Part 9 Prefabricated Vertical Drain (Draft Final)

1. Technical Notes

1-1. Characteristics of Vertical Drain

Terzaghi's one-dimensional consolidation theory demonstrates the relationship between the consolidation time of clay layers and the drainage distance. Specifically, the water discharge in the clay layer depends on the maximum drainage distance, and the shorter this distance, the shorter the time required for consolidation. Based on this theory; by effectively reducing the drainage distance, it is possible to accelerate the consolidation settlement of the clay layer.

The vertical drain method is an example of an application of this theory. In this method, drain wells are installed to artificially create water flow, thereby reducing the drainage distance. This significantly shortens the consolidation time. However, care must be taken as using poor-quality drain materials can lead to reduced permeability due to bending and clogging caused by settlement, delaying the consolidation.

Thus, Terzaghi's theory and the vertical drain method provide efficient ground improvement techniques in civil engineering, and their application can lead to reductions in project duration and costs.

1-2. Fundamental of Performance Verification

(1) Objectives and Expected Outcomes

The vertical drain method is designed to enhance soil properties to meet specific improvement goals:

- ✓ Achieve increases in soil strength that reach the targeted levels.
- ✓ Ensure that residual settlement remains within allowable limits.
- ✓ Maintain the stability required for infrastructural facilities.

(2) Integration with Facility Performance

Performance verification of the vertical drain method is intertwined with the broader verification processes of facilities, akin to other soil improvement techniques. Thus, it is essential to consider the following aspects:

- ✓ Targeted strength increases: Specific strength gains to be achieved.
- ✓ Allowable settlement: Maximum permissible settlement levels for facilities.
- ✓ Method coverage: The spatial extent of the vertical drain application.

(3) Ground Conditions Assessment

Key parameters influencing the performance of the vertical drain method include:

- ✓ Undrained strength of the original soil.
- ✓ Rates of strength increase.
- ✓ Physical soil properties like unit weight, consolidation coefficients, and volume compressibility.
- ✓ Pre-consolidation pressures and thicknesses of the layers undergoing consolidation.
- ✓ Characteristics of any embankment fill used, including its shear strength and unit weight.

(4) Verification Process

The implementation of the vertical drain method primarily aims to accelerate the consolidation time using preloading, surcharge, or vacuum consolidation techniques. Important steps include:

- ✓ Staged application: Since the original ground strength does not change immediately post-installation, consolidation loads are applied in stages.
- ✓ Monitoring and adjustment: Each stage's embankment fill height is adjusted based on the consolidation loads and the observed consolidation degree.
- ✓ Final layout checks: The arrangement of vertical drains is finalized to ensure all necessary embankment fill can be placed and soil consolidation completed within set timelines.

(5) Construction Management

Effective management is crucial for the success of the vertical drain method, involving:

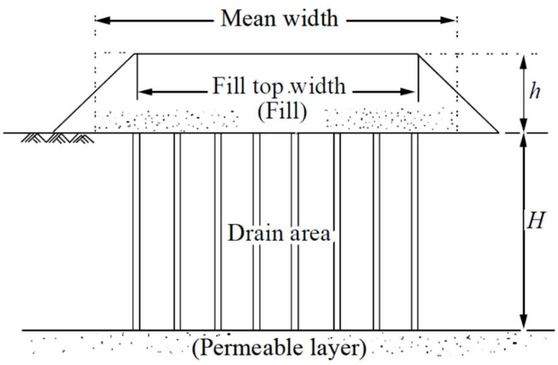
- ✓ Material management: Proper handling and specification of drain materials and installation depths.
- ✓ Drain continuity: Ensuring continuous drain function and integration with any sand mats or existing sandy layers below the improvement areas.
- ✓ Monitoring progress: Regular assessments to verify increases in soil strength, settlement progression, and overall stability, with adjustments made as necessary based on observed changes in pore water pressure and other relevant factors.

This structured approach ensures that all technical and practical aspects of the vertical drain method are comprehensively addressed, from planning through to execution and monitoring, facilitating effective soil improvement and stability enhancement.

1-3. Performance Verification of Embankment Fill

(1) Determination of Heights and Widths of Embankment Fill

TCVN 11820 Part 4-2: 2020, Hinh 34



Source: TCVN 11820-4-2-2020

Figure 1.1- Width of Embankment for the Vertical Drain Method

When using embankment fill for consolidation purposes in preloading and surcharge methods, careful planning is necessary to achieve the desired soil stabilization:

- ✓ Heights and widths:

These dimensions are critical for ensuring the increased strength required to stabilize the embankment fill both during and after its staged construction. They also affect the stability and permissible settlement of the facilities to be built on this improved ground, as well as the impacts on surrounding areas.

- ✓ Crown widths:

The widths of the embankment fill at the top should be at least as wide as the necessary ground improvement areas to ensure adequate coverage and effectiveness of the improvement process.

(2) Analysis of Strength Increases and Residual Settlement

✓ Strength and settlement equations:

Equations (1.1) and (1.2) are used to assess the increases in strength of the original ground and the expected residual settlements. The stress distribution can be estimated using Boussinesq's solution, or the Boston Code method for broader areas, considering uniform stress distribution across the depth of the consolidation layers.

$$c_a \leq \Delta c$$
$$\Delta c = c_u/p \, \Delta p' \, U \qquad (1.1)$$
$$\Delta p' = p_0' + \alpha \gamma_t h - p_c'$$

Where:

C_a	:	target increase in strength (kN/m²)
Δc	:	increases in strength (kN/m²)
c_u/p	:	increase ratio of strength
U	:	degree of consolidation
h	:	height of the embankment fill (m)
p_0'	:	initial pressure (vertical pressure before the commencement of construction) (kN/m²)
p_c'	:	pre-consolidation pressure (kN/m²)
α	:	coefficient of stress distribution, namely ratio of distributed stress in the ground and consolidation load (embankment load))
γ_t	:	unit weight of embankment fill (wet weight above water level and submerged unit weight below water level) (kN/m³)

$$S = \frac{\Delta e}{1+e_0} H$$

$$S = m_v (p_0' + \alpha \gamma' h - p_c') \, H$$

$$S = \frac{C_c}{1+e_0} H \log_{10} \frac{p_0' + \Delta p'}{p_0'} \qquad (1.2)$$

$$S = \left(\frac{C_s}{1+e_0} \log_{10} \frac{p_c'}{p_0'} + \frac{C_c}{1+e_c} \log_{10} \frac{p_0' + \Delta p' - p_c'}{p_c'} \right)$$

TCVN 11820 Part 4-2: 2020 Equation 33(a), (b), (c), (d)

Where:

C_c	:	compressive coefficient of ground
C_s	:	swelling coefficient of ground
e_0	:	initial void ratio of ground
e_c	:	void ratio of ground at pre-consolidation pressure
h	:	height of the embankment fill (m)
H	:	thickness of the consolidation layer (m)
m_v	:	volumetric coefficient of ground (m²/kN)
p_0'	:	initial pressure (vertical pressure before the commencement of construction) (kN/m²)
p_c'	:	pre-consolidation pressure (kN/m²)
S	:	settlement of ground (m)

Δe : increment of void ratio of clay ground

$\Delta p'$: consolidation pressure (kN/m^2)

(3) Performance Verification of the Circular Slip Failure

✓ Stability verification:

The stability of the ground in relation to the determined embankment fill dimensions needs to be verified through methods like circular slip failure analyses. If stability cannot be assured, the final stage of embankment fill may need to be subdivided into multiple stages with further stability checks.

