GEOSYNTHETICS ENGINEERING: IN THEORY AND PRACTICE

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Module - 9
LECTURE - 46
Geosynthetics for ground improvement
Recap of previous lecture.....

- Bearing capacity and settlement
- Principles and functions of vertical drains
- Basic principles of prefabricated vertical drains
- Design charts without and with smear effect
**DESIGN CHART WITH SMEAR EFFECT AND WELL RESISTANCE**

**Design Procedure:**

**Step 1:** Determine the characteristics of soil

- $C_h = \text{Coefficient of consolidation for horizontal drainage } m^2/\text{sec or } m^2/\text{month}$,
- $K_h = \text{Coefficient of horizontal permeability in undisturbed zone, } (m/\text{sec})$,
- $K_s = \text{Coefficient of permeability in the disturbed or smear zone } (m/\text{sec})$

**Step 2:** Determine following drain properties

- $d_w = \text{Diameter of the drain, } m$,
- $d_s = \text{Diameter of the disturbed (smear) zone, } m$, and
- $q_w = \text{Discharge capacity of the drain, } m^3/\text{sec}$
Step 3: Determine the following consolidation requirements

\[ U = \text{Average degree of consolidation, and} \]

\[ t = \text{Time required to achieve the degree of consolidation} \]

Step 4: Determine factor for soil disturbance \((F_s)\)

\[
F_s = \left( \frac{K_h}{K_s} - 1 \right) \ln \frac{d_s}{d_w}
\]

Assume, \(d_s/d_w = 2\) to 8

Now, \(F_s\) can be determined from following Figure.
Soil disturbance factor ($F_s$) versus $K_h / K_s$

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Step 5: Determine factor for drain resistance ($F_r$)

$$F_r = \pi z (L - z) \frac{K_h}{q_w}$$

$z$ = Distance from the drainage end of the drain (m),

$L$ = Length of the drain when drainage occurs at one end only (Put ‘$L/2$’ replacing ‘$L$’ when drainage occurs from both the ends)

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Well resistance ($F_r$) versus Length ($L$)

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Step 6: Determine the required consolidation time, $t$ in months and obtain product ($C_h \times t$) from the following Figure.

Product of $C_h$ and $t$ versus time ($t$)

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Step 7: Determine the parameter, $\lambda$ from the following Figure based on the required degree of consolidation (U) and ($C_h \times t$).

Product of $C_h$ and time ($t$) versus Lambda ($\lambda$)

$C_h = \text{Coefficient of consolidation in horizontal direction,}\n
t = \text{Required time for consolidation}$
Step 8: Add $F_s$ and $F_r$ obtained from steps 4 and 5 respectively.

$$F_{sr} = F_s + F_r$$

$$F = F_{sr} + F(n)$$

Determine the design diameter ‘D’ (in meter) from the following Figure based on $\lambda$ and appropriate $F_{sr}$ for $n = 20$.

$$\lambda = \frac{8 C_h t}{\ln \left( \frac{1}{1 - U} \right)} = D^2 F$$

$F_r = $ Well resistance factor

$F_s = $ Smear effect factor

$F(n) = $ Spacing factor

$n = $ spacing ratio

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Design diameter, $D (m)$ versus Lambda, $\lambda$ for $n = 20$

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Step 9: Find the spacing (S)

D = 1.05 S (For triangular pattern), and
D = 1.13 S (For square pattern)

- The above design is developed by Mandal and Fulzele (2008).

- The similar design charts are also developed by Mandal and Shiv (1992) for prefabricated geocomposite drain.
Example:

L = Length of the soil strata = 20 m, \( K_h/K_s = 5 \),

\( C_h = 3.9 \times 10^{-1} \, \text{m}^2/\text{month} \), \( d_s/d_w = 2 \), \( U = 80 \% \), \( t = 11 \, \text{months} \)

Determine the design diameter of the drain influence zone.

Solution:

- \( K_h/K_s = 5 \), and \( d_s/d_w = 2 \)

From Figure, \( F_s = 2.9 \).
L = 20 m, and \( \frac{K_h}{q_w} = 0.001 \)

From **Figure**, \( F_r = 0.9 \)
Therefore, \( F_{sr} = F_s + F_r = 2.9 + 0.9 = 3.8 \)

- \( U = 80 \% \) and \( C_h \times t = (3.9 \times 10^{-1}) \times 11 \approx 4 \)

From Figure, \( \lambda = 20 \)
F_{sr} = 3.8 \approx 4 \text{ and } \lambda = 20

From Figure, design diameter of influence (D) = 1.8 m

D = 1.05 S \text{ (For triangular pattern), and}
D = 1.13 S \text{ (For square pattern)}
Instrumentation of embankment on soft soil with PVDs

1. Marking of Points
2. Installation of PVD
3. Sand Blanket
4. Geotextile placement
5. Instruments Installation
6. Preloading stages

Inclinometer
Piezometer
Settlement gauge

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Pneumatic Piezometer: To monitor the pore water pressure at the desired depth of the compressible soil.

