

第5章 土的压缩性及地基变形计算

Chapter 5 Soil compressibility and calculation of foundation deformation

5.1 概 述

5.1 Introduction

- **沉降分类** Classification of Settlement
 - 均匀沉降 Uniform Settlement
 - 不均匀沉降 Nonuniform Settlement
- **沉降计算的必要性**
(Necessity of Settlement Calculation)

5.2 土的压缩性

5.2 Soil compressibility

5.2.1 基本概念 Basic Concept

- 土的压缩性 Compressibility of Soil
- 土体被压缩的主要原因
- 土的固结 Consolidation of Soils
 - 主固结
Primary Consolidation
 - 次固结
Secondary Consolidation
- 土体压缩和固结与土的性质有关
Compressibility Related to the Property of Soils

5.2.2 侧限压缩试验

Oedometer Test

➤ 试验仪器及方法

Apparatus and Method for Testing

➤ 压缩仪构造 Structure of the Oedometer ([图5-1](#))

➤ 试验步骤 Test Procedure

➤ 试验成果 Results of Test ([图5-2](#))

➤ 压缩量—时间关系曲线

➤ 稳定时压缩量—荷载关系曲线

➤ 稳定时孔隙比—荷载关系曲线



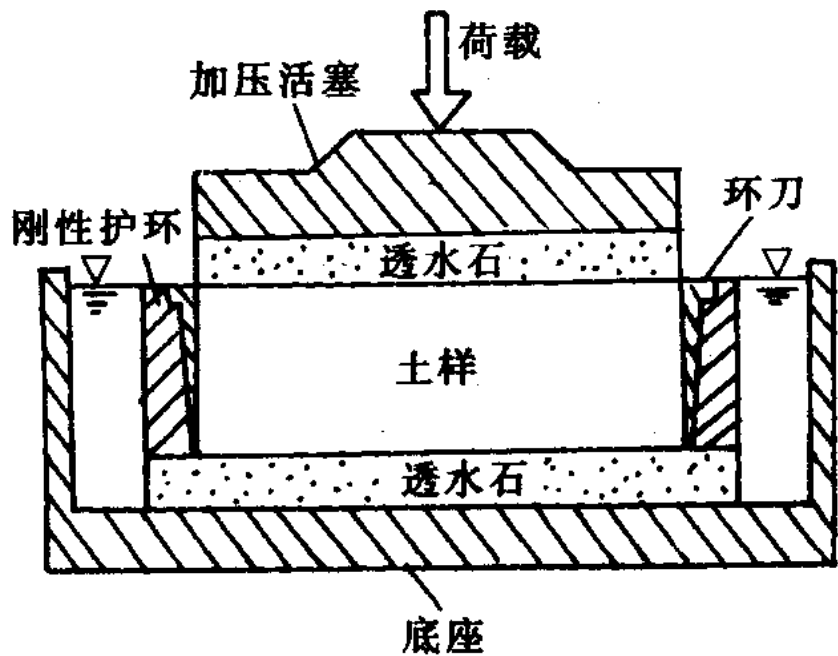
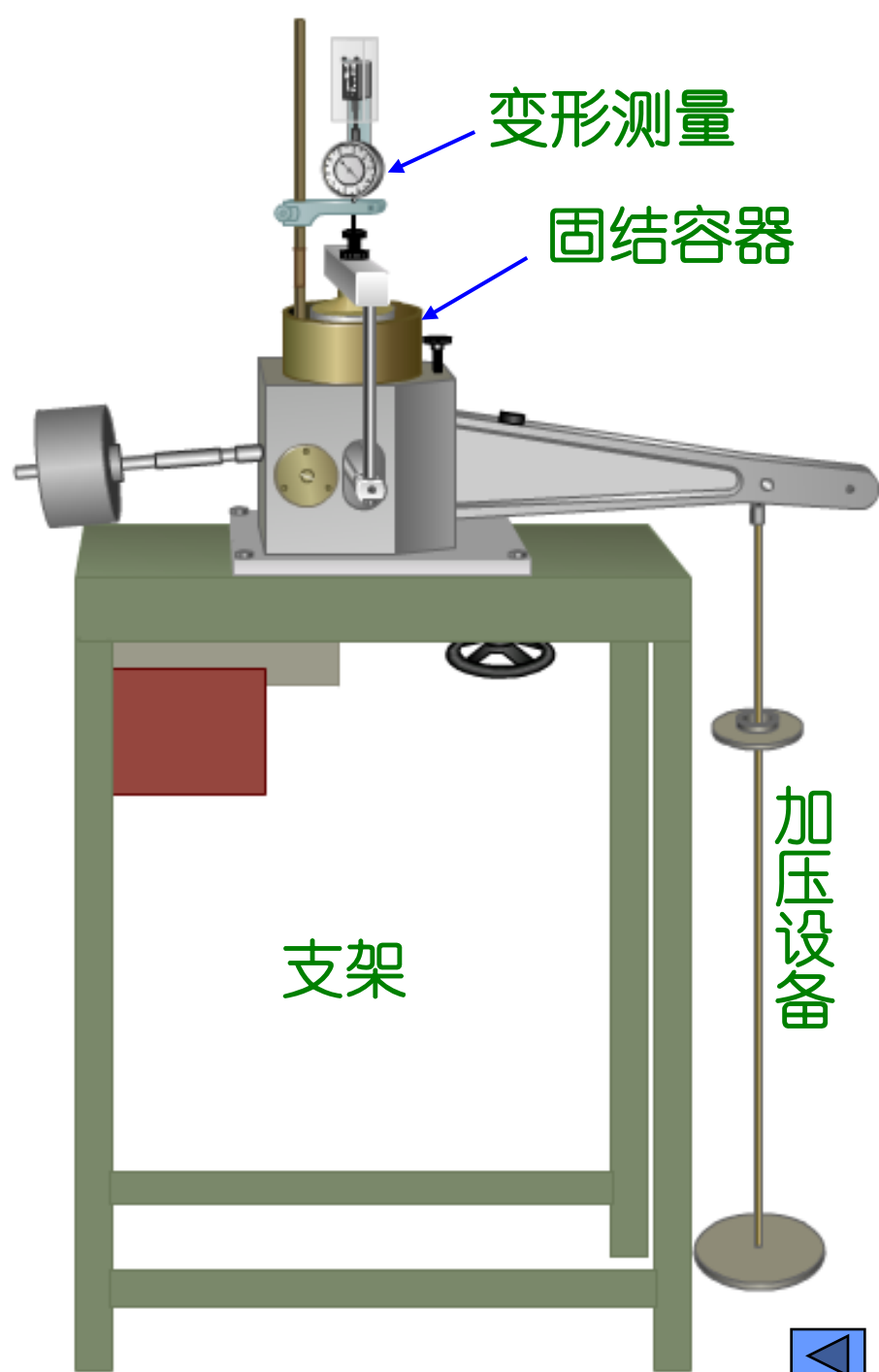