✓ Circular slip failure analysis:

The stability against slip failures is also critically analyzed, often referencing slope stability principles. The partial factors used in these analyses should consider the calculated increases in strength from Equation (1.1).

The modified Fellenius method assumes that the direction of the resultant force acting on vertical planes between slice segments is parallel to the base of the slice segments. This method is also referred to as the simplified method or Tschebotarioff method. When a circular arc and a slice segment are as shown in Figure 1.2, according to the modified Fellenius method is applicable.

The conventional design, using the safety factor method, is equivalent to the design where both *S* and *R* are 1.0: Factor *m*, that is, equivalent to the safety factor, was set at 1.30 or higher for permanent situations, but in cases where the reliability of the constants used in verification can be considered high, based on actual data for the same ground, and monitoring work is carried out by observing the displacement and stress of the ground during construction, factor m could be set at 1.10 or more for the same situations. In line with these rules, when partial factors *S* and *R* have not been determined, they can be set as 1.0, in accordance with the conventional method, and the adjustment factor m can be set to a value equivalent to the conventional safety factor to verify stability.

$$m \cdot \frac{S_d}{R_d} \leq 1.0 \quad R_d = \gamma_R R_k \quad S_d = \gamma_S S_k$$

$$S_k = \Sigma \left\{ \left(W_k + q_k \right) \sin\theta + \frac{1}{R} a P_{Hk} \right\} \qquad (1.3)$$

$$R_k = \Sigma \ c_k s + \ W'_k + q_k \ \cos^2\theta \cdot \tan\varphi_k \ \sec\theta$$

TCVN 11820 Part 1: 2025 Equation (I.102) (I.103)

Where:

m : adjustment factor

S_d : value to be used for design of the action term (kN/m)

R_d : value to be used for design of the resistance term (kN/m)

S_k : characteristic value of the action term (kN/m)

R_k : characteristic value of the resistance term (kN/m)

γ_S : partial factor multiplied by action term

γ_R : partial factor multiplied by resistance term

W_k : characteristic value of total weight of a segment, total weight of soil and water (kN/m)

q_k : characteristic value of vertical action from top of slice segment (kN/m)

θ : angle of bottom of slice segment to horizontal (°)

a : arm length from the center of slip circle in circular slip failure at position of P_H action (m)

P_{Hk} : characteristic value of horizontal action on slice segment of

Modified from TCVN 11820 Part 4-1: 2020, Equation (F.1)

Modified from TCVN 11820 Part 6:

soil mass per unit of length in circular slip (kN/m)

R : radius of circular slip failure (m)

c_k : characteristic value of undrained shear strength in case of clayey ground, or characteristic value of apparent cohesion in drained condition in case of sandy ground (kN/m^2)

s : width of slice segment (m)

W'_k : characteristic value of effective weight of slice segment per unit of length (weight of soil. When submerged, unit weight in water) (kN/m)

φ_k : characteristic value in case of cohesion soil ground, 0, and in case of sandy ground, characteristic value of angle of shearing resistance in drained condition (°)

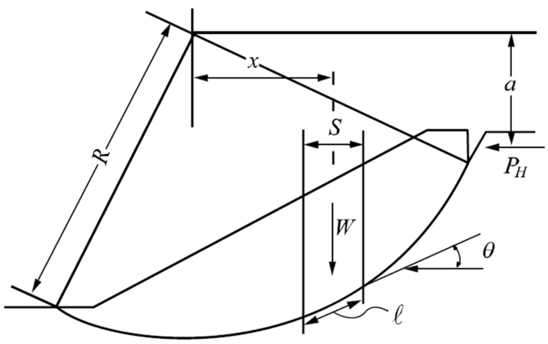
2023, Equation (7)

Table 1.1- Partial Factors for the Performance Verification of Circular Slip Failure

Verification object	Coefficient of variation of cohesive soil in the representative soil layer CV	Partial factor multiplied by resistance term γ_R	Partial factor multiplied by action term γ_S	Adjustment factor m
Circular slip failure (Permanent situation)	No cohesive soil	0.83	1.01	(1.0)
	CV <0.10	0.86	1.05	(1.0)
	0.10 ≤ CV < 0.15	0.85	1.04	(1.0)
	0.15 ≤ CV < 0.25	0.80	1.02	(1.0)
	0.25 ≤ CV	(1.0)	(1.0)	1.30

Source: TCVN 11820-6-2023

TCVN 11820 Part 6: 2023, Bang 6



Source: TCVN 11820-2-2025, TCVN 11820-4-1-2020

Figure 1.2- Circular Slip Failure Analysis Using Modified Fellenius Method

TCVN 11820 Part 1: 2025 Hinh I.37

TCVN 11820 Part 4-1: 2020, Hinh F.1

(4) Management of Construction Stages

✓ Staged construction:

The embankment fill is constructed in stages, with each stage's dimensions determined by the strength increases in the underlying consolidation layers from the previous stages. The degree of consolidation for each stage is typically set around 80% but can range from 50 to 90%.

✓ Economic efficiency vs. structural integrity:

Larger degrees of consolidation per stage can speed up the drainage intervals or extend the retention periods, impacting economic efficiency. Conversely, smaller degrees can lead to more construction stages due to insufficient strength gains to support subsequent embankment fill layers.

(5) Re-examination and Preloading Removal

- ✓ Cross-sectional re-assessment:

After setting the drainage intervals, it's advisable to reassess the cross sections of the embankment fill based on precise calculations of consolidation degrees. This ensures the consolidation has adequately progressed to meet the design expectations, particularly under conditions such as high groundwater levels.

