Lecture 10

NPTEL Course

GROUND IMPROVEMENT

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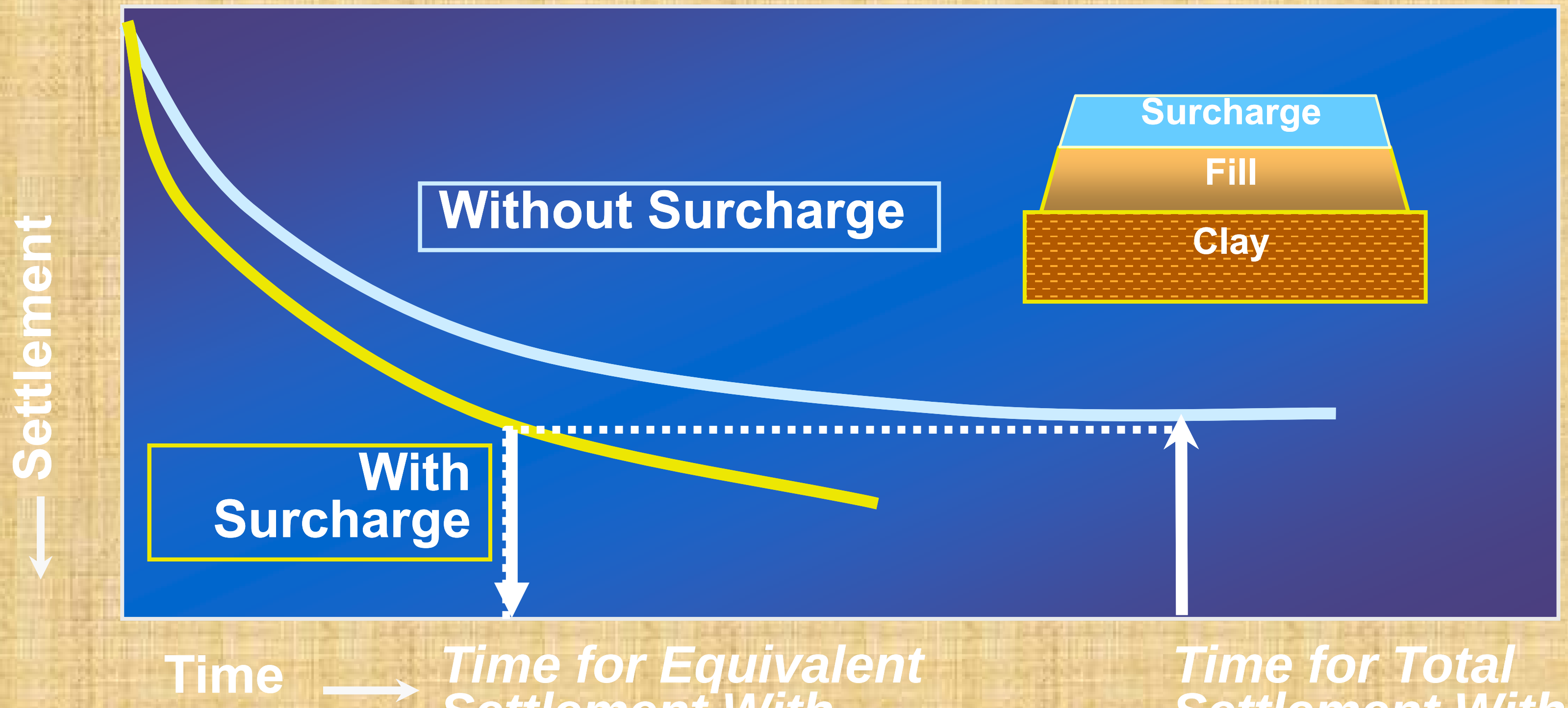
Preloading and vertical drains

When highly compressible, normally consolidated clayey soil layers lie at limited/large depths, large consolidation settlements are expected as the result of the loads from large buildings, highway embankments, or earth dams etc. Pre-compression and provision of vertical drains in soft soil may be used to minimize post-construction settlement.

This approach has resulted in a number of techniques involving

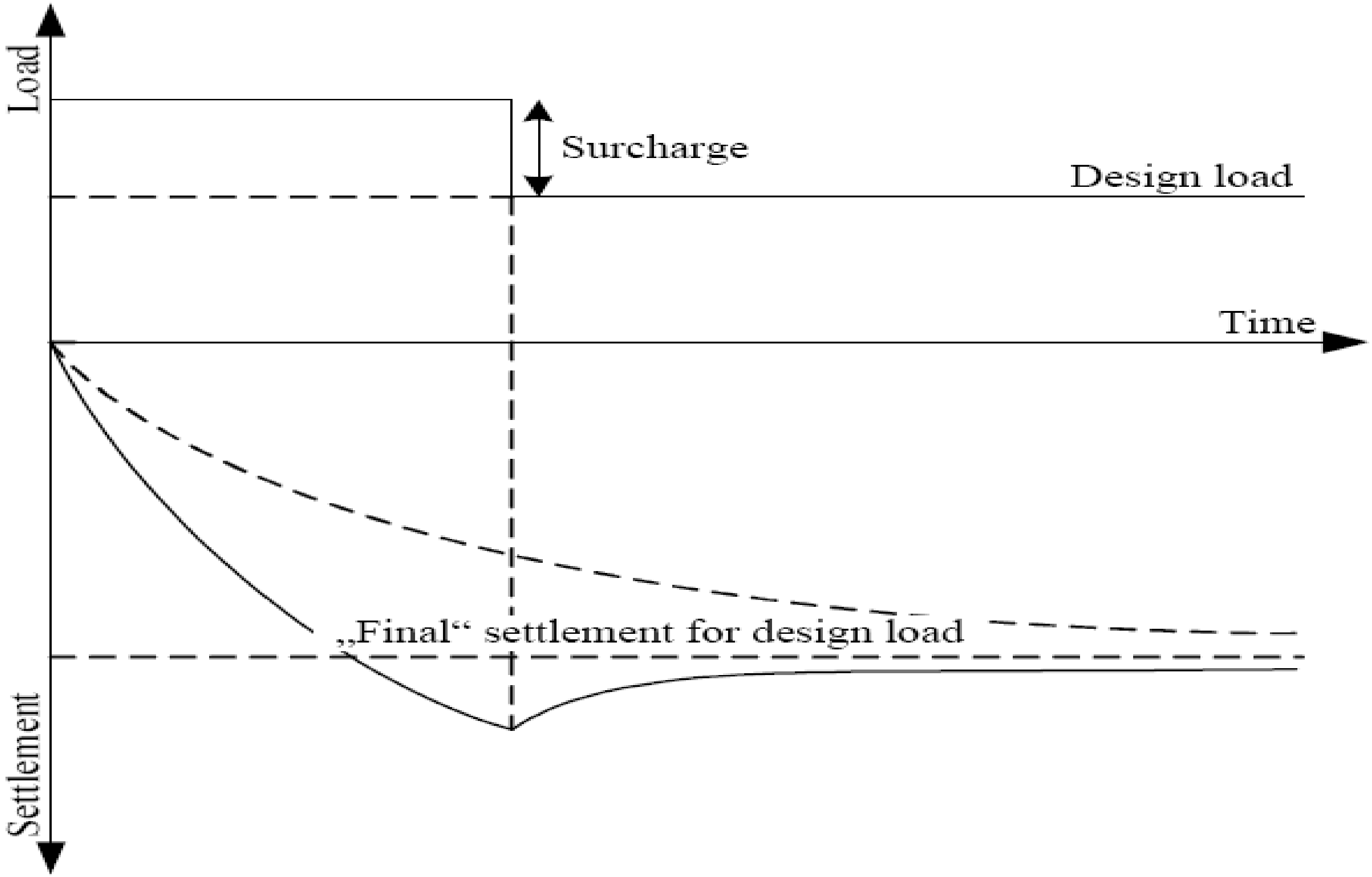
- Pre-compression or Pre-loading
- Sand drains
- Pre-fabricated Vertical Drains
- Vacuum consolidation
- High Vacuum Densification Method (HVDM)

Embankment on Clay Foundation
Effect of Surcharge Treatment

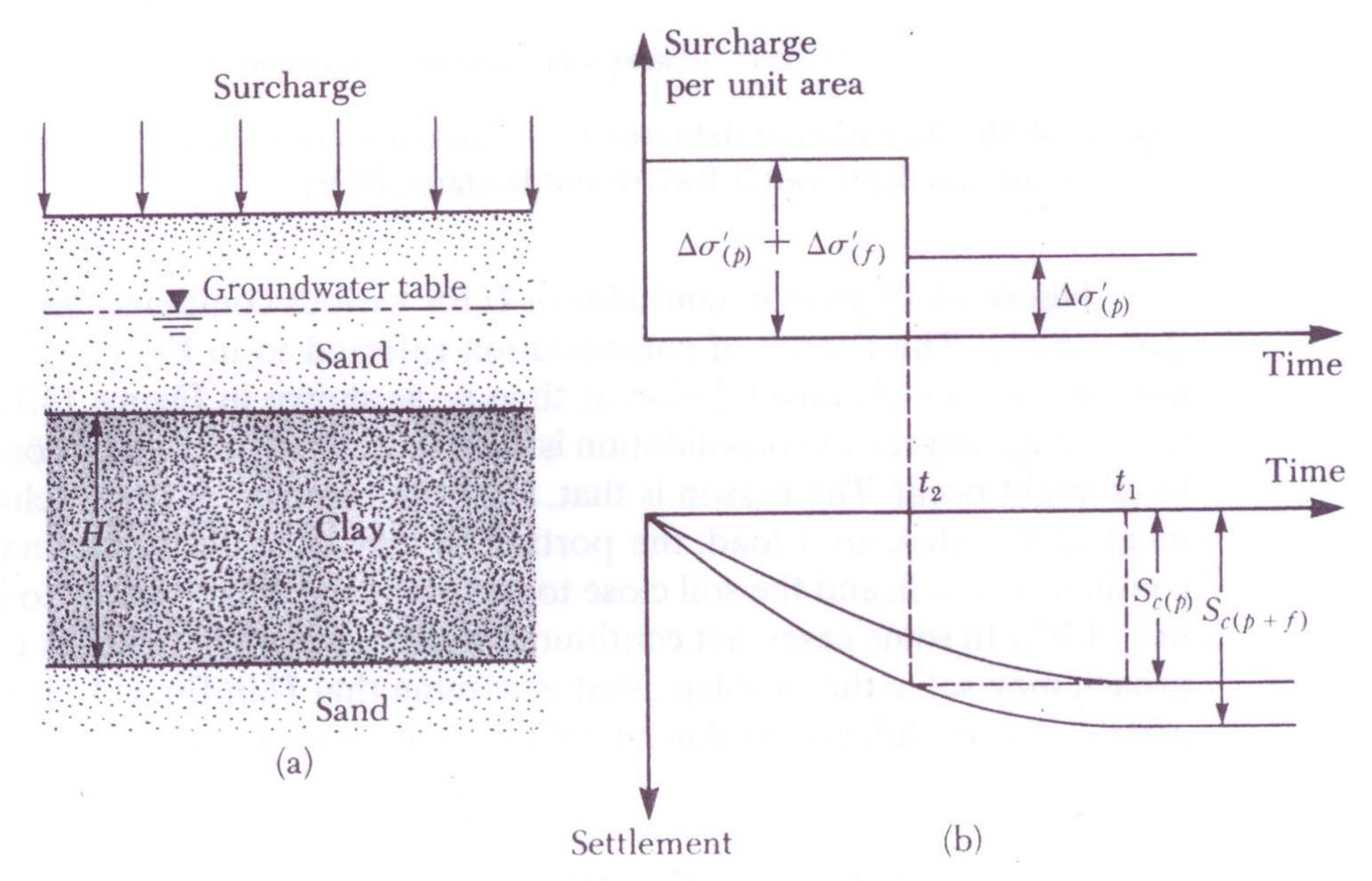


Time for Equivalent Settlement With Surcharge – Remove Surcharge at This Time

Time for Total Settlement Without Surcharge


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

The principle of pre-compression is explained in figure 1 shown below



The proposed structural load per unit area is $\Delta\sigma'_{(p)}$ and the thickness of the clay layer undergoing consolidation is H_c. The maximum primary consolidation settlement caused by the structural load is then

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

The settlement-time relationship under the structural load is shown in figure 1(b). However, if a surcharge of $\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}$ is placed on the ground, the primary consolidation settlement will be

$$S_{c(p+f)} = \frac{C_C H_C}{1 + e_o} \log \frac{\sigma'_o + \left[\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}\right]}{\sigma'_o} \qquad \text{Eq (2)}$$

Sequence of steps in “Precompression”:

- The total settlement of $S_{c(p)}$ will occur at time t_2, which is much shorter than t_1.
- Hence, if a temporary total surcharge of $\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}$ is applied on the ground surface for time t_2, the settlement will be equal to $S_{c(p)}$.
- At that time, if the surcharge is removed and a structure with a permanent load per unit area $\Delta\sigma'_{(p)}$ is built and no appreciable settlement will occur.