图 5-1 压缩仪的压缩容器简图



加压设备



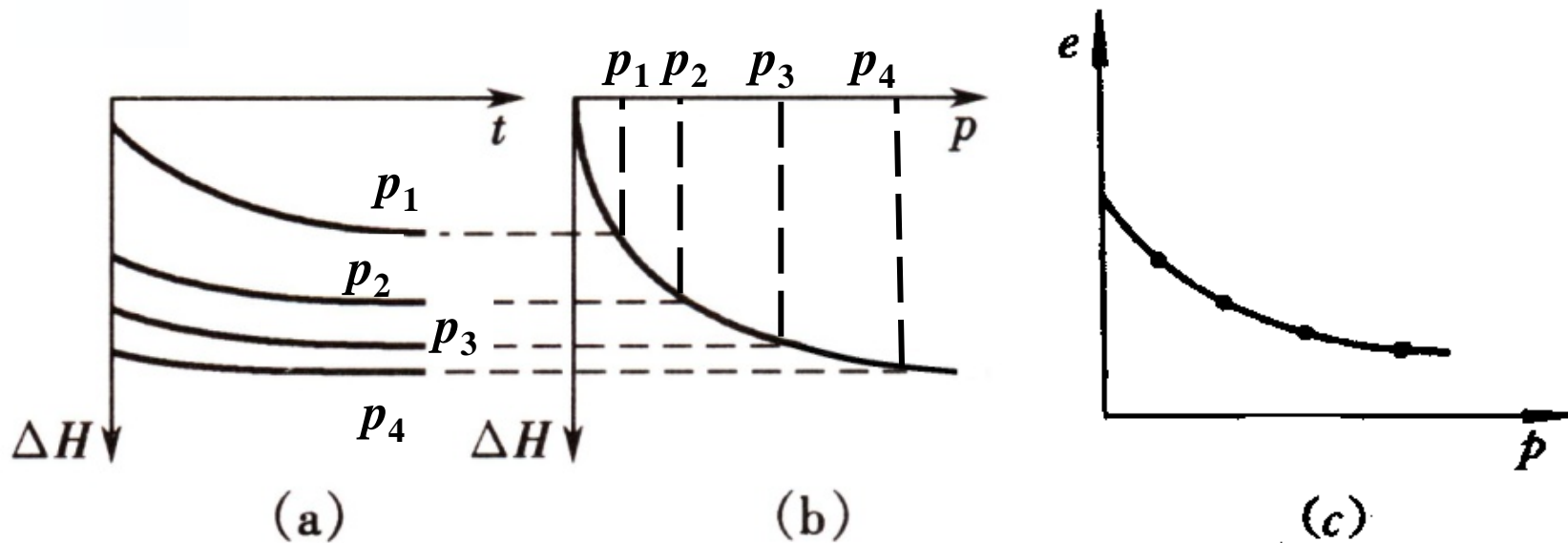


图 5-2 压缩试验中 $\Delta H-t$ 、 $\Delta H-p$ 、 $e-p$ 关系曲线

➤ 垂直压缩变形量 ΔH (图5-3)

