Lecture 11

NPTEL Course

GROUND IMPROVEMENT

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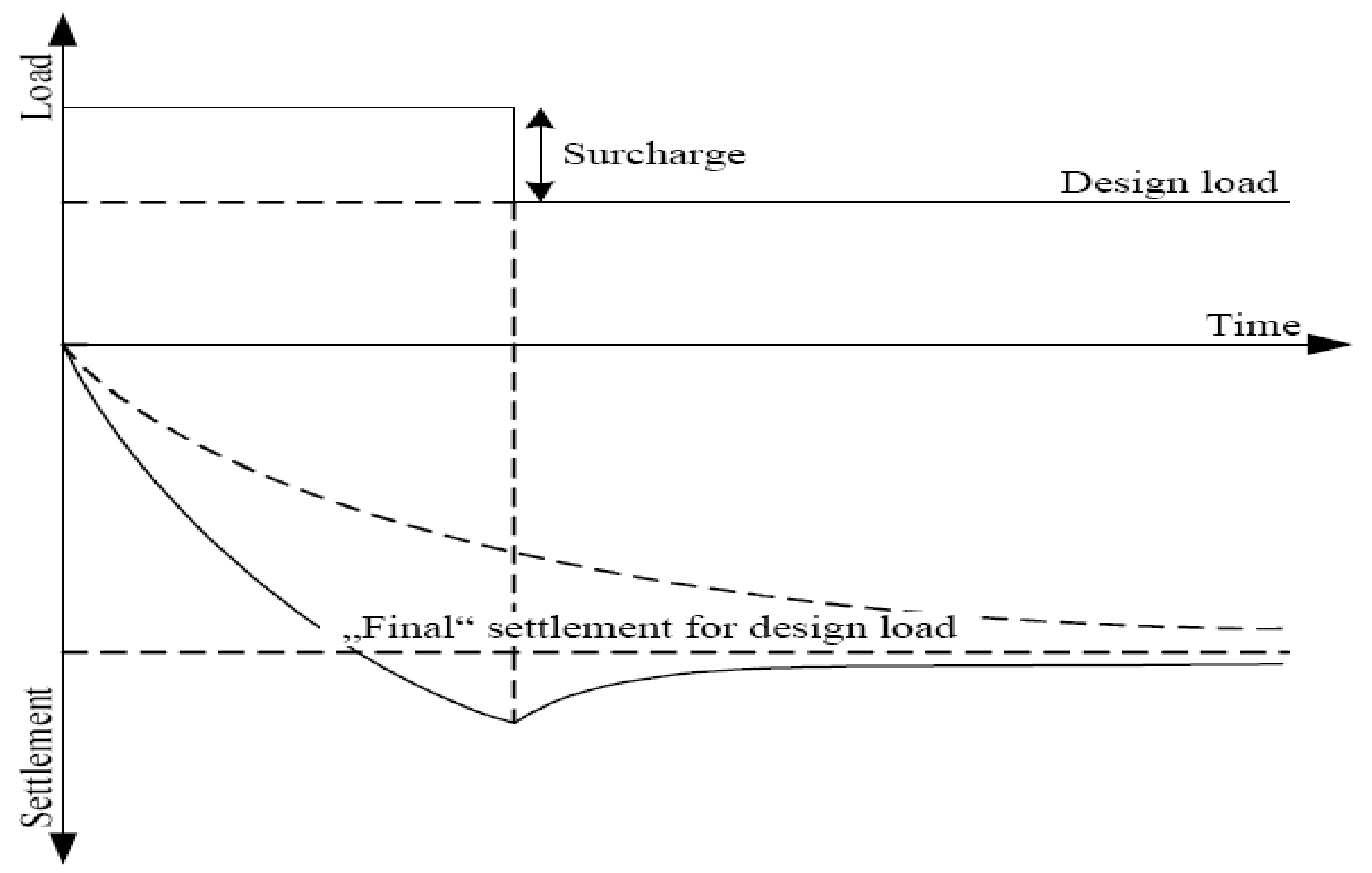
In lecture 10, we studied the preliminaries of pre-compression. This approach has resulted in a number of techniques involving for accelerated consolidation of soils.

- Sand drains
- Pre-fabricated Vertical Drains
- Vacuum consolidation
- High Vacuum Densification Method (HVDM)


Load
Surcharge
Design load
Time
„Final“ settlement for design load
Settlement

Example:

During construction of a highway bridge, the average permanent load on the clay layer is expected to increase by about 115 kN/m^3. The average effective overburden pressure at the middle of the clay layer is 210 kN/m^3. Here, H_c = 10m,C_c = 0.81, e_o = 2.7 and C_v = 1.08m^2/month. The clay is normally consolidated. Determine

a.The total primary consolidation settlement of the bridge without precompression.

b.The surcharge, $\Delta\sigma'_{(f)}$, needed to eliminate the entire primary consolidation settlement in nine months by precompression.

Solution

Part a

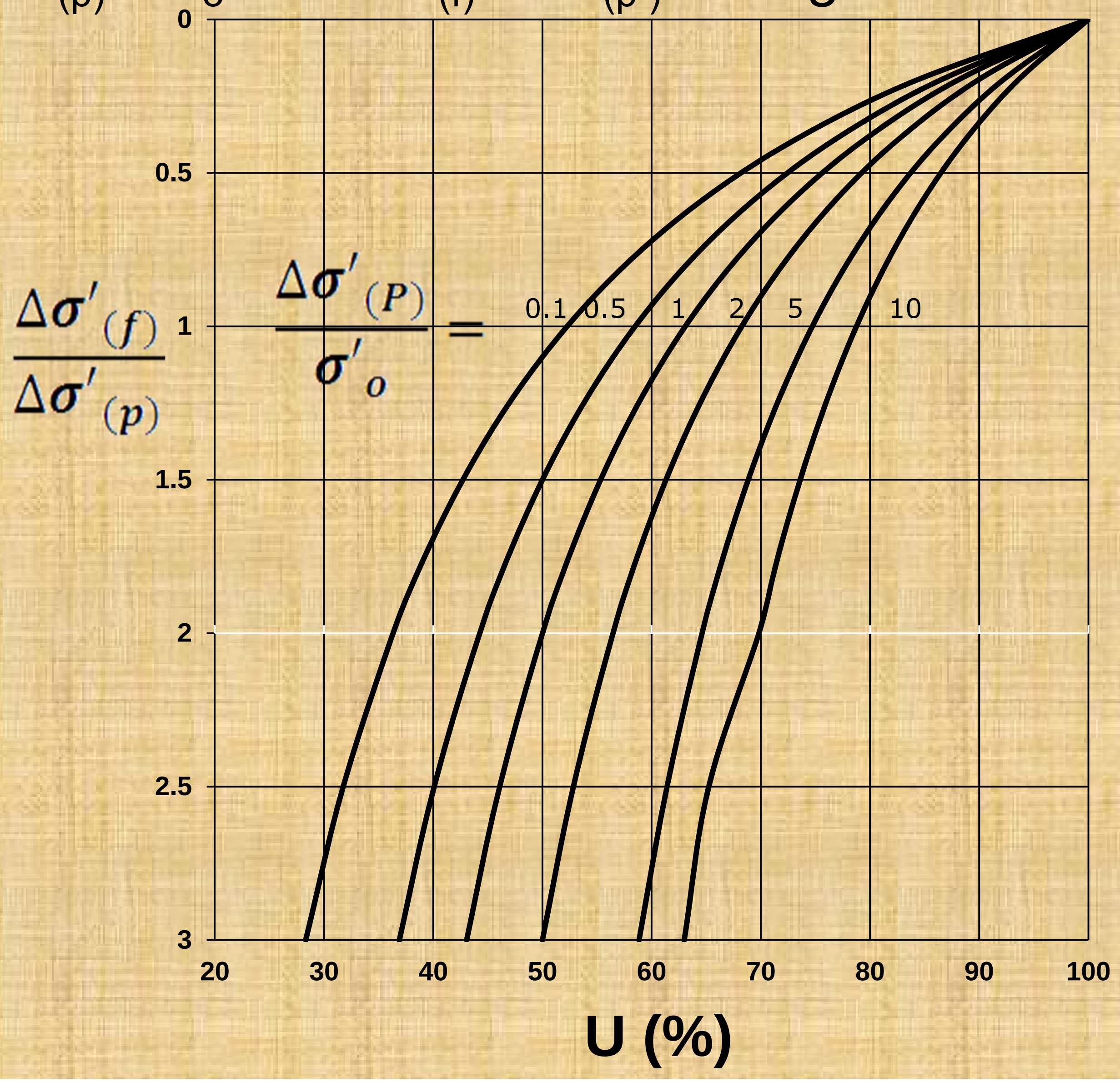
The total primary consolidation settlement may be calculated from Eq(1):

$$S_{c(p)} = \frac{C_c H_c}{1 + e_o} \log \frac{\sigma'_o + \Delta\sigma'_{(p)}}{\sigma'_o}$$

$$= \frac{(0.81)(10)}{1 + 2.7} \log \left[\frac{210 + 115}{115}\right]$$

= 0.4152m = 415.2mm

Figure gives magnitudes of U for varies combinations of $\Delta\sigma'_{(p)} / \sigma'_o$ and $\Delta\sigma'_{(f)} / \Delta\sigma'_{(p)}$. Figure 2



