Design of Ground Improvement System for construction of Embankment on Soft Soils

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Synopsis
A simple computer program for "Design of Ground Improvement system using Vertical Drains or Pre-fabricated Vertical Drains (PVD)" has been developed and uploaded on IRICEN's website (Link to the Excel File). This technical paper explains the usage of this simple program along with complete theoretical background for understanding this program as well concept of Ground Improvement for construction of Railway Embankment on Soft soils.

1. Soft soils: Soft soils are typically highly fine grained soils (containing more than 50% fines, passing 75 micron IS sieve), with moderate to high clay content. These soils have very high Liquid Limit and Plastic Limit values, tendency to retain moisture for longer duration thereby having high Natural Moisture Content (NMC), low material permeability, highly compressible and low shear strength.

As per RDSO Guidelines No. GE:G-14, the sub-soil (ground) is classified as "weak" or "soft" when the "N" value (determined from Standard Penetration Test) is less than 5 or Undrained Shear Strength C_u (determined from Triaxial Shear Test) is less than 25 kPa or the Elastic/Deformation Modulus of 2nd Stage Cyclic Plate Load test E_{v2} (determined as per DIN:18134-2012) is less than 20 MPa. In such cases, the ground needs suitable "Ground Improvement" before for construction of a safe and serviceable embankment.

2. Consolidation of Soft Soils: When embankment is constructed on soft soils, the water in the pores of sub-soil mass (which is at atmospheric pressure) develops excess pore water pressure due to the embankment load. Dissipation of this excess pore water pressure, in the process of consolidation, depends on the characteristics of sub-soil, the depth of sub-soil layer and drainage path available. This time may extend upto 2 or 5 years also in case of highly clayey soft soils upto considerable depth. During the process of consolidation, there will be dissipation of pore water pressure and settlement in the sub-soil layers, which will eventually reflect in the settlement of the embankment. The correlation between construction of embankment, buildup/ dissipation of excess pore water pressure and consolidation settlement are shown in Fig.01.

The shear strength of soil is given by following formulae (Coulomb):

$$\zeta = C + \sigma \tan Ø \quad \text{.....} \ (1)$$

Where:

ζ = Shear strength of soil
C = Cohesion value of soil
σ = Normal stress on the plane of failure
Ø = Angle of internal friction of soil

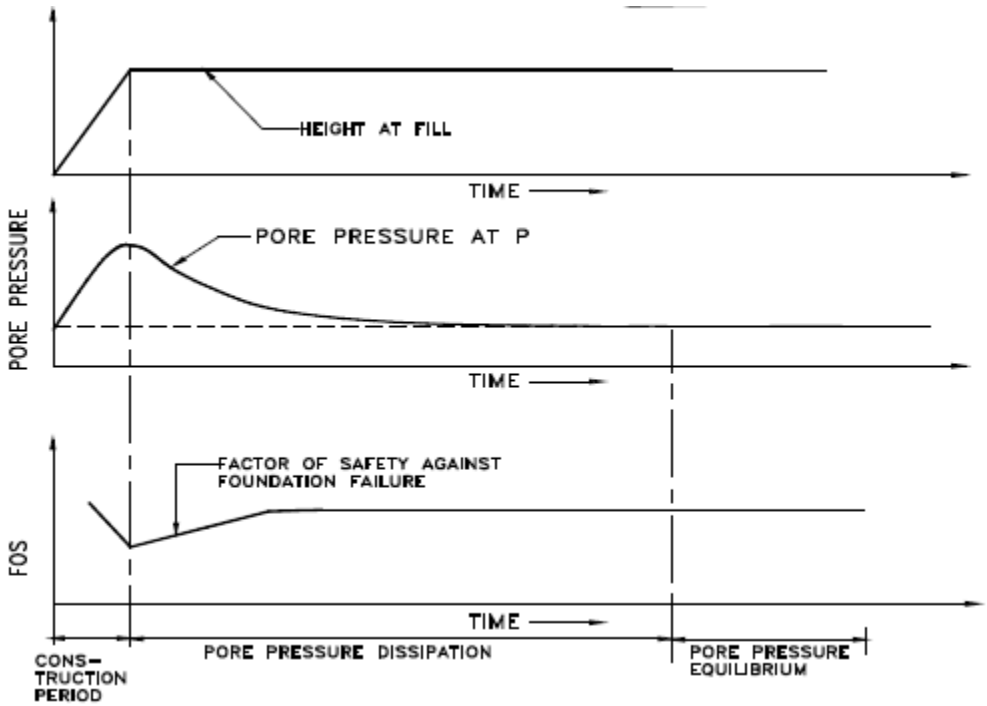

Fig.01: variation of Pore Water Pressure and Factor of Safety

Using the concept of "effective stress", Terzaghi modified the shear strength formulae taking into account the effect of pore water pressure and gave following equation:

$$\zeta = C' + (\sigma - U) \tan \emptyset' \quad \ldots\ldots\ldots (2)$$

Where:

C′ = effective Cohesion value of soil
U = Excess pore water pressure
Ø′ = Effective Angle of internal friction of soil

3. <u>Problems in construction of embankment on Soft Soils</u>: There are mainly two problems, which need to be addressed, for constructing embankment on soft soils.

