FAILURE MECHANISM OF DEEP EXCAVATIONS IN SOFT CLAY: CASE STUDIES

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Outlines

1. Introduction
2. Literature Review
3. Evaluation of Factors of Safety for Case Histories
4. Conclusions
1. Introduction
Collapses of deep excavations in urban area

Taipei Shi-Pai case

Taipei Rebar Broadway case
Nicoll Highway case in Singapore (4 casualties)

Hangzhou case in China (21 casualties)
2. Literature Review
2.1 Conventional Methods

Terzaghi’s method

\[ F_t = \frac{5.7 s_{u2}}{W' + q_s - s_{u1}H_e} \]

Bjerrum & Eide’s method

\[ F_{be} = \frac{N_c s_u}{W' + q_s} \]
Slip circle method

\[ F_{sc} = X \int_{0}^{\pi/2+\alpha} s_u X d\theta + M_s \] \[ \frac{W'X}{2} \]

Push-in gross pressure method

\[ F_p = \frac{P_p L_p}{P_a L_a} \]
2.2 Finite Element Method (FEM)

Donald and Giam (1988)  
Brinkgreve and Bakker (1991)

Failure based on convergence criterion  
Limited equilibrium state
Do et al. (2013)

(Elastic support system)

1/ Convergence criterion method: $FS = SR_1$
2/ Angle method: $FS = SR_2$ as wall kicks out
3/ Intersection method: $FS = SR_3$

Intersection method is most reasonable at 4 real failure excavations in clay
3. Evaluation of Factors of Safety for Case Histories

3.1 Taipei Rebar Broadway Case

<table>
<thead>
<tr>
<th>GL  (m)</th>
<th>Depth (m)</th>
<th>Material Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1.8</td>
<td></td>
<td>H300x300x10x15</td>
</tr>
<tr>
<td>-4.35</td>
<td></td>
<td>H350x350x12x19</td>
</tr>
<tr>
<td>-7.65</td>
<td></td>
<td>H400x400x13x21</td>
</tr>
<tr>
<td>-10.95</td>
<td></td>
<td>H400x400x13x21</td>
</tr>
<tr>
<td>-13.45</td>
<td></td>
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</tr>
</tbody>
</table>

Center post

Wall (0.7 m thickness)

GL -24.0 m

B = 25.8 m

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Material Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.55</td>
<td></td>
</tr>
<tr>
<td>-6.85</td>
<td></td>
</tr>
<tr>
<td>-10.15</td>
<td></td>
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</tbody>
</table>

For analysis

<table>
<thead>
<tr>
<th>Layer</th>
<th>Density (kN/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>20.3</td>
</tr>
<tr>
<td>ML-CL</td>
<td>19.2</td>
</tr>
<tr>
<td>SM-SP</td>
<td>19.7</td>
</tr>
<tr>
<td>CL</td>
<td>18.8</td>
</tr>
</tbody>
</table>
Finite element model
Wall deflection and soil heave at final stage

EP support system

Wall deflection, mm

-200 0 200 400

-24
-20
-16
-12
-8
-4
0

Depth, m
0 4 8 12 16 20 24 28

98% $\Sigma$Mstage max
99% $\Sigma$Mstage max
$\Sigma$Mstage max = 1.00

Heave, mm
500
400
300
200
100
0

Distance to wall, m
0 4 8 12 16 20 24 28

E support system

Wall deflection, mm

0 2000 4000

98% SRmax
99% SRmax
SRmax = 1.84937

Heave, mm
8000
6000
4000
2000
0

Distance to wall, m
0 4 8 12 16 20 24 28

Wall deflection and soil heave at final stage
Interaction diagram
EP support system

1st strut layer
2nd strut layer
3rd strut layer
4th strut layer
wall
BL of 1st strut layer
BL of 2nd strut layer
BL of 3rd and 4th strut layers
BL of wall

Struts start to yield before wall
Incremental displacement plot at $SR_{\text{max}}$ as using EP support system
Plastic point plot at $SR_{max}$ as using EP support system
Incremental displacement plot at $SR_{\text{max}}$ as using $E$ support system.
Plastic point plot at $SR_{\text{max}}$ as using E support system.
3.2 Taipei Shi-Pai Case

- B = 12.3 m
- GL -9.3 m
- GL -6.5 m
- GL -4.2 m
- GL -1.9 m
- GL 0.0 m

Fill $\gamma_t = 18 \, \text{kN/m}^3$
ML $\gamma_t = 18 \, \text{kN/m}^3$
CL $\gamma_t = 17.7 \, \text{kN/m}^3$
CL $\gamma_t = 18 \, \text{kN/m}^3$

Wall (0.5 m thickness)

Center post

For analysis (0.5 m thickness)
Wall deflection and soil heave at final stage

EP support system

Wall deflection, mm

0 1200 2400

98% ΣMstage max
99% ΣMstage max
ΣMstage max = 0.6734

E support system

Wall deflection, mm

0 1000 2000

98% SRmax
99% SRmax
SRmax = 1.54807

Heave, mm
Incremental displacement plot at $SR_{\text{max}}$ as using EP support system
Plastic point plot at $SR_{\text{max}}$ as using EP support system.
Incremental displacement plot at $SR_{\text{max}}$ as using E support system
Plastic point plot at SR_{max} as using E support system
3.3 Hangzhou Case