Inclinometer: To measure the lateral movement of the soil at the site slopes.

Settlement gauges: To measure the long term settlement at the original ground surface of drainage blanket.

Settlement Plate: To monitor the settlement readings.

Water stand pipe: To monitor the level of water in the compressible soil layer either the Piezometers or settlement gauges are installed immediately or during the installation of the vertical drains.
Settlement versus time curve without and with PVD

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Installation of PVD:

- The vertical drains are available in the form of a roll.
- The band drain is wrapped around a base plate or a steel bar at the bottom of the hollow steel lance.
- The lance, band drain and steel rod will be pushed into the soft cohesive soils to the desired depth.
- When the band drain is reached to the desired depth, the lance is to be withdrawn keeping behind the steel rod and band drains.
Installation of PVD drain (Photo Compliments of DBM Geotechnics)

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Installation of PVD at JNPT for national Highway Authority of India

Installed 7,00,000 Rmt (Sohams Foundation)

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- Installation of PVD at JNPT for Maersk India Ltd
- Installed PVD 8,50,000 Rmt in 40 Days Period

(Sohams Foundation)
Cross section of mandrel and drain (After Rixner et al., 1986)

Different base plates to maintain wick drains at the base of the installation lance

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Band drains can be installed very fast. It is prefabricated, lighter as well as easy to transport and store.

It is also economical with respect to the conventional sand drains. The equipment is lighter than the rigs.

15 m long drains at spacing of 1 m to 2.5 m at a placement rate of 375 m/hr is possible (Hausmann, 1990).

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Summary on band drain

- Geotechnical engineers generally faced problem to construct structures on very soft soil.
- It is necessary to prevent excessive settlement as well as improve the bearing capacity of soft soil. Therefore, ground improvement techniques are needed.
- Combination of preloading and installation of prefabricated vertical band drains in the subsoil layers can serve the purpose.
- Prefabricated vertical drains accelerate the consolidation process as well as dissipate excess pore water pressure within very short period.
The PVD drains have many advantages compared to the sand drains.

Rapid settlement of the soft soil is required for construction of embankments, oil tank foundations, landfills and underwater constructions.

PVD drains are efficient and most economical.
Example:

Compute time required for 60%, 70%, 80% and 95% consolidation at different spacing of Prefabricated Vertical Band Drain.

Size of PVD drain: 100 mm x 5 mm (Triangular Pattern) Assume $C_h = 6.27 \times 10^{-6}$ m$^2$/min
Solution:

Consolidation time,

\[ t = \frac{D^2}{8C_h} \left[ \ln\left(\frac{D}{d_w}\right) - \frac{3}{4} \right] \ln\left(\frac{1}{1-U}\right) \]

\( a = 100 \text{ mm (width of band drain)} \)
\( b = 5 \text{ mm (thickness of band drain)} \)
\( d_w = \text{equivalent diameter of PVD} = \frac{2(a + b)}{\pi} \)
\( D = \text{equivalent diameter of influence} = 1.05 \times S \) (for Triangular pattern)
\( S = \text{Drain Spacing (c/c between drains)} \) (m)
\( C_h = 6.27 \times 10^{-6} \text{ m}^2/\text{min} \)
$l = \text{Length of prefabricated vertical drain (m)}$

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<table>
<thead>
<tr>
<th>Spacing (m)</th>
<th>Consolidation time, t (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (m)</td>
<td>60% (U)</td>
</tr>
<tr>
<td>2</td>
<td>5.029</td>
</tr>
<tr>
<td>1.71</td>
<td>3.484</td>
</tr>
<tr>
<td>1.43</td>
<td>2.246</td>
</tr>
<tr>
<td>1.333</td>
<td>1.899</td>
</tr>
<tr>
<td>1.24</td>
<td>1.584</td>
</tr>
<tr>
<td>1.14</td>
<td>1.301</td>
</tr>
<tr>
<td>1.05</td>
<td>1.049</td>
</tr>
</tbody>
</table>

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Consolidation time versus spacing for Prefabricated vertical drain under different degree of consolidation

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Example: Design steps for Prefabricated Vertical Drain (PVD) in a runway

Subsoil condition: Available borehole information shows that very soft silty clays exist up to approximately 10 m to 14 m below the existing ground level underlain by firm to stiff clays.

