Combination of vacuum preloading and lime treatment for improvement of dredged fill

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Outline

1. Background
2. Technical Problems
3. Floc-vacuum Preloading Technique
4. Experiments and Results
5. Conclusions
Background

- Coastal cities of China are suffering a serious shortage of land
- More than 2.17 million hectare tideland in costal area of China
- Tideland reclamation has been recognized as a primary countermeasure to overcome the shortage of land

By 2015, some 150,000 hectare land have been reclaimed
In Zhejiang province, China

- In the 12th 5-Year Plan of China, more than 110 tideland reclamation projects have been approved with a total area of more than 1,280 km$^2$
- The Oufei Project in Wenzhou is the largest individual tideland reclamation program implemented so far in China
- Reclaim a total area of 323.4 km$^2$, 1.64 times the built-up area of Wenzhou
Background

- Dredged soil from nearby seabed is used as the main fill materials for tideland reclamation
- Improvement of dredged fill is indispensible because of its poor physical properties
- Vacuum preloading is widely adopted for dredged fill treatment
Technical Problems

- Problems of conventional vacuum preloading method
  - The bearing capacity of dredged fill after improvement is still insufficient to support construction machines
  - A layer of gravel-sand cushion with a thickness of 0.5~1 m is paved to provide the platform for construction machines
Technical Problems

- Engineering problems induced by poor foundation treatment

Soil instability

Piles inclination

Buildings tilting

Structural damage
Technical Problems

- At most tidelands
  The dredged soil consist mainly of clay slurry

- At a few tidelands
  Mainly silty sand comprises the dredged soil

Dredged fill in Wenzhou

Dredged fill in Tianjin
### Technical Problems

<table>
<thead>
<tr>
<th>Clays</th>
<th>Water content /(#)</th>
<th>Liquid limit /(#)</th>
<th>Plasticity index /(#)</th>
<th>Permeability m/h</th>
<th>d(0.5) /μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenzhou clay</td>
<td>90-230</td>
<td>42-55</td>
<td>25-34</td>
<td>0.05-2 × 10⁻⁹</td>
<td>7.07</td>
</tr>
<tr>
<td>Tianjin clay</td>
<td>80-210</td>
<td>30-45</td>
<td>13-27</td>
<td>1-3 × 10⁻⁹</td>
<td>30-50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle Size Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (%)</td>
</tr>
<tr>
<td>5.5</td>
</tr>
<tr>
<td>5.0</td>
</tr>
<tr>
<td>4.5</td>
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<tr>
<td>4.0</td>
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<td>0.5</td>
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<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

- d(0.1): 1.592 um
- d(0.5): 7.071 um
- d(0.9): 29.062 um
Technical Problems

- Clogging of PVDs by fine particles
- Formation of consolidated soil column surrounding PVDs
- Insufficient consolidation in deep soil layer
- Excessive settlement after construction

An enhanced vacuum preloading method is needed to address these issues.
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Floc-vacuum Preloading Technique

- Add hydrated lime to dredged clay slurry
  - Cation exchange reaction & Flocculation
    Agglomeration of tiny clay particles into larger-sized particles, and thereby increase void ratio and permeability
  - Pozzolanic reaction & Lime carbonation
    Formulation of calcium carbonate ($\text{CaCO}_3$), which enhances cementation and strength
Cation Exchange Reaction
- Additive of lime in a sufficient quantity supplies an excess Ca++
- Replace weaker metallic cations on clay mineral surface
- Decrease thickness of diffusion layer and inter-particle repulsive forces

Flocculation & agglomeration
- Tiny clay particles are absorbed and assembled together into larger-sized particles, thereby increases void ratio and permeability

\[ \text{Ca(OH)}_2 \rightarrow \text{Ca}^{2+} + \text{OH}^- \]
Floc-vacuum Preloading Technique

- Pozzolanic reaction

\[
\text{Ca(OH)}_2 + \text{SiO}_2 \rightarrow \text{CaO-SiO}_2-\text{H}_2\text{O} \quad (1)
\]

\[
\text{Ca(OH)}_2 + \text{Al}_2\text{O}_3 \rightarrow \text{CaO-Al}_2\text{O}_3-\text{H}_2\text{O} \quad (2)
\]

The products are calcium silicate hydrate and calcium aluminate hydrate, the same hydrate formed during the hydration of Portland cement.

- Lime carbonation

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \quad (3)
\]

The products are calcium carbonate, which can enhance the cementation and strength of the soil.
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Determination of LMO

- LMO (Lime Modification Optimum)
  - PH Method
    LMO is obtained when the PH firstly reach a high point.
  - E-P Curve Method
    Determining the LMO by compression test
Determination of LMO

- Experimental setup
  - Five soil samples with the same water content of 187%
  - Five different lime content of 0%, 1.0%, 1.5%, 2%, 2.5%
  - Determination of LMO in terms of discharged water, pore water pressure, vane shear strength, water content
Drainage completed within 48 hours for clay slurry with 2% lime, while it spent 168 hours for clay slurry without additive of lime.
Clay slurry with 2% lime achieved not only the maximum speed but also the maximum volume of pore water pressure dissipation.
Clay slurry with 2% lime had the maximum vane shear strength.
Water content generally increased with increasing lime content.
More water-bearing products generated as lime content increases.
Comparison Test

- Experimental setup
  - Natural clay slurry after one-year’s self weight consolidation with a water content of 103%
  - Clay slurry just dredged from seabed with a water content of 187% and mixed with 2% lime
  - The dry weight of both soil samples are uniform
Comparison Test

Plan view of vacuum system

Sealed area

PVDs

Cap

unsealed area

vacuum pump

10cm

2000mm
Comparison Test

- Plan view and side view of instrumentation

- Settlement
- Vane shear strength
- Water content
- Pore water pressure
- Vacuum pressure

Diagram showing various markers and instruments.
Comparison Test

- Vacuum pressure in PVDs

No obvious difference was observed between vacuum pressures in PVDs embedded in natural slurry and lime treated slurry.

**Natural slurry**

**Slurry with 2% lime**
Vacuum pressure in lime treated slurry increased right after the commencement of vacuum preloading, whereas it took 70 h for natural slurry to have any change in vacuum pressure.
Settlement of lime treated slurry completed earlier than that of natural slurry. Ultimate settlement of lime treated slurry was almost two times its counterpart of natural slurry.
Lime treated slurry had not only a larger rate of pore water pressure dissipation, but also a larger volume of pore water pressure dissipation.
Vane shear strength of lime treated slurry was larger than its counterpart of natural slurry at all depths. Gradient of vane shear strength along depth was smaller in lime treated slurry.
Water content of lime treated slurry was larger than its counterpart of natural slurry at all depths.
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Conclusions

- A combination of vacuum preloading and lime treatment is proposed for the treatment of dredged clay slurry.
- The LMO for the dredged clay slurry in Wenzhou with a water content of 187% is determined as 2%.
- The addition of hydrated lime to the clay slurry helps mitigate the clogging of PVDs and retard the formation of soil columns around the PVDs.
- The proposed floc-vacuum preloading technique outperforms the conventional vacuum preloading technique in terms of the vacuum pressure transfer, pore water pressure dissipation, settlement, and vane shear strength.
Thank You!

Questions?