- ✓ Preloading considerations:

If the preloading fill is to be incorporated into the final facility structures, its removal may not be necessary. However, if it is removed post-consolidation, a thorough performance verification must account for potential ground swelling and strength reduction over time due to moisture absorption.

This structured approach to performance verification ensures that each aspect of the embankment construction and subsequent soil stabilization is carefully planned and executed, aligning with the overall objectives of the ground improvement project.

1-4. Performance Verification of Drain

The performance verification of drains shall be carried out based on calculations while taking into consideration the drain intervals and diameters, the drainage conditions above and below the consolidation object layers, the permeability characteristics of the drain materials and sand mats, and the thicknesses of the sand mats.

(1) Drains and Sand mats

1) Drainage Functions of Drains and Sand Mats

Drains and sand mats utilized in soil consolidation must meet predefined drainage performance criteria to ensure they function as intended throughout the soil improvement process.

2) Consolidation Degrees and Drain Diameters

The efficacy of the drainage system in soil consolidation processes is influenced by the dimensions and arrangements of the drains:

- ✓ Proportional factors:

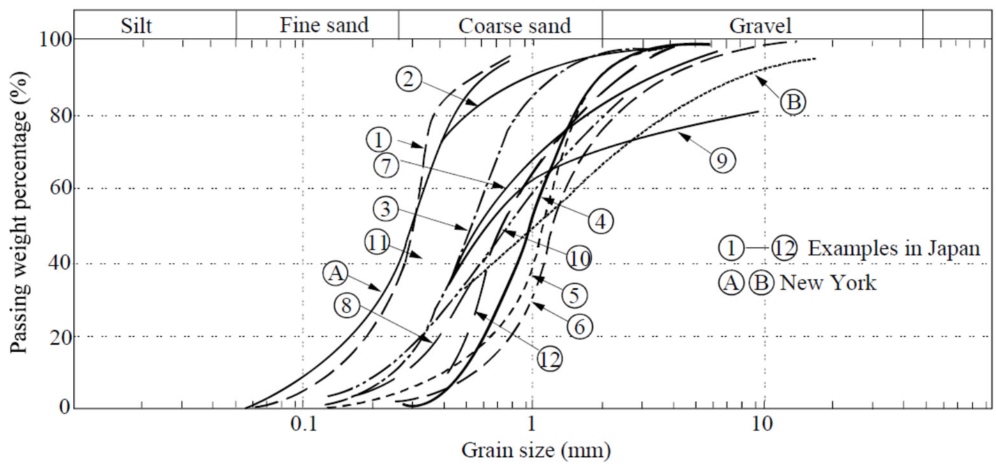
The rate of consolidation is almost directly proportional to the diameter of the drains used and inversely proportional to the square of the spacing between them.

- ✓ Optimal configuration:

Smaller diameter drains placed at closer intervals often require less material than larger drains placed further apart.

- ✓ Risk of clogging and structural integrity:

There is a concern with smaller diameter sand piles becoming clogged with cohesive soil particles or breaking under stress during ground deformation in preloading and retention periods. Most commonly, sand piles are 40 to 50 cm in diameter in the sand drain method.



Source: TCVN 11820-4-2-2020

Figure 1.3- Examples of Sand used in Sand Piles

TCVN 11820 Part 4-2: 2020, Hinh 35

3) Materials for Sand Piles

The sand chosen for sand piles plays a critical role in preventing clogging and ensuring effective water filtration:

- ✓ Grain size distribution:

According to Terzaghi's standards, the grain diameter of the sand used (D_{15}) should be at least four times that of the consolidating soil's D_{15} and no more than four times the soil's D_{85}.

- ✓ Coarse requirements:

The research papers suggest using coarser sand than Terzaghi's standard to account for potential drain pressure losses, indicating a need for sands with a specific grain size distribution to maintain permeability.

4) Materials for Prefabricated Drains

Advancements in vertical drain materials have led to the development of prefabricated drains:

- ✓ Design variations:

These include band-shaped drains with composite structures consisting of nonwoven fabric or synthetic resin cores, designed to facilitate easier installation and potentially greater effectiveness.

- ✓ Performance verification:

Prefabricated drains are often evaluated by equating their cross-sectional areas to equivalent circular sand drains, are usually assumed to have a diameter of about 5 cm. However, drains with low discharge capacities may impede timely consolidation, especially at the lower sections of the drains.

5) Sand Mats

Sand mats serve to expel water from the soil improvement area, aiding in the consolidation process:

- ✓ Material quality:

High-quality sand with suitable permeability characteristics is essential for effective sand mats.

- ✓ Thickness considerations:

Typically, sand mats are about 1.0 to 1.5 meters thick for offshore applications and 0.5 to 1.0 meters thick for land-based applications. The thickness must balance the need for effective water drainage without hindering the installation of vertical drains.

- ✓ Enhanced drainage solutions:

In scenarios where sand mats' permeability might be compromised, installing additional drainage pipes within the mats can enhance water expulsion.

- ✓ Innovative methods:

Recent developments have introduced methods that utilize extensions of vertical drains arranged in grid patterns, potentially obviating the need for traditional sand mats by maintaining effective horizontal drainage channels.

These considerations and advancements underscore the need for careful selection of materials and configurations in soil consolidation projects to optimize performance and manage risks effectively.

(2) Drains Intervals

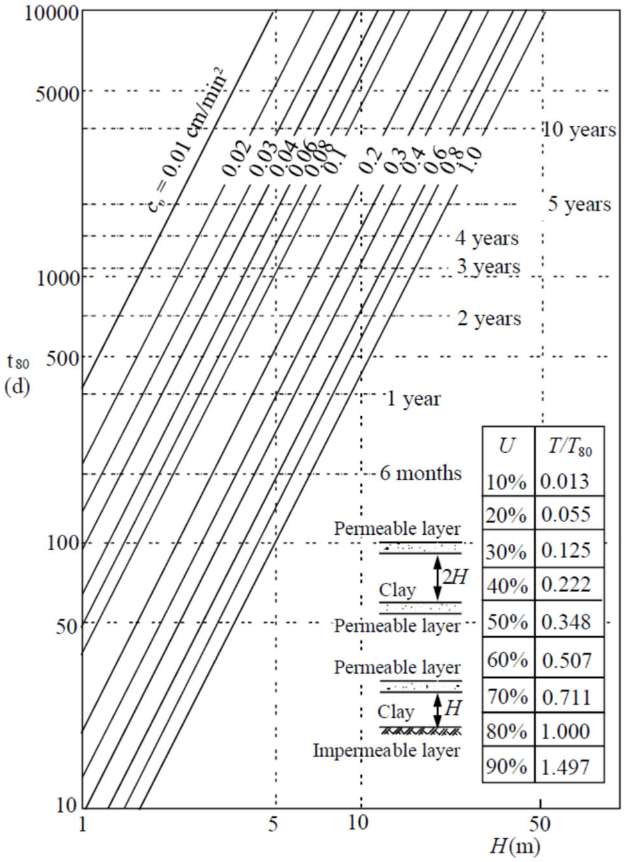
1) Determining Drain Intervals

Drain intervals are essential for achieving the desired degrees of consolidation within specified construction periods. The spacing must be calibrated to ensure efficient moisture extraction and soil stabilization.