3.1 <u>Safety of embankment during construction</u>: Embankments built on soft clays have been observed to fail along circular slip surfaces, with the slip circle passing through the sub-soil and exiting after the toe of embankment (Fig.02). Such failures are known as "base failures". In most of such cases, the failed soil mass heaves after the toe of embankment.

The factor of safety in such cases is ratio of "Resisting Forces" divided by "Disturbing Forces". The disturbing forces are components of self-weight of embankment, surcharge and any other external force, along the slip surface. The resisting forces mainly consists of the mobilized shear strength along the slip surface, as given in Eq. (2).

As seen from Fig.01, the excess pore water pressure (normally referred as pore water pressure) starts increasing from the time the embankment construction commences, reaches peak value when full height of embankment is constructed (i.e. end of construction) and then starts dissipating. Since increase in pore water pressure (U) decreases the mobilized shear strength, it reduces the factor of safety (FOS), with most critical stage being the "end of construction" when the pore water pressure is at its' peak value. Therefore, the FOS is verified at end of construction and RDSO

Guidelines (GE:G-1) stipulate the minimum value of FOS "at the end of construction" to be 1.20 (whereas normally it is 1.40). Therefore, first requirement from safety point of view is to ensure that FOS against circular failure (calculated using effective stress parameters) is minimum 1.20, at the end of construction stage.

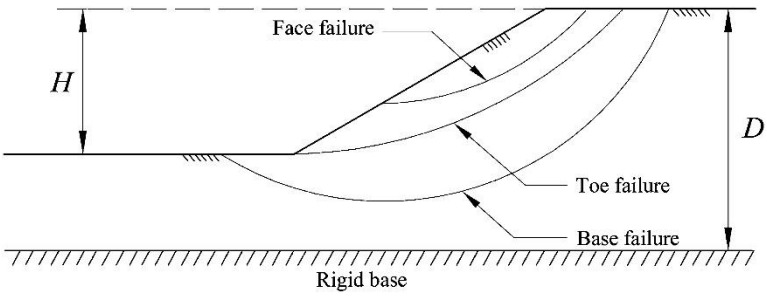

Fig.02: Base failure of Embankments

3.2 <u>Settlement of embankment</u>: During the process of consolidation, there will be settlement of soft sub-soil layers, which in-turn will reflect in the top surface of the embankment. Thus, the second requirement from serviceability point of view is that first of all the embankment should be constructed for a height equal to "design height of embankment" plus "expected settlement value for the sub-soil" and secondly the settlement (or most of the settlement) of sub-soil should have been completed before commissioning the track on the embankment. The time required for achieving total consolidation (or significant consolidation) depends on the "degree of consolidation".

4. <u>Stage construction methodology</u>: As explained in para 3.1 above, the safe rate of construction of embankment will depend on gain in shear strength of sub-soil with dissipation of pore water pressure. Normally this rate is very slow, which makes the construction time of high embankment on soft soil very long. Reduction of this time will either require very flat side slopes of embankment or wider sub-banks, both of which will make the construction uneconomical. One of the solution to this is adoption of "stage construction method", wherein total height of embankment is constructed in various stages. Height of any stage is decided based on the safety criteria as discussed in Para 3.1 above. After completion of any stage, a waiting period is given before commencing construction of next stage. This time is decided based on the gain in shear strength of sub-soil due to surcharge load of initial stage and consolidation in this time, which makes the embankment safe for subsequent stage construction. The safe height of every stage and waiting time to be given after very stage construction have been calculated subsequently. Due to many assumptions (associated with theory of consolidation) involved in calculation of waiting period after each stage and the sub-soil not being fully homogeneous, it is observed that actual waiting time required for safe construction of next stage varies from the theoretically calculated time. Therefore, the settlement and pore water pressures are monitored by adopting suitable instrumentation scheme and next stage of construction is taken up only when the settlement and pore water pressure readings indicate that the required degree of consolidation has been achieved, rather than merely relying on the calculated values of settlements and pore water pressure only. This approach is called "observational approach" also. The recorded values of settlement and pore water pressure in case of stage construction methodology will be in the the pattern shown in Fig.03.