Vertical Compression Deformation

$$\frac{\Delta H}{H_1} = \frac{H_1 - H_2}{H_1} = \frac{(H_1 - H_2)A}{H_1 A} = \frac{V_1 - V_2}{V_1} = \frac{V_{v1} - V_{v2}}{V_1} \quad (5-1)$$

$$\frac{\Delta H}{H_1} = \frac{e_1 - e_2}{1 + e_1}$$

$$\Delta H = \frac{-\Delta e}{1 + e_1} H_1 \quad (5-2)$$

$$e_2 = e_1 - \frac{\Delta H}{H_1} (1 + e_1) \quad (5-3)$$

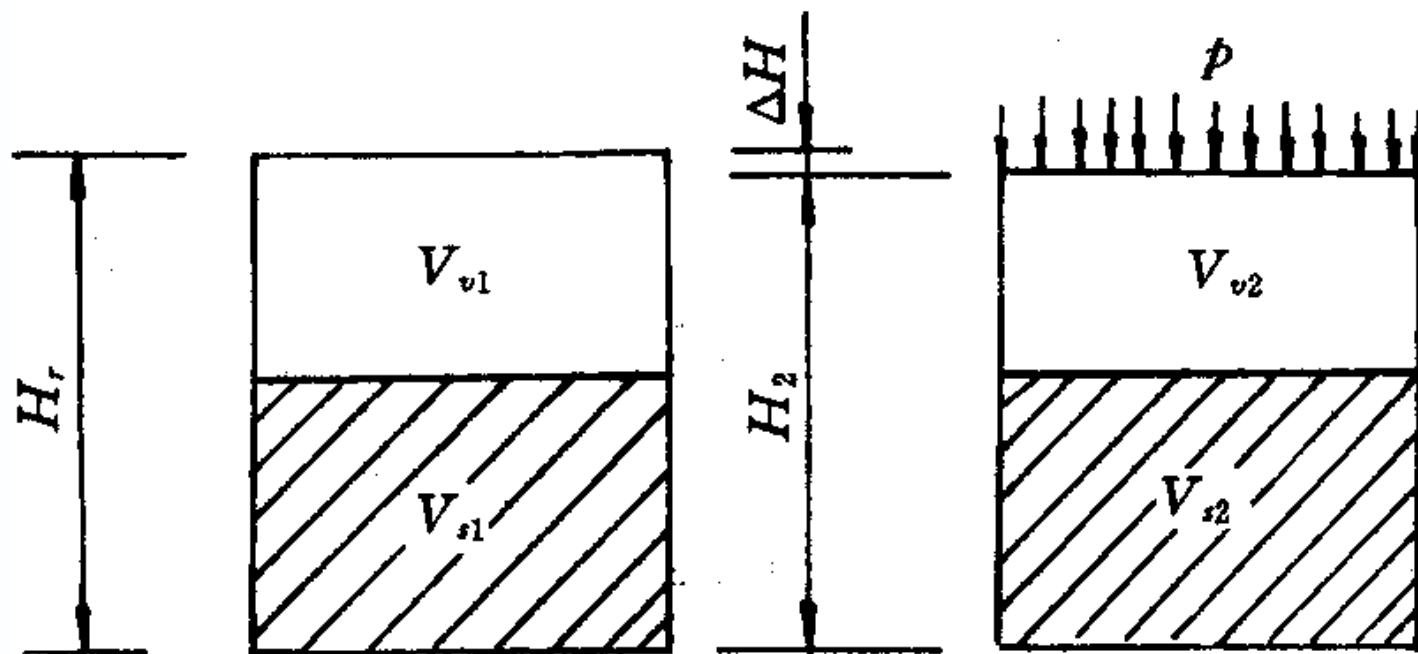


图 5-3 土样压缩前后体积变化示意图

5.2.3 压缩性指标 Compressibility parameters

➤ 压缩系数 Coefficient of Compressibility a_v (图5-4a)

$$a_v = \frac{e_1 - e_2}{p_2 - p_1} = \frac{-\Delta e}{\Delta p} \quad (5-4)$$

压缩系数的物理意义及土的压缩性分类:

$a_{1-2} < 0.1 \text{ MPa}^{-1}$ 低压缩性土

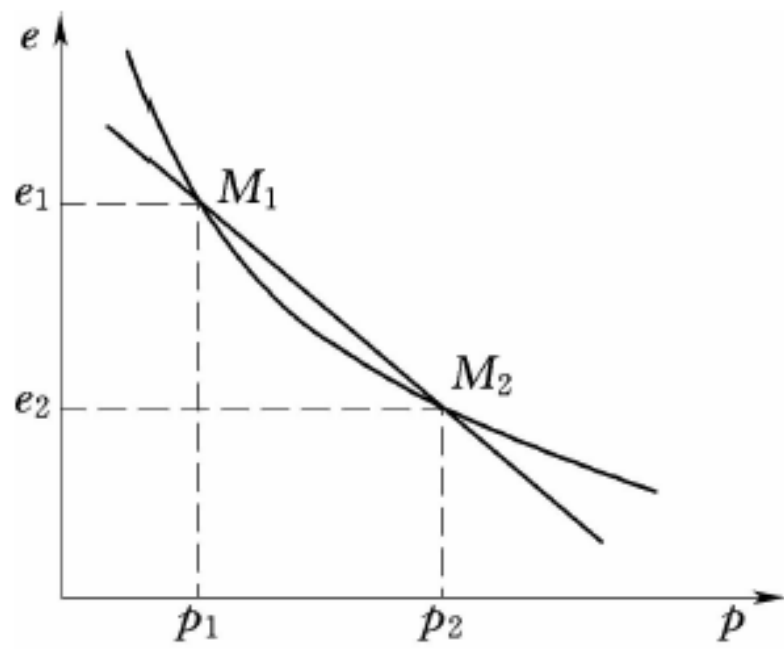
$0.1 \text{ MPa}^{-1} \leq a_{1-2} < 0.5 \text{ MPa}^{-1}$ 中压缩性土

