DESIGNING FOR DOWNDRAG ON UNCOATED AND BITUMEN COATED PILES

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Content Outline

1. What is downdrag?
2. Predicting pile behavior subjected to downdrag
3. Design and selection of bitumen
4. Example problem
5. Full scale field test in New Orleans, LA, USA
6. Full scale field test in Edmonton, AL, Canada
7. Conclusions
STEP 1: BEFORE PLACEMENT OF EMBANKMENT

STEP 2: PLACEMENT OF EMBANKMENT

STEP 3: DRIVING OF PILE

STEP 4: LOADING OF PILE

STEP 5: END OF USEFUL LIFE OF STRUCTURE

STEP 6: END OF SETTLEMENT OF EMBANKMENT
What is downdrag?

Diagram showing:
- Negative shaft resistance
- Positive shaft resistance
- Neutral point
- Depth
- Settlement
- Pile settlement
- Soil settlement
STEP 1: BEFORE PLACEMENT OF EMBANKMENT

STEP 2: PLACEMENT OF EMBANKMENT

STEP 3: DRIVING OF PILE

STEP 4: LOADING OF PILE

STEP 5: END OF USEFUL LIFE OF STRUCTURE

STEP 6: END OF SETTLEMENT OF EMBANKMENT
Settlement before embankment is placed

Settlement after embankment is placed

Settlement of pile before loading

Immediate settlement of pile due to loading from structure

Additional settlement of pile due to increase in negative shaft resistance with further consolidation

Driving of pile

Load-settlement curve for pile immediately after driving

Loading of pile

Load-settlement curve for pile at time of loading

Settlement during life of bridge

Load-settlement curve for pile at end of useful life of structure

End of useful life of bridge

Final settlement of embankment

Increase in ultimate load due to increase of shear strength with consolidation
(a) Evolution of Load Distribution Without Downdrag

1. Immediately After Driving
2. Significant Time After Driving
3. Immediately After Load Applied
4. Significant Time After Load Applied

(b) Evolution of Load Distribution With Downdrag

1. Immediately After Driving
2. Significant Time After Driving
3. Immediately After Structural Load Applied
4. Significant Time After Structural Load Applied
When to Design for Downdrag

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The total settlement of the ground surface will be larger than 100 mm</td>
</tr>
<tr>
<td>2.</td>
<td>The settlement of the ground surface after the piles are driven will be larger than 10 mm</td>
</tr>
<tr>
<td>3.</td>
<td>The height of the embankment to be placed on the ground surface exceeds 2 m</td>
</tr>
<tr>
<td>4.</td>
<td>The thickness of the soft compressible layer is larger than 10 m</td>
</tr>
<tr>
<td>5.</td>
<td>The water table will be drawn down by more than 4 m</td>
</tr>
<tr>
<td>6.</td>
<td>The piles will be longer than 25 m</td>
</tr>
</tbody>
</table>

WARNING: Downdrag can occur even if the above conditions are not met.
Design to Avoid these Three Conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The settlement of the top of the pile after the dead load of the structure is placed will be larger than can be tolerated by the structure</td>
</tr>
<tr>
<td>2.</td>
<td>The stresses in the pile will exceed the allowable stress for the pile material</td>
</tr>
<tr>
<td>3.</td>
<td>The load placed at the pile top does not lead to an acceptable factor of safety against plunging of the pile into the soil.</td>
</tr>
</tbody>
</table>
Static Equilibrium

\[ Q_{\text{max}} = Q_t + F_n = F_p + Q_p \]
Finding the Depth of Neutral Point

\[ \omega_{\text{pile}}(\text{NP}) = \omega_{\text{soil}}(\text{NP}) \]

\[ \omega_{\text{soil}}(\text{NP}) = \text{read on consolidation settlement profile (given)} \]

\[ \omega_{\text{pile}}(\text{NP}) = \omega_{\text{point}} + \omega_{\text{elastic}} \]

\[ \omega_{\text{point}} = \omega_{\text{soil}}(@Z=L) + \omega_{\text{punch}} \]

\[ \omega_{\text{elastic}} = \text{elastic compression from bottom to NP} \]
Pile Point Behavior

\[ \omega_{\text{punch}} = \frac{\pi}{4} (1 - \nu^2) \frac{Q_p D}{A E_s} \]