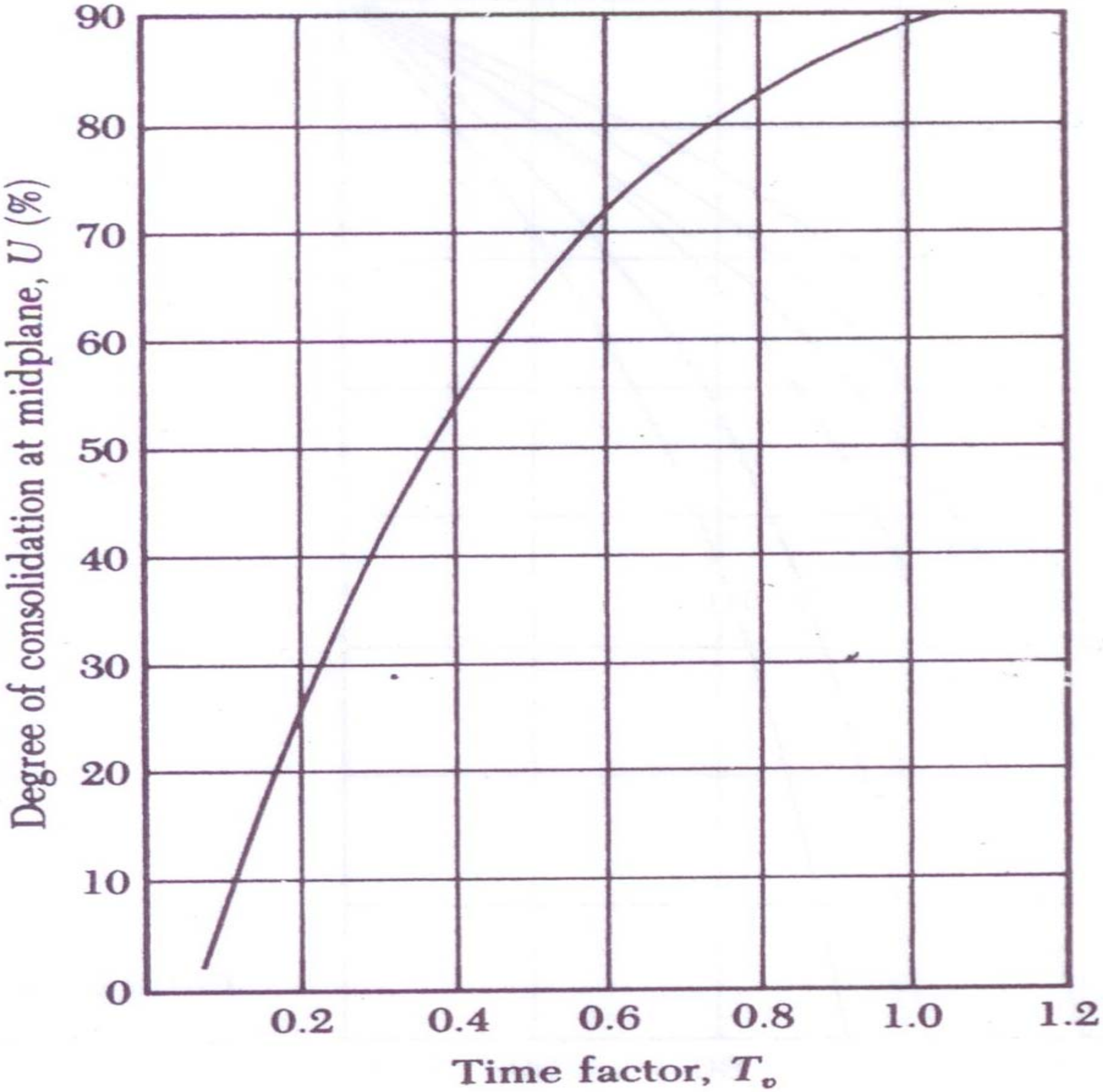

Degree of consolidation at midplane, U (%)
90
80
70
60
50
40
30
20
10
0
0.2
0.4
0.6
0.8
1.0
1.2
Time factor, T_v

Figure 3

Part b

We have,

$$T_v = \frac{C_v t_2}{H^2}$$

C_v = 1.08 m^2/month.

H = 6m (two way drainage)

t_2 = 9 months.

Hence,

$$T_v = \frac{(1.08)(9)}{6^2} = 0.27$$

According to Figure 3, for T_v = 0.27, the value of U is 40%.

we have,

$\Delta\sigma'_{(p)} = 115\ \text{kN/m}^2$

and $\Delta\sigma'_o = 210\text{kN/m}^2$

so

$$\frac{\Delta\sigma'_{(P)}}{\sigma'_o} = \frac{115}{210} = 0.548$$

According to Figure 2, for U=40% and $\Delta\sigma'_{(p)}/\sigma'_o = 0.548$, $\Delta\sigma'_{(f)}/\sigma'_{(p)} = 2.5$; $\Delta\sigma'_{(f)} = (2.5)(115) = 287.5\text{kN/m}^2$

Assuming a bulk density of 20 kN/m^3 for fill material and a height of 5m gives a pre-load of 100 kN/m^2. The required surcharge is higher than pre-load and hence consolidation by sand drains/PVDs is required.

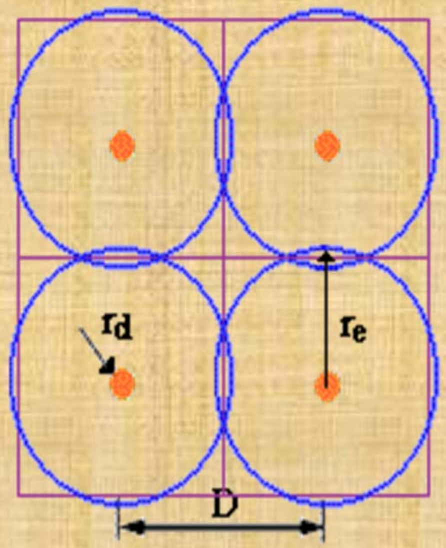
Example 2

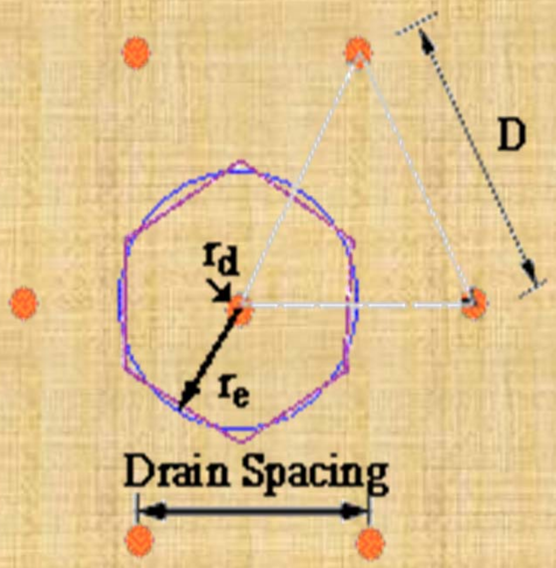
Redo Example 1, with the addition of some sand drains. Assume that $r_w = 0.1$ m, $d_e = 3$ m, $C_v = C_{vr}$, and the surcharge is applied instantaneously. Also, assume that this is a no-smear case.

Solution

The total primary consolidation settlement will be 415.2mm, from example 1.

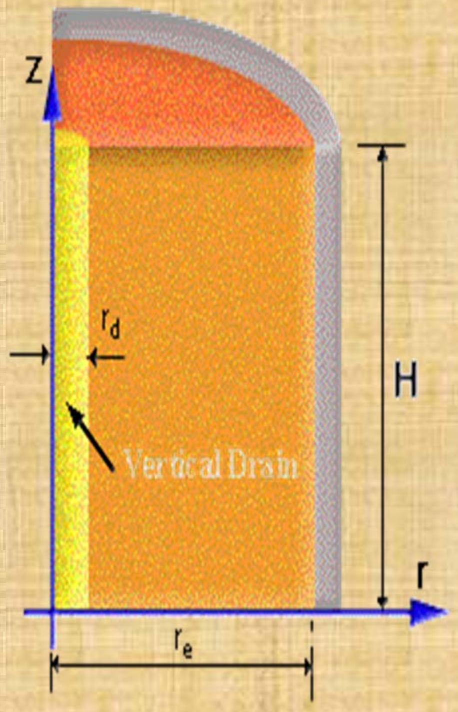
Layout of sand drain patterns





Vertical Drain Spacing

- Vertical drains are generally installed in either triangular or square patterns.
- The consolidation problem is simplified to an axisymmetric one in most vertical drain consolidation theories, in which a drain well is enclosed by a cylinder of soil.
- An equivalent radius of the soil cylinder based on the same total area for different installation patterns is used in the analysis.



from Example 1, T_v = 0.27. Using the following Eq (which is valid from 0 to 60% consolidation)

$$T_v = \frac{\pi}{4}\left[\frac{U_v(\%)}{100}\right]^2$$

or

$$U_v = \sqrt{\frac{4T_v}{\pi}} X100 = \sqrt{\frac{(4)(0.27)}{\pi}} X100 = 58.63\%$$

Also,

$$n = \frac{d_e}{2r_w} = \frac{3}{2X0.1} = 15$$

Sand drains enhance radial consolidation. The relevant equations which relate the degree of consolidation to spacing of drains for no smear case (for ramp loading) are as follows. Plots or tables can be prepared using the equations (Das, 2003)

$$m = \left(\frac{n^2}{n^2 - 1}\right) In(n) - \frac{3n^2 - 1}{4n^2}$$

$$U_r = \frac{T_r - \frac{1}{A}[1 - exp(-AT_r)]}{T_{rc}} \qquad \mathrm{A} = \frac{2}{\mathrm{m}}$$

$$T_{rc} = \frac{C_{vr} t_c}{d_e^2}$$

$$T_r = \frac{C_{vr} t_2}{d_e^2} = \frac{(0.27)(9)}{3^2} = 0.27$$

From table for n= 15 and T_r = 0.27, then value of U_r is about 67%, Hence,

$$U_{v,r} = 1- (1-U_v)(1-U_r)=1-(1-0.58)(1-0.67)$$

$$= 0.861=86.1\%$$

Now, from Figure 2, for $\Delta\sigma'_p/\sigma'_o$ =0.548 and $U_{v,r}$ = 86.1%, the value of $\Delta\sigma'_f/\ \Delta\sigma'_p$ = 0.22. Hence,

$$\Delta\sigma'_{(f)} = (0.22)(115) = 25.3 kN/m^2$$

Example 3

Calculate degree of consolidation at different times after the installation.

Clay: H_c = 10m (two way drainage)

C_c = 0.81

e_o = 2.7

Effective overburden pressure at the middle of the clay layer = 210kN/m^2

C_v = 0.036 m^2/day

Sand drain: $r_w = 0.1\text{m}$

$d_e = 1.8\text{m}$

$C_v = C_{vr}$

Ramp load of 96 kN/m^2 is applied over a period of 60 days.