Note: The total surcharge $\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}$ can be applied by means of temporary fills.

Derivation of equations for obtaining $\Delta\sigma'_{(f)}$ and t_2:

From the figure 1(b), under a surcharge of $\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}$ the degree of consolidation at time t_2 after the application of load is

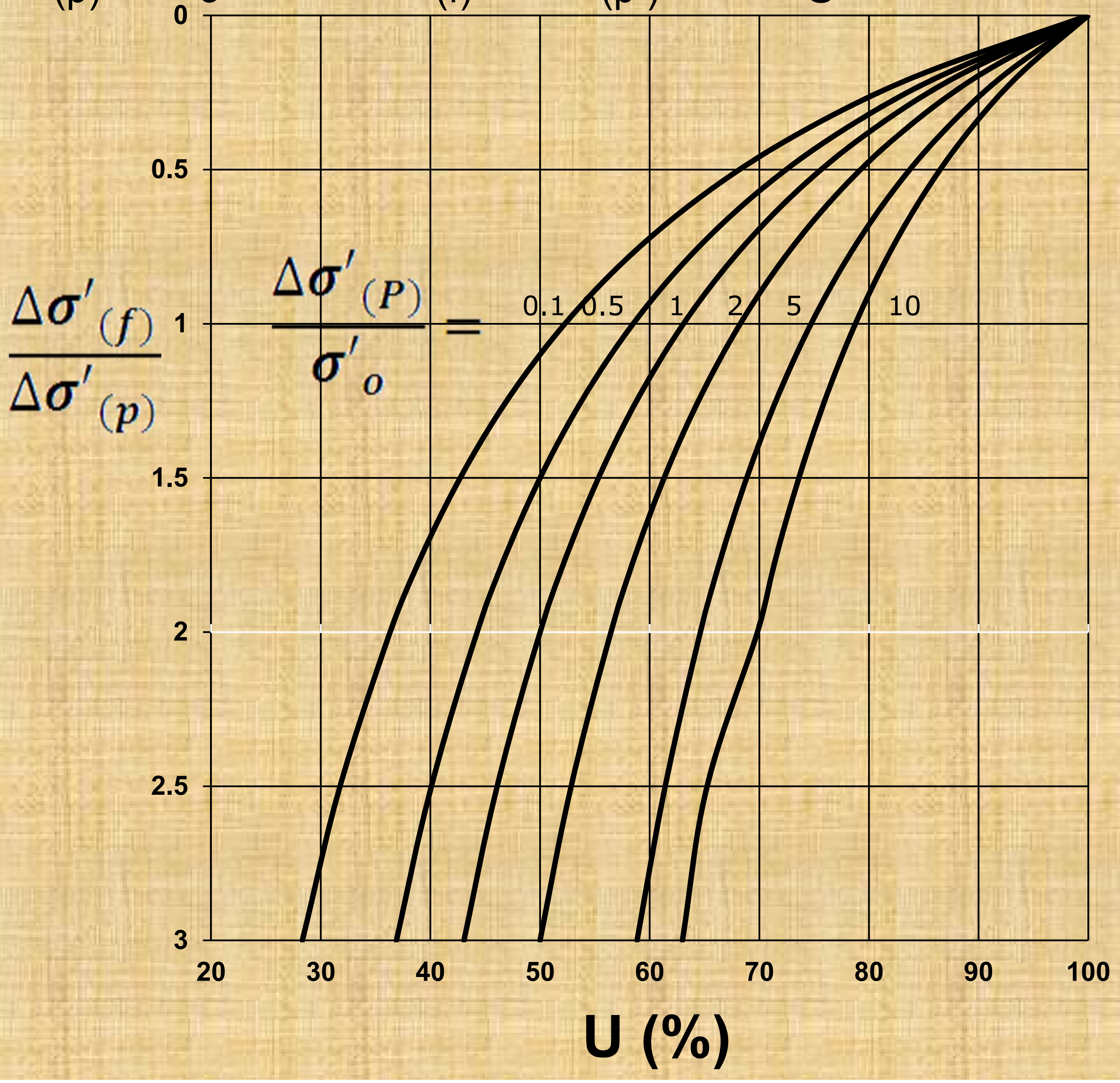
$$U = \frac{S_{c(p)}}{S_{c(p+f)}} \qquad \text{Eq(3)}$$

By substituting Eq(1) and Eq(2) in Eq(3) we get

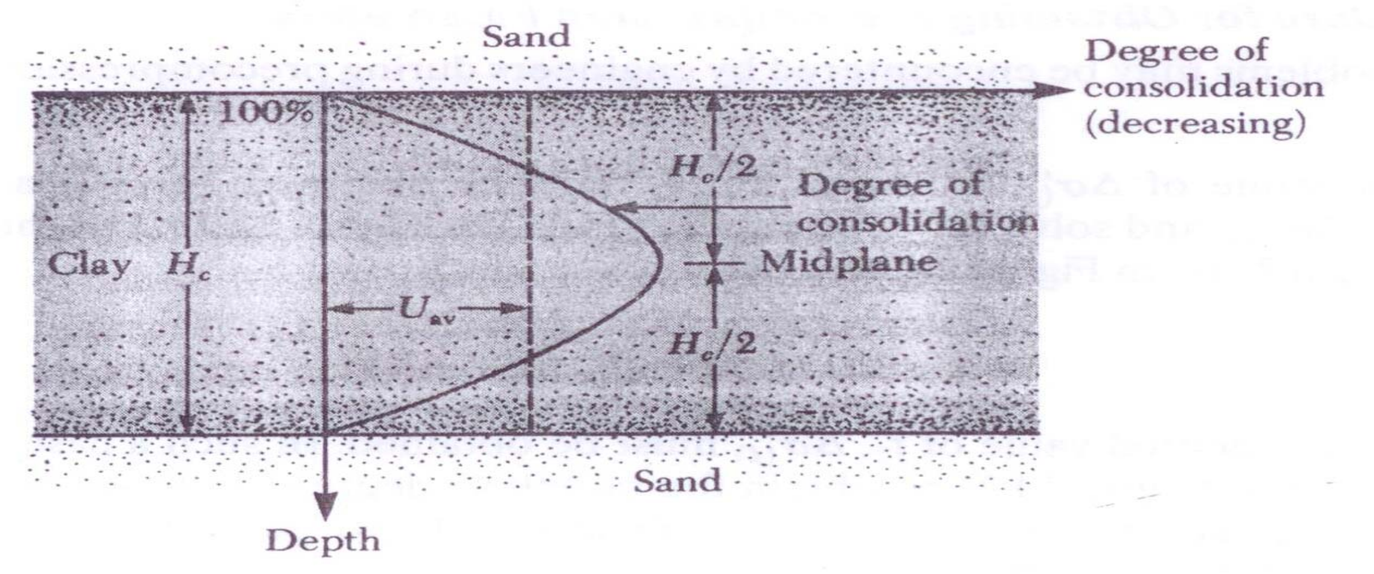
$$U = \frac{\log\left[\dfrac{\sigma'_o + \Delta\sigma'_{(p)}}{\sigma'_o}\right]}{\log\left[\dfrac{\sigma'_o + \Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}}{\sigma'_o}\right]} = \frac{\log\left[1 + \dfrac{\Delta\sigma'_{(p)}}{\sigma'_o}\right]}{\log\left\{1 + \dfrac{\Delta\sigma'_{(p)}}{\sigma'_o}\left[1 + \dfrac{\Delta\sigma'_{(f)}}{\Delta\sigma'_{(p)}}\right]\right\}}$$

Eq(4)

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



- The degree of consolidation from Eq(4) is actually the average degree of consolidation at time t_2 as shown in figure 1(b).
- But due to the removal of surcharge and placement of structural load, the portion of clay close to the drainage surface will continue to swell, and the soil close to the midplane will continue to settle.
- A conservative approach may solve this problem i.e., assume that U in Eq(4) is the midplane degree of consolidation



$U = f\ (T_v)$

where U = midplane degree of consolidation

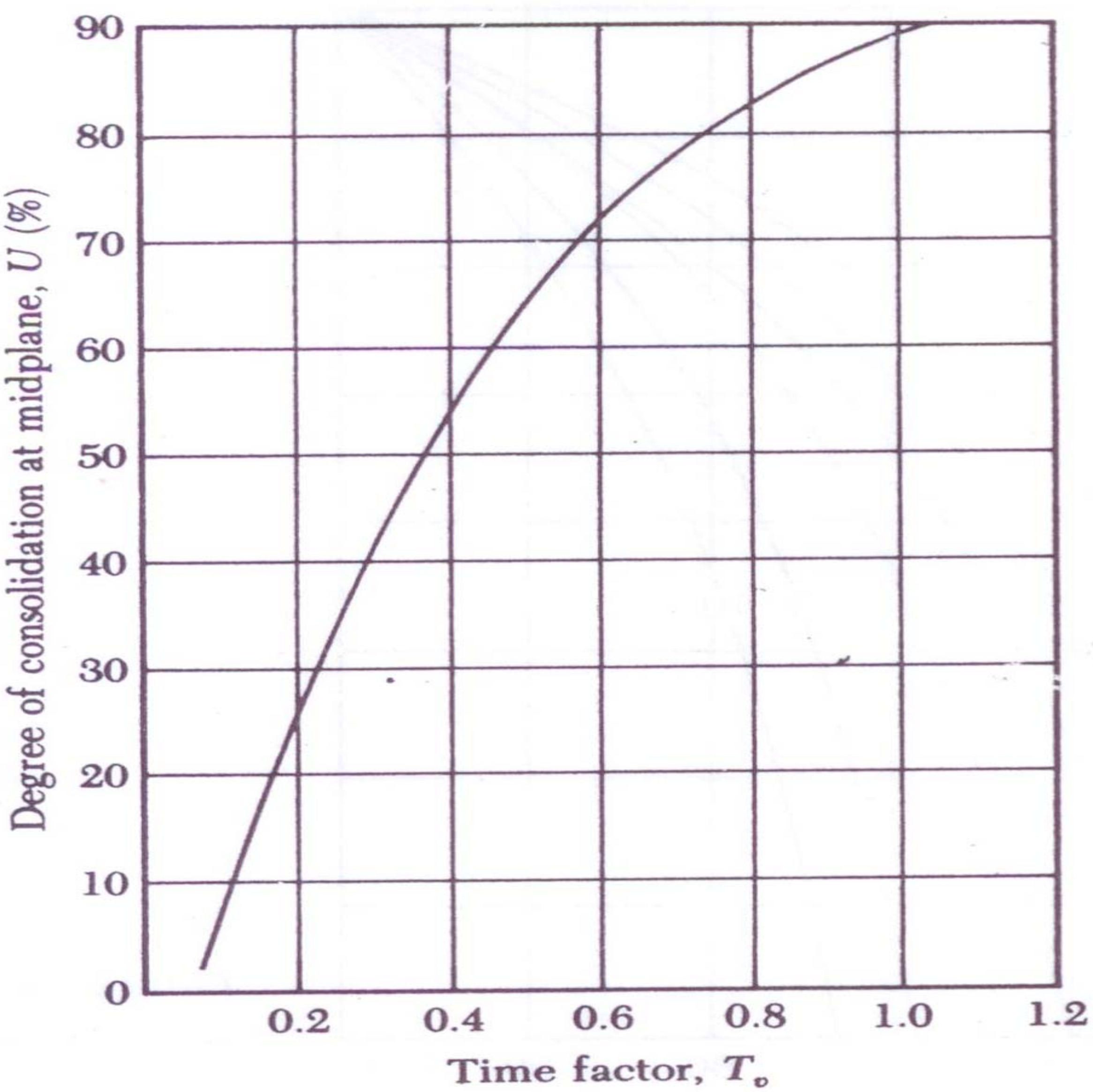
T_v = time factor = $C_v t_2/H^2$

C_v = coefficient of consolidation

t_2 = time

H = maximum drainage path

The variation of U and T_v is given in figure 3.