- \( \omega_{\text{punch}} \) = Pile point movement
- \( \nu \) = Poisson’s ratio
- \( Q_p \) = Point resistance
- \( A \) = Area of pile point
- \( D \) = Diameter of pile point
- \( E_s \) = Soil modulus

For clays
\( E_s = 100 \ S_u = E_{\text{pmt}} \)

For sands
\( E_s (\text{kPa}) = 800 \ N = 2 \ E_{\text{pmt}} \)
Pile Point Behavior

\[ \omega_{\text{elastic}} = \left( Q_p + \frac{1}{2} F_p \right) \frac{L - Z}{AE} \]

- **\( \omega_{\text{elastic}} \)** = Elastic compression of pile
- **\( Q_p \)** = Point resistance
- **\( F_p \)** = Positive friction force
- **\( L \)** = Depth of pile point
- **\( Z \)** = Location of NP
- **\( A \)** = Area of pile point
- **\( E \)** = Pile modulus
Maximum Friction

FOR PILES IN CLAY (short term and long term)

\[ f_{\text{max}} = \alpha S_u \]

\[ f_{\text{max}} = \beta \sigma'_{ov} \]

Short Term (Undrained) Friction in Clay

For Driven and Bored Piles

Long Term (Drained) Friction in Clay and Silt

For Bored Piles Use:

\[ f_{\text{max}} \text{ (Bored)} = 0.75 f_{\text{max}} \text{ (Driven)} \]

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FOR PILES IN SAND

\[ f_{\text{max}} (\text{kPa}) = 5 \times (N)^{0.7} \]

\( N = \text{SPT blow count} \)

\[ f_{\text{max}} = \beta \sigma'_{ov} \]
Maximum Point Resistance

FOR PILES IN SANDS AND IN CLAYS

Clay (short term) \[ q_{\text{max}} = 9 \, S_u \]

Clay (long term) \[ q_{\text{max}} = \sigma'_{ov} \, N_q \]

Sand (short & long term) \[ q_{\text{max}} (\text{kPa}) = 1000 \, (N)^{0.5} \]

Sand (short & long term) \[ q_{\text{max}} = \sigma'_{ov} \, N_q \]

\[ \omega_{\text{max}} = \frac{\pi}{4} (1 - v^2) \frac{q_{\text{max}} D}{AE_s} \]
Downdrag on Pile Groups
Downdrag on Pile Groups

After Okabe, 1977
Reduction Factors for Downdrag in Pile Groups

\[ S/D = 5 \]
\[ F_{n\text{(corner)}} = 0.9 \, F_{n\text{(single)}} \]
\[ F_{n\text{(side)}} = 0.8 \, F_{n\text{(single)}} \]
\[ F_{n\text{(interior)}} = 0.5 \, F_{n\text{(single)}} \]

\[ S/D = 2.5 \]
\[ F_{n\text{(corner)}} = 0.5 \, F_{n\text{(single)}} \]
\[ F_{n\text{(side)}} = 0.4 \, F_{n\text{(single)}} \]
\[ F_{n\text{(interior)}} = 0.15 \, F_{n\text{(single)}} \]

- \( S \) = center-to-center spacing
- \( D \) = pile diameter
- \( F_{n\text{(single)}} \) = downdrag force on the single pile
- \( F_{n\text{(corner)}} \) = downdrag force on a corner pile in the group
- \( F_{n\text{(side)}} \) = downdrag force on a side pile in the group
- \( F_{n\text{(interior)}} \) = downdrag force on an interior pile in the group
PILENNEG

- Developed at Texas A&M University
- Analyzes axially-loaded single piles under both positive and negative skin friction
- Bitumen coated piles can also be analyzed with the program

http://ceprofs.tamu.edu/briaud/pileneg/pileneg.zip
# PILENEG Inputs

- **Top load on pile**
- **Pile data** (cross section area of the pile, pile perimeter, embedded pile length, pile modulus)
- **Soil data** (profile of maximum friction, soil settlement profile, soil modulus and Poisson’s ratio at point, ultimate bearing pressure at point)