B = 21.2 m

Left wall

Right wall

GL -0.0 m

Field Vane (V01 undisturbed)

Field Vane (V07 undisturbed)

Chen et al., 2013

FILL

CL

OL

OL

OL

Diaphragm wall (0.8 m thickness)

GL -15.7 m

Center post

2x(280x82x7.5x12.5)

Not installed

Bored pile (Ø 800)

GL -15.7 m

GL -46.0 m

0 20 40 60 80 100

su, kPa

Depth, m

Field Vane (V07 undisturbed)

Field Vane (V01 undisturbed)

Chen et al., 2013
Wall deflection and soil heave at final stage

**EP support system**
Wall deflection, mm

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Heave (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>800</td>
<td>800</td>
</tr>
</tbody>
</table>

98% $\Sigma M_{stage \ max} = 0.6652$

**E support system**
Wall deflection, mm

<table>
<thead>
<tr>
<th>Distance to wall (m)</th>
<th>Heave (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^4$</td>
</tr>
<tr>
<td></td>
<td>$2 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$3 \times 10^4$</td>
</tr>
</tbody>
</table>

98% $SR_{max}$
99% $SR_{max}$

$SR_{max} = 3.07975$
Incremental displacement plot at SR$_{\text{max}}$ as using EP support system.
Plastic point plot at $SR_{\text{max}}$ as using **EP** support system.
Incremental displacement plot at $SR_{\text{max}}$ as using $E$ support system
Plastic point plot at $SR_{\text{max}}$ as using E support system
3.4 Nicoll Highway Case

Whittle and Davies (2006)

Fluvial deposit

Fill

Estuarine

Upper marine clay

2H-400 (G50)

2H-400

2HR-400

H-414 (G50)

2H-400 (G50)

2H-414 (G50)

2H-400 (G50)

Diaphragm wall (0.8 m thickness)

Jet grout piles

Estuarine

Fluvial deposit

Lower marine clay

Old alluvium

Center post

GL -30.6 m

GL -44.3 m

GL -0.0 m

B = 20.1 m

10.05 m 10.05 m

0 20 40 60 80 100

su, kPa

0 10 20 30 40 50

Depth, m

Whittle and Davies (2006)
Wall deflection and soil heave at final stage

**EP support system**

Wall deflection, mm

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>0</th>
<th>3x10^3</th>
<th>6x10^3</th>
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</thead>
<tbody>
<tr>
<td>SR max</td>
<td>98% SR max</td>
<td>99% SR max</td>
<td></td>
</tr>
</tbody>
</table>

**E support system**

Wall deflection, mm

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>0</th>
<th>5x10^3</th>
<th>10^4</th>
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<tbody>
<tr>
<td>SR max</td>
<td>98% SR max</td>
<td>99% SR max</td>
<td></td>
</tr>
</tbody>
</table>

SR max = 1.13033

SR max = 5.26420

Heave, mm

Distance to wall, m

Distance to wall, m

Wall deflection and soil heave at final stage
Incremental displacement plot at $SR_{\text{max}}$ as using EP support system.
Plastic point plot at $SR_{\text{max}}$ as using EP support system
Incremental displacement plot at $\text{SR}_{\text{max}}$ as using E support system
Plastic point plot at $SR_{\text{max}}$ as using E support system
<table>
<thead>
<tr>
<th>Case history</th>
<th>FEM</th>
<th>Conventional method</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Using EP support system</td>
<td>Using E support system</td>
<td>Terzaghi’s</td>
<td>Bjerrum &amp;</td>
<td>Slip circle</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>method</td>
<td>Eide’s method</td>
<td>method</td>
<td>method</td>
</tr>
<tr>
<td>Taipei Rebar Broadway case</td>
<td>1.00</td>
<td>1.849</td>
<td>1.088</td>
<td>0.952</td>
<td>0.809</td>
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<tr>
<td>Taipei Shi-Pai case</td>
<td>$\Sigma M_{\text{stage}} = 0.673$ (at final excavation stage)</td>
<td>1.548</td>
<td>0.901</td>
<td>0.792</td>
<td>0.732</td>
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<tr>
<td>Hangzhou case</td>
<td>$\Sigma M_{\text{stage}} = 0.665$ (at final excavation stage)</td>
<td>3.080</td>
<td>1.071</td>
<td>0.983</td>
<td>1.043</td>
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<tr>
<td>Nicoll highway case</td>
<td>1.13</td>
<td>5.264</td>
<td>&gt;1.342</td>
<td>&gt;1.750</td>
<td>&gt;1.222</td>
<td></td>
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</tbody>
</table>
4.6 Failure Mechanisms of Excavations in Clay

- Center post
- Broken wall
- Failure surface
- Overlapped area of failure surfaces

Overall failure of excavations
Overall failure of excavations

Overlapped area of failure surfaces

Failure surface

Broken wall

Center post
4. Conclusions

1. The FEM using the EP support system gives more reasonable results than that using the E support system based on case studies.

2. Terzaghi’s method, Bejerrum & Eide’s method, and slip circle method could give reasonable results of FS at these cases.

3. There are two possible failure mechanisms of deep excavations in clay.
THANK YOU