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

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):

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

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

$= 0.4152m = 415.2mm$

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,

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

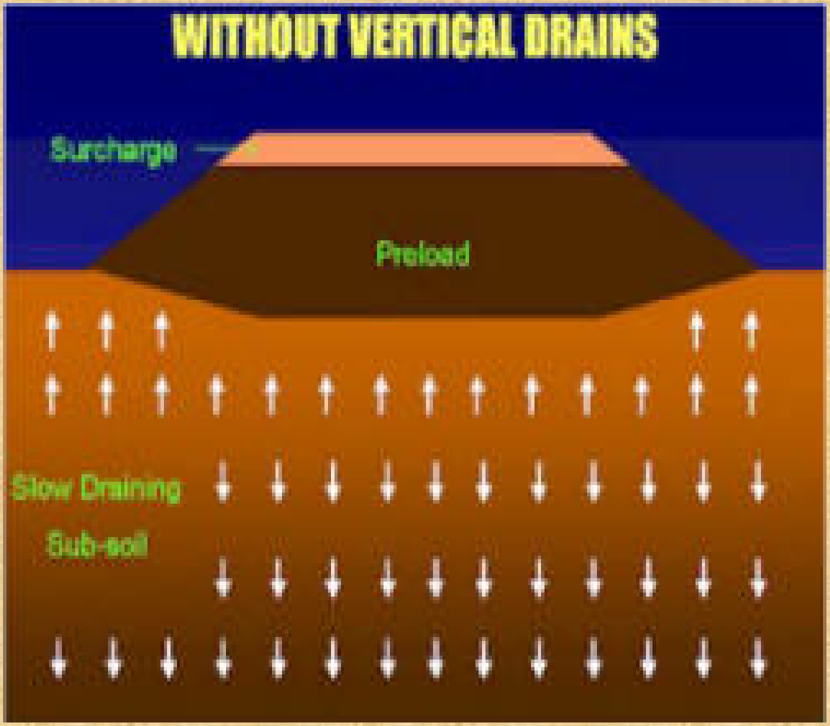
and $\Delta\sigma'_{o} = 210\text{kN/m}^2$

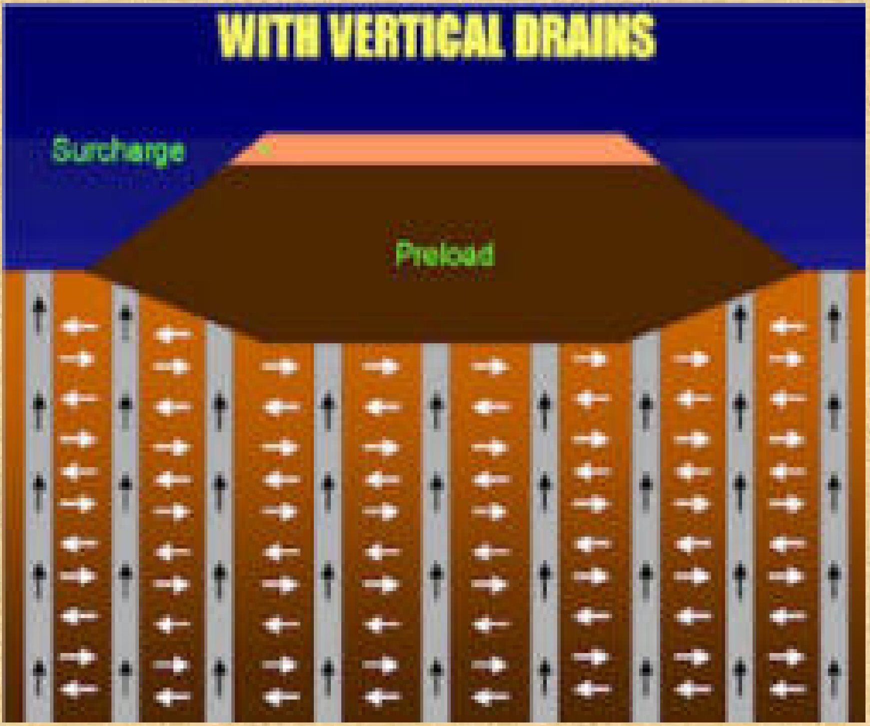
so

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

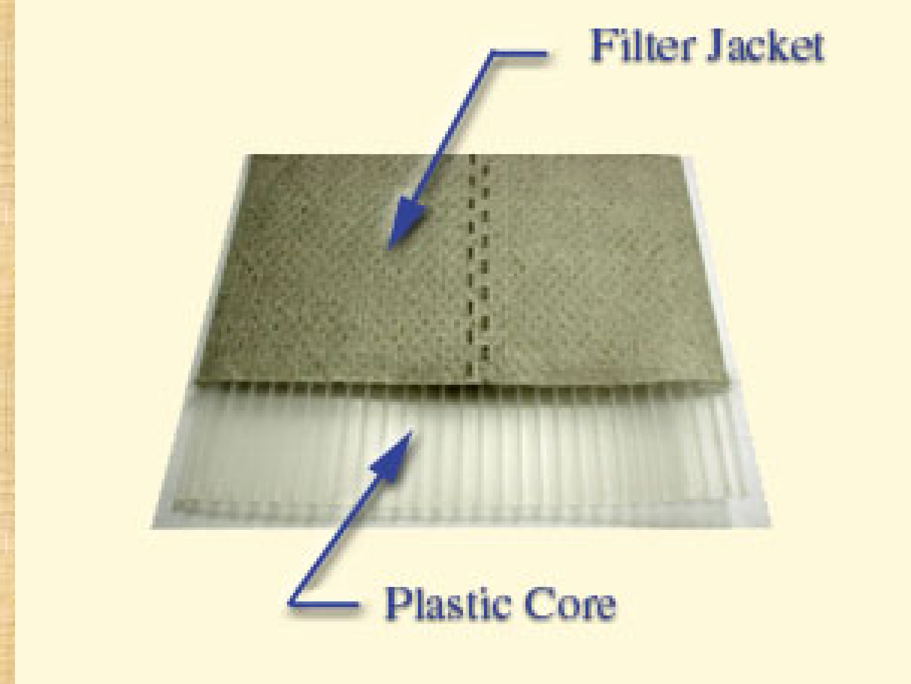
According to Figure 2, for U=40% and $\Delta\sigma'_{(p)}/\sigma'_{o} = 0.548$, $\Delta\sigma'_{(f)}/\sigma'_{(p)} = 2.5$; $\Delta\sigma'_{(f)} = (2.5)(115) = 287.5\text{kN/m}^2$

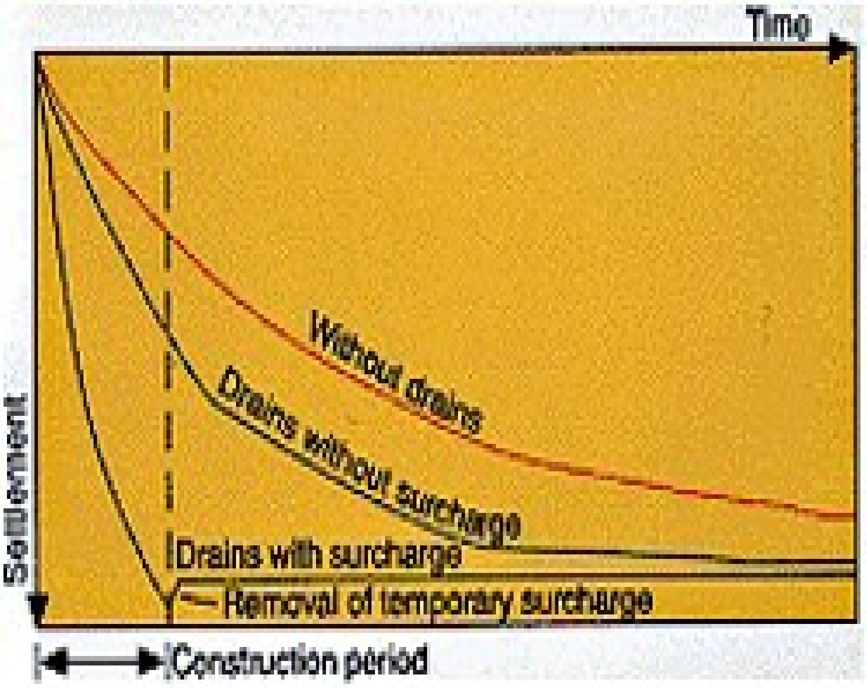
Assuming a bulk density of 20 kN/m^3 for fill material and a height of 5m gives a pre-load of 100 kN/m^2. The required surcharge is higher than pre-load and hence consolidation by sand drains/PVDs is required.


WITHOUT VERTICAL DRAINS
Surcharge
Preload
Slow Draining
Sub-soil


WITH VERTICAL DRAINS
Surcharge
Preload

Prefabricated Vertical Drains





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 = $d_e = \frac{2(B+t)}{\pi}$

Where B= width of the strip, t = thickness

Pre-load enables consolidation of soil in vertical direction only and hence sand drains in addition to pre-loading are used to accelerate the consolidation of soils. This results in reduction of lesser pre-load. It facilitates radial consolidation in addition to vertical consolidation, significantly increasing the consolidation rates.

Sand drains were used since 1930s and pre-fabricated vertical drains in the form of card board wicks were used initially. Now pre-fabricated vertical drains are being used.

In addition, vacuum consolidation along with pre-loading and PVDs is done to increase the efficiency of the whole process.

To increase degree of consolidation using sand drains/PVDs, average degree of consolidation due to drainage in ($U_{v,r}$)

$$U_{v,r} = 1-(1-U_r)(1-U_v) \qquad \text{Eq (1)}$$

where U_r = average degree of consolidation with radial drainage only

U_v = average degree of consolidation with vertical drainage only

Average degree of consolidation due to radial drainage only

$$U_r = 1 - \exp\left(\frac{-8T_r}{m}\right)$$ Eq (2)

where

$$m = \frac{n^2}{n^2 - S^2} \mathrm{In}\left(\frac{n}{S}\right) - \frac{3}{4} + \frac{S^2}{4n^2} + \frac{k_h}{k_s}\left(\frac{n^2 - S^2}{n^2}\right) \mathrm{In}\ S$$ Eq (3)

in which

$$n = \frac{d_e}{2r_w} = \frac{r_e}{r_w}$$ Eq (4)

$$S = \frac{r_s}{r_w}$$ Eq (5)

k_h =hydraulic conductivity of clay in the horizontal direction in the unsmeared zone

k_r = horizontal hydraulic conductivity in the smeared zone

T_r = non-dimensional time factor for radial drainage only

$$T_r = \frac{C_{vr} t_2}{d_e^2}$$ Eq (6)

C_{vr} = coefficient of consolidation for radial drainage

$$= \frac{k}{\left(\frac{\Delta e}{\Delta\sigma'(1+e_{av})}\right) r_w} \qquad \text{Eq (7)}$$

For a no-smear case, $r_s = r_w$ and $k_h = k_r$, so S=1 and Eq (3) becomes

$$m = \left(\frac{n^2}{n^2-1}\right) In(n) - \frac{3n^2-1}{4n^2} \qquad \text{Eq (8)}$$

Drain Design

- Vertical drains and preloading are very effective and economical ground modification techniques for accelerating primary consolidation and compensating some secondary compression of soft compressible soils.
- The design of vertical consolidation using wick drains is based on theory developed by S. Hanbo in 1979, which is used to calculate the spacing of the wick drains based on the horizontal coefficient of consolidation (Ch) of the subsoil. The drains are normally installed in a triangular or square pattern

- The rate of soil consolidation or settlement is controlled by how rapidly the pore water can escape from the soil
- The controlling variables are the spacing between the wick drains and the permeability of the soil.
- The amount of consolidation is independent of whether wick drains are present and is determined by the soil compressibility and the weight of the fill above the wicks.
- By developing a set of design curves of drain spacing, fill height, and consolidation time, the most economical drain spacing and height of fill can be selected to achieve a given degree of consolidation in a specified time period.

Advantages of PVDs over sand drains

- The installation rate of PVDs is typically 5,000 linear meters per day, which results in a significantly lower project cost.
- There is no risk of PVDs breaking installation, while sand drains may have discontinuities if the mandril is withdrawn too fast.
- There is no risk of shear failure of PVDs during settlement, while sand drains are vulnerable to shear failure during settlement.
- PVDs have discharge capacities, typically 30 X 10^{-6} to 90 X 10^{-6} m^3/s, while a 0.35 m diameter sand drain has a discharge capacity of 20 X 10^{-6} m^3/s (Van Santvoort 1994)

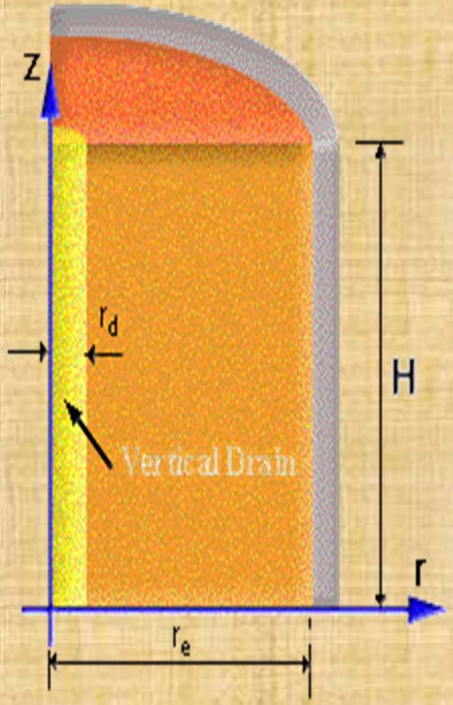
- When installed with a properly designed mandril, smear effects are much less for PVDs than for large diameter sand drains. The zone of smear is directly proportional to the diameter of mandril used for installation.
- PVDs are factory produced materials and are quality controlled, whereas sand drains are subject to the quality variance of naturally occuring sands.