$a_{1-2} \geq 0.5 \text{ MPa}^{-1}$ 高压缩性土

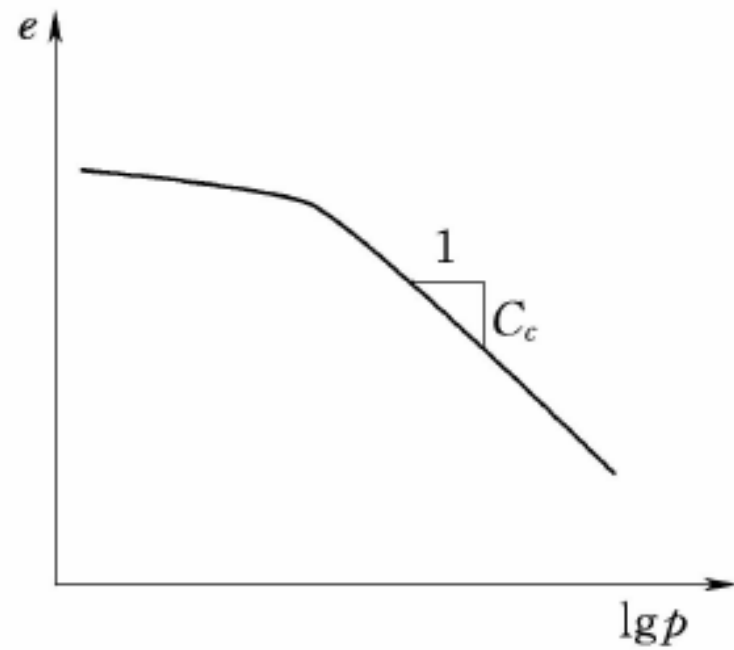
➤ 压缩指数 Compression index C_c (图5-4b)

$$C_c = \frac{e_1 - e_2}{\lg p_2 - \lg p_1} = \frac{e_1 - e_2}{\lg \frac{p_2}{p_1}} = \frac{-\Delta e}{\lg \left(\frac{p_1 + \Delta p}{p_1} \right)} \quad (5-5)$$





(a)



(b)

图 5-4 压缩曲线

(a) $e-p$ 曲线；(b) $e-\lg p$ 曲线

按压缩指数对土的压缩性的判别：

$C_c < 0.2$ 低压缩性土

$0.2 \leq C_c \leq 0.35$ 中压缩性土

$C_c > 0.35$ 高压缩性土

➤ a_v 与 C_c 的关系 Relationship between a_v and C_c

➤ 差分关系 Differential Relationship

由式 (5-4) 和 (5-5)，得

$$a_v = \frac{\Delta e}{\Delta p} = \frac{C_c}{\Delta p} \lg \frac{p_1 + \Delta p}{p_1} = \frac{C_c}{\Delta p} \lg \frac{p_2}{p_1} \quad (5-6)$$

➤ 微分关系 Derivative Relationship

$$de = C_c d(\lg p) = \frac{C_c}{2.3} d(\ln p) = \frac{C_c}{2.3} \frac{dp}{p} \quad (5-7)$$

$$de = a_v dp$$

$$a_v dp = \frac{C_c}{2.3} \frac{dp}{p}$$

$$a_v = \frac{C_c}{2.3} \frac{1}{p} \quad (5-8)$$

➤ 体积压缩系数 m_v 及侧限压缩模量 E_s

Coefficient of Volume Compressibility m_v and Oedometric Modulus E_s

➤ 压缩模量 E_s

$$E_s = \frac{\sigma_z}{\varepsilon_z} = \frac{\Delta p}{\frac{\Delta V}{V_1}} = \frac{\Delta p}{\frac{-\Delta e}{1+e_1}} = \frac{1+e_1}{a_v} \quad (5-9)$$

按压缩模量对土的压缩性的判别：

$E_{s1-2} < 4 \text{ Mpa}$ 高压缩性土

$4 \text{ MPa} \leq E_{s1-2} \leq 15 \text{ MPa}$ 中压缩性土

$E_{s1-2} > 15 \text{ Mpa}$ 低压缩性土

➤ 体积压缩系数 m_v

$$m_v = \frac{\frac{\Delta V}{V_1}}{\Delta p} = \frac{-\Delta e}{\Delta p} = \frac{a_v}{1+e_1} = \frac{1}{E_s} \quad (5-10)$$