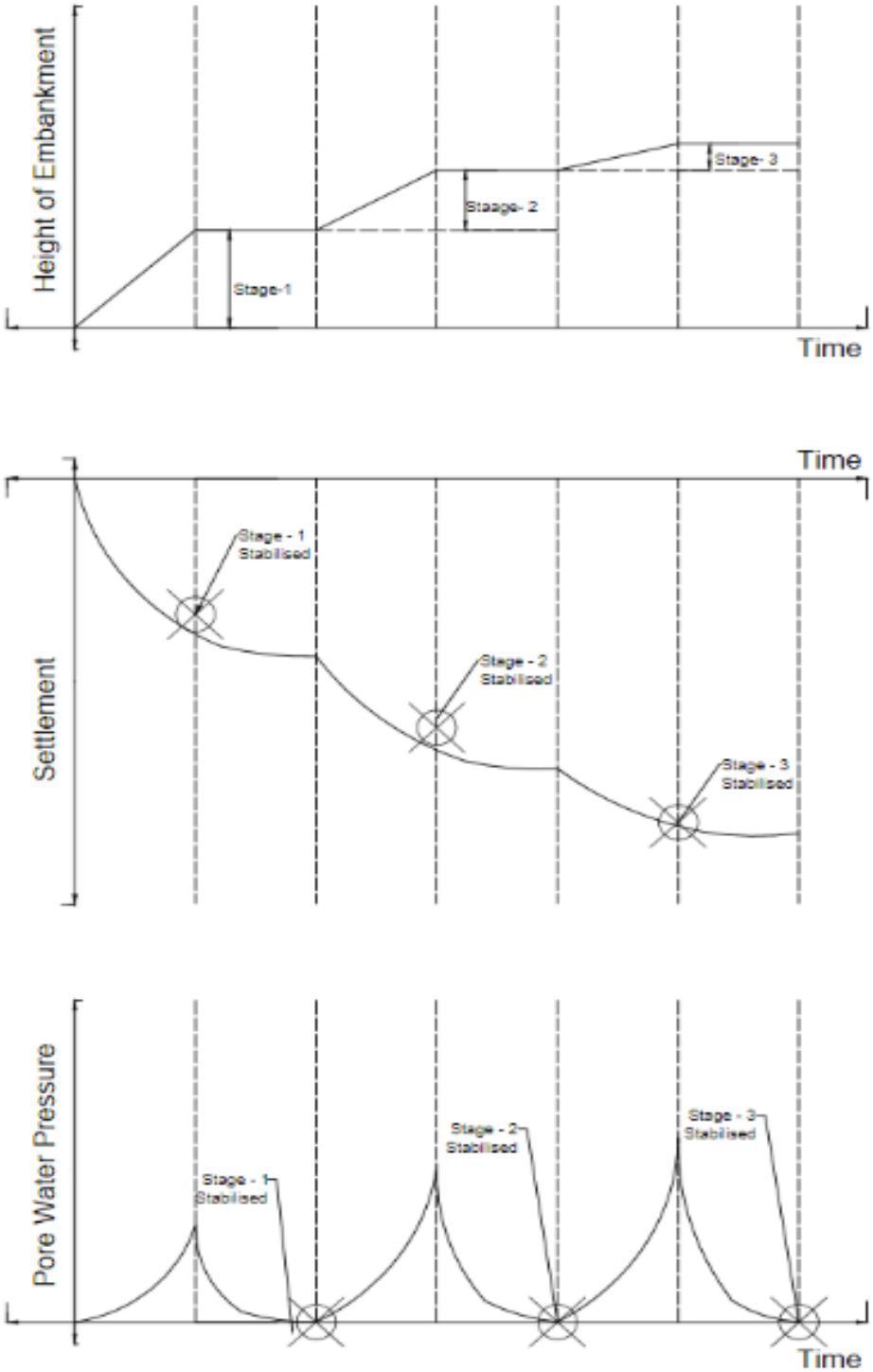

Fig.03: variation of Settlement and Pore Water Pressure with Time

4. <u>Time required for achieving required degree of consolidation</u>: Using one-dimensional consolidation theory of Terzaghi, time required for achieving any degree of consolidation can be calculated by following formula:

$$t = T_V * H_T^2/C_V \quad \ldots\ldots\ldots \quad (3)$$

Where:

t = Time required for consolidation

T_V = Dimensionless Time factor, depending on degree of consolidation (Ref. Table.01)
H_T = Drainage Path (equal to depth of sub-soil layers in case of drainage from one face of sub-soil only and equal to half of this depth in case of drainage from both faces of sub-soil)
C_V = Coefficient of consolidation of sub-soil (determined from Oedometer test)

Table.01: Values of T_V v/s Degree of Consolidation (U)

U (%)	T_V	U (%)	T_V	U (%)	T_V	U (%)	T_V
5	0.002	30	0.071	55	0.238	80	0.567
10	0.008	35	0.096	60	0.287	85	0.684
15	0.018	40	0.126	65	0.342	90	0.848
20	0.031	45	0.159	70	0.403	95	1.129
25	0.049	50	0.197	75	0.477	100	Infinity

From experience, it is observed that actual rate of settlements is 5-8 times faster than the theoretical value. Hence, actual time of settlement will be 5-8 times less than the calculated value of "t".

5. <u>Degree of Consolidation achieved in any Time Period</u>: Value of time factor for any given time can be calculated using Eq. (3), as following:

$$T_V = t * C_V / H_T^2 \quad \ldots\ldots\ldots \quad (4)$$

From the calculated value of T_V, the degree of consolidation achieved (U in %) can be worked out using Table.01. The value of "t" will be divided by a factor of 5-8 before using it in the Eq.(4), due to reasons stated in Para.4 above.

6. <u>Settlements</u>: The total settlement will consist of following parts:

6.1 <u>Elastic settlement</u>: This is settlement of sub-soil layers due to their elastic deformation, when subjected to stress by embankment loading. This settlement is normally very small and can be neglected for all practical purposes.