Prefabricated Vertical Drains

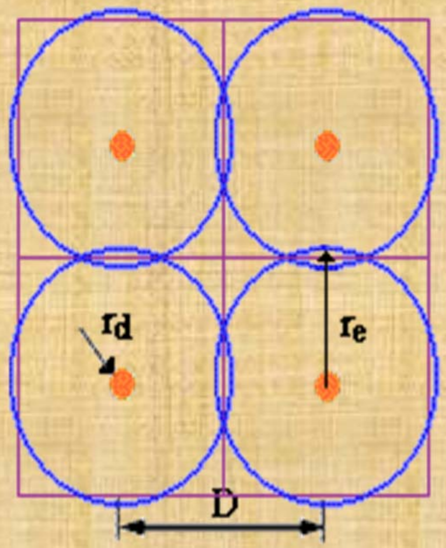
- The prefabricated band drains are used for accelerating the consolidation of marine deposits or soft soils.
- In general, prefabricated band drains consist of a central core, whose function is primarily to act as a free drainage channel, and a non-woven filter jacket, which prevents the soil surrounding 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.

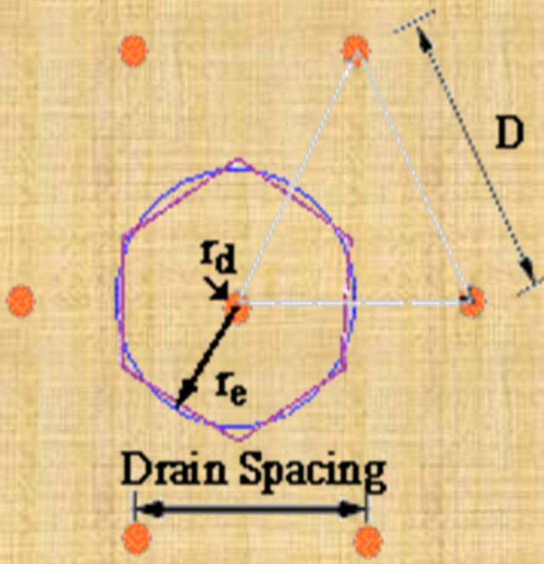
Vertical Drain Spacing

- 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.



Layout of square grid pattern

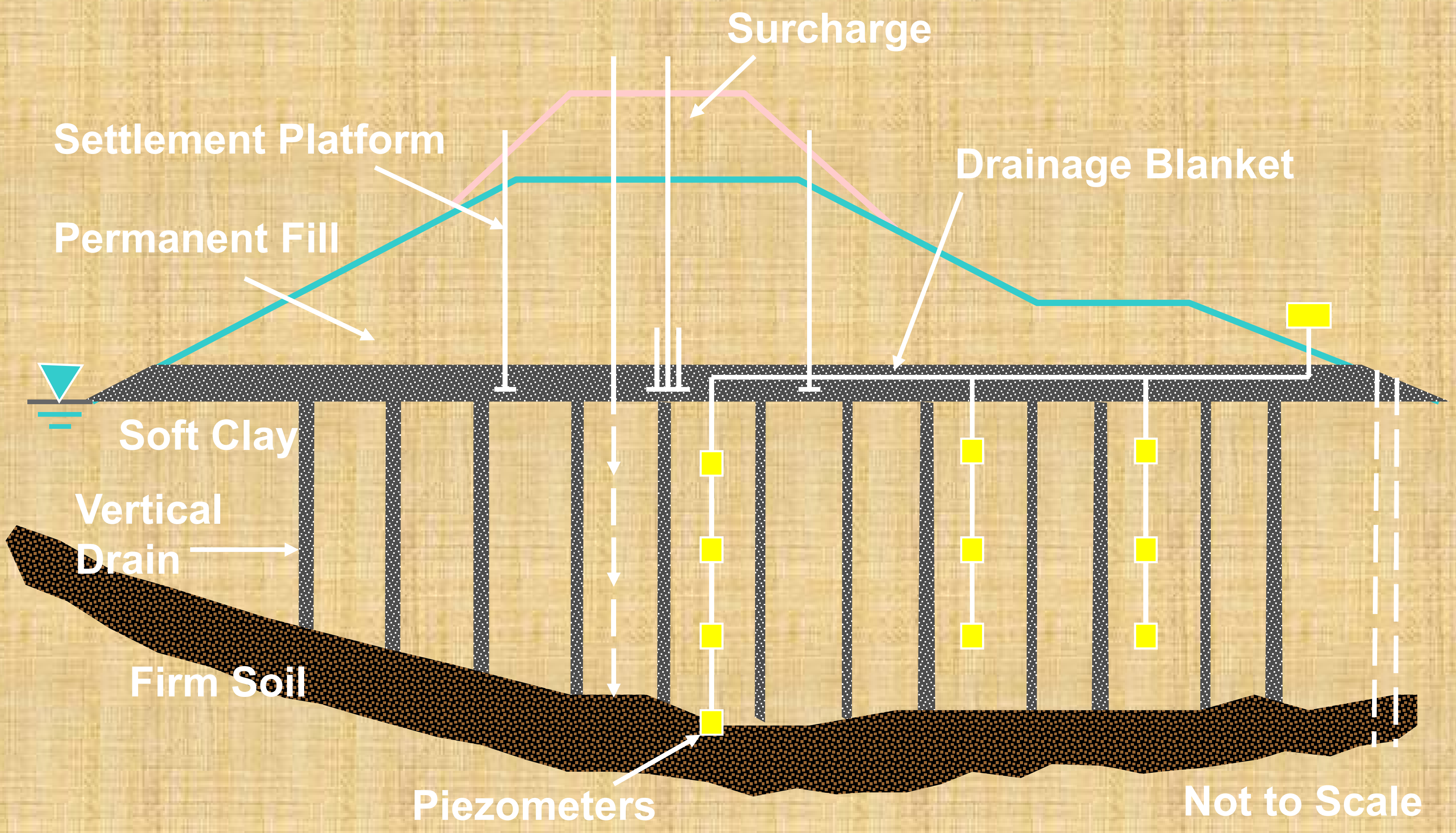




Trial Embankments

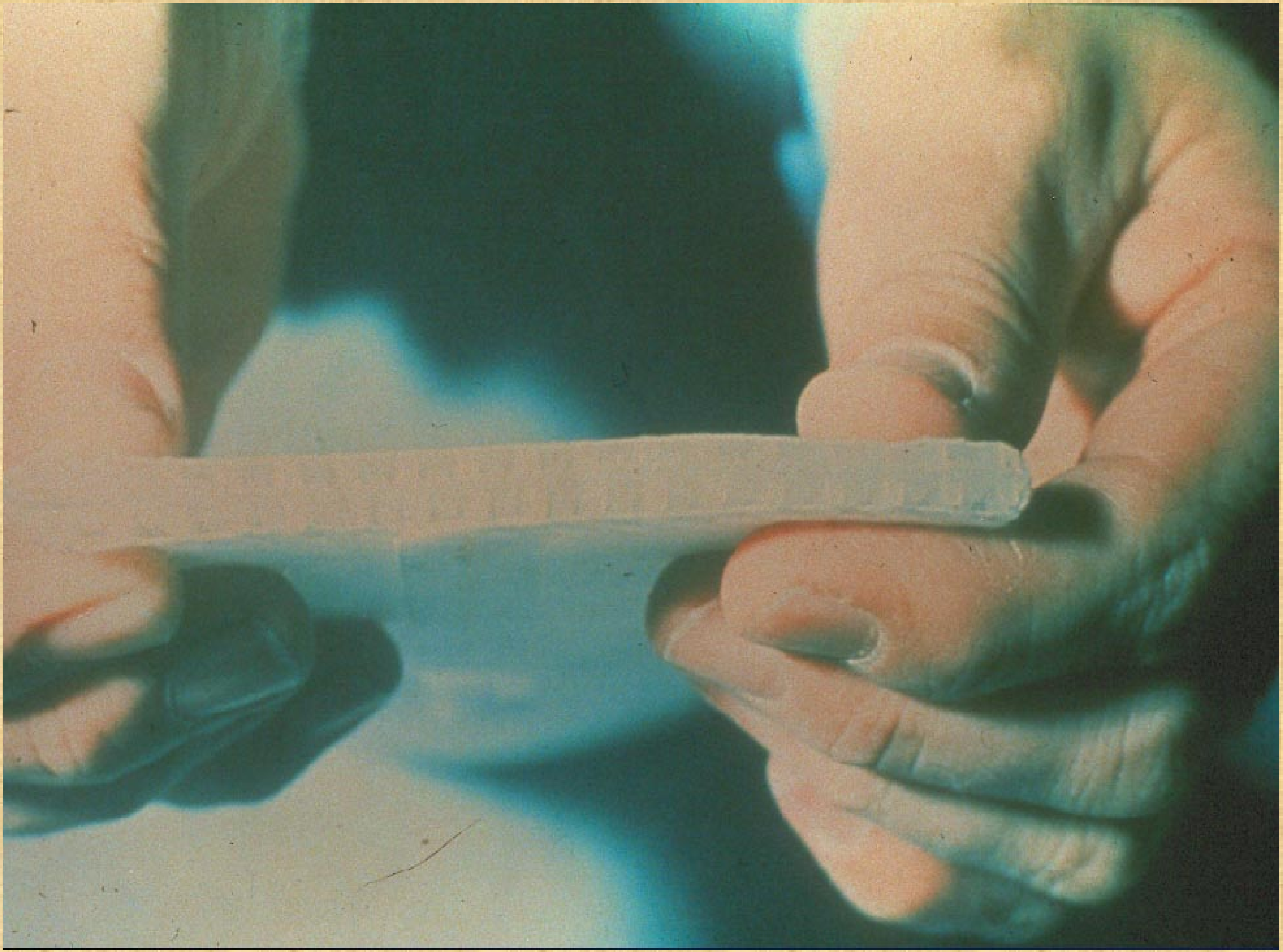
- These are useful to determine the feasibility of preloading and vertical drains in the field and avoids uncertainties in sampling, field properties and installations.
- It needs to reproduce stress and field conditions that are representation of actual structure.
- It should be part of final structure.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