$$n = \frac{d_e}{2r_w} = \frac{1.8}{2X0.1} = 9$$

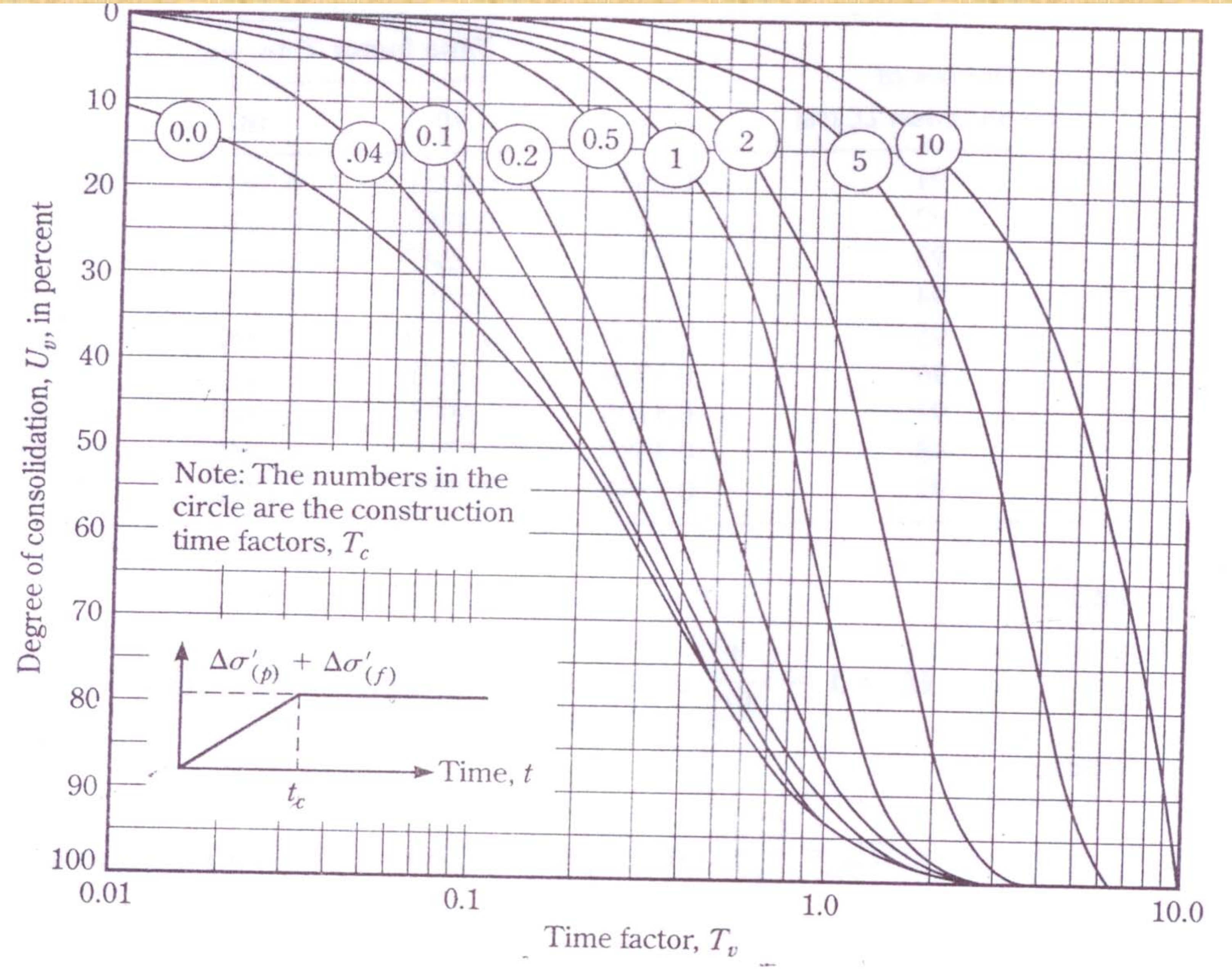
Solution

From Eq, $T_c = \frac{C_v t_c}{H^2} = \frac{(0.036)(60)}{\left(\frac{10}{2}\right)^2} = 0.086$

for one month

$$T_v = \frac{C_v t_2}{H^2} = \frac{(0.036)(30)}{\left(\frac{10}{2}\right)^2} = 0.043$$

Using figure given below, for $T_c = 0.086$ and $T_v = 0.043$, we have $U_v \underline{\sim} 6$.



Note: The numbers in the circle are the construction time factors, T_c

Variation of U_v with T_v and T_c

From Eq,

$$T_{rc} = \frac{C_{vr} t_c}{d_e^2}$$

$$= \frac{(0.036)(60)}{1.8^2} = 0.666$$

and

$$\mathrm{T_r} = \frac{\mathrm{C_{vr} t_2}}{\mathrm{d_e^2}} = \frac{(0.036)(30)}{(1.8)^2} = 0.333$$

Again from Eq,

$$U_r = \frac{T_r - \frac{1}{A}[1 - exp(-AT_r.)]}{T_{rc}}$$

Also, for the no-smear case,

$$m = \left(\frac{n^2}{n^2 - 1}\right) In(n) - \frac{3n^2 - 1}{4n^2}$$

$$= \left(\frac{9^2}{9^2 - 1}\right) In(9) - \frac{3(9)^2 - 1}{4(9)^2} = 1.478$$

and

$$\mathrm{A} = \frac{2}{\mathrm{m}} = \frac{2}{1.478} = 1.353$$

so

$$U_r = \frac{0.333 - \frac{1}{1.353}[1 - exp(-1.353X0.333)]}{0.666} = 0.097 = 9.7\%$$

From Eq,

$U_{v,r}$= 1- (1- U_r)(1-U_v)=1-(1-0.06)(1-.097)=0.151=15.1%

The total primary settlement is thus

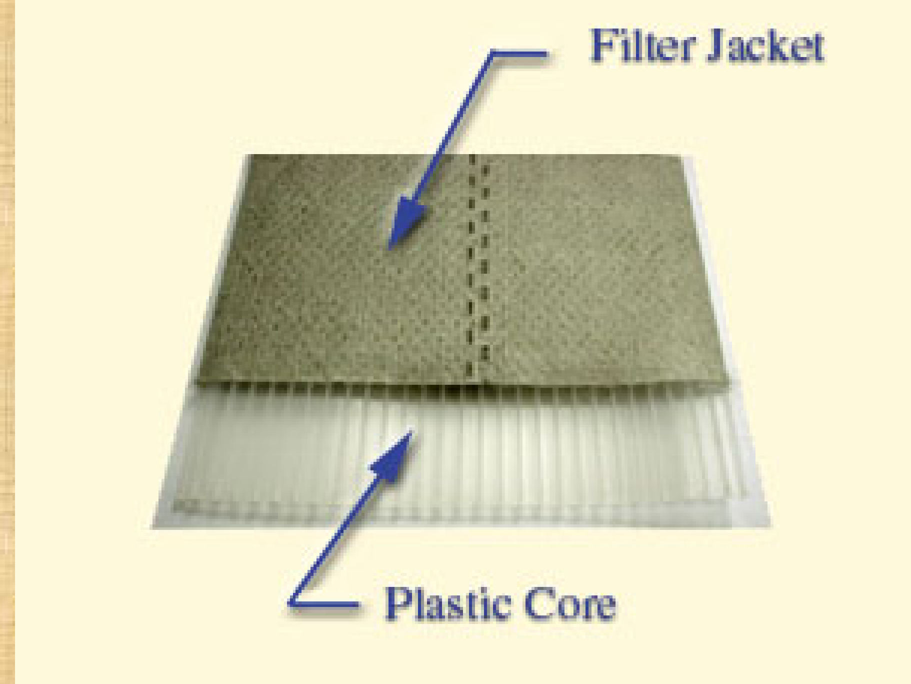
$$S_{c(p)} = \frac{C_c H_c}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'_{(p)} + \Delta\sigma'_f}{\sigma'_o}\right)$$

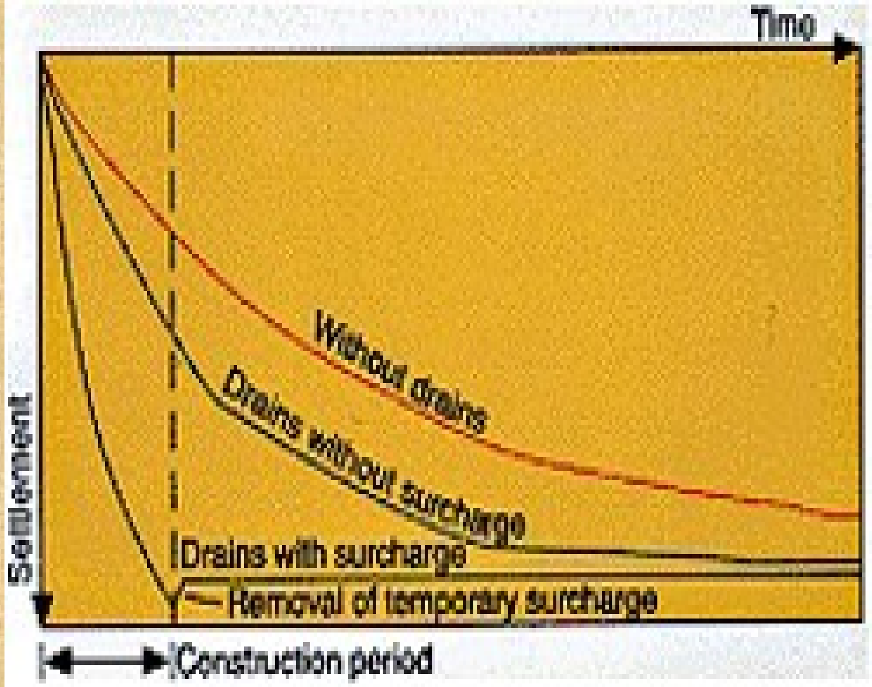
$$= \frac{(0.81)(10)}{1+2.7} \log\left(\frac{210+96}{210}\right) = 0.36 \text{ m}$$

The settlement after 30 days is

Sc(p)Uv,r = (0.36)(0.151)(1000) = 54.36 mm.

Prefabricated Vertical Drains





Prefabricated Vertical Drains

- The prefabricated band drains are used for accelerating the consolidation of marine deposits or soft soils.

- In general, prefabricated band drains consist of a central core, whose function is primarily to act as a free drainage channel, and a non-woven filter jacket, which prevents the soil surrounding the drain from entering the central core but allows water to flow in.

- Band drain is commonly used because of its easy prefabrication, easy quality control, economy and small disturbance to the surrounding soil during installation.

Equivalent Drain Radius of Band-shaped Vertical Drain

- The radius of sand drains, or their derivatives such as sand wicks or plastic tube drains, can easily be determined from the size of the mandrel, which is usually circular in cross section.
- For prefabricated drains, however, the situation different.
- The band shape of prefabricated drains, the flow pattern around the drain is considerably altered from the cylindrical case. Therefore, an equivalent drain radius ought to be calculated.