### PILE DATA

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area (m²)</td>
<td>1.450 E -1</td>
</tr>
<tr>
<td>Area of pile point (m²)</td>
<td>1.450 E -1</td>
</tr>
<tr>
<td>Perimeter (m)</td>
<td>1.390 E +0</td>
</tr>
<tr>
<td>Embedded length (m)</td>
<td>4.176 E +1</td>
</tr>
<tr>
<td>Modulus (kN /m²)</td>
<td>2.410 E +7</td>
</tr>
</tbody>
</table>

### BEARING SOIL DATA

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus of bearing soil (kN /m²)</td>
<td>2.153 E +4</td>
</tr>
<tr>
<td>Poisson’s ratio of bearing soil</td>
<td>0.30</td>
</tr>
<tr>
<td>Ultimate bearing capacity of bearing soil (kN /m²)</td>
<td>7.097 E +3</td>
</tr>
</tbody>
</table>
PILENEG Outputs

- Top load, top settlement, depth of bitumen coating, depth to neutral point, maximum load, maximum stress and pile point load
WHAT IS BITUMEN?

A black viscous substance. The residue left at the end of the refining process of crude oil, made of high molecular weight hydrocarbons.

WHAT IS A PRIMER?

A liquid made of half bitumen and half solvent to liquefy the bitumen for easy application and filling the holes. The layer left is largely the bitumen after drying.
Behavior of Bitumen

Bitumen is a viscous material

\[ \tau = \eta \left(\frac{d\gamma}{dt}\right) \]
\[ \tau = \eta \left( \frac{d\gamma}{dt} \right) \]

Master Curves
Soft Bearing Pile Lubricant

<table>
<thead>
<tr>
<th></th>
<th>Cold</th>
<th>Hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>OK</td>
<td>No</td>
</tr>
<tr>
<td>Driving in air</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Driving in soil</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Downdrag</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

Viscosity, kPa.s

Shear Strain Rate, 1/s
$$\tau = \eta \,(d\gamma/dt)$$

$\eta$ decreases when $d\gamma/dt$ increases
$d\gamma/dt \times 10$ leads to $\sim \eta / 2$

$\eta$ decreases when $T$ increases
$T \times 2$ leads to $\sim \eta / 10$

$\eta$ much more sensitive to $T$ than $d\gamma/dt$
\[ \tau = \eta \left( \frac{d\gamma}{dt} \right) \]

- Storing
- Driving
- Downdrag
- Particle penetration
Storage Criterion

\[ \eta_{\text{req}(\text{storage})} = \frac{\tau}{\dot{\gamma}} = \frac{\rho g t d^2}{h} \]

\( \rho \) = Bitumen mass density
\( g \) = Acceleration due to gravity
\( t \) = Max anticipated storage period
\( d \) = Bitumen coating thickness
\( h \) = Allowable bitumen flow distance (usually taken as equal to \( d \))

Storage requires:
\[ \eta > \eta_{\text{req}(\text{storage})} \]
Driving Criterion

\[ \eta_{\text{req}(\text{driving, air})} = \frac{\tau_a}{\dot{\gamma}_a} = \frac{\rho v_a d^2}{h} \]

\[ \eta_{\text{req}(\text{driving, soil})} = \frac{\tau_s}{\dot{\gamma}} = \frac{f_{\text{max}} t d}{h} \]

\( \rho \) = Bitumen mass density
\( v_a \) = Velocity of bitumen in the air (taken as the velocity of the hammer at time of impact)
\( d \) = Bitumen coating thickness
\( h \) = Allowable bitumen flow distance (usually taken as equal to \( d \))
\( f_{\text{max}} \) = Maximum friction
\( t \) = Max anticipated storage period

Driving in air requires:
\[ \eta > \eta_{\text{req}(\text{driving, air})} \]

Driving in soil requires:
\[ \eta > \eta_{\text{req}(\text{driving, soil})} \]
Downdrag Criterion

\[ \eta_{\text{req(downdrag)}} = \frac{\tau_{\text{bit}}}{\dot{\gamma}_s} = \frac{d\tau_{\text{bit}}}{\dot{s}} = \frac{d\tau_{\text{bit}}}{\left(\frac{s_2 - s_1}{t_2 - t_1}\right)} \]