✓ Standard penetration test value (N) within the very soft layer does not exceed 5, whereas it exceeds 10 in the firm/stiff layer. The stratum is found to contain considerable organic materials.

✓ Area for the proposed runway extension is a low line area where the ground water table has been observe close to the ground level approximately 1.0 m to 1.5 m below the existing ground level.

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For the construction of runway and taxiway extension, the existing ground level is needed to be raised by filling about 2 meter to 3 meter.

After construction, considerable live loads are expected due to heavy aircraft movements. It is required to improve the very soft sub-soil by accelerating its consolidation; thereby increasing its bearing capacity as well.

Most cost effective way to improve the underlying very soft clay is installation of prefabricated vertical drains (PVD) or band drains and preloading.

The required drain spacing, time required for consolidation etc. are designed based on the soil characteristics and period available for consolidation.

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The pre-loading requirements consist of the following:

(a) Load from pavement

- Concrete- 0.45 m thick x 2.4 t/m\(^3\) = 1.1 t/m\(^2\)
- GSB layer- 0.90m thick x 1.8 t/m\(^2\) = 1.7 t/m\(^2\)

(b) Live load from aircraft on pavement (estimated) = 4.6 t/m\(^2\)

Total load from aircraft at sub-grade level = 7.4 t/m\(^2\)
Pavement cross-section

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Solution:

Step 1: Calculate safe bearing capacity of soft soil stratum

\[ Q_u = \frac{CN_c}{F.S.} \]

- \( Q_u \) = Safe bearing capacity (t/m\(^2\)),
- \( C \) = Undrained cohesion (t/m\(^2\)),
- \( N_c \) = Bearing capacity factor (5.7),
- F.S. = Factor of safety

Calculation of Safe Bearing Capacity

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Cohesion (T/sqm)</td>
<td>2.5</td>
</tr>
<tr>
<td>2  Bearing Capacity Factor</td>
<td>5.7</td>
</tr>
<tr>
<td>3  F.S.</td>
<td>3</td>
</tr>
</tbody>
</table>

CALCULATE

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Safe bearing capacity of soil = 4.75 t/m² < 7.4 t/m².

Therefore, we have to go for ground improvement.

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Step 2: Calculate the settlement of soft soil stratum using general consolidation theory

\[ \delta = \frac{C_c H}{1+e_0} \log \left( \frac{p_0 + \Delta p}{p_0} \right) \]

\( \delta = \) Settlement (m),
\( C_c = \) Compression index of soil,
\( H = \) Thickness of compressible clay layer (m),
\( p_0 = \) Effective overburden pressure at the middle of compressible clay layer (kPa),
\( \Delta p = \) Increase in surcharge (kPa), and
\( e_0 = \) Initial void ratio of soil
Calculation of settlement

In put data

1. Thickness of compressible clay layer (m)  10
2. Height of embankment (m)  4.35
3. Compression Index  0.243
4. Initial void ratio  1.2
5. Bulk Unit weight of soil (T/cum)  1.7
6. Unit weight of embankment (T/cum)  1.8

Output value of settlement

Total Settlement of compressible clay layer in mm  563.497
Step 3: Calculate the time required for total settlement (calculated in earlier step)

\[ t = \frac{T_v \times H^2}{C_v} \quad T_v = \frac{\pi}{4} U^2 \]  

(For \( U \leq 60\% \))

\[ T_v = 1.781 - 0.933 \log(100 - U \%) \]  

(For \( U > 60\% \))

\( t \) = Time to achieve required degree of consolidation (month),  
\( T_v \) = Time factor,  
\( H \) = Thickness of compressible clay layer in meter (\( H \) for single way drainage and \( H/2 \) for both way drainage),  
\( C_v \) = Coefficient of consolidation of soil in \( m^2/\text{month} \), and  
\( U \) = Degree of consolidation in %

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### General Consolidation Theory

#### Design Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical coefficient of consolidation ($C_v$) in $m^2$/month</td>
<td>0.334</td>
</tr>
<tr>
<td>Average degree of consolidation (U) %</td>
<td>90</td>
</tr>
<tr>
<td>Thickness of the compressible layer (H) in meter</td>
<td>10</td>
</tr>
</tbody>
</table>

#### Design Output

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time required for the given degree of consolidation (years)</td>
<td>21.167</td>
</tr>
<tr>
<td>Time Factor ($T_v$)</td>
<td>0.848</td>
</tr>
</tbody>
</table>

➢ Time required to attain 90% consolidation without any ground improvement is 21.167 years.