2) General Implementation

Vertical drains are often employed when natural soil consolidation rates do not meet the requirements of the project timeline. Relationships between consolidation time, drainage distances, and consolidation coefficients are typically modeled to inform these implementations. Figure 1.4 shows the relationships when implementing the preloading.

OCDI 2020, Part III Chapter 2 Figure 5.4.4



Source: OCDI 2020

Figure 1.4- The Number of Days Required to Achieve Consolidation Degree of Cohesive Layers

3) Determination of Drain Intervals

Drain spacing can be determined using specific theoretical models, such as those proposed by Baron or Bio, which are illustrated in diagrams and formulas like those in Figure 1.5 and Equation (1.4). Caution is advised as too narrow intervals may result in delayed consolidation due to the smearing effects of cohesive soil.

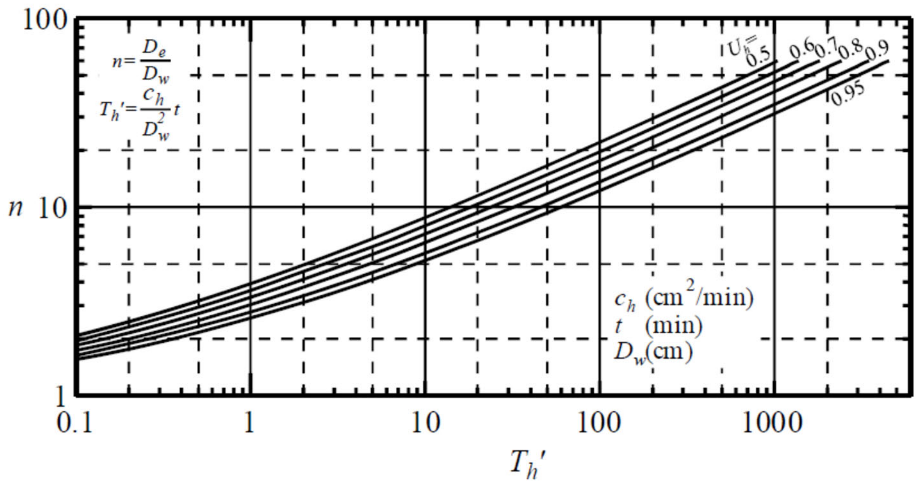
OCDI 2020, Part III Chapter 2 Equation (5.4.3)

$$d = \beta n\, d_w \tag{1.4}$$

Where:

- d : drain interval (cm)
- β : coefficient related to the arrangement of drains
  β= 0.886 in the case of a square arrangement; β= 0.952 in the case of a regular triangle arrangement
- n : $n=d_e/d_w$ (n can be obtained from Fig.1.4)
- d_e : equivalent diameter of a drain (cm)
- d_w : diameter of a drain (cm)
- T_h' : parameter similar to a time factor $T_h' = C_h t / (D_w^2)$
- C_h : coefficient of consolidation related to water flow in the horizontal direction (cm²/min)
- t : consolidation time (min)

OCDI 2020, Part III Chapter 2 Figure 5.4.5



Source: OCDI 2020

Figure 1.5- Calculation Chart for the n-value

4) Equivalent Drain Diameters

An equivalent drain diameter (d_e) is a diameter of a circle with an area equivalent to the equivalent area of the drain. Equivalent diameters have the following relationships with drain intervals (d).

- ✓ Square arrangement: $d_e = 1.128d$
- ✓ Triangular arrangement: $d_e = 1.050d$

5) Vertical Water Flow Considerations

While horizontal drainage is primary, vertical drainage can also play a significant role, especially in thinner consolidation layers. The impact of vertical water flow should not be underestimated and must be considered in performance evaluations.

6) Coefficient of Consolidation in Horizontal Direction

The horizontal coefficient of consolidation (c_h) is often higher than in the vertical direction, though findings vary. In practical applications, the vertical coefficient of consolidation (c_v) is sometimes used as a substitute for horizontal calculations when precise data is unavailable.

7) Calculating Degrees of Consolidation

After determining the drain intervals, the relationships between the degrees of consolidation and elapsed time can be obtained from the Equations (1.5) as well as Figure 1.6.

$$U = 1 - \exp\left(-\frac{8T_h}{F(n)}\right)$$

$$F(n) = \frac{n^2}{n^2 - 1}\ln(n) - \frac{3n^2 - 1}{4n^2} \qquad (1.5)$$

$$T_h = \frac{C_h t}{d_e^2}$$

$$n = \frac{d_e}{d_w}$$

TCVN 11820 Part 4-2: 2020, Equation (34)

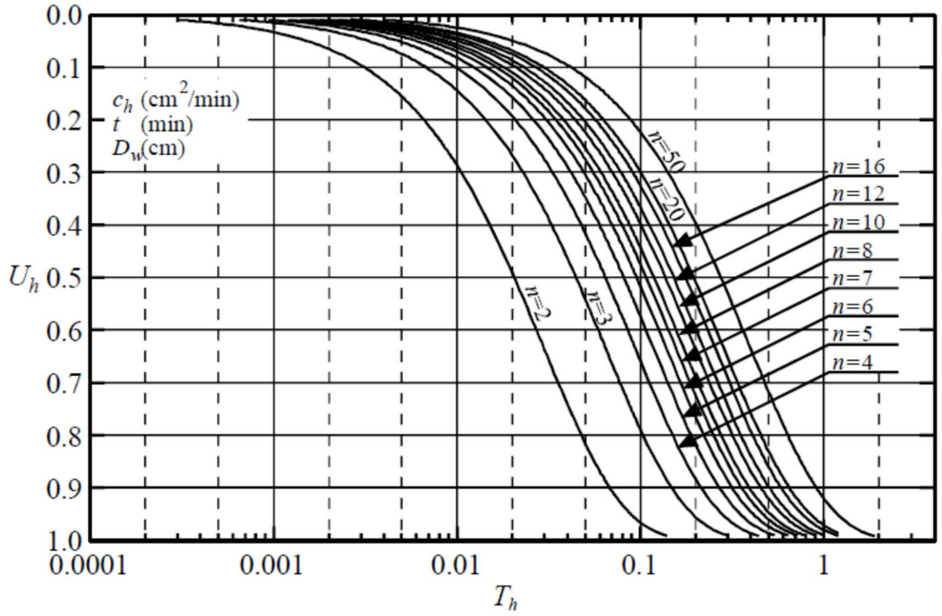
Where:

U	:	average degree of consolidation
T_h	:	time factor for consolidation due to water flowing in a horizontal direction
C_h	:	coefficient of consolidation due to water flowing in a horizontal direction (cm^2/day)
t	:	elapsed time since the commencement of consolidation (day)
d_e	:	equivalent diameter of a drain (cm)
d_w	:	diameter of a drain (cm)

The diameter of drain, d_w, should be calculated by either equation (1.6) in the case prefabricated vertical drain is used. However, are usually assumed to have a diameter of about 5 cm.

$$d_w = 2(a+b)/\pi$$
$$d_w = (a+b)/2 \qquad (1.6)$$

TCVN 11820 Part 4-2: 2020, Equation (35)



Source: OCDI 2020

Figure 1.6- Calculation Chart for the Degrees of Consolidation

OCDI 2020, Part III Chapter 2 Figure 5.4.6

8) Factors Influence Consolidation Speed

The consolidation process is influenced by many factors, such as the smear effect, well and mat resistances, which can be incorporated in the design for precise evaluation.

A zone surrounding the drain whose permeability and consolidation characteristics have been influenced by soil disturbance. The effect of smear zone becomes dominant in the case the drain spacing is small.

The effects of the well resistance and mat resistance should be incorporated in calculating the degree of consolidation accordingly when the resistances cannot be negligible. In the case of long drains, well resistance is likely to occur, so the permeability of the drain must be considered from the Equations (1.7).

TCVN 11820 Part 4-2: 2020, Equation (37)

$$U = 1 - \exp\left(-\frac{8T_h}{F(n+0.8(L_w+L_m))}\right)$$

$$F(n) = \frac{n^2}{n^2-1}\ln(n) - \frac{3n^2-1}{4n^2}$$

$$T_h = \frac{C_h t}{d_e^2} \qquad (1.7)$$

$$n = \frac{d_e}{d_w}$$

$$L_m = \frac{32}{\pi^2}\frac{Hk_c}{n^2H_mk_m}\left(\frac{B}{d_w}\right)$$

$$L_w = \frac{32}{\pi^2}\frac{k_c}{k_w}\left(\frac{H}{d_w}\right)^2$$

Where:

B : length of drainage blanket (m)
H : length of drain (m)
H_m : thickness of drainage blanket (m)
k_c : permeability of ground (m/min)
k_m : permeability of drainage blanket (m/min)
k_w : permeability of drain (m/min)
L_m : coefficient of mat resistance
L_w : coefficient of well resistance factor

9) Settlement Behavior

Settlement typically occurs faster near the drains. The concept of even settlement, where pressure is distributed more uniformly due to arching effects, contrasts with free settlement, where pressure distribution remains constant. Understanding these dynamics is crucial for accurate site analysis.

10) Incremental Load Consolidation

In projects where embankment fill is applied in stages, incremental loading allows for gradual increase in consolidation pressure. Simplified methods are available to calculate the consolidation under these conditions.

11) Partial Penetration Drains

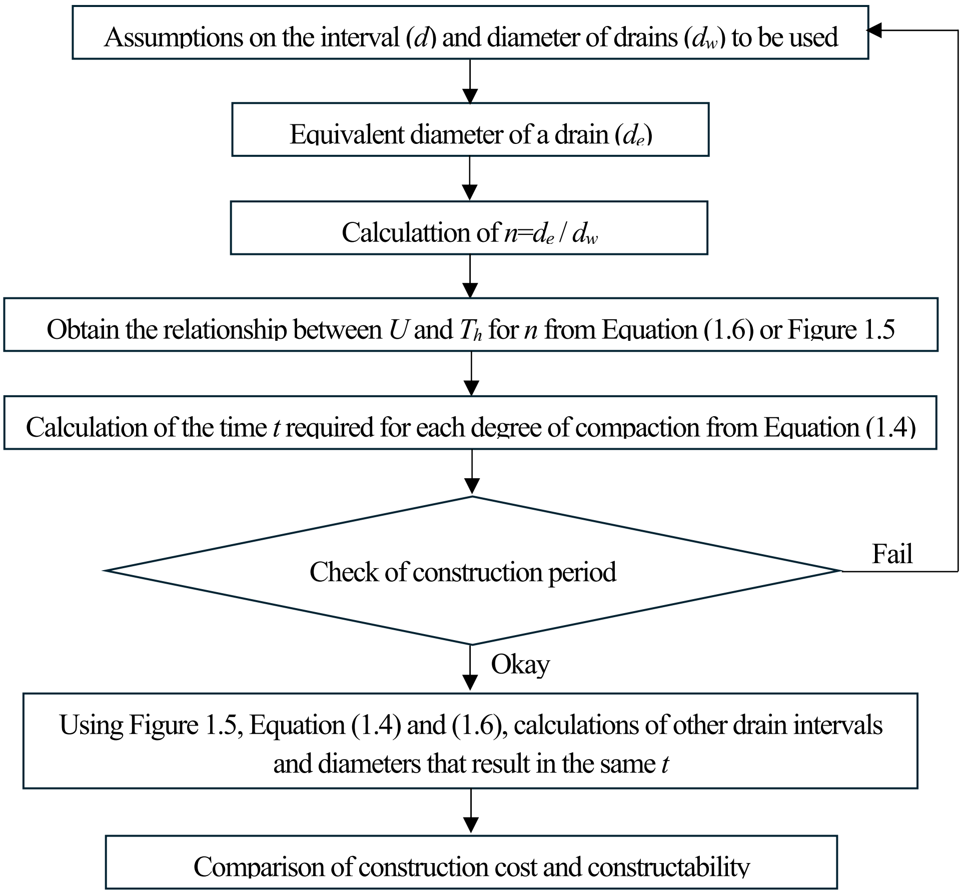
In scenarios where drains cannot fully penetrate the soil layer, consolidation can be significantly prolonged. Simplified methods help estimate the consolidation in these less-than-ideal conditions.

12) Inhomogeneous Cohesive Soil Layers

Inconsistent soil layers require a detailed, layer-by-layer analysis to accurately predict and manage consolidation outcomes. Specific references and methodologies can guide these complex assessments.