5.2.3 现场载荷试验判定土的压缩性

Evaluate Soil Compressibility using Field Load Test

➤ 试验方法 Test Method (图5-5)

➤ 荷载 p — 沉降 S 关系曲线 (图5-6)

Relationship Between Load p and Settlement S

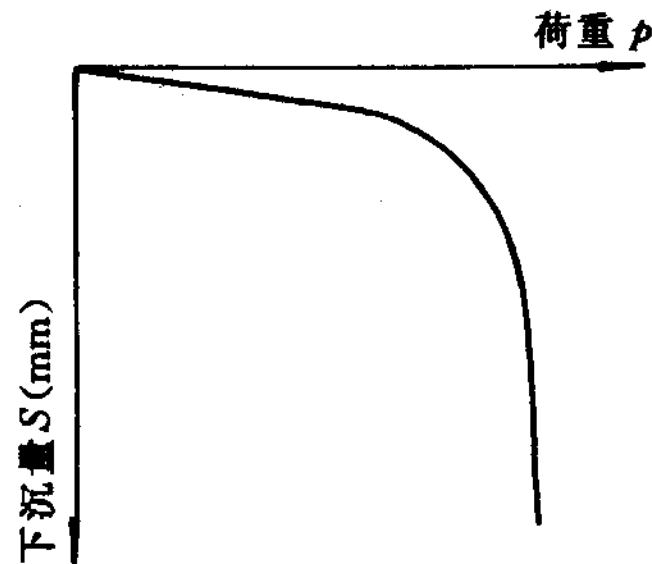
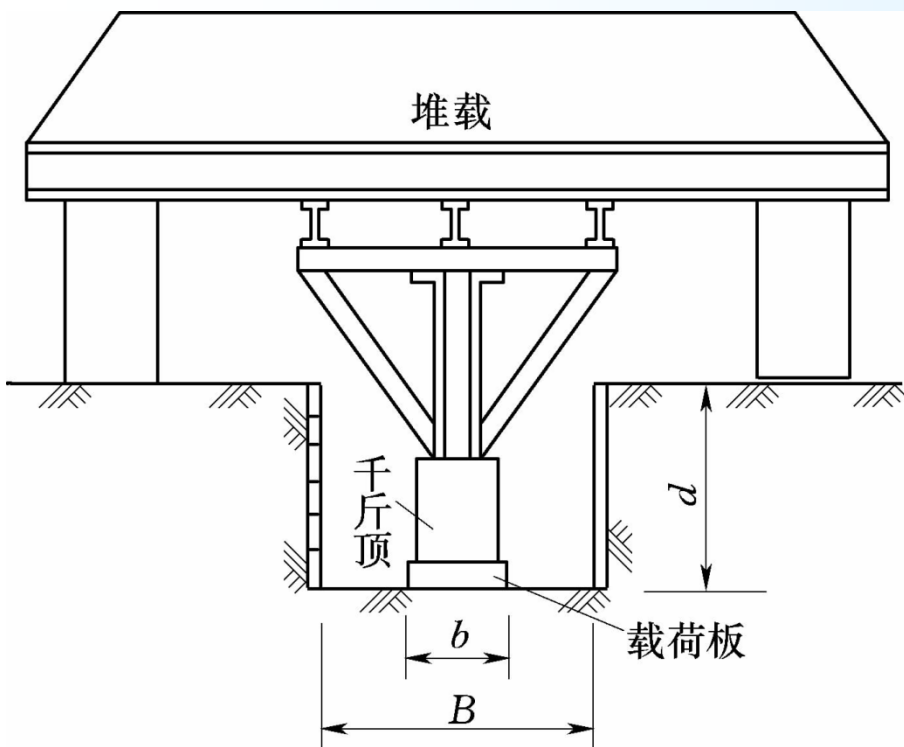