6.2 <u>Consolidation settlement</u>: This is settlement caused by volume change of sub-soil by draining out of water from its' pores, due to application of embankment loading on the sub-soil. This can be determined using classical Terzaghi's theory for one-dimensional consolidation. A typical embankment with two different types of sub-soil layers and three stages of construction is shown in Fig.04:

h = Height of embankment
H = Total depth of compressible layers
a = Horizontal distance between toe of embankment and end point of the berm/cess
b = Horizontal distance between centre of embankment and end point of the berm/cess
Z = Vertical distance between the bottom of embankment/stage constructed and mid-point of the sub-soil layer under consideration

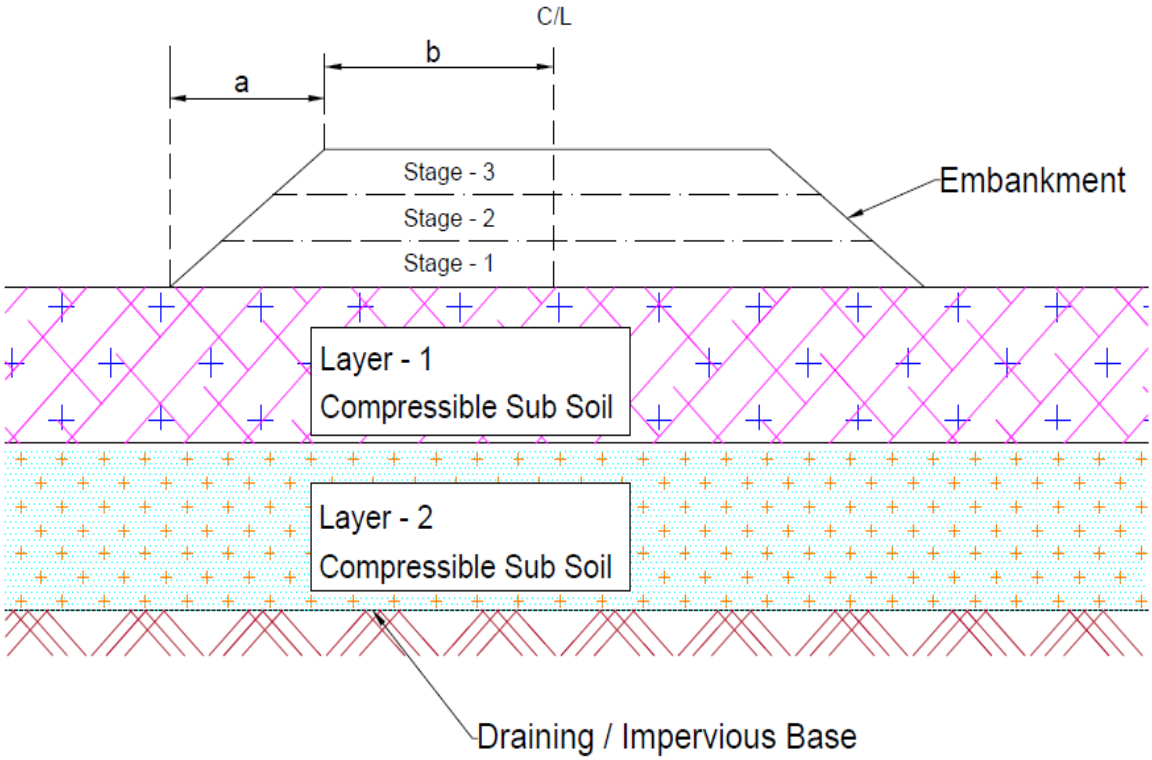

Fig.04: Details of a typical embankment

The effective overburden pressure at the centre of any sub-soil layer (P_0) before construction of embankment/at any stage will be equal to weight of the sub-soil layers and weight of the embankment soil layer above the centre of that layer. Weight of sub-soil/embankment layers is calculated by multiplying the saturated/submerged density of the concerned layer (submerged density for the portion below water table and saturated density for the portion above water table) with the thickness of the layer concerned. The submerged and saturated density can be calculated by following formula:

$$\gamma_{sat} = \{(G-1)/G\} * \gamma_d + \gamma_w \quad \text{.....} \quad (5)$$

$$\gamma_{sub} = \{(G-1)/G\} * \gamma_d \quad \text{.....} \quad (6)$$

Where:

γ_{sat} = Saturated density of soil
γ_{sub} = Submerged density of soil
γ_d = Dry density of soil
G = Specific gravity of soil
γ_w = Density of water (= 10 kN/m^3)

Now, if an embankment is constructed, with the details as shown in Fig.04, then Influence Value (I) of half embankment loading, for the given values of a/z and b/z, can either be found from Osterberg Charts shown in Fig.05 or the formulae given in Eq.(7).

$$I = 1/\pi\ [\tan^{-1}\{(a/z)+(b/z)\} + \{(b/z)/(a/z)\}* \tan^{-1}\{(a/z)+(b/z)\} + \{(b/z)/(a/z)\}* \tan^{-1}(b/z)] \quad \text{.....} \quad (7)$$