Typical dimensions of strip drain

Type	Core	Filter	Dimension (mm)
Kjellmann	Paper	Paper	100*3
PVC	PVC	PVC	100*2
Geodrain	PE	Cellulose	95*2
Colbond	Polyester	polypropylene	100*6

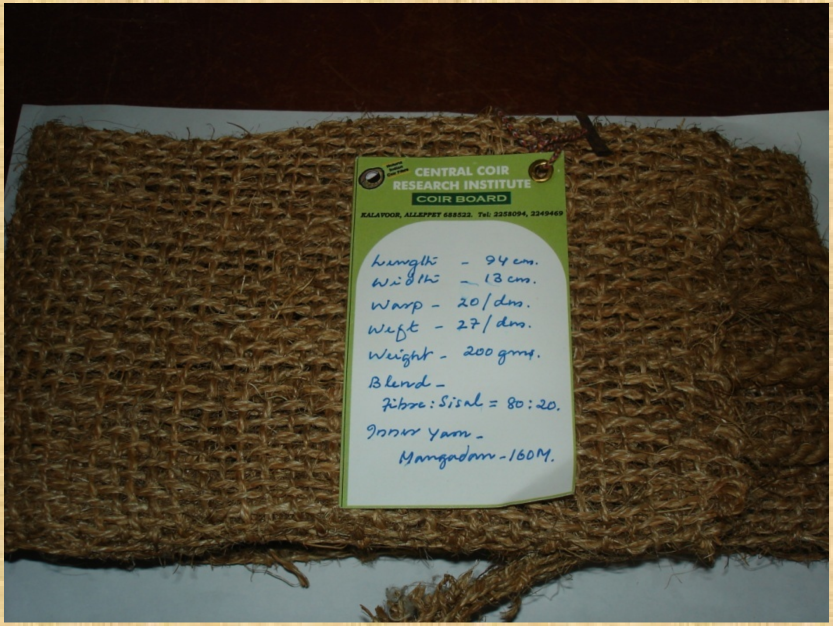
Equivalent diameter = $d_e = \dfrac{2(B+t)}{\pi}$

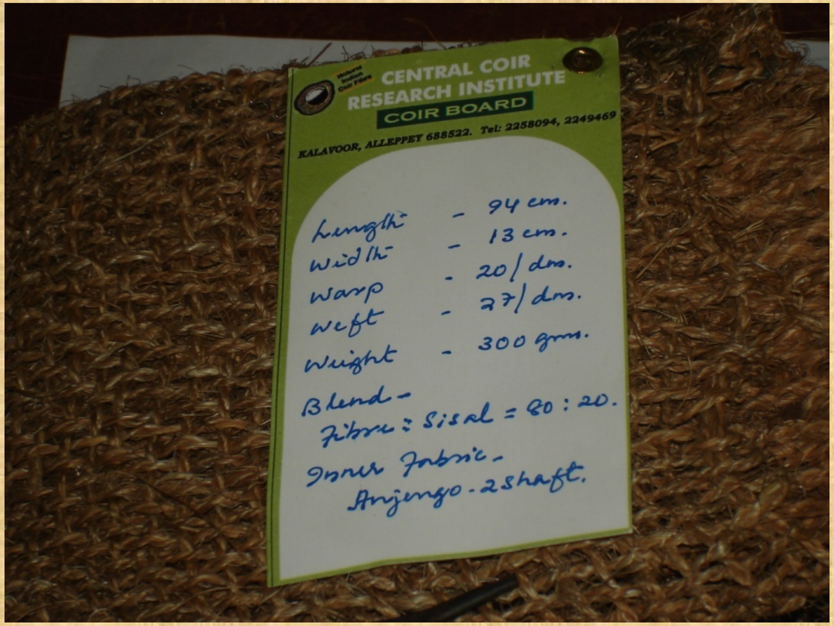
Where B= width of the strip, t = thickness. For the last product, equivalent dia is 67.48mm.

Trial Embankments

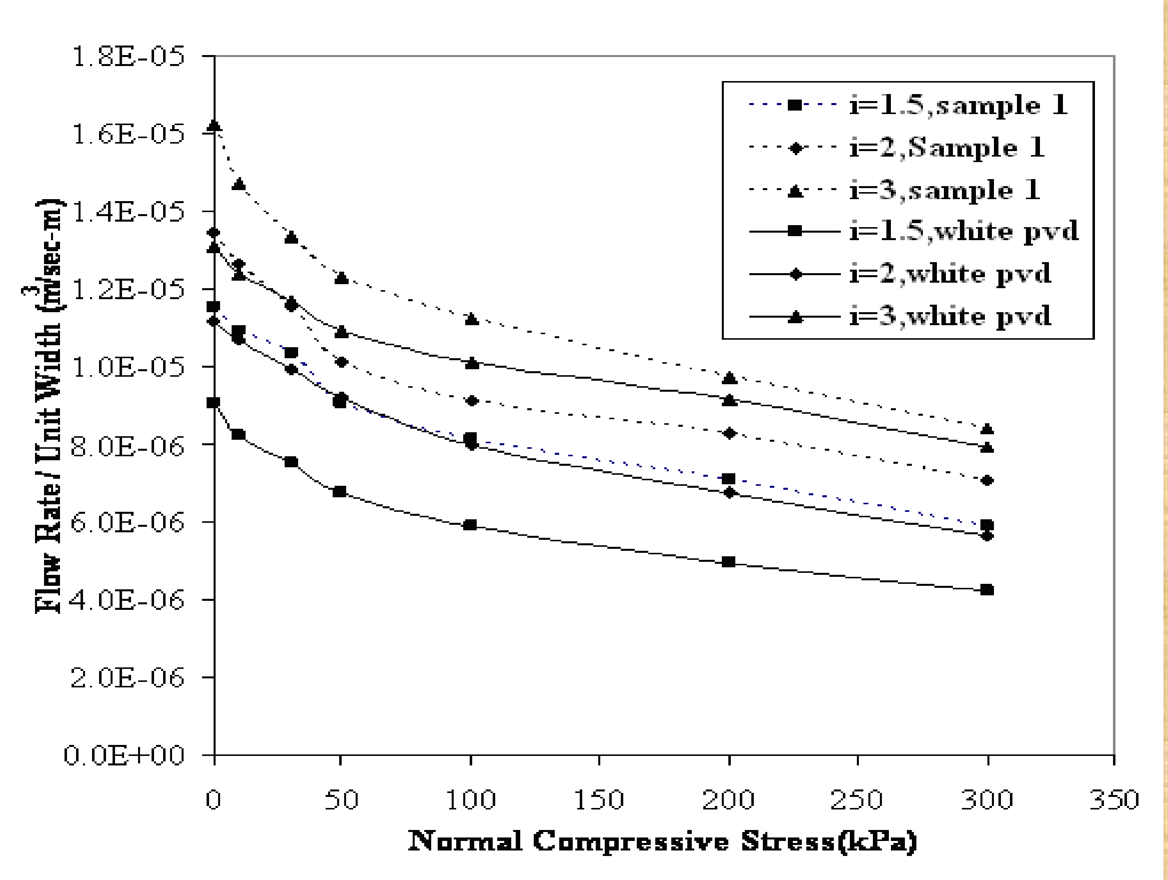
- These are useful to determine the feasibility of preloading and vertical drains in the field and avoids uncertainties in sampling, field properties and installations.
- It needs to reproduce stress and field conditions that are representation of actual structure.
- It should be part of final structure.
- It needs to be instrumented using piezometers, settlement gauges, levelling points etc.