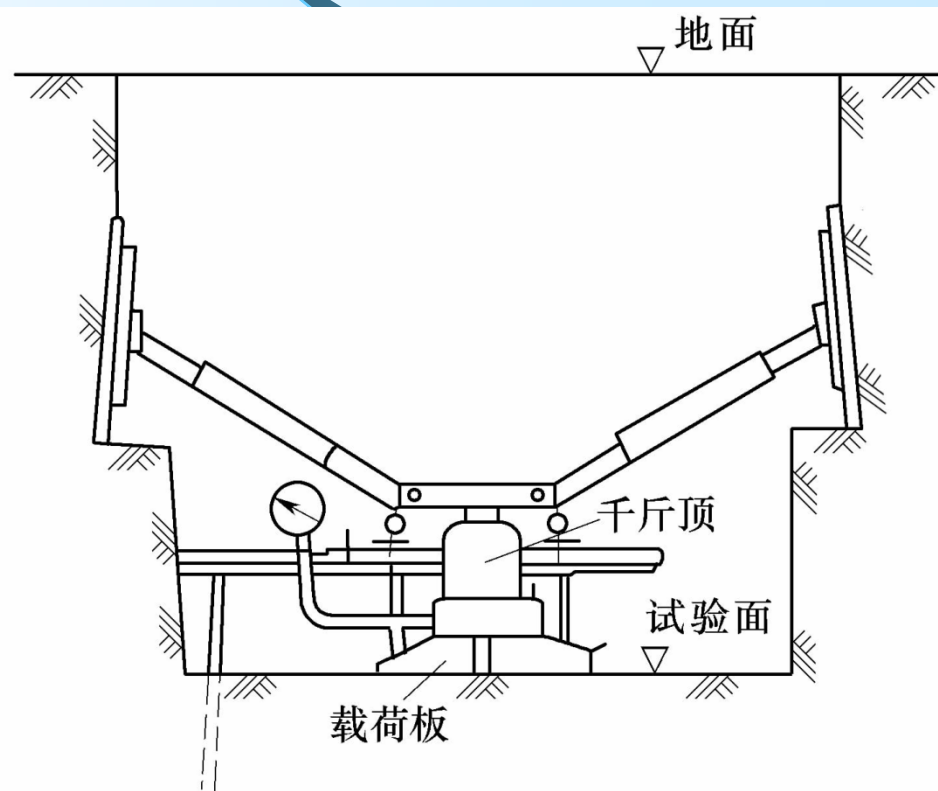
图5-6 荷载强度与变形量的关系

➤ 变形模量计算 Calculation of Deformation modulus

$$E = \frac{pB(1 - \mu^2)C_d}{S} \quad (5-11)$$



(a) 堆载反力



(b) 基坑侧壁反力

图5-5 荷载试验装置试验图

► 变形模量 E 的推求

$$\varepsilon_z = \frac{\sigma_z}{E} - \frac{\mu(\sigma_x + \sigma_y)}{E} \quad (5-12)$$

$$\sigma_z = p, \quad \sigma_x = \sigma_y = \frac{\mu}{1-\mu} p$$

$$\varepsilon_z = \frac{p}{E} \left(1 - \frac{2\mu^2}{1-\mu} \right) \quad (5-13) \quad \longrightarrow \quad E = \frac{p}{\varepsilon_z} \left(1 - \frac{2\mu^2}{1-\mu} \right) \quad (5-14)$$

$$\varepsilon_z = \frac{\Delta H}{H_1} = \frac{e_1 - e_2}{1 + e_1}$$

$$E = \frac{p}{\frac{e_1 - e_2}{1 + e_1}} \left(1 - \frac{2\mu^2}{1-\mu} \right) = \frac{1 + e_1}{a_v} \left(1 - \frac{2\mu^2}{1-\mu} \right) \quad (5-15)$$

$$E_s = \frac{1 + e_1}{a_v}$$

$$E = E_s \left(1 - \frac{2\mu^2}{1-\mu} \right) \quad (5-16)$$

5.2.4 土的应力历史与压缩性

Stress History and Compressibility of Soil

➤ 回弹再压缩曲线 (图5-8)