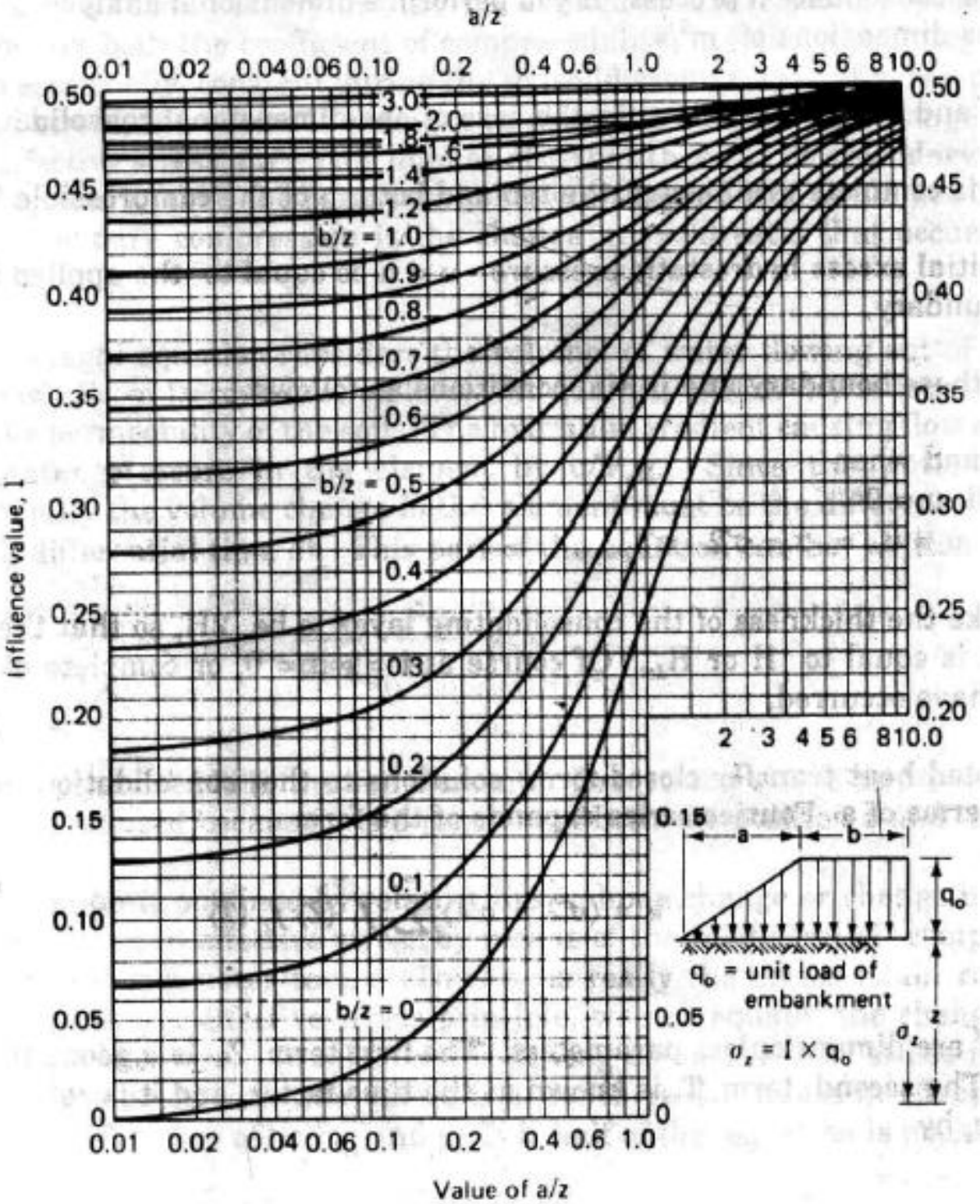

Fig.06: Osterberg Charts for Embankment Loading

For symmetrical embankment, this value of "I" will get doubled to take into account the effect of both parts. The increase in overburden pressure (ΔP_0) at the centre of any sub-soil layer will be given by the following formulae:

$$\Delta P_0 = H_b * \gamma_{bsat} * I \quad \text{.....} \ (7)$$

Where:

H_b = Height of embankment constructed

γ_{bsat} = Saturated density of embankment soil

The settlement of embankment is calculated in two parts i.e. change in overburden from P_0 to P_C and then from P_C to $P_0+\Delta P_0$. Here, P_C is "Pre-consolidation Pressure" for the given sub-soil strata. The settlement due to change in overburden pressure from P_0 to P_C can be calculated from following formulae:

$$S_1 = (C_S/1+e_0) * H * \log_{10} (P_C/P_0) \quad ..... (8)$$

Where:

C_S = Re-compression/swelling index of sub-soil (From Oedometer test)
e_0 = Initial void ratio of sub-soil layer
H = Thickness of the sub-soil layer under consideration

In case, P_C is less than P_0, the value of settlement "S1" will be taken as zero.

