-control x

Displacement-control y

x

y

y x

2.

Load history

y p_y)

p_y)

p_y-y y

x

x y p-y

p_x-x p_y-y p_x-x p_y-y

Cyclic Loading)

กิตติกรรมประกาศ

เอกสารอ้างอิง

[1] Sørum, S.H., Krokstad J.R. and Amdahl J. ( ). Wind-wave directional effects on fatigue of bottom-fixed offshore wind turbine. *The 16th Deep Sea Offshore Wind R&D conference*, January , Trondheim, Norway.

[2] Reese, L.C. and Impe, W.F. (2001). p-y curves developed from static and cyclic load test of 641 mm-diameter pile.

Single piles and pile groups under lateral loading. Taylor & Francis, A.A. Balkema Publishers London, pp. 6.

[3] Reese, L.C., Cox, W.R. and Koop, F.D. (1974). Analysis of Laterally Loaded Piles in Sand. *Offshore Technology Conference*, May 5-7, Dallas, Texas, USA., pp. 473-480.

[4] Hellier, A.K.; Chaphalkar, P.P. and Prusty, B.G. (2017). Fracture toughness measurement for aluminium 6061-T6 using notched round bars. *Proceedings of the 9th Australasian Congress on Applied Mechanics 2017 (ACAM 9)*, 27–29 November, Sydney, Australia, p. 2.

[5] Ni, P., Mangalathu, S., Song, L., Mei, G. and Zhao, Mei. (2018). Displacement-Dependent Lateral Earth Pressure Models. *International Journal of Physical Modelling in Geotechnics*, Vol. 16, No. 4, pp. 160-172.

[6] Su, D. and Yan, W.M. (2013). A multidirectional p–y model for lateral sand–pile interactions. *Soils and Foundations*, Vol. 53, No. 2, pp. 199-214.

[7] Rathod, D., Nigitha, D. and Krishnanunni, K.T. (2021). Experimental Investigation of the Behaviour of Monopile under Asymmetric Two-Way Cyclic Lateral Loads. *International Journal of Geomechanics*, Vol. 21, No. 3, pp. 1-12.

[8] Su, D. (2012). Resistance of Short, Stiff Piles to Multidirectional Lateral Loadings. *Geotechnical Testing Journal*, Vol. 35, No. 2, pp. 16.

[9] Georgiadis, M., Anagnostopoulos, C. and Saflekou, S., 1991. Centrifugal testing of laterally loaded piles in sand. *Canadian Geotechnical Journal*, Vol. 29, No. 2, pp. 208-216.

[10] Naval Facilities Engineering Command. (1986). *DESIGN MANUAL 7.02*. Naval Facilities Engineering Command, Virginia, USA.

[11] Verdure, L., Garnier, J. and Levacher, D. (2003). Lateral cyclic loading of single piles in sand. *International Journal of Physical Modelling in Geotechnics*, Vol. 3, pp. 17-28.

[12] Matlock, H. (1970). Correlations for design of laterally loaded in soft clay. *Offshore Technology Conference*, Houston, Texas, USA, pp. 77-94.

[13] Reese, L.C., Cox, W.R. and Koop, F.D. (1975). Field testing and analysis of laterally loaded piles in stiff clays. *Offshore Technology Conference*, May 4-7, Houston, Texas, USA, pp. 671-686.

[14] Parkes, J., Castelli, R., Zelenko, B., O'Connor, R., Montesi, M. and Godfrey, E. (2018). *Design, Analysis, and Testing of Laterally Loaded Deep Foundations that Support Transportation Facilities*, Federal Highway Administration, pp. 93-94.

[15] Clausen, C.J.F. (1994). Documentation of computer program package for Structural/Pile/ Soil Interaction analysis. Engineering Documentation, Computer Program SPLICE.

[16] API. (2000). Recommended practice for planning, designing, and constructing fixed offshore platforms Working stress design. 21st ed., API Publishing Services, Washington.

[17] Reese, L.C. and Welch, R.C. (1975). Lateral loadings of deep foundations in stiff clay. *Journal of Geotechnical Engineering*, Vol. 101, No. 7, pp. 633-649.

[18] Wesselink, B.D., Murff, J.D., Randolph, M.F., Nunez, I.L and Hyden, A.M. (1988). Analysis of centrifuge model test data from laterally loaded piles in calcareous sand. *Engineering for Calcareous Sediments*, CRC Press, 1st ed., New Jersey.

[19] Dyson, G.J. and Randolph, M.F. (2001). Monotonic lateral loading of piles in calcareous sand. *Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 4, pp. 346-352.

[20] Reese, L.C. (1997). Analysis of laterally loaded piles in weak rock. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 11, pp. 1010-1017.

[21] Lovera, A., Ghabezloo, S., Sulem, J., Randolph, M.F., Kham, M. and Palix, E. (2020). Pile response to multi-directional lateral loading using P–y curves approach. *Géotechnique*, Vol. 71, No. 4, pp. 288-298