- \( \tau_{\text{bit}} \) = Allowable shear stress on bitumen (\( \tau_{\text{bit}} \sim 0.1 \tau_{\text{s,avg}} \))
- \( \tau_{\text{s,avg}} \) = Soil shear strength
- \( d \) = Bitumen coating thickness
- \( s \) = Settlement rate
- \( s_1, s_2 \) = Settlements of the ground surface at times \( t_1 \) and \( t_2 \), respectively (after placement of an embankment or other load)

Downdrag requires:
\[ \eta < \eta_{\text{req(driving)}} \]
Particle Penetration Criterion

\[ \sigma'_H = K \sigma'_{OV} \]

FOR DRIVEN PILES: \( K = 1 \)

FOR BORED PILES: \( K = K_0 = (1-\sin \Phi) \text{OCR}^{0.5} \)
Bitumen Design Criteria Summary

(a) WINDOW OF ACCEPTABLE $\eta$

(b) NO WINDOW OF ACCEPTABLE $\eta$
EXAMPLE:

Find allowable top load for a top settlement < 14 mm

1) Pile Ult. Capacity

\[ Q_u = (25 \times 1.2 \times 30) + 1000 \]

\[ Q_u = 900 + 1000 = 1900 \text{ kN} \]
EXAMPLE:

2) Assume a top load = 500 kN and find the maximum depth to NP

\[500 + X = 1000 + (900 - X)\]

\[X = 700 \text{ kN or 23.3 m of friction}\]

\[\omega_{NP(\text{soil})} = 35 \text{ mm (settlement profile)}\]

\[\omega_{\text{top}} = 35 + \frac{(850 \times 23300)}{(0.09 \times 2 \times 10^7)} = 46 \text{ mm (This is more than the allowable settlement)}\]
EXAMPLE:

3) Assume a top load = 100 kN and NP = 29 m

$$Q_p = 100 + 870 - 30 = 940 \text{ kN}$$

$$\omega_p = 4.7 \text{ mm}$$

$$\omega_{NP(pile)} = 4.7 + \frac{(955\times1000)}{(0.09\times2\times10^7)}$$

$$= 5.2 \text{ mm} \sim \omega_{NP(soil)}$$

$$\omega_{top} = 5 + \frac{(535\times29000)}{(0.09\times2\times10^7)}$$

$$= 13.6 \text{ mm}$$
EXAMPLE:

4) Use bitumen coating with shear strength = 2.5 kN/m² and try a top load of 500 kN (Assume NP = 29 m)

\[ \omega_{NP(\text{soil})} = 5 \text{ mm} \]
\[ Q_p = 500 + 87 - 30 = 557 \text{ kN} \]
\[ \omega_p = 2.8 \text{ mm} \]

\[ \omega_{\text{top}} = 5 + \frac{(543.5 \times 29)}{(0.09 \times 2E7)} \times 1000 \]
\[ = 13.8 \text{ mm} \]
\( \omega_{\text{top}} = 46 \text{ mm} \)

\( \omega_{\text{top}} = 14 \text{ mm} \) with bitumen

(a) \hspace{2cm} (b) \hspace{2cm} (c)
### ALBERTA TEST SITE

#### Soil Profile

<table>
<thead>
<tr>
<th>DEPTH (m)</th>
<th>TYPE</th>
<th>SOIL DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td>COMPACTED CLAYEY FILL</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>SAND (fine)</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>CLAY with some silt soft, wet</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>CLAY (silt), Sandy softer, wet</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>SAND (dense)</td>
</tr>
</tbody>
</table>

- **Bitumen Coating**: 18 m
- **18 m**: Below
- **24 m**: Below

**Full Scale Field Test:**

Alberta, Edmonton, Canada
Maximum Downdrag Loads – Alberta
Test Piles – Approx. 335 days

C1 – Intellisolve
C2 – Soft Bearing Pile Lubricant
C3 – Culvert Compound
U4 – Uncoated

Depth, m

Axial Load, kN

[Graph showing the relationship between depth and axial load for different piles.]
CONSTRUCTION AND SPECIFICATIONS

