Case 4

Bearing Capacity Failure:
Transcona Grain Elevator, Canada

加拿大特朗斯康谷仓
Outline

4.1 Case description
4.2 The theory
4.3 The analyses
4.4 Mitigation measures
4.5 Lessons learnt
Where is it?

- Transcona existed because of the railroad that ran through it.
- Transcona got its name from a combination of "transcontinental" and "Strathcona".
Because Transcona was a transportation hub, it would make sense to locate a grain elevator there to relieve the loads during the months of peak grain-shipment.

Construction started in 1911 and completed in Sep 1913.

Residents of the Transcona area flocked to the site of the collapsed grain elevator.

Photo courtesy of the Transcona Historical Museum
Structure

- Work house
- Bin house
The Failure

Photo taken before failure

Photo taken after failure

Photo courtesy of the Transcona Historical Museum
The Failure

18 Oct, 1913

11 am
- Movement noticed on the bridges

Noon
- The bin house had settled about 30 cm
- The 7.5-9.0 m wide strip of ground around the bin house (except for the south side, where the work house stood) heaved up 1.2-1.5 m.

19 Oct, 1913

Noon
- The structure continued settling and tilting
- The earth on that side bulged up, forming a cushion which slowed down the movement.
- The connecting bridges carrying the conveyor belts breaking down and crashing to the ground

Night
- The cupola structure housing the conveyor over the bins suddenly collapsed and fell to the ground.
The Failure

Heaved soil

1.5 m

27°

9 m
The Problem

Differential settlement?
The Problem

Bearing Capacity Failure?

Plate loading test
The Problem

Bearing Capacity Failure?

Plate loading test

p-s curve

$P_{cr}$  $P_u$
The Problem

Bearing Capacity Failure?

- The smaller-scale plate loading tests predicted a safety factor of more than 1.3 !!!
The Problem

Bearing Capacity Failure?

(After Peck and Bryant, 1953)
The Problem

Unconfined compression test

\[ \phi_u = 0 \]

\[ \tau_f = c_u = q_u / 2 \]
The Problem

Bearing Capacity Failure?

(After Peck and Bryant, 1953)
The Problem

Excessive settlement vs. Bearing capacity failure

- Fast settlement
- Ground heave
Outline

4.1 Case description
4.2 The theory
4.3 The analyses
4.4 Mitigation measures
4.5 Lessons learnt
The theory

Prandtl solution (1920)

Reissner (1924)

Taylor (1948)

\[ \sigma_f = \gamma b N_\gamma + q N_q + c N_c \]
The theory

Prandtl solution (1920)

Undrained bearing capacity $\varphi_u = 0$
The theory

Prandtl solution (1920)

Undrained bearing capacity $\phi_u = 0$

$N_c = 5.14$
The theory

The ultimate bearing capacity

\[ \sigma_f = \gamma b N_\gamma + q N_q + c N_c \]

Undrained bearing capacity formula

\( \varphi_u = 0, \ c_u \)

\( N_\gamma = 0, \ N_q = 1, \ N_c = 5.14 \)

Terzaghi formula

\[ \sigma_f = q + c N_c \]

Shape correction factor

\[ s_c = 0.2 \frac{b}{L} \]

Depth correction factor

\[ d_c = 0.4 \frac{t}{b} \]
The theory

The ultimate bearing capacity

\[ \sigma_f = (\gamma \cdot t + q) + c_u N_c (1 + s_c + d_c) \]

Safety Factor

\[ F_s = \frac{\sigma_f}{\sigma} \]
The theory

Simplification

Scoop failure mechanism
Two-layer strata

1. Prandtl solution (1920)

\[ c_u = c_{u1} m + c_{u2} (1 - m) = c_{u1} (m + n - mn), \]

\[ m = \frac{2D}{b}, \quad n = \frac{c_{u2}}{c_{u1}} \]

\[ \sigma_f = (\gamma \cdot t + q) + c_u N_c \left(1 + s_c + d_c\right) \]
Two-layer strata

2. Scoop failure mechanism

\[ \sigma_f = (\gamma \cdot t + q) + c_u N_c \]
Two-layer strata

2. Scoop failure mechanism

\[ \sigma_f = (\gamma \cdot t + q) + c_{u1} N_c \]
1. For homogeneous soils, Prandtl solution provides an exact solution.

2. For two-layer strata, Prandtl solution cannot be applied directly, and its approximation using a weighted average of shear strength with depth is not rigorous.

3. Upper Bound Limit Analysis can provide some useful results, using simpler kinematic failure mechanisms, such as the scoop mechanism.