Studies on coir geotextiles

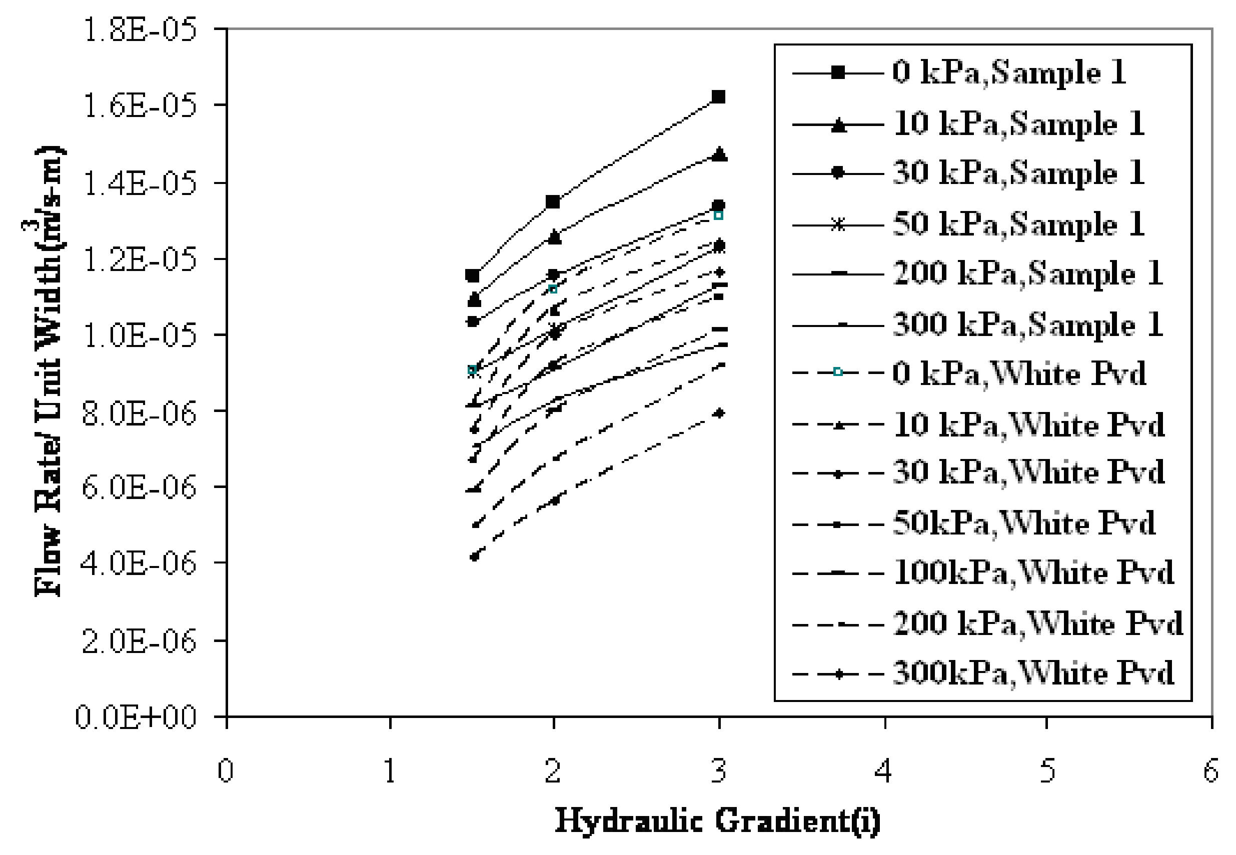




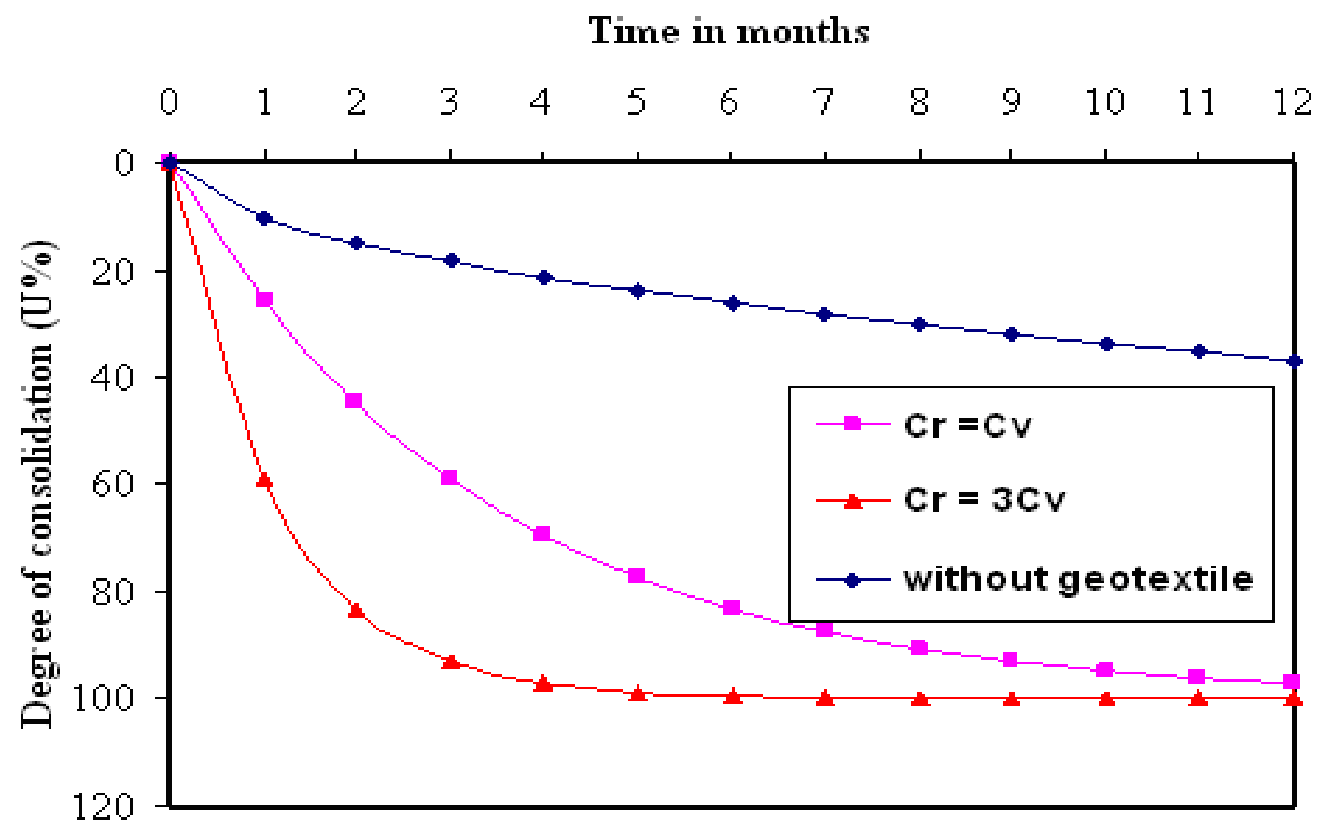
	unit	Sample 1	Sample 2
Weight	gms	200	300
Length	cm	94	94
Width	cm	13	13
Thickness	cm	1.298	1.293
Tensile strength(max)	kN/m	252	338
Elongation at max.tensile strength	%	33	33.8
Weft	dm	27	27
Warp	dm	20	20
Blend	Fiber: sisal	80:20	80:20



Variation of Normal Compressive stress with Flow rate/unit width for different Hydraulic gradients for coir PVD and Synthetic PVD.



Variation of Hydraulic gradient with flow rate/unit width for different compressive stresses for Coir PVD and Synthetic PVD.



Variation of degree of consolidation with time for different radial drainage conditions.

Installation of vertical drains

- Drains shall be installed with approved modern equipment of a type which will cause a minimum of disturbance of the subsoil during the installation operation
- The first step in the installation is to prepare a working surface for the installation rig. This working surface must be level and have enough bearing capacity so that the installation rig can operate
- Typically this working surface is also part of the gravel drainage layer. After the site is stripped a geogrid is often placed for support and then the drainage/working layer placed.

Continued…

- Once the working layer is in place the installation unit starts work. Layfield's new bottom-mount hydraulic wick drain rig is mounted on an excavator. It presses a steel mandrel into the ground up to 120 ft deep. The PVDs are placed in a pattern as specified by the project engineer
- Typically it is a triangular pattern 2 m (6 ft) on center. In some cases there will be a cap of hard soil on top of the soft subsoil. In these cases pre-drilling may be required. A suitable drill will operate ahead of the PVD installation rig to prepare holes through the hard upper layer
- Once the wick drains (PVDs) are placed a drainage layer is placed on top to preventing PVDs. This drainage layer is typically a free draining gravel or a drainage geosynthetic

Continued…

- The drainage layer needs to be sloped so that the water will flow away from the foundation. The slope needs to take into account any planned settlement so that water flow is maintained throughout the consolidation phase of the project.

INSTALLATION METHODS OF VERTICAL DRAINS

GROUP DESCRIPTION	PARTICULAR METHODS	REMARKS
DISPLACEMNT METHODS	Driving Vibration Pull Down(static Force) Washing Combinations Of Above	A mandrel with or without a disposal shoe is used in each case

Continued…

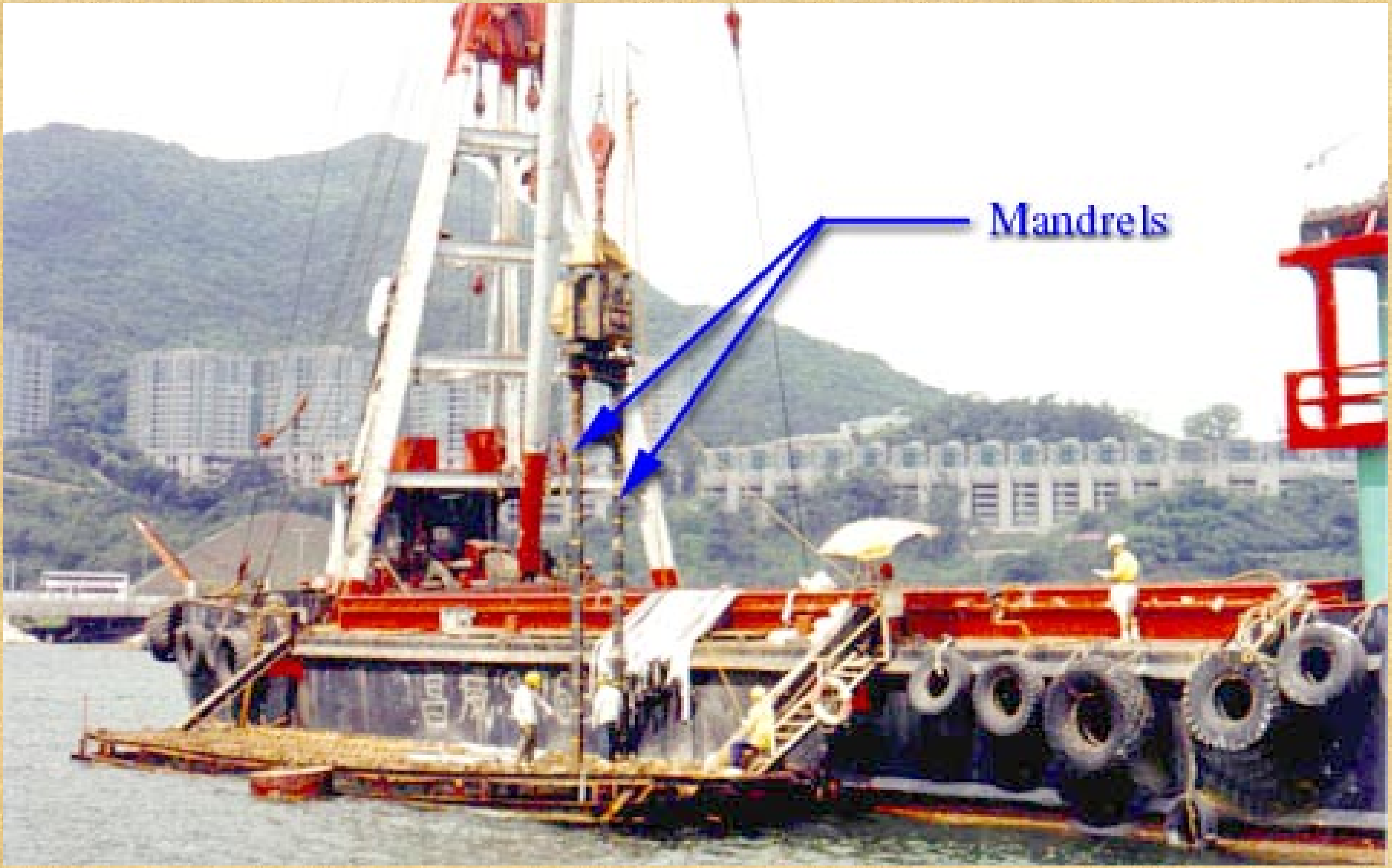
GROUP DESCRIPTION	PARTICULAR METHODS	REMARKS
DRILLING METHODS	Rotary drill, with or without a casing Rotary anger, including continuous standard and hollow fight augers Percussive(shell and auger) methods, with or without casing Hand auger	A mandrel with or without a disposal shoe is used in each case.

Continued…

GROUP DESCRIPTION	PARTICULAR METHODS	REMARKS
WASHING METHODS	Rotary wash jet Washed open ended case Weighted wash jet head on flexible hose	Methods in which sand is washed in via the jet pipe are not suitable for prefabricated drains

Vertical Drain

Installation of drains on a barge




AMERICAN DRAINAGE SYSTEMS

Case Study For Ground Improvement Using PVD With Preloading For Coal & Iron Ore Stackyard

Project Details

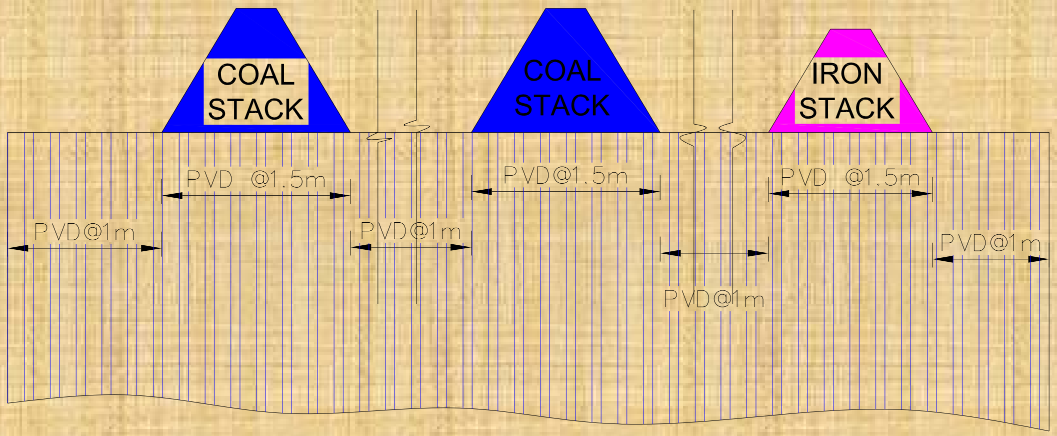
Development of New Port at Gangavaram at 15 km south of Visakhapatnam Port , AP

Development of Port Facilities included development of backup facility for coal and iron ore storage and stacking and handling facilities

The Proposed Heights were –

Coal Stacks : 12.00 m

Iron Stacks : 10.00 m



Sub-soil stratification

Geotechnical Investigation

- Ascertain Design Parameters
- 8 Nos Boreholes

Stratification

- Dredged Sand: 0.20~0.30 m thick
- Marine Clay with Shells: 1.00~3.00 m thick
- Soft Marine Clay: 7.00~15.00 m thick
- Below 12- 18m N values increased to a tune of 30

The available SBC was 3 T/m^2 which was very less than required – Ground Improvement Required