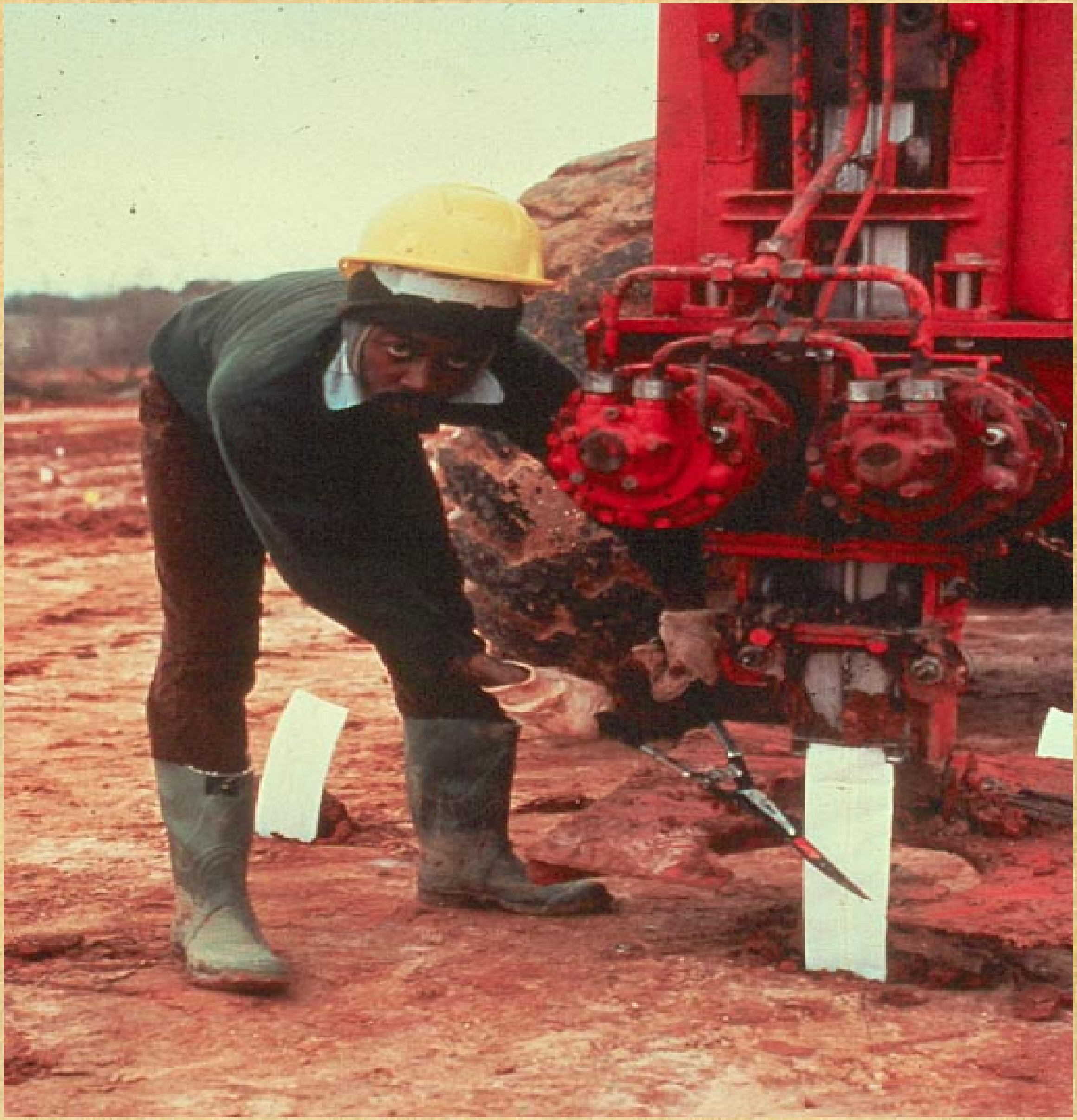
Instrumentation of Vertical Drains



Vertical Drain Installation Sequence

- Position Rig at Drain Location
- Place Anchor on Drain End
- Penetrate Mandrel to Desired Depth
- Withdraw Mandrel
- Cut Drain Material Above Drainage Blanket





POTENTIAL ADVANTAGE OF VERTICAL DRAINS

The advantages of vertical drains are threefold:

1.INCREASED RATE OF GAIN OF SHEAR STRENGTH OF CLAY

- ❖Enable the load to be applied more rapidly, thus better use of construction plant
- ❖In case of embankments, steeper slopes and provision of berms can be avoided
- ❖Lower amount of fill required
- ❖Increased rate of consolidation
- ❖Consequent savings in construction cost

2.INCREASED RATE OF CONSOLIDATION

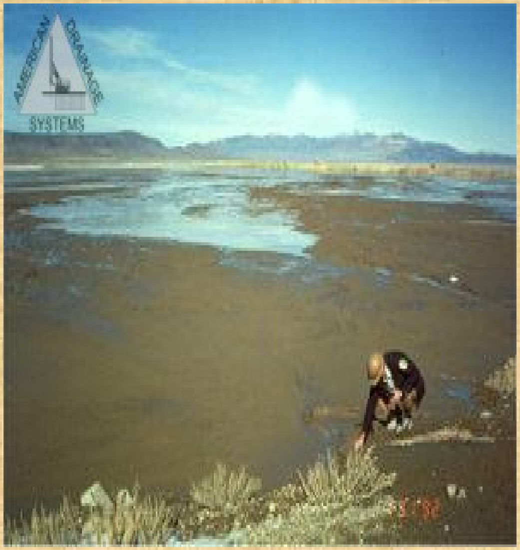
- Reduction in time required for primary settlement.
- Structure or embankments can put into commission and use far earlier
- Reduction in cost of maintenance

3.STABILITY TO EMBANKMENTS

- Many soft clay strata contain thin band, or parting, of sand or silt
- Excess horizontal spread of pore pressure along these partings take place
- Vertical drains installed can relieve these excess pore pressure

Application of PVDs

- Airport Runways
- Golf Courses
- Dredge Consolidation
- Mine Tailings Consolidation
- Tailing Ponds
- Swampland/Wetland Development
- Building Foundations
- Retaining Walls
- Parking Lots
- Landfills



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…

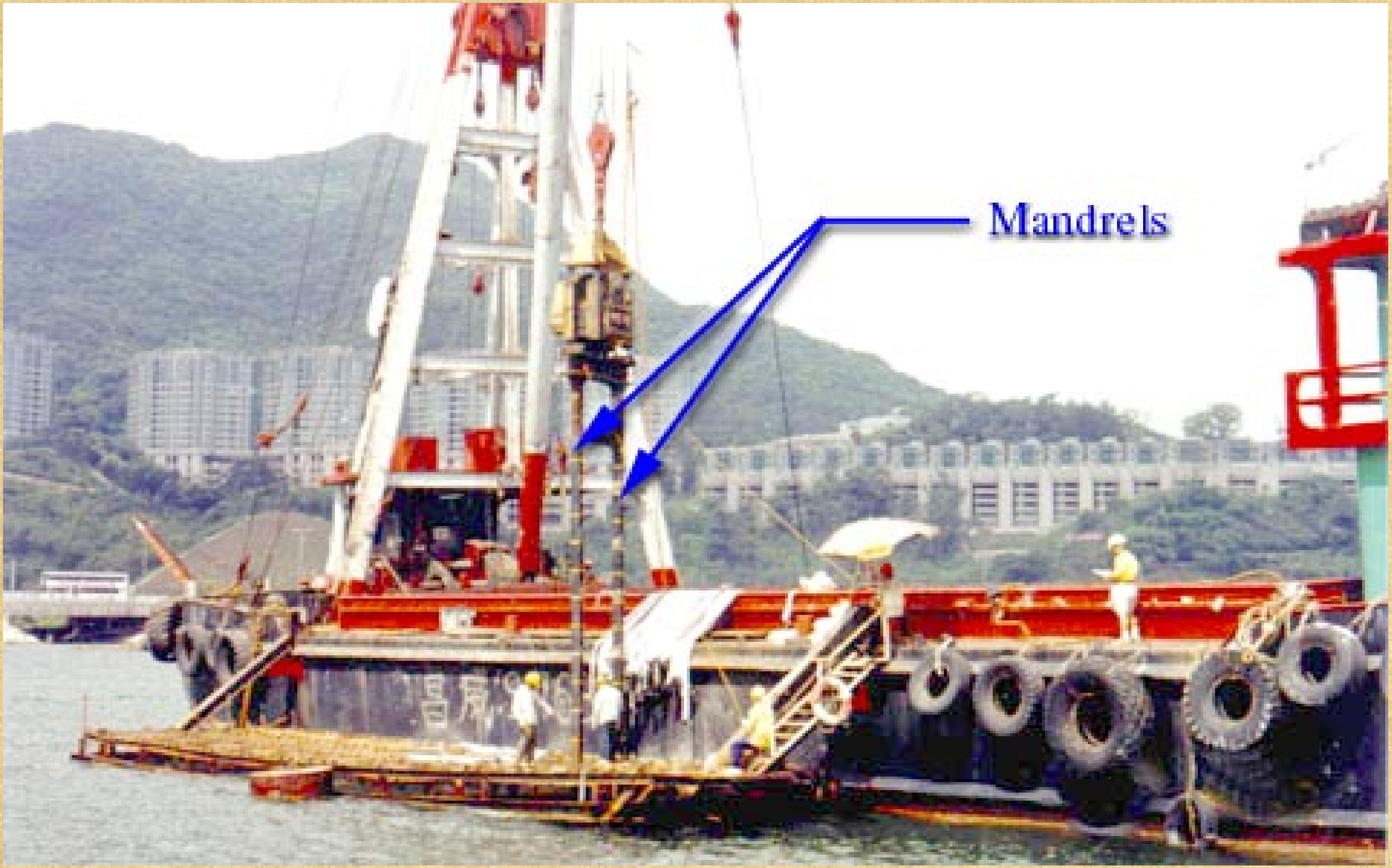
GROUP DESCRIPTION	PARTICULAR METHODS	REMARKS
DRILLING METHODS	Rotary drill, with or without a casing Rotary anger, including continuous standard and hollow fight augers Percussive(shell and auger) methods, with or without casing Hand auger	A mandrel with or without a disposal shoe is used in each case.

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

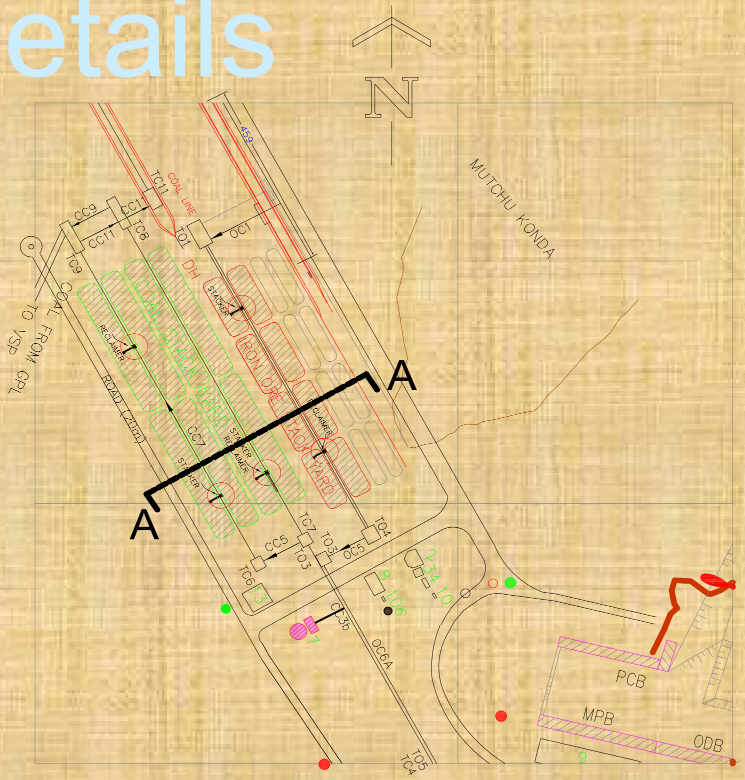
Development of New Port at Gangavaram at 15 km south of Visakhapatnam Port , AP

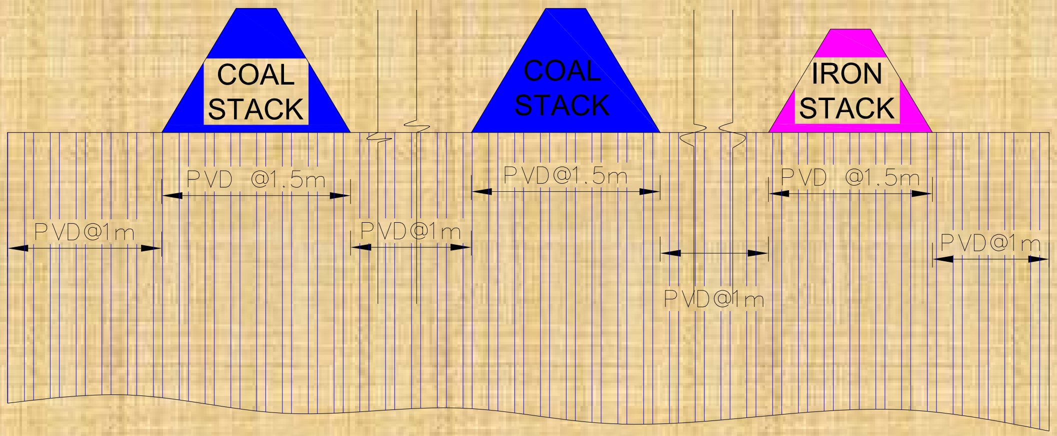
Development of Port Facilities included development of backup facility for coal and iron ore storage and stacking and handling facilities