Rebounding and Recompression Curve

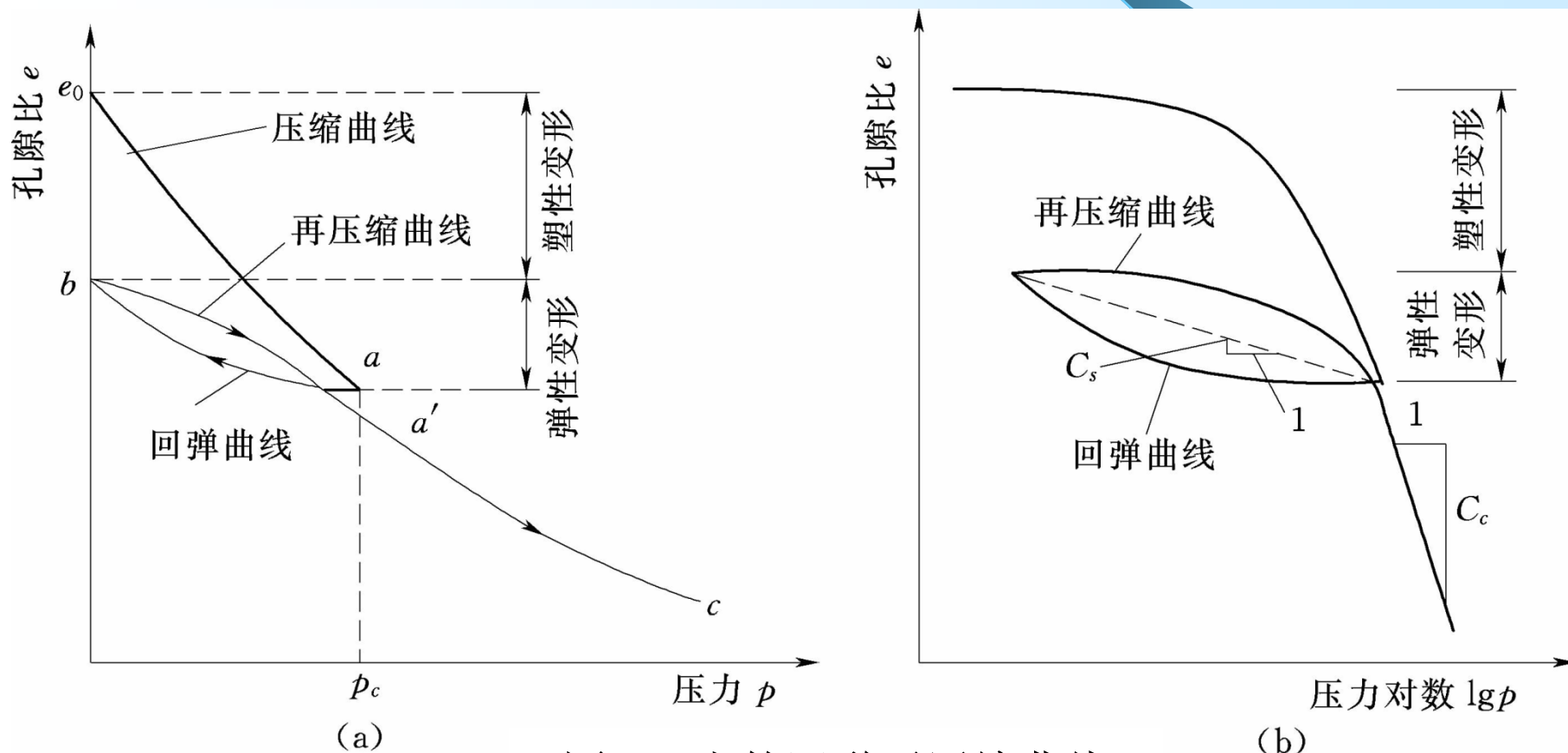


图5-7 土的回弹再压缩曲线

➤ **先期固结压力 p_c**

➤ **先期固结压力 Preconsolidation Pressure p_c**

土层在历史上所经受的最大有效固结压力

➤ **超固结比 Over Consolidation Ratio OCR**

先期固结压力与土层的现有压力的比值

➤ **正常固结土、超固结土和欠固结土 (图5-8)**