These guidelines and considerations are crucial for optimizing the design and implementation of vertical drains in soil improvement projects, ensuring that the desired consolidation effects are achieved efficiently and effectively within the project constraints.

Figure 1.7 indicates the flow chart of vertical drain design.



Source: JICA Team

Figure 1.7- Flow Chart of Vertical Drain Design

1-5. Vacuum Consolidation Method

The vacuum consolidation method presents a unique approach to soil improvement by increasing the effective stress in soil through the reduction of pore water pressure, rather than applying external loads such as surcharges. This method is frequently used in conjunction with vertical drains, enhancing the speed of consolidation significantly. Here are some key points regarding the vacuum consolidation method:

(1) Key Characteristics and Advantages

- ✓ No additional shear stress:

Unlike methods that involve applying surcharge, the vacuum consolidation method does not introduce additional shear stress to the soil. This absence of added load reduces the risk of stability issues, making it a safer option especially in sensitive areas.

- ✓ Speed of construction:

By reducing the need for staged loading, which is typical in preloading and surcharge methods, the vacuum consolidation method can shorten construction timelines. This is particularly beneficial in projects with tight schedules.

(2) Limitations and Disadvantages

- ✓ Lower consolidation ratios:

The vacuum consolidation method has been observed to achieve lower ratios of consolidation compared to preloading and surcharge methods. This suggests that while faster in initiating consolidation, it might not always be as effective in soil densification over the same period.

✓ Delayed strength increases:

The increase in ground strength during the initial phases of consolidation tends to occur later with vacuum consolidation than with methods involving surcharges. This can impact the early stages of construction and may require adjustments in project scheduling and management.

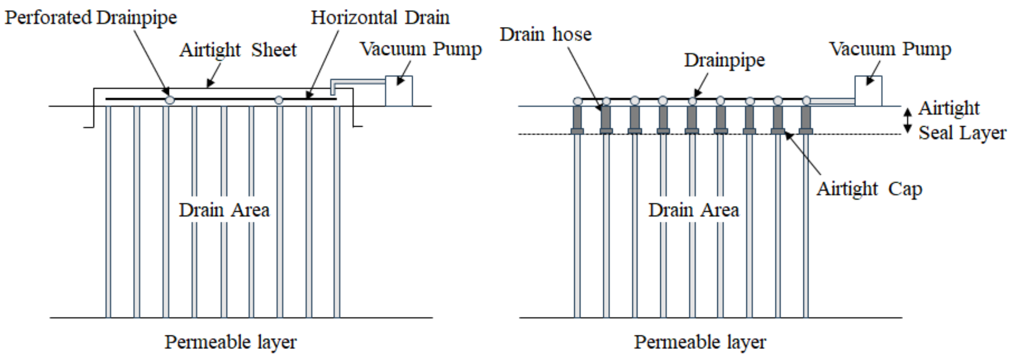
(3) Application Considerations

The vacuum consolidation method is particularly suited for projects where minimizing additional surcharge soil and speeding up construction are priorities.

In practical applications, careful monitoring and evaluation of the soil's response to vacuum consolidation are crucial. This ensures that the desired soil properties are achieved without unforeseen delays or issues.

(4) Typical Methods

A vacuum pressure of approximately 50 to 80 kPa is applied to promote consolidation. In the airtight sheet method, the ground surface is sealed with a sheet to prevent air from entering and maintain negative pressure in the entire treatment area. On the other hand, in the airtight cap method, caps are placed on the top of vertical drains and sealed individually, applying negative pressure to each drain.



Source: JICA Team

Figure 1.8- Airtight Sheet Method (Left) and Airtight Cap Method (Right)

1-6. Pneumatic Flow Mixing Method

From the perspective of environmental conservation and effective use of resources, there is a movement to reuse dredged soil rather than disposing of it as waste. Dredged soil has a high water content and low strength, so it has been considered difficult to use directly as a construction material, but with appropriate treatment, it can be reused as reclamation material, etc. The PVD method is a consolidation method in which drainage material is inserted into soft ground such as dredged soil to promote the discharge of interstitial water. On the other hand, the pneumatic flow mixing method is a method that can create a strong improved ground that can be immediately used as a supporting ground by solidifying the dredged soil itself in situ. In particular, a major advantage is that dredged soil generated on-site can be reused in situ and used for reclamation, water proofing layer, etc. The design method is introduced in TCVN Part 4-2: 2019 Chapter 9.

TCVN 11820 Part 4-2: 2020, Phu Luc A

(1) Key Characteristics and Advantages

✓ Constructability:

Since the reclamation material utilizes dredged soil, the need for dredged soil disposal is minimal, reducing handling and transportation. Since solidifier slurry is added directly to water added dredged soil while pumping it through pipes, high efficiency mixing of the slurry and soil can be achieved.

- ✓ Quality control:

The mixing process can be continuously monitored, allowing for the creation of uniformly solidified improvement ground with consistent quality.

- ✓ Applicability:

The method is suitable for use in confined areas, directly beneath existing structures, and in locations with high groundwater levels.

(2) Limitations and Disadvantages

- ✓ Soil selection and amount control:

Pre-treatment laboratory tests should be performed to carefully select the appropriate type and amount of solidification material. Inappropriate selection may result in insufficient strength gain and long-term durability problems.

- ✓ Mixing uniformity:

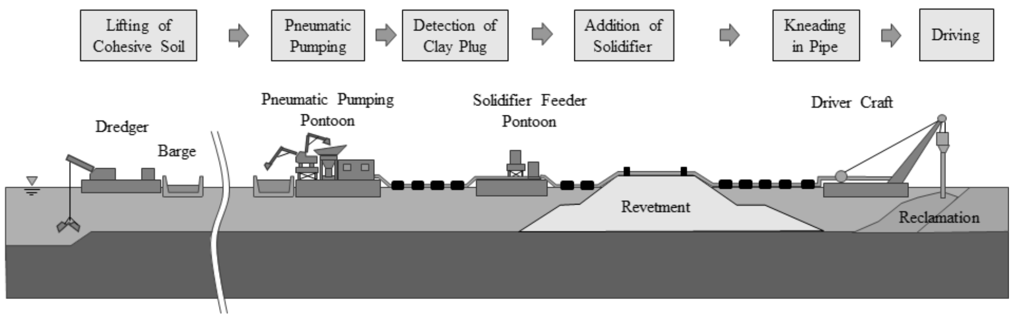
Insufficient or uneven mixing may result in a non-homogeneous improved body, which may cause localized weakening and settlement.

- ✓ Cost:

This method reduces waste and transportation cost but may be expensive due to the costs of solidification material and special vessels.