The settlement due to change in overburden pressure from P_C to $P_0+\Delta P_0$ can be calculated from following formulae:

$$S_2 = (C_C/1+e_0) * H * \log_{10} (P_0+\Delta P_0/P_C) \quad ..... (9)$$

Where:

C_c = Compression index of sub-soil (From Oedometer test)

In case, $P_0+\Delta P_0$ is less than P_C, the value of settlement "S_2" will be taken as zero. The total value of settlement "S" will be sum of S_1 and S_2. The total consolidation settlement will be equal to λ*S, where "λ" is a factor given by Skempton & Bjerrum and reproduced in IS:8009-1976 (Part-I) "Code of Practice for Calculation of Settlement of Foundations", as given in Table.02 below:

Table.02: Values of "λ"

Type of Clay	Value of "λ"
Very sensitive clays (Soft Alluvial, Estuarine and Marine clays)	1.0 to 1.2
Normally consolidated clays	0.7 to 1.0
Over-consolidated clays	0.5 to 0.7
Heavily over-consolidated clays	0.2 to 0.5

7. <u>Safety in Stage Construction methodology</u>: In case, the embankment is constructed in stages, then the safety of each stage height needs to be checked by checking the value of Factor of safety (FOS) and in addition the waiting time required after each stage needs to be calculated. This is done in following manner:

7.1 <u>Factor of Safety after each stage of construction</u>:

Calculate values of "D/H" and "$N = C_U/\gamma H$".

Where:

D = Total depth/thickness of sub-soil layers
H = Total height of embankment after construction of proposed stage height
C_U = Undrained shear strength of the sub-soil
γ = Saturated density of embankment soil

For the calculated values of "D/H", "N" and "Ø" (angle of internal friction of embankment soil), the FOS can be determined from the charts given in Fig.07. These

charts were developed by Pilot G. and Moreau M. For any intermediate values of "N", than those given in these charts, linear interpolation may be done.

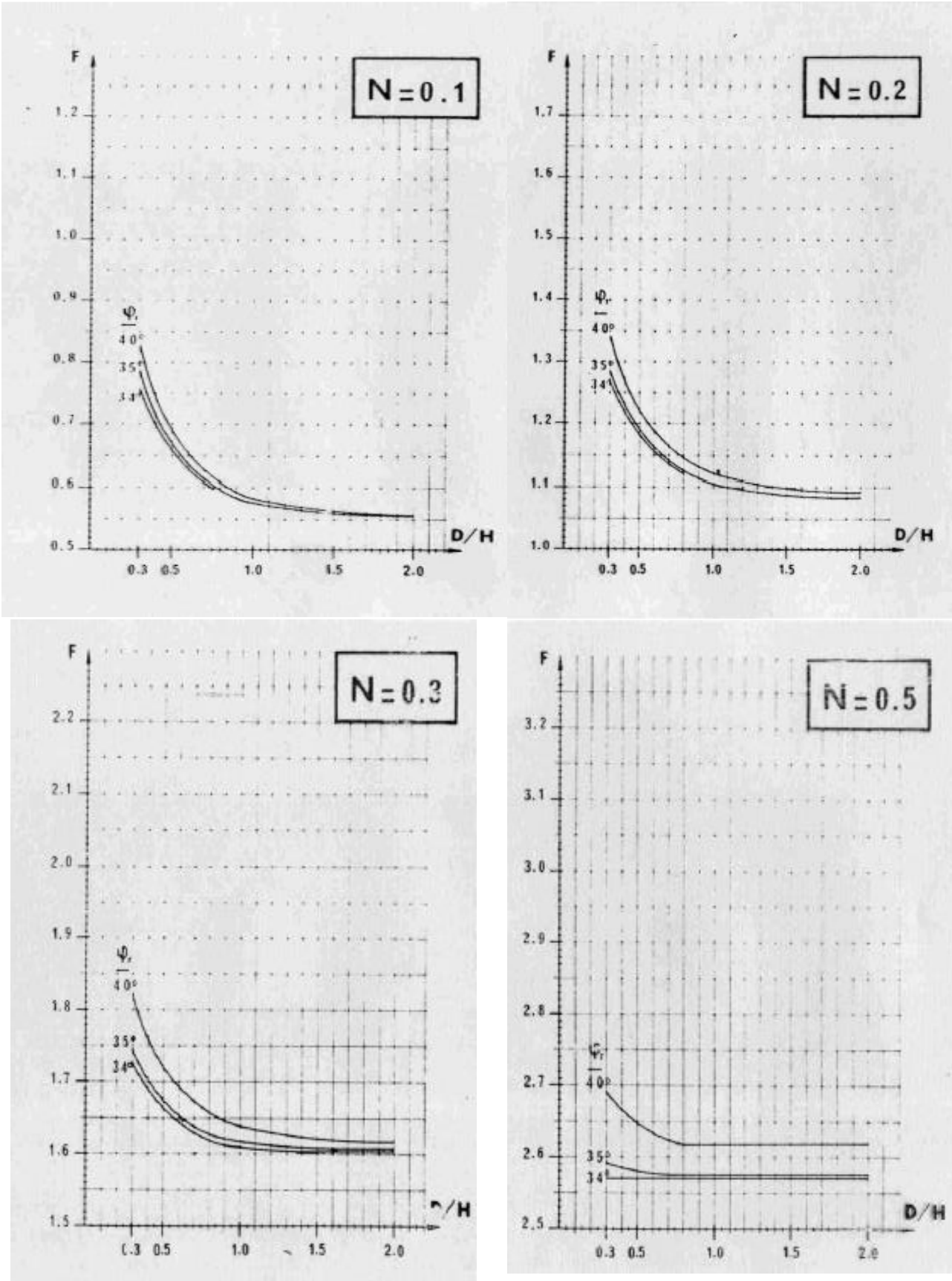

Fig.07: Stability Charts

In case, the FOS comes out to be more than the stipulated value (1.20 for Short tern end of construction stability of railway embankments), then the proposed stage height can be adopted, otherwise the stage height should be revised downwards till it is found safe. This check has to be done for each stage of construction of embankment.

