A Case Study on Seepage Failure of Bottom Soil within a Double-Sheet-Pile-Wall-Type Ditch

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A double-sheet-pile-wall-wall-type ditch (or prefabricated ditch)

Boiling occurred in the bottom soil during puddling

Ditch border collapsed

Analyses of FEM seepage flow and stability against seepage failure using Pfc

Discussion on causes of the failure, effects of 2DC flow, effects of backfills, and countermeasures against seepage failure
Plane of the site

Piping failure occurred

Piping failure did not occur
Cross sectional view of the ditch near Bo.1

- **Plow layer**
- **Upper fine sand**
- **Bottom soil**
- **Silt**
- **Lower fine sand**
Cross sectional view of the ditch near Bo.1

- Bottom soil
- Plow layer
- Upper fine sand
- Fine sand containing silt

Arm: 1.14m
Panel: 1.2m

(unit m)

EL..3.877  Bo.1
EL..2.050
EL..2.580
EL..2.665
EL..2.681
EL..2.780
EL..3.495
EL..3.200
EL..3.121
EL..2.400
EL..0.400
EL..1.950
Physical properties of soils

The backfill and boiled-out sand are the same soil as the upper fine sand containing silt.

The backfill is very soft, and is also more permeable than neighboring soils.

\[ k_{BF} = 2.265 \times 10^{-3} \text{ cm/s} > 1.310 \times 10^{-3} \text{ cm/s} = k_{UFS} \]
Groundwater levels and water levels in the ditch (continuous observation)
Surface boiling was observed

\[ H = 0.317\text{m} \text{ on 2004/11/20,} \]
\[ H = 0.373\text{m} \text{ on 2005/11/12,} \]
\[ H = 0.273\text{m} \text{ on 2006/04/23.} \]

\[ H = 0.600\text{m} \text{ was recorded on 2004/05/16 after heavy rain, and } H = 0.456\text{m} \text{ on 2004/05/22 during puddling.} \]

Two days after the latter,
On 2004/05/24, the ditch border again collapsed about 10m from the observation point Bo.1.

The head difference at failure $H_f$ was estimated to be 0.878m.

Here, we consider the two conditions: $H$ equals to (1) 0.212m and (2) 0.456m, and the three cases: not considering backfill, considering backfill and considering a less permeable backfill.
Seepage flows are only limited to either side of the ditch and interactions with the other side’s flow are small in this case.
Stability against seepage failure of the bottom soil within the ditch

<table>
<thead>
<tr>
<th>Condition</th>
<th>Date (H)</th>
<th>(a) No backfill</th>
<th>(b) Considering backfill (in fact)</th>
<th>(c) Less permeable backfill (on an assumed condition)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$H_{PF}$ (m)</td>
<td>$F_s$</td>
<td>$H_{PF}$ (m)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>$F_s$</td>
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<td>$H_{PF}$ (m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$F_s$</td>
</tr>
<tr>
<td>2003/12/12 (0.212 m)</td>
<td>0.416</td>
<td>1.961</td>
<td>0.362</td>
<td>1.706</td>
</tr>
<tr>
<td>2004/05/22 (0.456 m)</td>
<td>0.460</td>
<td>1.008</td>
<td>0.394</td>
<td>0.864</td>
</tr>
</tbody>
</table>

In the case of $H = 0.212$ m (2003/12/12),
- $F_s = 1.961$ when not considering backfill,
- $F_s = 1.706$ when considering backfill, and
- $F_s = 3.216$ when considering less-permeable backfill.

The ditch bottom is stable for seepage failure.

In the case of $H = 0.456$ m (2004/05/22),
- $F_s = 1.008$ when not considering backfill,
- $F_s = 0.864$ when considering backfill, and
- $F_s = 1.641$ when considering less permeable backfill.

The ditch bottom was near critical or was subject to boiling for the first two cases.

The ditch bottom would be stable against boiling if the back fill was one order less permeable, as an assumed condition. Thus it is proved that a less-permeable backfill has a distinctive effect of increasing the stability.
Effect of 2DC flow condition in stability against seepage failure of soil

In the excavation of soil between double sheet pile walls, as shown in the right figure, seepage water concentrates into the soil two-dimensionally from the outside, which is called two-dimensional concentrated flow (2DC flow). The 2DC flow of water lowers the safety factor regarding the seepage failure than 2D flow.

From the analyses, the effects of 2DC flow are not the case for this problem.
Countermeasures against seepage failure

Three methods:

1. increase in the penetration depth of the panel,

2. decrease in the coefficient of permeability of backfills, and

3. replacing the upper part of the bottom ditch soil with an inverted filter.
Countermeasures against seepage failure

(1) increase in the penetration depth of the panel,
(2) decrease in the coefficient of permeability of backfills, and
(3) replacing the upper part of the bottom ditch soil with an inverted filter.