- Clean surfaces (free of dust and grease)
- Apply the primer (wait 24 hrs for drying)
- Apply the bitumen (10 mm thick)
- Storing (cold, hot)
- Handling in the field (pad eye, no strap)
- Drive the piles (splice, temperature)
• Clean surfaces (free of dust and grease)
• Apply the primer (wait 24 hrs for drying)
Applying the bitumen (10 mm thick)
Applying the bitumen (10 mm thick)
APPLYING BITUMEN COATING OUTSIDE IN THE COLD

BITUMEN BECOMES BRITTLE DUE TO COATING OUTDOORS
Handling in the field
Storing the coated piles

In hot weather, store under cover away from direct sunlight

In cold weather, wait until bitumen cools down before storing
Driving the piles (splice, temperature)
AVERAGE ANNUAL AIR TEMPERATURE = SOIL TEMPERATURE
General Observations

1. Downdrag does not reduce the ultimate capacity of a pile

2. Downdrag increases the load in the pile

3. Downdrag increases the settlement of a pile; downdrag is a case where settlement controls the pile design

4. Live loads should not be included in settlement calculations including downdrag
General Observations

6. Downdrag makes a pile come out of the ground

7. Bitumen reduces downdrag significantly (90%?) when properly chosen and properly applied

8. Bitumen is most easily applied when the air is colder than the soil (winter) but when the temperature is above freezing

9. Piles located on the inside of a pile group experience less downdrag than the perimeter piles
Videotape on Bitumen Coating (email: briaud@tamu.edu)


https://ceprofs.tamu.edu/briaud/NCHRP_Downdrag.pdf
THANK YOU

http://www.issmge.org/

http://ceprofs.civil.tamu.edu/briaud/
Full Scale Field Test: New Orleans, Louisiana, USA
Full Scale Field Test:
New Orleans, Louisiana, USA

LEGEND

P1—PIEZOMETER 1 (20 FT DEPTH)
P2—PIEZOMETER 2 (50 FT DEPTH)
STOPPED WORKING 7/31/90
P3—PIEZOMETER 3 (80 FT DEPTH)
STOPPED WORKING 7/27/90
P4—PIEZOMETER 4 (45 FT DEPTH)
INSTALLED 9/5/90
P5—PIEZOMETER 5 (70 FT DEPTH)
INSTALLED 9/6/90
EX1—SETTLEMENT EXTENSOMETER
CPT— CONE PENETROMETER TEST
TB1—TEST BORING 1

SPU—STEEL PIPE, UNCOATED
TPU—TIMBER PILE, UNCOATED
CPU—PPC PILE, UNCOATED
SP3—STEEL PIPE, TYPE 3
ROOFING COMPOUND
TP1—TIMBER PILE, TYPE 1
ROOFING COMPOUND
TPM—TIMBER PILE
WATERPROOFING
MASTIC
CPI—PPC PILE, U.S. INTEC
BLUE COMPOUND
CPM—PPC PILE, U.S. INTEC
BLUE MEMBRANE
R—REACTION PILES
### LOUISIANA TEST SITE

#### Soil Profile

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Type</th>
<th>Soil Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td>Sand fill</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Gray silty clay</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Gray silty sand</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>Gray silty, sandy clay</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>Gray clay with sand</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>Med. gray clay with silt</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>Stiff gray clay with silt, sand</td>
</tr>
</tbody>
</table>

Full Scale Field Test: New Orleans, Louisiana, USA
APPLYING PRIMER

COATING WITH BITUMEN
Maximum Downdrag Loads
Louisiana

- CPU - Concrete Pile, Uncoated
- CPI - Concrete Pile, U.S. Intec Blue Compound
- CPM - Concrete Pile, U.S. Intec Blue Membrane
- TPU - Timber Pile, Uncoated
- TP1 - Timber Pile, Trumbull Type 1 Roofing Compound
- SPU - Steel Pile, Uncoated
- SP3 - Steel Pile, Trumbull Type 3 Roofing Compound

Depth, m

Axial Load, kN
Full Scale Field Test:
Alberta, Edmonton, Canada