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Step 4: Calculate the time required for particular degree of consolidation using PVDs

\[
t = \frac{D^2}{8C_h} \left[ \frac{\ln(D/d)}{1-(d/D)^2} - \frac{3-(d/D)^2}{4} \right] \ln \frac{1}{1-U}
\]

- \( t \) = Time required for the given degree of consolidation,
- \( D \) = Effective diameter of influence for the PVD
  - \( = 1.13 \ S \) (for square pattern),
  - \( = 1.05 \ S \) (for triangular pattern)
- \( S \) = Spacing of PVDs
- \( d \) = Equivalent diameter of the PVD

\[
d = \frac{2(b + t)}{\pi}
\]

- \( b \) = Width of the PVD,
- \( t \) = Thickness of the PVD,

\( C_h \) = Horizontal coefficient of consolidation

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### Designing with Prefabricated Vertical Drains

#### Design Input

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal coefficient of consolidation (C_h) in (m^2/\text{month})</td>
<td>(6.7\times10^{-1})</td>
</tr>
<tr>
<td>Average degree of consolidation (U) %</td>
<td>(90)</td>
</tr>
<tr>
<td>Width of the PVD (b) in mm</td>
<td>(100)</td>
</tr>
<tr>
<td>Thickness of the PVD (t) in mm</td>
<td>(4)</td>
</tr>
<tr>
<td>PVD Spacing (s) in m</td>
<td>(1.2)</td>
</tr>
<tr>
<td>Effective Diameter of influence of PVD (D)</td>
<td>1.26</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1. For Triangle Pattern = 1.05 x Spacing</td>
<td></td>
</tr>
<tr>
<td>2. For Square Pattern = 1.13 x Spacing</td>
<td></td>
</tr>
</tbody>
</table>

- **In triangular pattern**, time required for 90% consolidation with PVD is 1.52 months i.e. 45 days.

- **In square pattern**, the time required for 90% consolidation with PVD and 1.81 month i.e. 55 days.

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Step 5: Calculate the required height of embankment that can be safely placed on soft soil stratum

\[ h_{\text{safe}} = \frac{Q_u}{\gamma_{\text{soil}}} \]

\( h_{\text{safe}} = \) Height of embankment that can be safely placed on soft soil stratum in meter,

\( Q_u = \) Safe bearing capacity of soil = 4.75 t/m\(^2\), and

\( \gamma_{\text{soil}} = \) Unit weight of compressible soil = 1.7 t/m\(^3\)

\[ h_{\text{safe}} = \frac{4.75}{1.7} = 3 \text{ m} \]
**Step 6**: Decide the number of stages and days required for application of embankment loading in such a manner that the total number of days (D) should be greater than the days required for desired settlement using the PVDs.

**Step 7**: Determine the improvement in initial cohesion and thus in shear strength in each stage

\[
\frac{C_u(\text{increased})}{\Delta p} = \left[0.15 + 0.0045 \times \text{P.I.}(\%)\right] \times \left(\frac{U\%}{100}\right)
\]

\[
c_u(\text{final}) = c_u(\text{initial}) + c_u(\text{increased})
\]

\[
c_u(\text{final}) = c_u(\text{initial}) + [0.15 + 0.0045 \times \text{P.I.}(\%)] \times \left(\frac{U\%}{100}\right) \times \Delta p
\]

**C\text{u(increased)}** = Increment in initial cohesion,

**C\text{u(final)}** = Cohesion after the improvement

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$C_{u\text{ (initial)}} = 2.5$ t/ m$^2$

$U\% = \text{Desired degree of consolidation} = 91\%, 55\%, 33\%$

$P.I. = \text{Plasticity Index of soil} = 27\%$, and

$\Delta p = \text{Increase in overburden pressure}$

$= \text{height of fill} \times \text{fill density}$,

$\text{fill density} = 1.8$ t/m$^3$

Improvement in cohesion due to consolidation in stage I,

$c_{u\text{ (final)}} = 2.5 + \left[0.15 + 0.0045 \times 27\right] \times \left(\frac{91}{100}\right) \times (3 \times 1.8) = 3.83$ t/m$^2$

$\Delta p = (3 \times 1.8)$ t/ m$^2$

Improvement in cohesion due to consolidation in stage II,

$c_{u\text{ (final)}} = 3.83 + \left[0.15 + 0.0045 \times 27\right] \times \left(\frac{55}{100}\right) \times (4 \times 1.8) = 4.9$ t/m$^2$

$\Delta p = (4 \times 1.8)$ t/ m$^2$

Improvement in cohesion due to consolidation in stage III,

$c_{u\text{ (final)}} = 4.9 + \left[0.15 + 0.0045 \times 27\right] \times \left(\frac{33}{100}\right) \times (5 \times 1.8) = 5.7$ t/m$^2$

$\Delta p = (5 \times 1.8)$ t/ m$^2$
Please let us hear from you

Any question?
THANKS FOR LISTENING