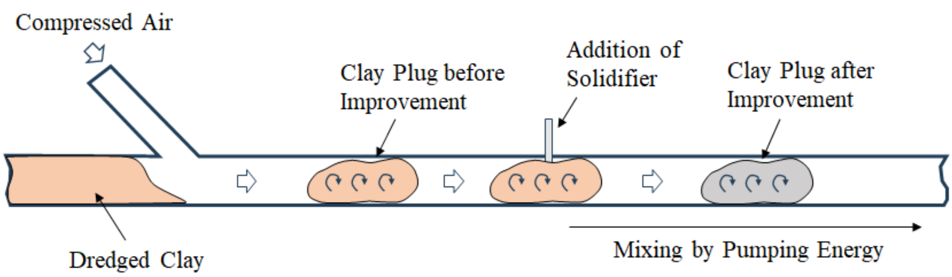
(3) Typical Methods

TCVN 11820 Part 4-2: 2020, Hinh A.5



Source: TCVN 11820-4-2-2020

Figure 1.9- Typical Scheme of Pneumatic Flow Mixing Method

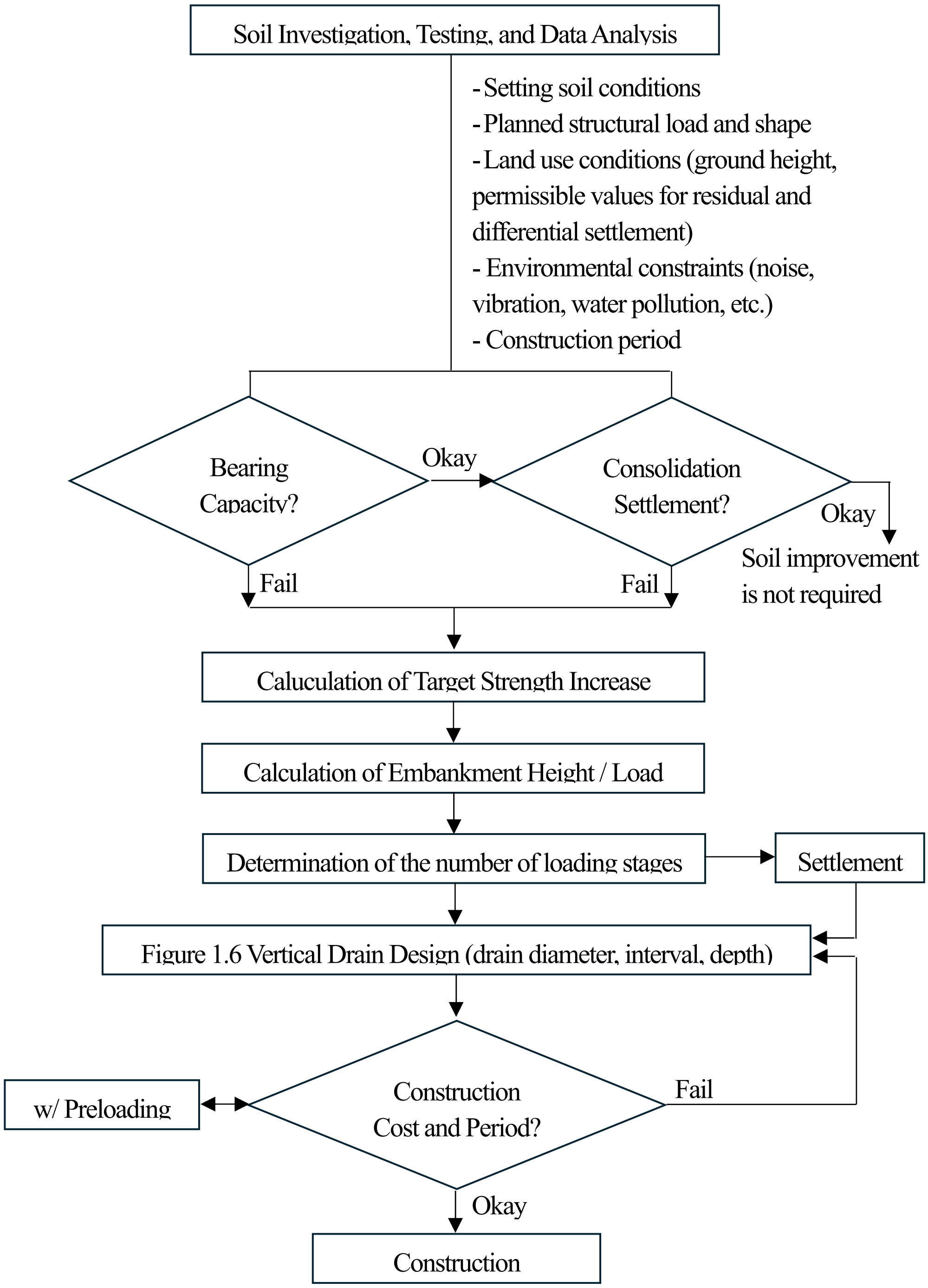


Source: JICA Team

Figure 1.9- Mixing Scheme of Pneumatic Flow Mixing Method

2. Design Example

(1) Design Flow Chart



Source: JICA Team

Figure 2.1- Flow Chart of Soil Improvement Design

(2) Typical Section and Design Condition for Performance Verification

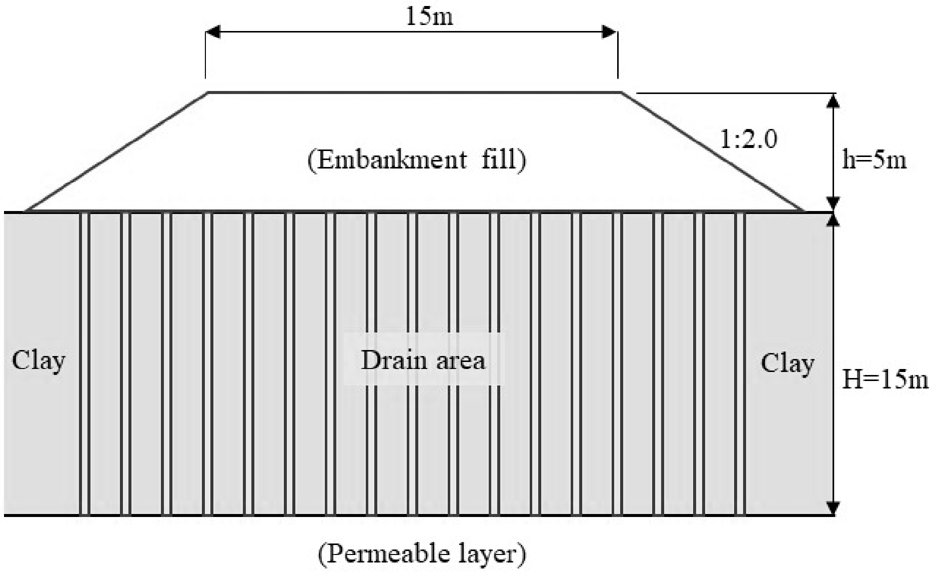


Figure 2.2- Design Example

- ✓ Clay layer thickness: 15.0m double drainage
- ✓ Soil properties: Normal consolidation clay
- ✓ Initial soil strength: $c=c_0+kz$ (c_0=1.0kN/m^2, k=2.5kN/m^3)
- ✓ Increase ratio of strength: c_u/p = 0.3
- ✓ Coefficient of consolidation: $C_v=C_h$=0.05cm^2/min
- ✓ Target strength increase: 20kN/m^2
- ✓ Target consolidation rate at each stage of embankment: 80%
- ✓ Construction period: 1 year
- ✓ Embankment height: 5m (unit weight: 20kN/m^3, see calculation (4))

(3) Evaluation of Improvement Width

Considering slope stability, it is determined to perform ground improvement across the entire width of the embankment.

(4) Calculation of Embankment Height

The embankment height, when aimed at increasing ground strength, is given by Equation (1.1).

$$\Delta c = c_u/p\ \Delta p'\ U$$
$$\Delta p' = p'_0 + \alpha \gamma_t h - p'_c \qquad (1.1)$$

Here, $p'_0=p'_c$=0, and transforming Equation (1.1) gives Equation (2.1):

$$\gamma_t h = \frac{1}{\alpha}\left(\frac{\Delta c}{\left(\frac{c_u}{p}\right) U}\right) \qquad (2.1)$$

The coefficient of stress distribution (α) is the ratio of stress distribution within the ground to the embankment load, given by Boussinesq's elastic solution or the Boston Code method. The central part of the ground values is summarized in Table 2.1.

Table 2.1- Coefficient of Stress Distribution

Method	Coefficient (α)
Boussinesq	0.83
Boussinesq (incl. slope)	0.90
Boston Code	0.63

Source: OCDI 2020

To ensure strength increases at the center of the ground, the height of the embankment required (h) can be determined by the following formula based on Equation (2.1).

$$\gamma_t h = \frac{1}{0.90}\left(\frac{20.0}{0.3\times 0.8}\right)$$

$$= 92.6 \simeq 100 \text{ kN/m}^2$$

$$h = 100/20.0 = 5.0 \text{ m}$$

(5) Determination of the Number of Loading Stages

Before determining on the number of loading stages, a circular slip failure analysis will be conducted to evaluate whether the final embankment (with a height of 5 meters and a pressure of 100 kN/m²) can be constructed at once. While the detailed analysis for circular slip failure is omitted in this casebook, the result of the analysis is safety factor of 0.42, indicating that the final embankment cannot be loaded at once and staged construction is necessary.