Natural Moisture content	**12 - 81**	**%**
Specific Gravity	**2.52 – 2.65**	
Bulk Density	**1.24 – 1.52**	**g/cc**
Gravel	**00**	**%**
Sand	**2 – 31**	**%**
Silt + Clay	**7 – 63**	**%**
Liquid Limit	**21 – 102**	**%**
Plastic Limit	**15 – 47**	**%**
Initial Void Ratio, e_0	**0.627 – 2.249**	
Compression Index, Cc	**0.38 – 0.92**	
Coefficient of Consolidation, C_v	**0.72 – 1.95**	**m^2/yr**
Cohesion, Ccu	**0.19 – 1.05**	**kg/cm^2**
Angle of Friction, Φcu	**18 – 29**	**Deg**
Shear Strength from VST	**0.095 – 0.991**	**kg/cm^2**

Ground Improvement Scheme

Depth of PVD	10.00 m to 18.00 m below OGL
Spacing of PVD (Triangular)	1.00 m c/c below stacker reclaimers 1.50 m c/c in other area
Consolidation Period	For 1.00 m spacing: 65 days For 1.50 m spacing: 174 days
Thickness of Sand Mat	300 mm
Horizontal Drainage System	Geotextile pipes filled by boulders / gravels; PVD laid horizontally
Machinery Used	Hydraulic Stitchers

Post treatment Assessment & Analysis

Post Treatment Assessment

Piezometers

Casagrande : 5 Nos

Vibrating Wire : 14 Nos

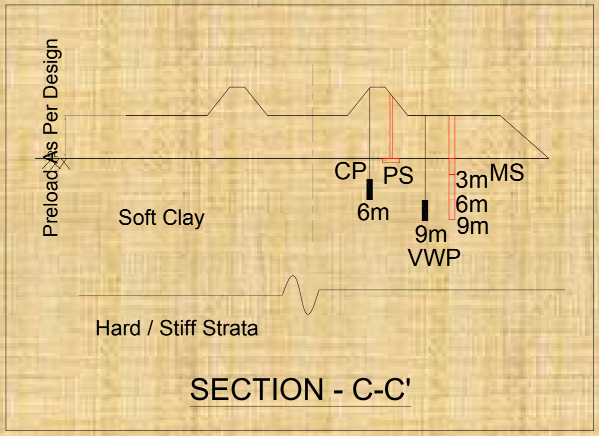
Settlement Recorders

Plate Type: 13 Nos

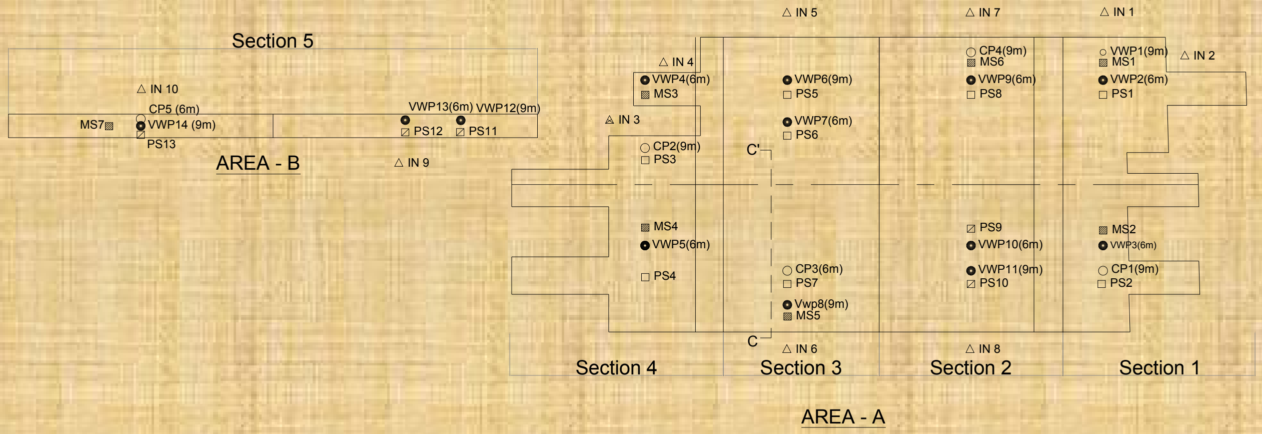
Magnetic: 7 Nos

Readings every 4 days when loading started.

Later at every 7 days



SECTION - C-C'



Analysis of Data

Excess Pore Pressure

$$\%U = \frac{U\max - Ut}{Ut - Ui} x100$$

Settlement

$$\%U = \frac{S_t}{S_{100}} x100$$

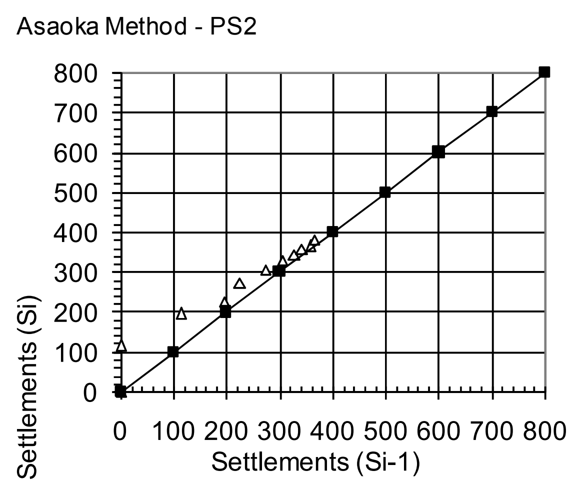
Asaoka Method

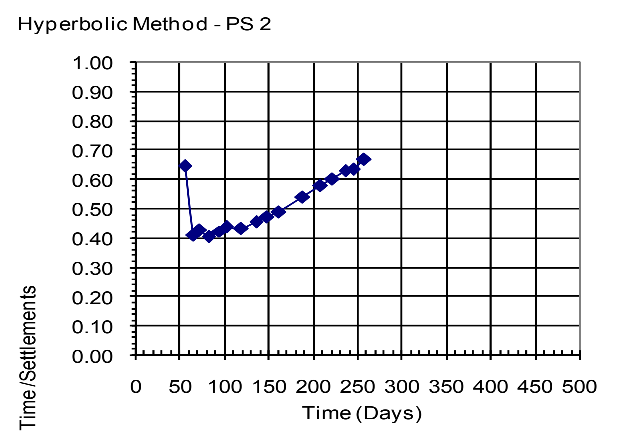
Settlement at equal time interval Δ t

Points (Si, Si-1) are plotted

Interception of this line with line having slope = 1

Settlement S_{100}


Asaoka Method - PS2


Hyperbolic Method - PS 2

Hyperbolic Method

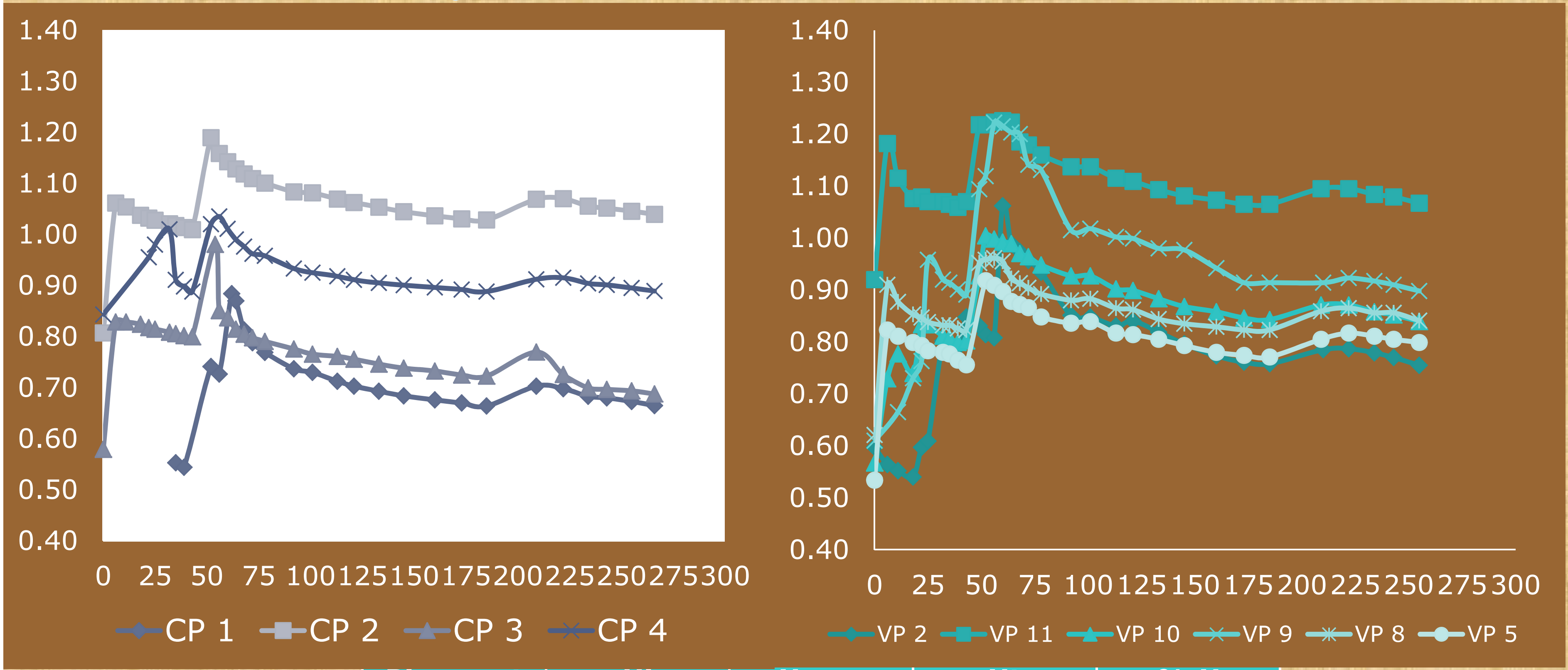
Graph of Time / settlement Vs Settlement