↓ concluded

The first method is the most effective. For the penetration depth of the panel $D = 0.18$ m, the ditch bottom is stable against seepage failure even for the estimated maximum hydraulic head difference.

And establishing less permeable backfills and replacing the upper part of the bottom ditch soil with an inverted filter would also be effective in increasing stability against boiling of the bottom soil.
CONCLUSIONS

(1) The largest hydraulic head difference, $H$, was 0.212m, during continuous observation period for about four months. On intermittent observation for the following two years, the $H$ values ranged from 0.600m after heavy rain to 0.456m during puddling. The greatest $H$ value at the time of transplanting was estimated to be 0.878m, when boiling failure occurred.

(2) The bottom soil within the ditch was stable at $H = 0.212$m, but was near or beyond the critical condition for seepage failure at $H = 0.456$m.

(3) A less-permeable backfill has a distinctive effect of increasing the stability.
(4) The seepage flows are only limited to either side of the ditch, so the effects of 2DC flow are not the case for this problem.

(5) Three countermeasures against boiling were considered:
1) increase in the penetration depth of the panel,
2) decrease in the coefficient of permeability of backfills, and
3) replacing the upper part of the bottom ditch soil with an inverted filter.

The first method was the most effective. The combination of the other two methods would also be effective in increasing stability against boiling of the bottom soil.
Thank you very much for your kind attention.
Stability against Heaving of Bottom Clay Soil in the Ditch where Boiling has not occurred

At a site 240m from Bo.1, boiling did not occur even under a similar sheet-pile-wall condition. We concluded the reason why the bottom soil of the ditch consisted of clay of low plasticity (CL).

We examined the stability against heaving for the ditch bottom soil under the following two cases:

Two cases:
(1) $H = 0.370\text{m (2004/02/29)}$, the maximum hydraulic head difference during the continuous observation period,
(2) $H = 0.934\text{m (2005/05/07)}$, the maximum hydraulic head difference after heavy rain.
Even under the most severe condition on 2005/05/07 ($H=0.934\text{m}$ after heavy rain),
(1) Stability number $N_b$ against heaving of the bottom soil of the ditch were equal to $1.804 (<4.0)$.

(2) Safety factor $F_s$ against heaving of the bottom soil of the ditch were $F_s=3.160 > 1.5$ based on the method proposed by Terzaghi & Peck, $F_s=3.483 > 1.2$ based on the method of the Architectural Institute of Japan.

The bottom soil of the ditch consisted of clay of low plasticity (CL), so boiling did not occur even with a high ground water level. And the bottom soil of the ditch was also very stable against heaving.
Prismatic failure Concept considering Friction (PFC)

Forces exerted on a prism

\[ F_s = \frac{W' + F_L + F_R}{U_s} \]  

(3)

The critical prism is determined by the condition that the minimum safety factor \( F_s \text{ min} \) becomes just equal to 1.0 among all of the prisms.

The hydraulic head difference at the condition \( H=H_c \) is defined as the critical hydraulic head difference.
Countermeasures against seepage failure

(1) Increase in the penetration depth of the panel

Right figure shows the relationship between the depth of the panel \( D \) and the theoretical critical hydraulic head difference \( H_{PF} \).

It is observed from Figure 14 that \( H_{PF} \) efficiently increases with increase in \( D \). \( H_{PF} \) however does not increase more with increase in \( D \) beyond 0.18 m, because the less permeable silt layer appears for the depth \( D \geq 0.18 \) m in this site.
Countermeasures against seepage failure

(2) Decrease in the coefficient of permeability of backfills

Right figure shows the relationship between $k_{BF}$ and $H_{PF}$, it is found from the figure that the value of $H_{PF}$ increases and converges in the vicinity of 1.0 m with decreasing $k_{BF}$. Less-permeable backfill is also effective in increasing stability against boiling of the bottom soil.
Countermers against seepage failure

(3) Replacing the upper part of the bottom ditch soil with an inverted filter

Right figure shows the relationship between $k_F$ and $H_{PF}$. It is observed from the figure that $H_{PF}$ effectively increases with increase in $k_F$. The $H_{PF}$ value is given as 0.729 m for $k_F = 1.31 \times 10^{-5}$ m/s which corresponds to the case with no replacement, and is given as 1.390 m for the coefficient ($k_F = 1.31 \times 10^{-4}$ m/s) ten times as large as the above one. Thus replacing the upper part of the bottom ditch soil with an inverted filter is also effective in increasing stability against boiling.