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 & lysis

Post Treatment Assessment

Piezometers

Casagrande : 5 Nos

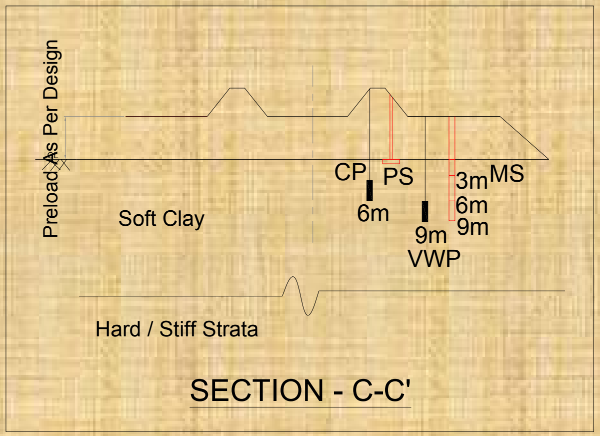
Vibrating Wire : 14 Nos

Settlement Recorders

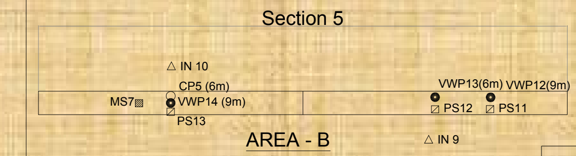
Plate Type: 13 Nos

Magnetic: 7 Nos

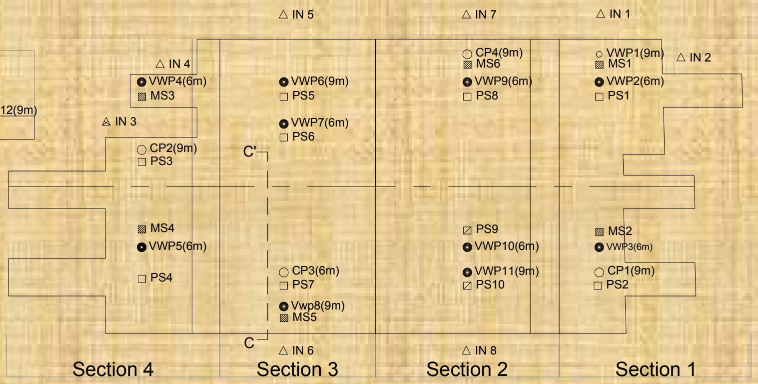
Readings every 4 days when loading started.
Later at every 7 days



SECTION - C-C'



AREA - B



AREA - A

Analysis of Data

Excess Pore Pressure

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

Settlement

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

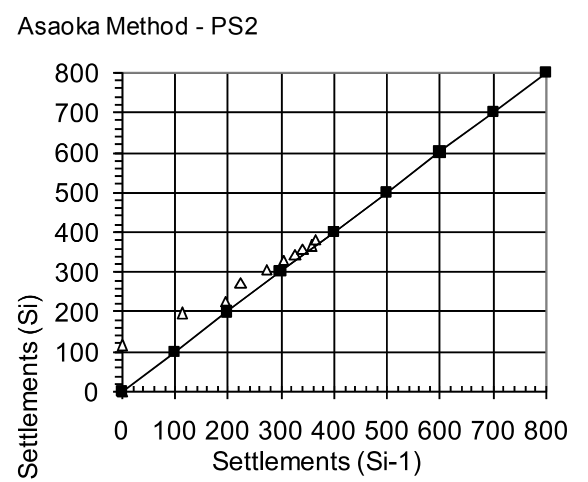
Asaoka Method

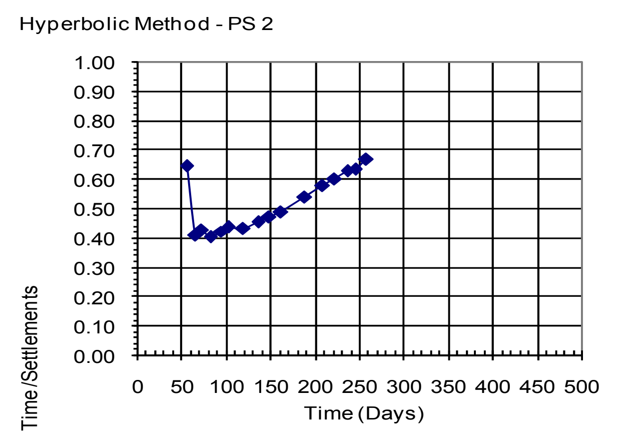
Settlement at equal time interval Δ t

Points (Si, Si-1) are plotted

Interception of this line with line having slope = 1

Settlement S_{100}





Hyperbolic Method

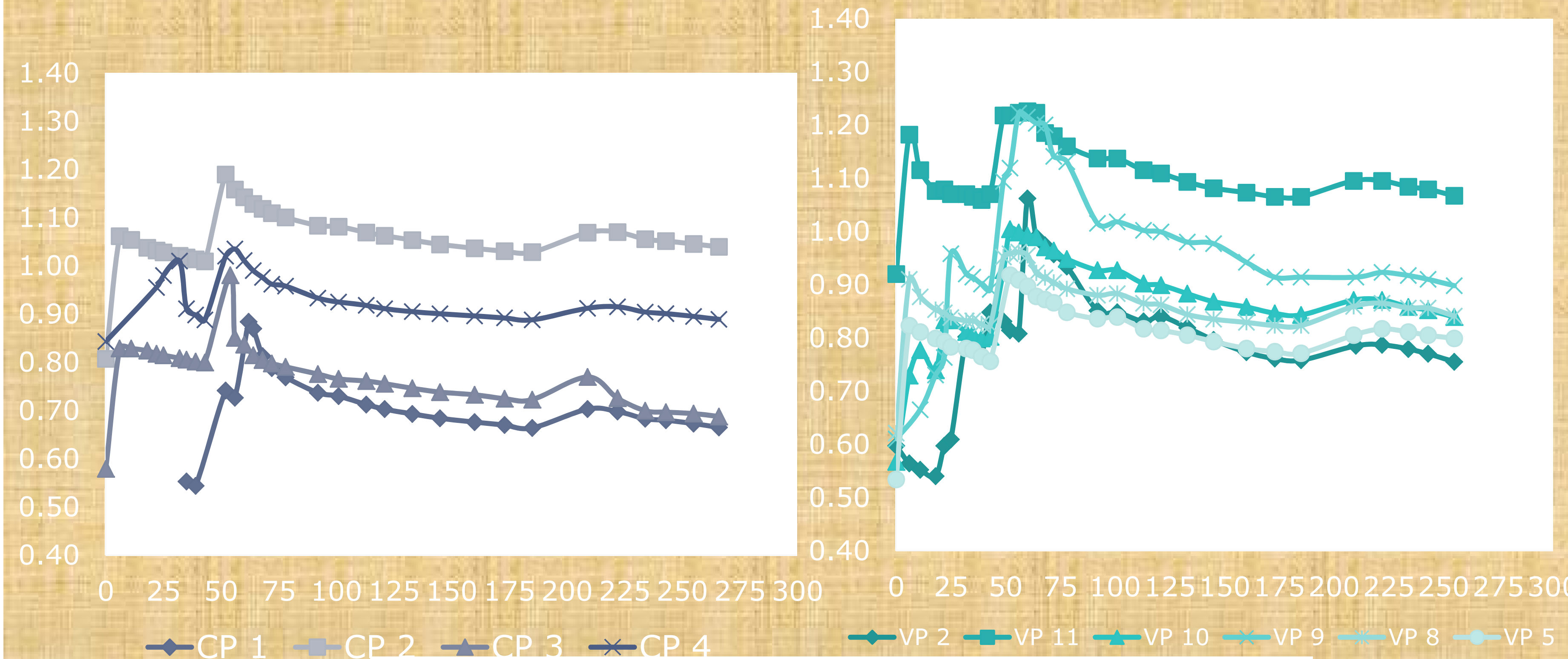
Graph of Time / settlement Vs Settlement

Graph in the form of Hyperbole

Inverse of slope of Hyperbola

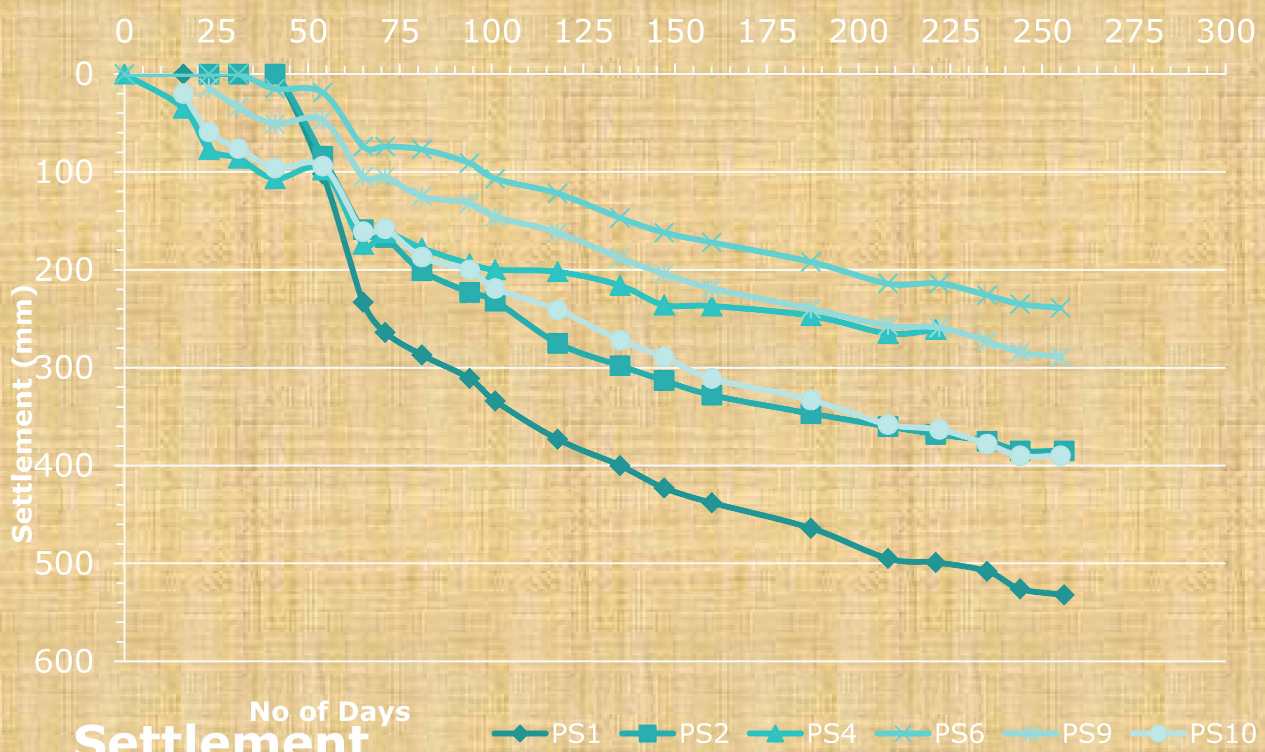
Settlement S_{100}

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

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

Vacuum consolidation was first proposed in the early 1950s by Kjellman (1952), the developer of the prefabricated vertical "wick" drain. In the 1960s, isolated studies of vacuum induced or assisted consolidation continued for the next two decades (Holtz 1975). 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 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.