This check is a fast and quick check and it is always advisable that after stage heights are fixed, final check is done using any software for slope stability analysis.

7.2 <u>Waiting time after each stage of construction</u>: To start with assume some waiting time after first stage of construction. For this time, calculate the Time Factor (T_V) using Eq.(4) and for this value of "T_V" calculate "Degree of Consolidation (U)" from Table.01. The increase in effective stress on sub-soil due to construction of first stage of embankment ($\Delta\sigma'$) will be given by following formula:

$$\Delta\sigma' = \text{Stage height} * \text{Saturated density of embankment soil} * U \quad \ldots\ldots\ldots (10)$$

The increase in undrained shear strength of sub-soil (ΔC_U) due to this stress increment will be given by following formula:

$$\Delta C_U = \Delta\sigma' * \tan\emptyset_s \quad \ldots\ldots\ldots (11)$$

Where: $\emptyset_s$ is angle of internal friction for sub-soil.

Using the increased value of undrained shear strength of sub-soil after first stage construction (i.e. initial value + ΔC_U), check the FOS for the embankment for its' fitness to construct second stage by using stability charts as explained in Para 7.1 above (with value of "H" now being total height of bank after second stage construction). If the FOS value comes out to be less than the stipulated value, then increase the waiting period after first stage or reduce second stage proposed height and repeat the calculation till acceptable value of FOS is obtained. This procedure shall be repeated for calculating the required waiting time after each stage of construction.

8. <u>Settlements with stage construction methodology</u>: The settlement was calculated in Para.6 above, when the whole embankment was constructed in one go without any stage construction. In case of construction of embankment in stages, settlement can be calculated after each stage also, using the same methodology. It is observed that normally the total settlement calculated with stage construction is more than the total settlement calculated for single stage construction.

9. <u>Ground Improvement using Vertical Drains</u>: In case the waiting time after each stage, as calculated in Para.8 above, needs to be reduced for optimizing the project completion, then suitable "ground improvement measure" has to be adopted and one of them is using "Vertical Drains". In this method, vertical drains are constructed in sub-soil in either Square or Triangular pattern, as shown in Fig.08. These drains are filled by material of high permeability (normally sand) which introduces the element of "radial consolidation" also in addition to the "vertical or one-dimensional" consolidation, thereby making the overall consolidation faster. If spacing of vertical drains is "s", then the diameter of drain influence area (d_e) will be equal to "1.128s" for drains in square pattern and equal to "1.05s" for drains in triangular pattern.

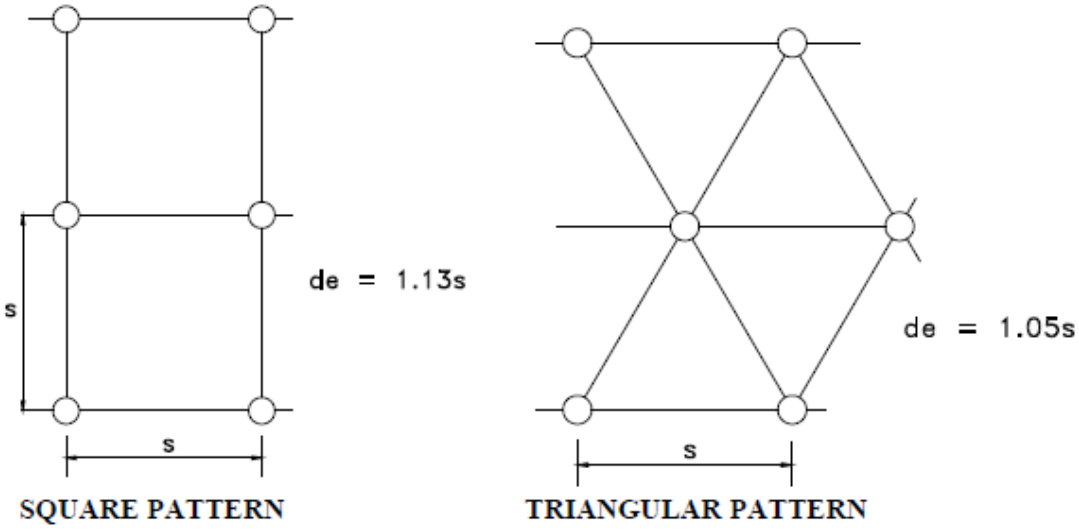

Fig.08: Pattern of installing Vertical Drains

9.1 <u>Smear effect</u>: Due to wiping action, caused by the casing or the hollow mandrel used to form the well for vertical drain when it is driven down in the ground and then pulled out, the sub-soil at the drain periphery is smeared. This reduces the horizontal permeability of the sub-soil in the smear zone and thereby reducing the horizontal flow of water to the drain. This in-turn slows down the process of radial consolidation. The extent of smear is expressed by Smear factor (S).