4. The values of the bearing capacity factor are rigorous upper bounds and are larger than the true collapse load. Therefore, they are not conservative and an important question has to be answered: how far are we from the true collapse load?
Outline

4.1 Case description
4.2 The theory
4.3 The analyses
4.4 Mitigation measures
4.5 Lessons learnt
- width of the rectangular footing: \( b = 23.5 \text{ m} \);
- length of the rectangular footing: \( L = 59.5 \text{ m} \);
- depth of the foundation: \( t = 3.7 \text{ m} \).
- thickness of the upper clay layer below the footing $D = 6.0$ m; 
- undrained shear strength of the upper layer $c_{u1} = q_{u1} / 2 = 54$ kPa; 
- undrained shear strength of the lower layer $c_{u2} = q_{u2} / 2 = 31$ kPa; 
- total unit weight of clay in both layers $\gamma = 18.7$ kN/m$^3$. 
Loads (Allaire, 1916; Peck and Bryant, 1953):
- surface surcharge load \( q = 0 \);
- failure contact pressure from the plate load tests: \( \sigma_f \approx 400 \text{ kPa} \);
- true contact pressure at failure: \( \sigma_f = 293 \text{ kPa} \).
1. The bearing capacity assumed in the original design

\[ \sigma_f = (\gamma \cdot t + q) + c_u N_c \left( 1 + s_c + d_c \right) \]

<table>
<thead>
<tr>
<th>Shape correction factor</th>
<th>Depth correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_c = 0.2 \frac{b}{L} )</td>
<td>( d_c = 0.4 \frac{t}{b} )</td>
</tr>
</tbody>
</table>

Consider the stiff layer

\[ N_c \approx 5.14, \quad s_c = 0.2 \frac{23.5}{59.5} = 0.08, \quad d_c = 0.4 \frac{3.7}{23.5} = 0.06 \]

\[ \sigma_f = (18.7 \times 3.7 + 0) \div 54 \times 5.14 \times (1 + 0.08 + 0.06) = 386 \text{ kPa}. \]

Close to plat-loading test result!!

It will not fail in a load of 300 kPa!!
Predictions

1. The bearing capacity assumed in the original design

Terzaghi formula

$$\sigma_f = (\gamma \cdot t + q) + c_u N_c \left(1 + s_c + d_c\right)$$

Shape correction factor

$$s_c = 0.2 \frac{b}{L}$$

Depth correction factor

$$d_c = 0.4 \frac{t}{b}$$

- Consider the soft layer layer

$$N_c \approx 5.14, \quad s_c = 0.2 \frac{23.5}{59.5} = 0.08, \quad d_c = 0.4 \frac{3.7}{23.5} = 0.06$$

$$\sigma_f = 69.2 + 31 \times 5.14 \times 1.14 = 251 \text{ kPa}.$$ 

It will fail in a load of 300 kPa !!!

Only 20% conservative than the true failure pressure.
2. Consideration of two-layer strata

**Plandtl solution**

\[
c_u = c_{u1}m + c_{u2}(1-m) = c_{u1}(m + n - mn),
\]

\[
\sigma_f = (\gamma \cdot t + q) + c_u N_c \left(1 + s_c + d_c\right)
\]

\[
c_u = 54 \times (0.51 + 0.57 - 0.51 \times 0.57) - 43 \text{ kPa}.
\]

\[
\sigma_f = 69.2 + 43 \times 5.14 \times 1.14 = 321 \text{ kPa},
\]

10% larger than the true failure pressure !!

It will not fail in a load of 300 kPa !!
Predictions

2. Consideration of two-layer strata

\[ \gamma t + q \]

\[ \sigma_f \]

\[ \gamma t + q \]

\[ c_{u1} \]

\[ b \]

\[ \alpha \]

\[ r \]

\[ D \]

\[ c_{u1} \]

\[ c_{u2} \]

\[ N_e \approx 3.7. \]

\[ \sigma_f = 69.2 + 54 \times 3.7 \times 1.14 = 297 \text{ kPa}. \]

- Scoop mechanism

Marginally larger than the true failure pressure!!

It will fail in a load of 300 kPa!!
The analysis confirms that insufficient bearing capacity was the most likely cause of the Transcona Grain Elevator failure.

The Prandtl mechanism would provide a reasonably good prediction of the bearing capacity if the soil was homogeneous, as confirmed by the plate load tests, where the failure mechanism was entirely confined to the upper clay layer.

The real mechanism was much deeper due to the large foundation width and penetrated a weaker lower layer.

An approximate approach using the Prandtl formula with averaged shear strength appeared to be neither accurate nor conservative.

The upper bound limit analysis using a scoop mechanism provided a remarkably good prediction.
Mitigation

1. Emptying of the elevator

Belt conveyor
2. Underpinning of the work-house  By June 1914

- Reinforcing the foundation and the structure before underpinning operation.
- Excavating access tunnels under the foundation mat.
- Sinking a 1.5 m diameter pier under each of the 24 columns of the building.
Mitigation

3. Straightening of the bin-house Feb - Oct 1914

Under-excavation at the east (high) side
Mitigation

3. Straightening of the bin-house  Feb - Oct 1914

Jacking-up the west (low) side
4. Underpinning of the bin-house

The elevator in righted position after mitigation (October 1914)
Outline

4.1 Case description
4.2 The theory
4.3 The analyses
4.4 Mitigation measures
4.5 Lessons learnt
Lessons learnt

- Site investigation
  ✓ The importance of the proper geotechnical site investigation.

- Field load tests
  ✓ The field plate load tests also did not help to avoid the failure. This happened due to the scale effect.
  ✓ In order to be able to make meaningful predictions based on the field load tests, these tests have to be performed at their one-to-one scale or at different elevations.

- Conservative design
  ✓ A conservative prediction may be achieved by assuming that the soil is homogeneous with the undrained shear strength of the weaker layer.

- Upper bound limit analysis
  ✓ An upper bound limit analysis using a simple kinematic mechanism can provide a useful tool.