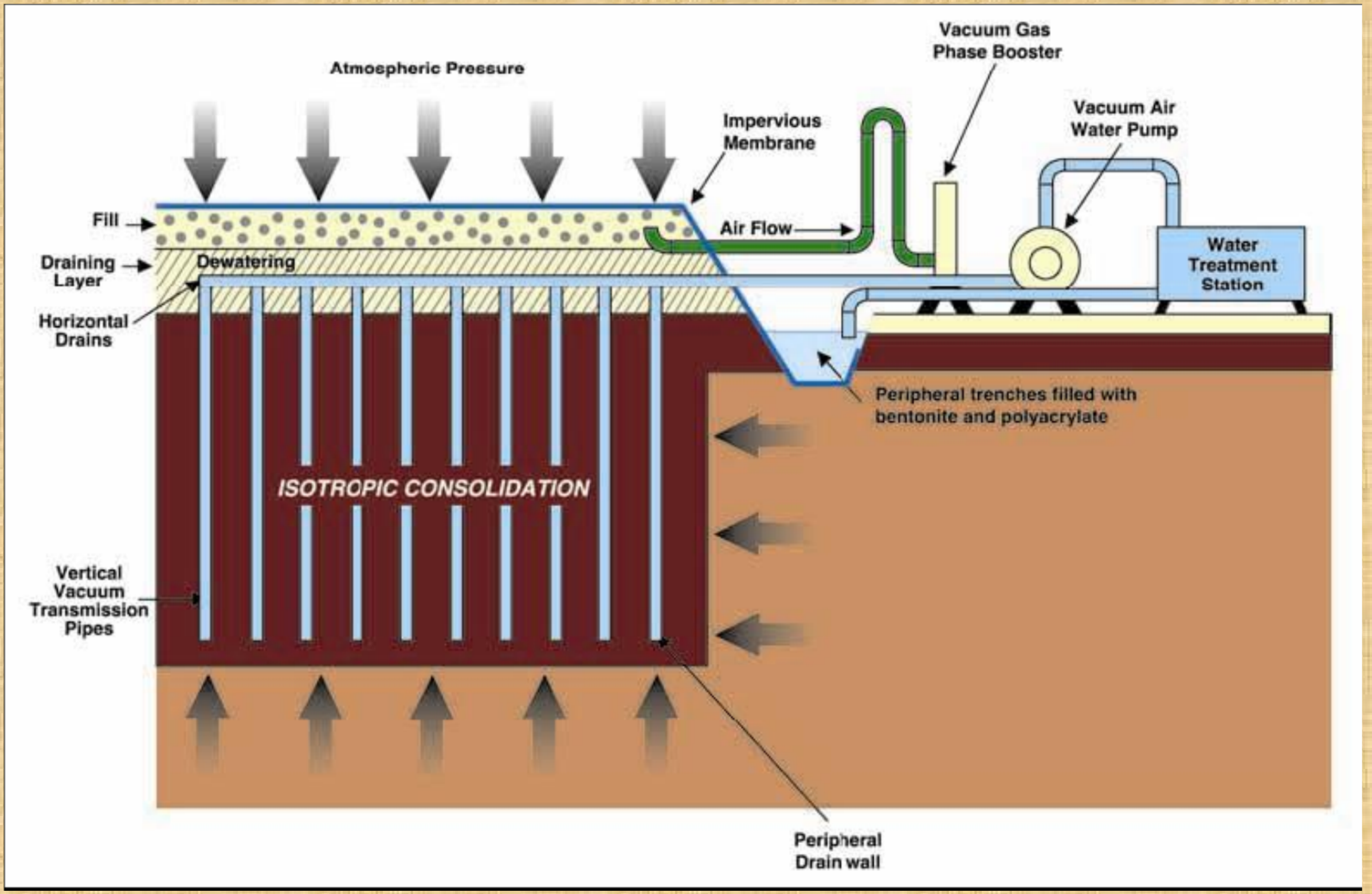


Figure1: Menard Vacuum Consolidation

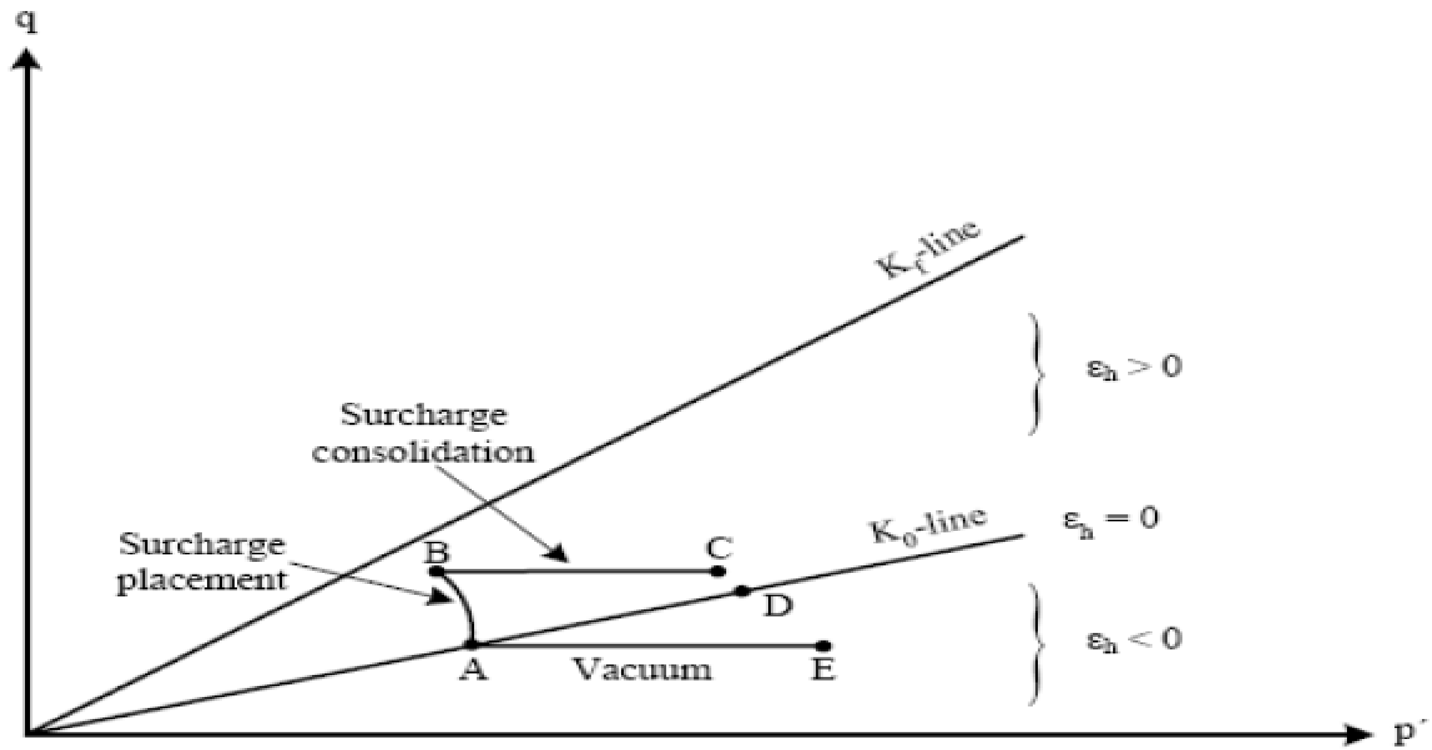
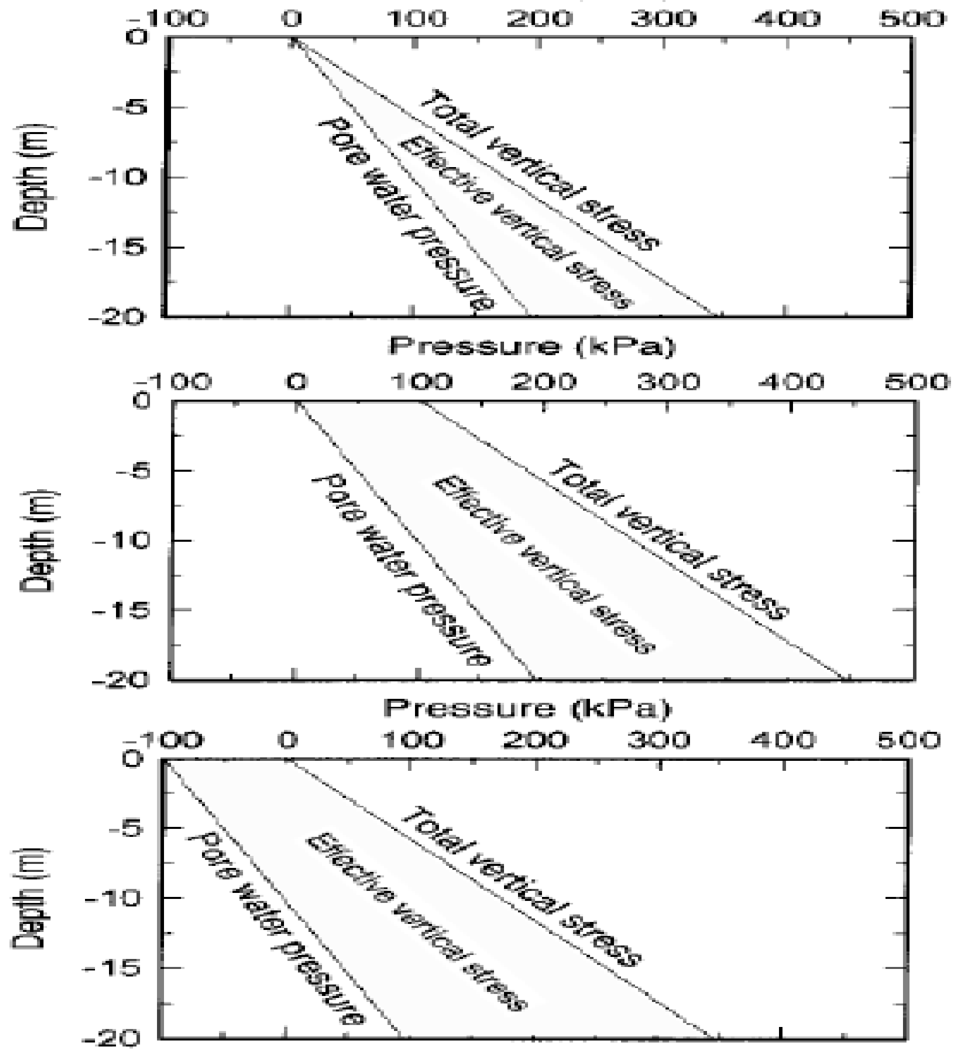


Figure 5: (p´, q) – diagram


-100
0
100
200
300
400
500
0
-5
-10
-15
-20
Depth (m)
Total vertical stress
Effective vertical stress
Pore water pressure
Pressure (kPa)
-100
0
100
200
300
400
500
0
-5
-10
-15
-20
Depth (m)
Total vertical stress
Effective vertical stress
Pore water pressure
Pressure (kPa)
-100
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300
400
500
0
-5
-10
-15
-20
Depth (m)
Total vertical stress
Effective vertical stress
Pore water pressure

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.

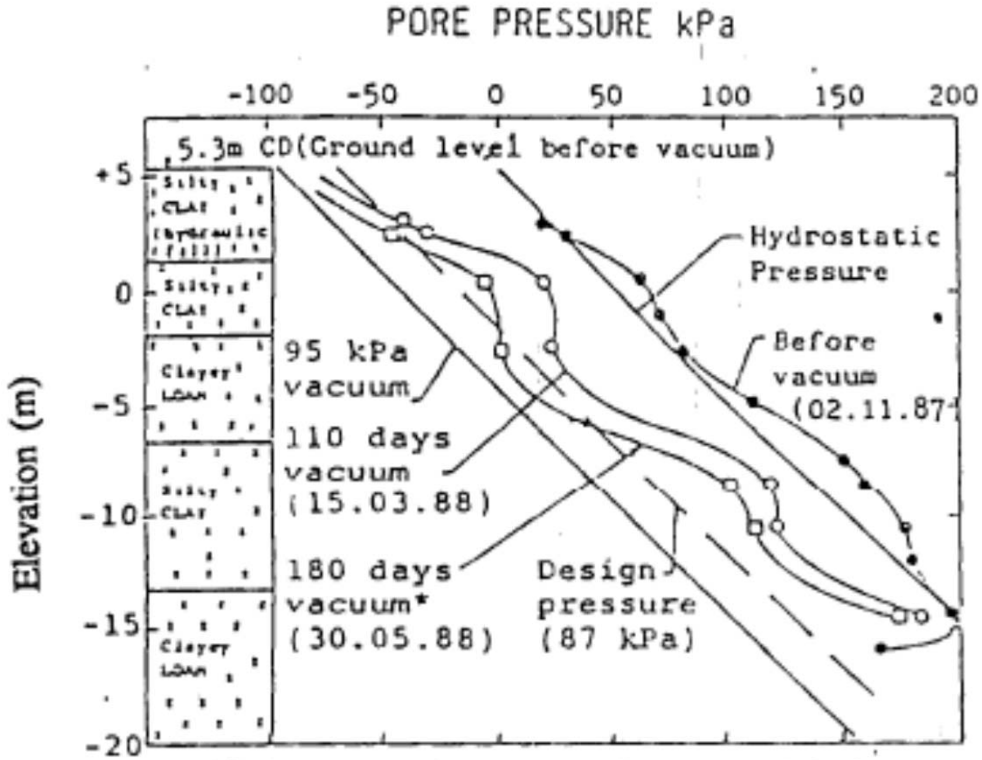
The process combines dewatering and vacuum action to maintain the water table at the base of the granular platform during the entire application of the consolidation process. Eventually an additional drainage system is installed at a required depth to allow for a conventional de-watering under the membrane. 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.

Figure 3 shows a typical pore pressure at the end of vacuum consolidation measured in China (Choa, 1989) during vacuum consolidation. The Tianjin Harbor site consisted of about 4m thick hydraulic fill (thinly laminated silty clay/clayey silt) underlain by 15 m of silty clay, 3m of clayey loam, and another 3m of sandy loam, respectively. The site overlies a fine sand deposit. The groundwater level was very close to the ground surface at this site. Vertical band drains (100mm*4mm) were installed at a spacing of 1.3 m up to a depth of about 20-m into the clayey loam above the sandy loam.

Figure 3 portrays two profiles of initial hydrostatic pressures and final pore pressures measured during vacuum consolidation after 110 days and 180 days of vacuum application at the site. The straight lines indicate theoretical pore pressures under various vacuum pressures.