Graph in the form of Hyperbole

Inverse of slope of Hyperbola

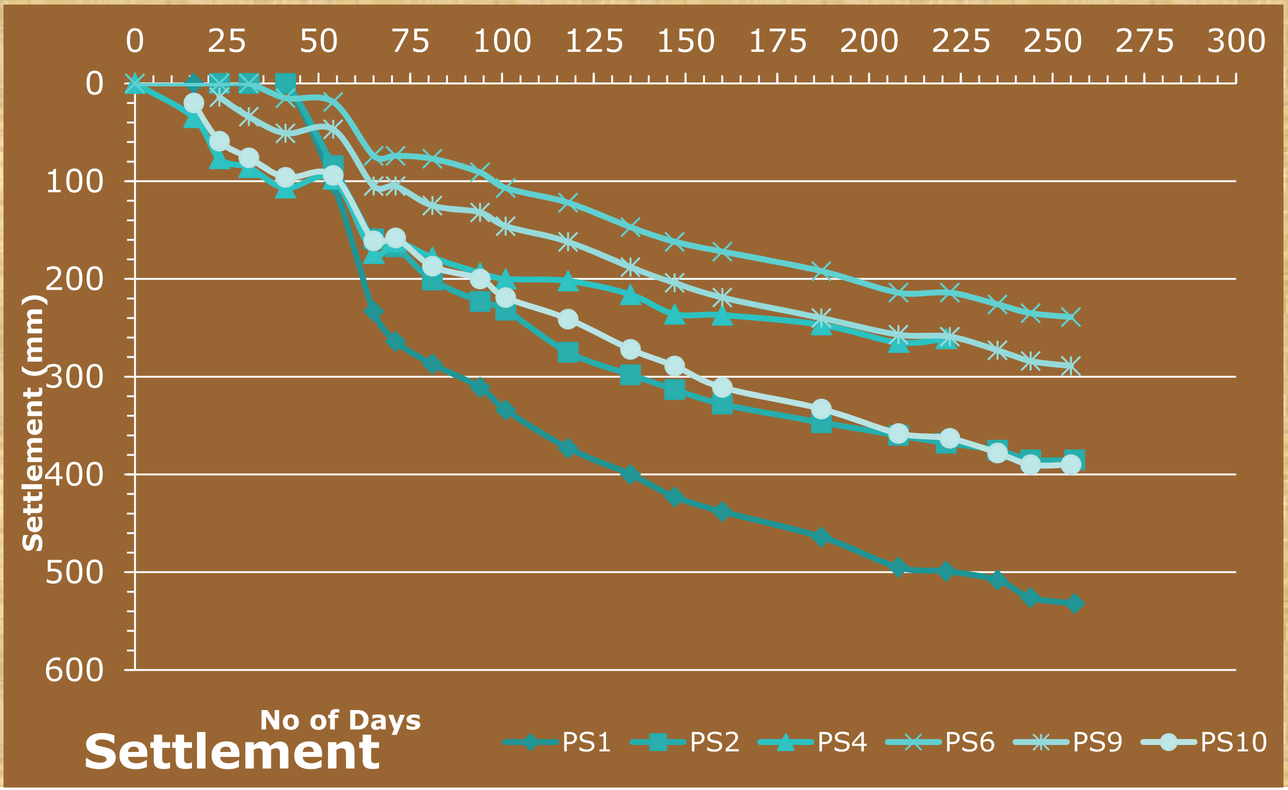
Settlement S_{100}

Analysis of Data – Pore Pressure



Piezometer	Ui	Umax	Ut	% U
CP 1	0.543	0.884	0.665	64.22
CP 3	0.579	0.981	0.688	72.89
CP 4	0.843	1.035	0.889	76.04
VP 2	0.597	1.062	0.753	66.45
CP 2	0.807	1.189	1.039	39.27
VP 5	0.534	0.918	0.793	32.55
VP 8	0.621	0.961	0.835	37.06
VP 10	0.567	1.004	0.833	39.13
VP 11	0.920	1.226	1.070	50.98
VP 9	0.610	1.222	0.894	53.59

Analysis of Data



Settlement Marker	Observed Settlement	Asaoka Method		Hyperbolic Method	
		S_{100}	% U	S_{100}	% U
PS 1	532	460	115.65	833	63.87
PS 2	385	380	101.32	556	69.24
PS 4	261	335	77.91	500	52.20
PS 10	390	450	86.67	732	53.28
PS 6	239	260	91.92	735	32.52
PS 9	289	340	85.00	667	43.33

Conclusions

- Plate Settlement Recorders are more reliable than the Magnetic Settlement Recorders for marine clays.
- With the application of the load the pore pressure increased and dropped down slowly with time. The pore pressure variation indicated about 55 - 60 % dissipation i.e. degree of consolidation.
- Hyperbolic Method is more comparable with the Pore Pressure Dissipation Results. Further the results obtained with theoretical slope of hyperbola as 1.00 are more closer to the predicted by pore water pressure analysis.
- The consolidation settlements worked out theoretically from laboratory test results were much higher than that predicted by Asaoka and Hyperbolic Method

VACUUM CONSOLIDATION

Vacuum consolidation was first proposed in the early 1950s by Kjellman (1952), the developer of the prefabricated vertical “wick” drain. However, except for specialized applications like landslide stabilization, vacuum consolidation was not seriously investigated as an alternative to conventional surcharging until recently due to the low cost of placing and removing surcharge fills and the difficulties involved in applying and maintaining the vacuum. The steadily increasing direct and indirect costs of placing and removing surcharge fill and the advent of technology for sealing landfills with impervious membranes for landfill gas extraction systems have now made vacuum-consolidation an economically viable method as a replacement for or supplement to surcharge fill.

Vacuum Consolidation is an effective means for accelerating the improvement of saturated soft soils.

The soil site is covered with an airtight membrane and a vacuum is created underneath it by using a dual Venturi and vacuum pump.

The technology can provide an equivalent pre-loading of about 4.5 m high as compared with a conventional surcharging fill.

Instead of increasing the effective stress in the soil mass by increasing the total stress as in conventional mechanical surcharging, vacuum-assisted consolidation preloads (VCP) the soil by reducing the pore pressure while maintaining a constant total stress.

The effectiveness can be increased when applied with combination of a surcharge fill. Field experience indicates a substantial cost and time savings by this technology compared to conventional surcharging.