$$S = d_s/d_w \quad \text{..... (12)}$$

Where:

d_s = Diameter of smear zone
d_w = Diameter of vertical drain

9.2 <u>Well resistance</u>: If during consolidation, the discharge capacity of drain is reached, the overall consolidation process is retarded and the drain presents resistance to the water flowing in them. The Well Resistance Factor (L) is calculated by following formula:

$$L = (32/\pi^2) * (k_h/k_w) * (H_T^2/d_w) \quad \text{..... (13)}$$

Where:

k_h = Horizontal permeability of sub-soil
k_w = Longitudinal permeability of vertical drain fill material
H_T = Drainage path for the sub-soil layers
d_w = Diameter of vertical drain

9.3 <u>Radial Consolidation</u>: The time factor for radial consolidation (T_r) due to vertical drain is given by the following formula:

$$T_r = C_r*t/d_e^2 \quad \text{..... (14)}$$

Where:

C_r = Coefficient of radial consolidation for the sub-soil
t = Time period for consolidation (same as for vertical consolidation)

The degree of radial consolidation (U_r) is calculated by the following formula:

$$U_r = 1 - \exp^{(-8Tr/\alpha + 0.8L)} \quad \text{..... (15)}$$

Where:

L = Length factor, from Eq. (13)
α = A Lumped parameter = A + B + C
$A = \{n^2/(n^2 - S^2)\} * \log_n (n/S)$ ..... (16)
$B = (3n^2 - S^2)/4n^2$ ..... (17)
$C = (k_h/k_s) * \{(n^2-s^2)/n^2)\} * \log_n S$ ..... (18)
$n = d_e/d_w$
S = Smear factor, from Eq. (12)
K_h/k_s = Normal horizontal permeability of sub-soil divided by horizontal permeability in smear zone of sub-soil

For the same time period (t), the time factor for vertical consolidation (T_v) is calculated using Eq. (3) and for this time factor, the degree of vertical consolidation (U_V) is worked out from Table.01. The overall degree of consolidation, in three dimensional consolidation, is given by the following formula:

$$U = 1- \{(1-U_V)* (1-U_r)\} \quad \text{..... (19)}$$

To calculate the reduced waiting period, with same stage height, the drain parameters (i.e. its' diameter and spacing) shall be varied to achieve the same overall degree of consolidation as was achieved in one-dimensional consolidation without ground improvement. The same procedure is repeated for each stage to calculate the reduced waiting period, with same stage heights.

10. <u>Ground Improvement using Pre-fabricated Vertical Drains (PVD)</u>: In case of use of pre-fabricated vertical drains (PVD), the procedure followed is same, as in Para.9 above for vertical drains, except following changes:

(i) Equivalent diameter (d_w) is given by the following formula:

$$d_w = 2(b + tp)/\pi \quad \text{..... (20)}$$

Where:

b = Width of PVD (normally in range of 95-105 mm)
tp = Thickness of PVD (normally in range of 3-6 mm)

(ii) Longitudinal permeability of PVD (k_w) is calculated by following formula:

$$k_w = Q/(b*tp) \quad \text{..... (21)}$$

Where, Q is least discharge capacity of PVD (taking into account the deformation of PVD and damage to PVD, at maximum value of earth pressure to which PVD is subjected).

11. <u>Software for Ground Improvement calculations</u>: For calculating numerous values and parameters as described above, a computer program has been developed in MS-Excel and being uploaded on the website of IRICEN. This program computes following parameters:

(i) Time required for achieving any Degree of Consolidation.

(ii) Degree of Consolidation achieved for any given Time

(iii) Total Settlement

(iv) Design of various stages for constructing the bank, without ground improvement, duly verifying Safety for each stage

(v) Settlement at the end of each stage

(vi) Reduced time for each stage of construction with use of vertical drains as ground improvement measure (including design of vertical drain)

(vii) Reduced time for each stage of construction with use of pre-fabricated vertical drains (PVD) as ground improvement measure (including design of PVD)

The generic sketch of the problem solved in this program is as shown in Fig.04. In this program it is assumed that:

(i) Embankment consists of one type of soil only.

(ii) In case of stage construction of embankment, maximum number of stages is three (3).

(iii) The sub-soil consists of two layers of compressible soils. In case sub-soil consists of more than two layer, then convert their thicknesses into two layers of equivalent thicknesses, from consolidation point of view, by the formulae given below:

$$H_i = H_1 * (C_{vi}/C_{v1})^{0.5}$$

Where:

H_i = equivalent thickness of with layer w.r.t. 1st layer
H_1 = Thickness of 1st layer
C_{vi} = Coefficient of Consolidation for layer "i"
C_{v1} = Coefficient of Consolidation of 1st layer

(iv) The strata beneath the compressive sub-soil layers can be either free draining type (which will make the drainage path as "Double draining") or impervious type (which will make the drainage path as "Double draining")

This simple program not only performs various calculations but also explains the flow of computations in a sequential manner, thereby helping the users in developing the better understanding of the subject.

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