* 17 kPa surcharge preload applied from 26.03.88

Figure 3: Initial and final pore pressure data during Vacuum Pre-loading: Tianjin Harbor (Choa, 1989)

An atmospheric pressure corresponds to about 100 kPa. For a site where the water level is at the ground surface, cavitation of water at negative 1 atmosphere (gage pressure) theoretically limits on-land vacuum- consolidation to an effective surcharge pressure of about 100 kPa, equivalent to approximately 6 m of surcharge.

Practical problems in maintaining the efficiency of a vacuum system may reduce its effectiveness in the field. A system with an efficiency of 75 percent results in only 4.5 m of equivalent surcharge height.

For the case presented in Figure 3, about 70 to 80 per cent efficiency is evident near the ground surface. At large depths, however, the efficiency was only about 50 percent or less. Vacuum consolidation in underwater site conditions (off-shore land reclamation) can yield much higher equivalent preloads.

In essence, geotechnical design analyses used to evaluate wick drain spacing, and strength gain for preload fills are equally applicable to the engineering design of vacuum consolidation system. There are many technical and operational factors, which play important roles in vacuum consolidation.

Primary considerations governing the effectiveness and economics of a selected VCP scheme include:

(1) integrity of the membrane at the ground surface

(2) seal between the edges of the membrane and the ground

(3) soil stratification including permeable and seams within the clay deposit, and

(4) depth to groundwater.

Breaks in the membrane, a poor seal between the membrane and the ground, and wick drains extending into layers of high hydraulic conductivity all tend to reduce vacuum efficiency, reducing equivalent surcharge height and increasing pumping yields and pumping costs. The success of a vacuum consolidation system depends upon a combination of technical know-how and careful implementation of design details.

Case History

The advantages of vacuum assisted consolidation is well demonstrated by the pilot testing conducted in Ambes, France, for the construction of a highway embankment on a very compressible saturated clayey soil (Cognon et al, 1996).

As shown in Figure 4a, the soil profile at this site indicates the presence of about 1.7 m thick peat layer with a moisture content ranging from 400% to 900 % underlain by about 2.0 m thick highly organic, compressible clay layer with moisture content ranging from 140% to 210%.

Case History

The project plan called for the construction of a highway embankment, 2.15 m high, across the site in order to protect the highway from floods. Alternative solutions, including soil replacement, raft foundation supported by piles and conventional surcharge pre-loading were considered and rejected for economic reasons.

For example, due to stability concerns, the conventional pre-loading system required very gently sloping embankment with a base width of 65 m, which was economically prohibitive.

Case History

As vacuum consolidation has not been previously applied under such soil and moisture conditions, a pilot field-testing program was implemented. The combined application of surcharge (1.3 m) and vacuum provided an equivalent pre-load of about 150 kPa after only two months of vacuum application, where as under conventional surcharge, slope failure would have occurred at this site under a pre-loading stress of 35 kPa.

Case History

Figure 4 b depicts the monitored settlement record during the consolidation process. It indicates that the recorded settlement with vacuum consolidation is approximately equivalent to that induced by a 4.5m high surcharge embankment. Analysis of the settlement records indicated that at the end of the consolidation process the settlement of the peat layer reached about 80% of the reference settlement that would have been induced by a 4.5 m high surcharge embankment, while the settlement of the underlying highly organic clay reached about 50% of that reference settlement.

Case History

At the end of the vacuum application the ground surface rebounded by about 3 cm during 48-hour period and then stabilized. During the vacuum application the groundwater level rose by about 40 cm up to the level of the horizontal drains while the upper part of the granular fill remained dry.

Following the pilot testing the vacuum consolidation was selected as the best available solution for the consolidation of about 17,550 m^2 along this highway construction site.

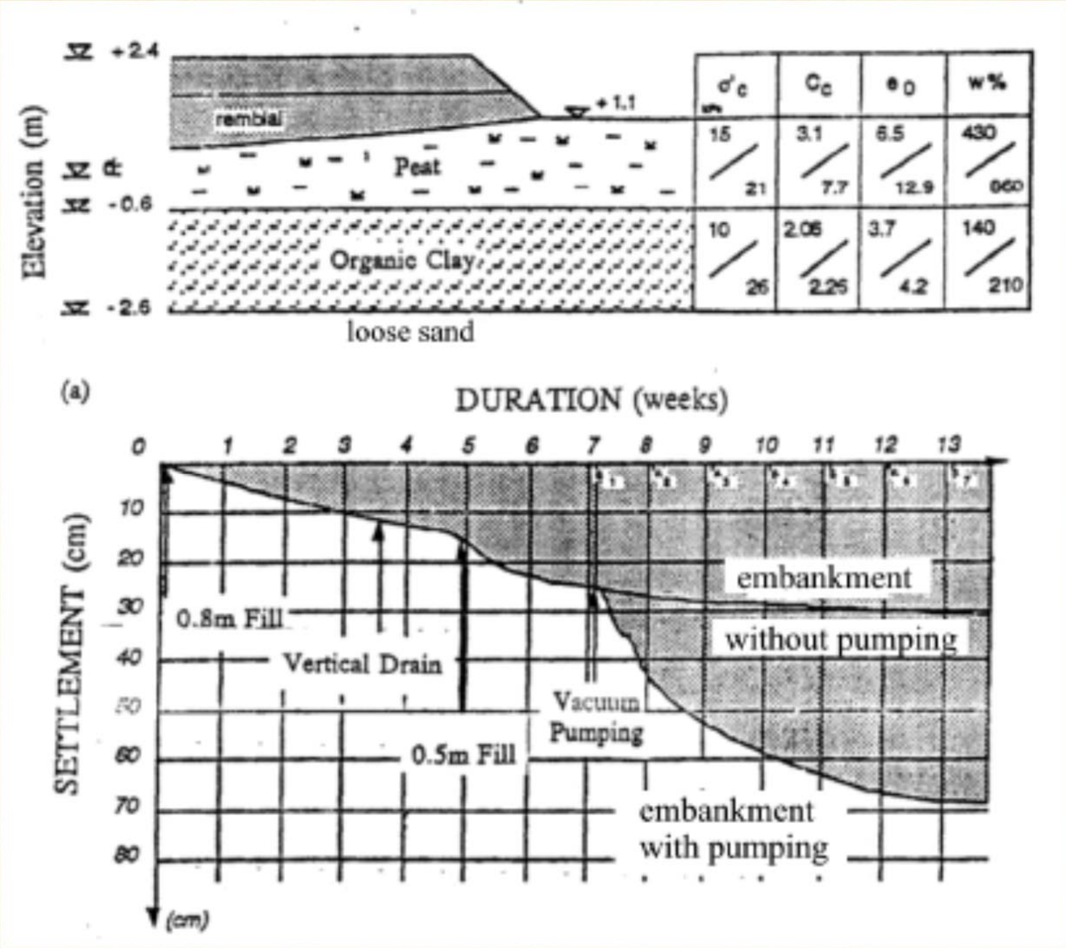


Figure 4: (a) Typical Soil Profile at Ambes Site, France, and (b) Measured Settlement vs. Time Record during Vacuum Consolidation (Cognon et al. 1996).

Case History

The A837 Highway in the western part of France, crosses three (3) swamps. The site is divided into three parts each distant of 15 km. The first two swamp crossings are 500 meters long (1640') and the third one 70 meters (230') long.

The thickness of the highly compressible material reaches 12 meters

(40'). The final embankment height varies between 4 and 9 meters (13' - 30') above grade.

An initial study of the potential settlement had indicated that approximately 2 meters (6') were to be expected for a 4 meter (13') embankment height over a period of more than fifty years. Thus, preloading became necessary to accelerate the consolidation and to reduce the post-construction settlement to a manageable magnitude.

Case History

In view of the project size and the highly developed agriculture tenure surrounding the proposed embankment, the transportation of additional fill for surcharge from a long distance (50 miles) became economically prohibitive.

The Vacuum Consolidation Process was thus selected as the only viable alternative to Conventional Surcharge.

Figure 5 shows the settlement recorded during construction, first due to the vertical drains only, and then the substantial increase as vacuum is applied. V.C.P. has permitted the construction of up to a 6-meter (20') high embankment within a 3-month period. Total settlement during this period was 1.7 meters (5.5') and the residual deformation anticipated for the next thirty years is estimated at 10 cm (4") only.

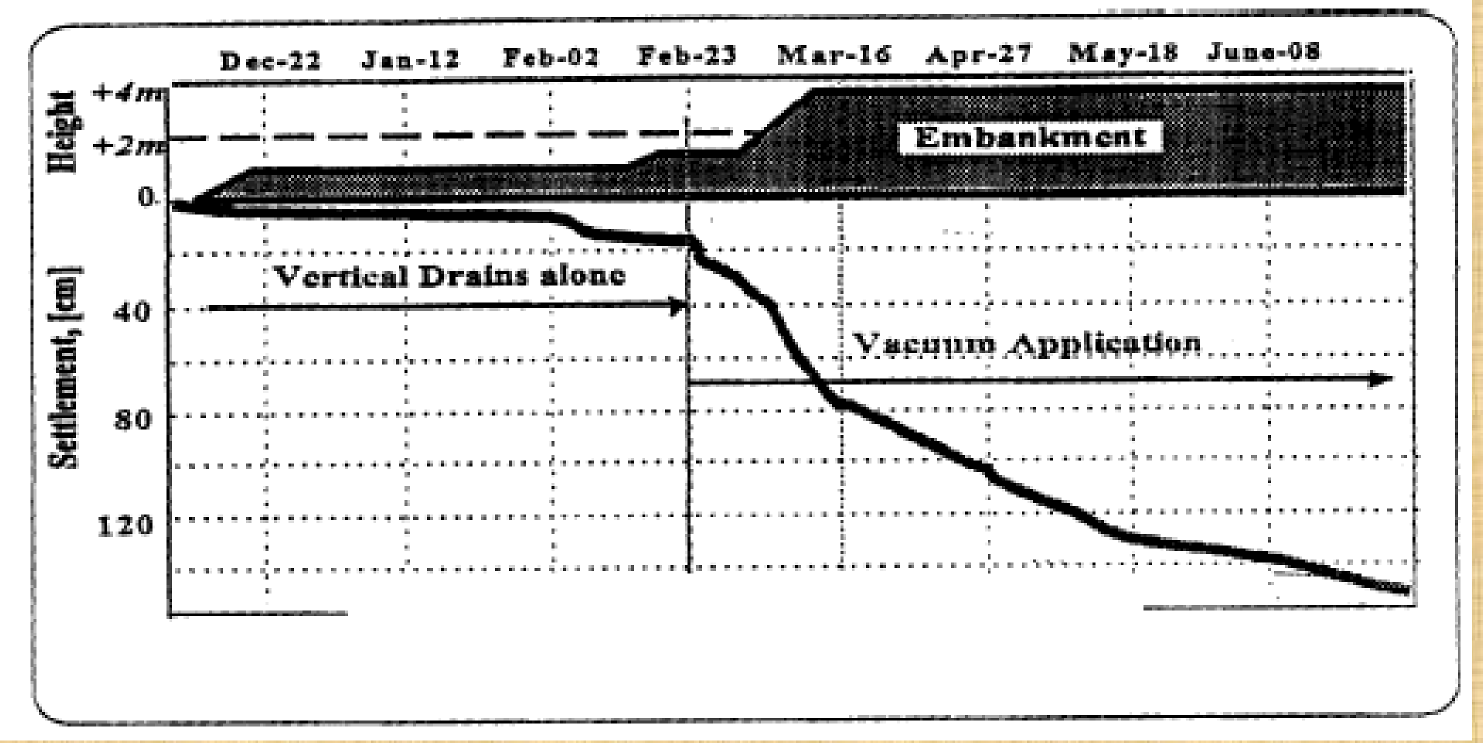


Figure 5: A837 Saintes Rochefort Highway, France, Measured Settlement (Cognon, 1991)

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.

CONCLUSIONS

Experience from on-land field applications of this technology indicates a high potential for use of vacuum technology for improvement of existing hydraulic fills, strengthening weak sediments in the sea floor adjacent to or beneath waterfront retaining facilities, and consolidation of fine-grained hydraulic fills during construction. As indicated by Thevanayagam et al. (1996) in the new land reclamation works the benefits of vacuum consolidation can be realized by inclusion of prefabricated horizontal drains and selective placement of dredge materials.

Underwater applications or on-land applications with dewatering (Figure 6) appear to be most beneficial in such cases. Lack of performance data on prefabricated drains as well as of field trials directly applicable for such cases appears to limit its potential uses for further major land reclamation projects at present time.

Acknowledgments

http://www.haywardbaker.com/

/http://www.menard-web.com/

Haussmann M R (1990) Engineering principles of ground modification

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