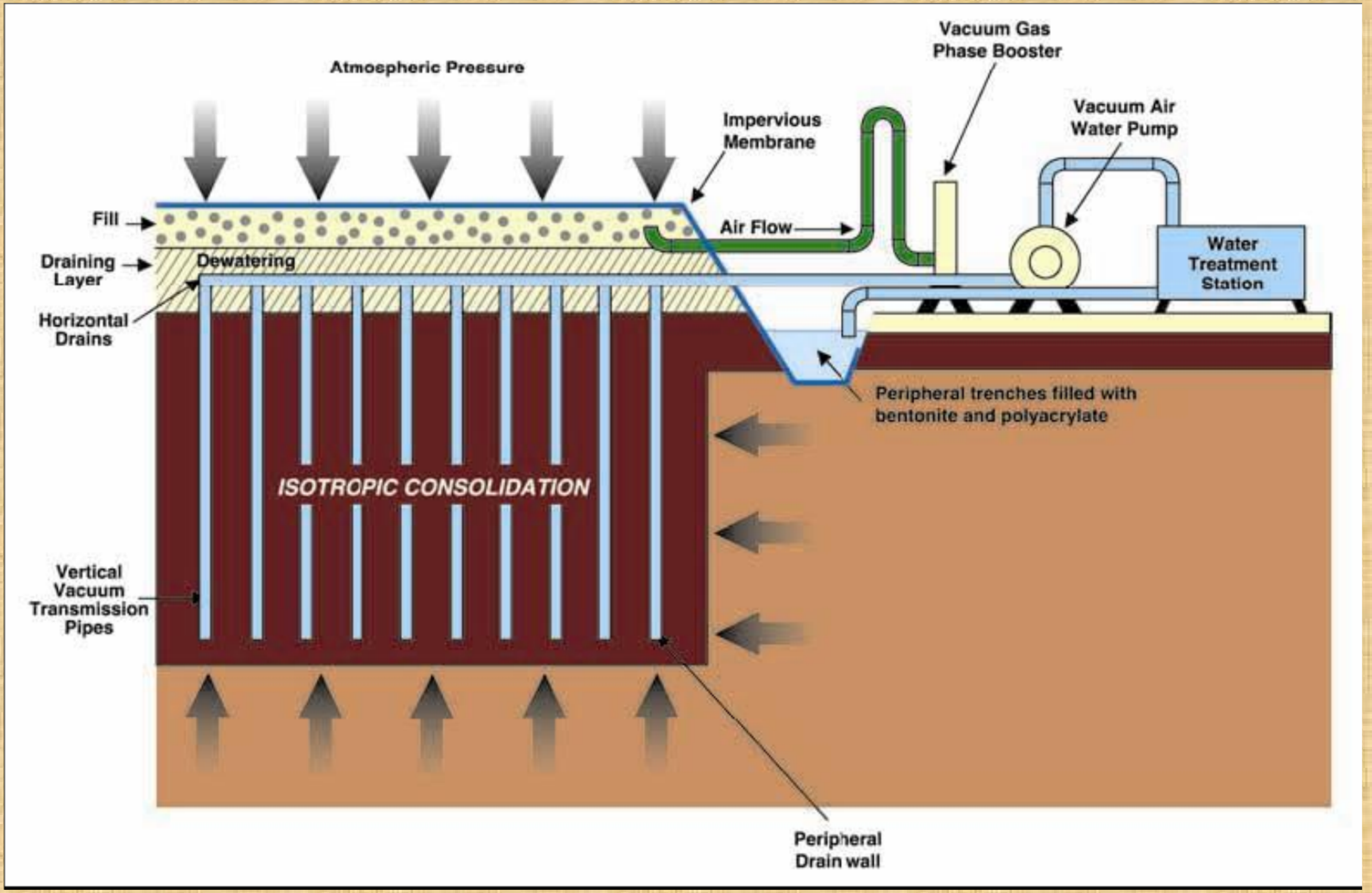


Figure1: Vacuum Consolidation

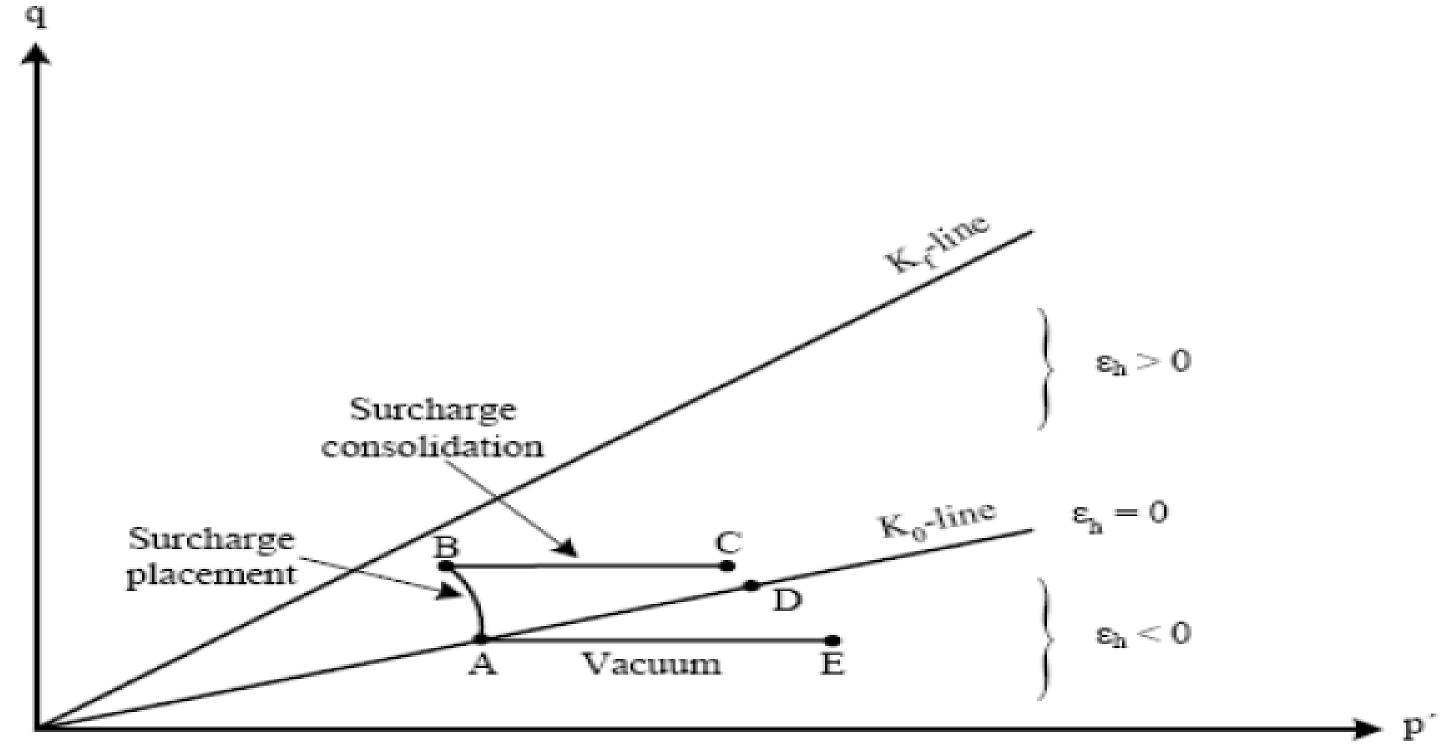
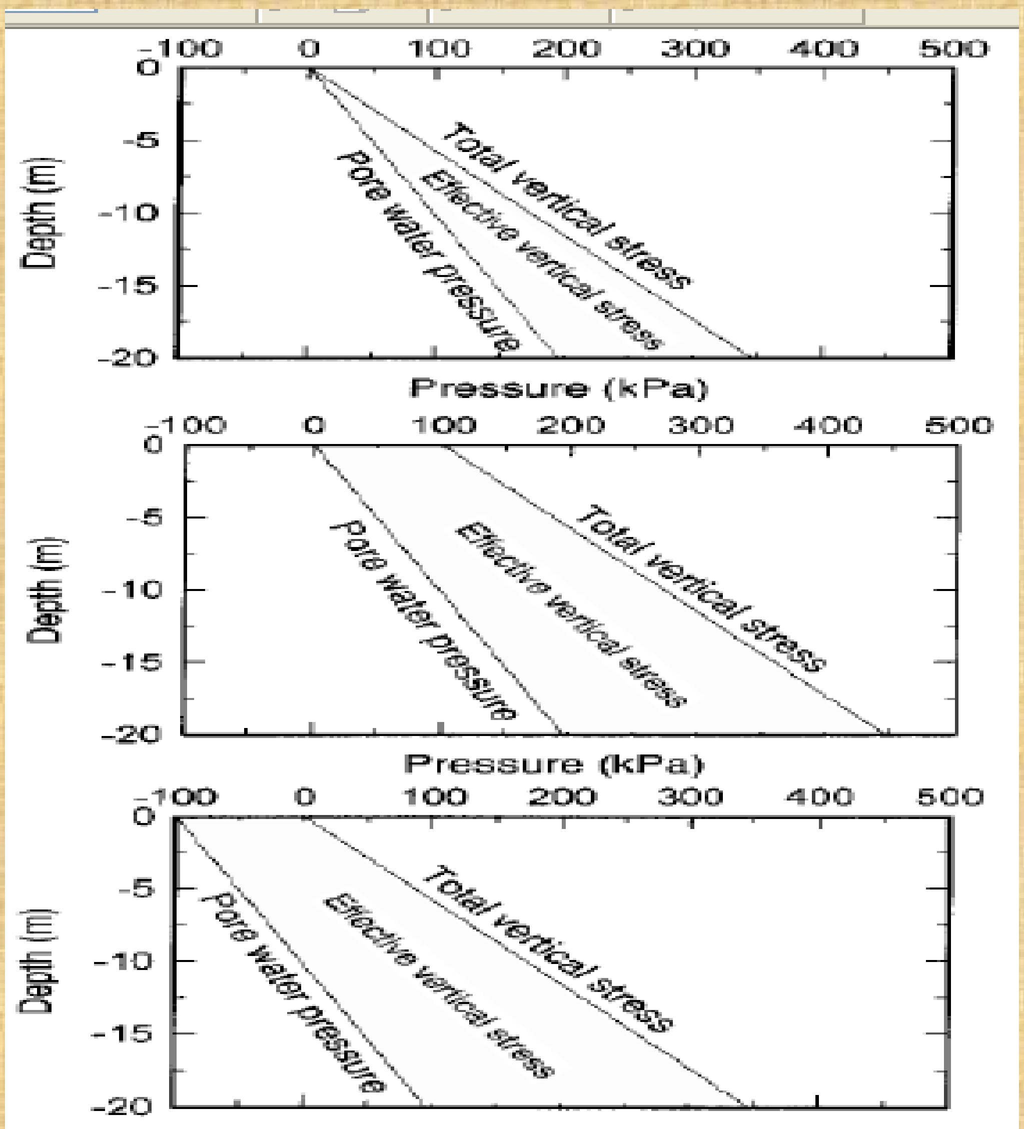


Figure 5: (p´, q) – diagram



Vertical stress profiles: (a) initial in situ conditions, (b) conventional surcharge and (c) vacuum induced surcharge (Elgamal and Adalier, 1996)

The current main application of vacuum assisted consolidation include:

- Replacement of standard pre-loading techniques, eliminating the risk of pre-loading induced foundation failures.
- Combining VCP with water pre-loading in scare fill areas. The method has been used to build large development projects on thick compressible soil.
- Combining VCP with surcharge pre-loading to increase foundation stability and thereby optimize pre-loading stage sequence and reduce project time.

Field trials conducted over the past two decades in China (Choa, 1989), France (Cognon, 1991; Cognon et al., 1996), USA (Jacob et al., 1996; TETC, 1990), Japan (Shinsha et al., 1991), Bangkok (Woo et.al., 1989), Sweden (Tortenssen, 1984; Holm, 1996) and elsewhere have verified the effectiveness of vacuum-assisted consolidation in conjunction with vertical drains for site improvement.

Cost estimates based on these projects indicate a significant potential for cost savings over conventional surcharge fill pre-loading for an equivalent surcharge of 4.5m height.

Equipment and Construction Process

The Vacuum Consolidation construction process involves (Cognon et al, 1996):

1. Placing a free drainage sand blanket (60 – 80 cm thickness) above the saturated ground in order to provide for a working platform.

2. Installation of vertical drains, generally of 5 cm in equivalent diameter, as well as relief wells from the sand blanket.

3. Installation of closely spaced horizontal drains at the base of the sand blanket using a special laser technique to maintain them horizontal.

4. The horizontal drains in the longitudinal and transverse directions are linked through connections.

Equipment and Construction Process

The Vacuum Consolidation construction process involves

5. Excavation of trenches around the perimeter of the preload area to a depth of about 50 cm below the groundwater level and filled with an impervious Bentonite Polyacrolyte slurry for subsequent sealing of the impermeable membrane along the perimeter.

6. The transverse connectors are linked to the edge of the peripheral trench. They are then connected to a prefabricated module designed to withstand future pressure due to the vacuum.

7. Installation of the impermeable membrane on the ground surface and sealing it along the peripheral trenches. The membrane is delivered to the site folded and rolled in elements of approximately 1000m^2.

Equipment and Construction Process

The Vacuum Consolidation construction process involves (Cognon et al, 1996)

The membrane elements are welded together and laid in the peripheral trench where they are sealed with the Bentonite Polyacrolyte slurry. The trenches are backfilled and filled with water to improve the tight sealing between the membrane and the Bentonite Aquakeep slurry.

8. Vacuum pumps are connected to the prefabricated discharge module extending from the trenches. The vacuum station consists of specifically designed high-efficiency vacuum pumps acting solely on the gas phase in conjunction with conventional vacuum pumps allowing liquid and gas suction.

The process combines dewatering and vacuum action to maintain the water table at the base of the granular platform during the entire application of the consolidation process. Eventually an additional drainage system is installed at a required depth to allow for a conventional de-watering under the membrane. Indeed, the fill will maintain a non-submerged action even when it has settled below the original ground water level. Therefore, with this technology, unlike the case of a surcharge preloading, the load intensity will not decrease during the vacuum application. The discharge drains are manufactured by extrusion of cylindrical and perforated PVC .Use of a suitable filter cloth with proper filtering properties to cover the perforated PVC avoids infiltration of sand and fines during vacuum application. The discharge drains are brought to the surface at every 150 meters spacing where they are connected by transverse drains to the vacuum station

Conceptual Design

Vacuum-assisted consolidation provides an effective alternative to surcharging for pre-loading soils. Instead of increasing the effective stress in the soil mass by increasing the total stress, using a conventional mechanical surcharging, vacuum-assisted consolidation preloads the soil by reducing the pore pressure while maintaining a constant total stress.

Technology Assessment

The efficiency of this technology has been demonstrated under different site conditions where it has successfully provided cost effective solutions to substantially accelerate the consolidation process while leading to significant savings in project costs.

Unlike the case of a conventional surcharge, VCP does not raise any stability concerns, while resolving the environmental problems associated with the conventional method of surcharge preloading.

The vacuum consolidation technique is often combined with surcharge preloading either by placing an additional backfilling surcharge or by using water placed at the top of the impervious membrane.

Technology Assessment

The major practical advantage of the vacuum consolidation is that it generates in the granular layer an apparent cohesion due to the increase of the effective stress and the granular layer provides a useful working platform to accelerate the surcharge backfilling process.

Experience indicates that within days after vacuum pump is turned on, construction vehicles can maneuver on the top of the membrane.

CONCLUSIONS

Vacuum consolidation is an effective means for improvement of highly compressible soft soils. In essence, vacuum consolidation can yield an effective equivalent preload of about 4 to 5 m of conventional surcharge fill.

A combination of conventional surcharge with vacuum application can yield much higher equivalent preload.

Experience from US and China, and the case histories from France indicate that this technology can be applied cost effectively under various challenging site conditions.

In certain difficult site conditions where the stability under the conventional surcharge is of concern, VCP allows to cost-effectively accelerate the consolidation process as compared to conventional stage loading.

CONCLUSIONS

In Europe, the engineering use of vacuum consolidation is currently rapidly expanding and it is of interest to note that this technology has been used to cost effectively replace conventional surcharge preloading for the development of about 57,000 m^2 of industrial on land applications at the Channel Euro Tunnel Terminal.

On-land applications are most suitable for soft soil sites with shallow ground water level.

Presence of stratified soils can render vacuum consolidation ineffective unless deeper vertical cut-off-systems are installed. Recent field trials also indicate that on-land vacuum consolidation combined with dewatering can be an effective solution to further accelerate the consolidation process.

Acknowledgments

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