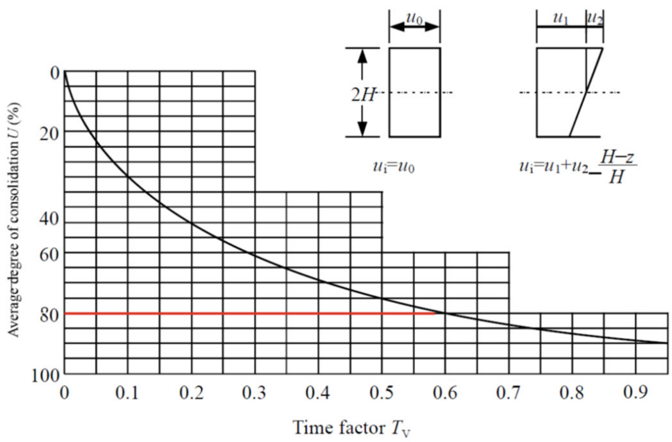
Additionally, as a simpler calculation, TCVN 11820 Part 4-1: 2020 B.3 Bearing Capacity of Foundations on Cohesive Soil Ground can be used to evaluate the stability of the embankment.

(6) Evaluation of Consolidation Time Without Soil Improvement

Before designing the interval of the drains, the consolidation time without soil improvement should be calculated. Assuming one-dimensional consolidation due to the relatively large width of the embankment compared to the thickness of the clay layer, the time required to achieve 80% consolidation is given by the following formula:

$$t = \frac{(H/2)^2}{C_v} T_V = \frac{(1{,}500/2)^2}{0.05} \times 0.567$$

$$= 6{,}378{,}750 \text{ min} = 4{,}429 \text{ days}$$



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Source: OCDI 2020

Figure 2.3- Relationship between the Average Degree of Consolidation and Time Factors

The consolidation time without soil improvement is quite long, and it is desirable to use vertical drains to accelerate consolidation.

(7) Vertical Drain Design

Based on calculations (5) and (6), it is confirmed that staged construction utilizing vertical drains is essential for embankment fill. The number of construction stages should be determined through trial and error, taking into consideration the specifications for improvement, the stability of the embankment at each stage, and the consolidation periods. In this casebook, it is assumed that the embankment construction is segmented into four stages, with each stage having a waiting period of 365 days divided by 4, equating to 91 days.

The calculations are demonstrated for a scenario where sand drains of 30cm diameter are installed at 1.5m intervals and prefabricated vertical drains at 1.0m intervals. The time required to achieve 80% consolidation, according to this setup, is detailed in Tables 2.2 and 2.3.

Table 2.2- Calculation Result (Sand Drain)

Drain arrangement	Square	Triangular
Drain interval	1.5m	1.5m
Equivalent diameter of a drain (d_e)	1.692m	1.575m
Diameter of drains (d_w)	0.3m	0.3m
$n = d_e/d_w$	5.64	5.25
F(n) from Equation (1.5)	1.044	0.980
Time factor for consolidation (T_h)	0.210	0.197
Time required to achieve 80%	83.5 days	67.9 days

Table 2.3- Calculation Result (Prefabricated Vertical Drain)

Drain arrangement	Square	Triangular
Drain interval	1.0m	1.0m
Equivalent diameter of a drain (d_e)	1.128m	1.050m
Diameter of drains (d_w)	0.05m	0.05m
$n = d_e/d_w$	22.5	21.0
F(n) from Equation (1.5)	2.370	2.302
Time factor for consolidation (T_h)	0.477	0.463
Time required to achieve 80%	84.3 days	70.9 days

\- End -