Normally Consolidated, Overconsolidated and Underconsolidated Soil

OCR=1 $p_0=p_c$ 正常固结土

OCR>1 $p_0<p_c$ 超固结土

OCR<1 $p_0>p_c$ 欠固结土

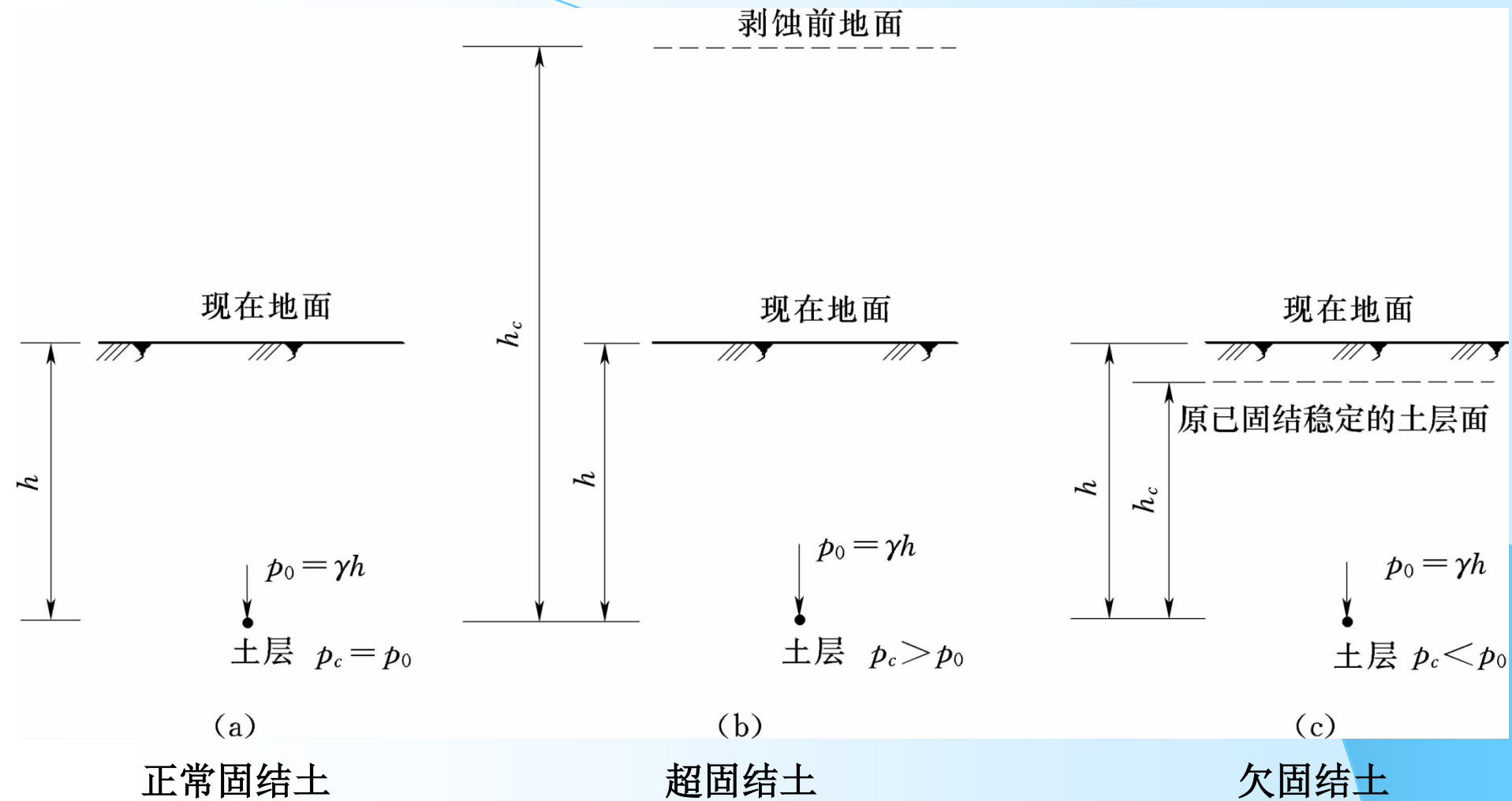


图5-8 不同应力历史的土层形成示意图

➤ 先期固结压力 p_c 的确定

Determination of Preconsolidation Pressure p_c

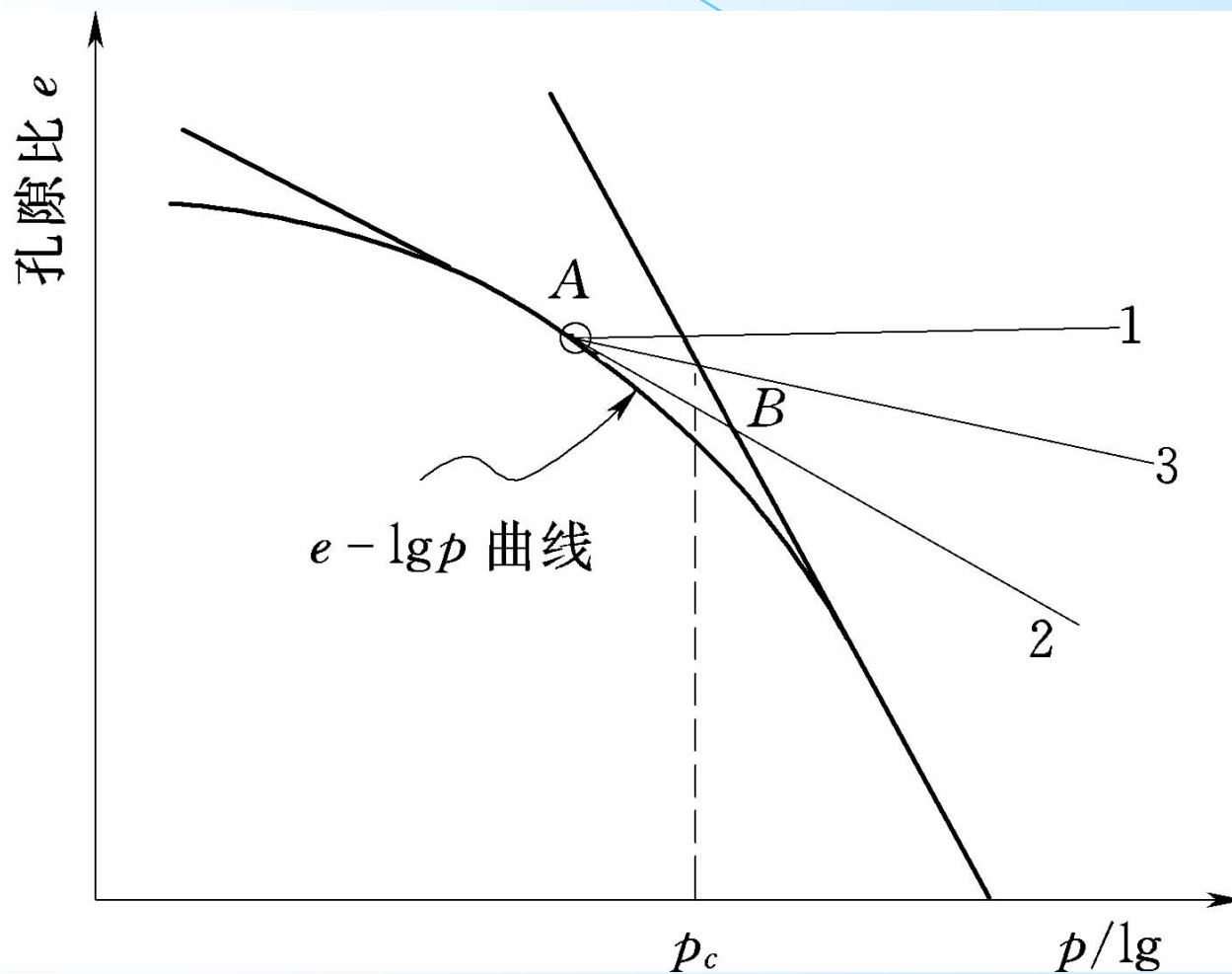
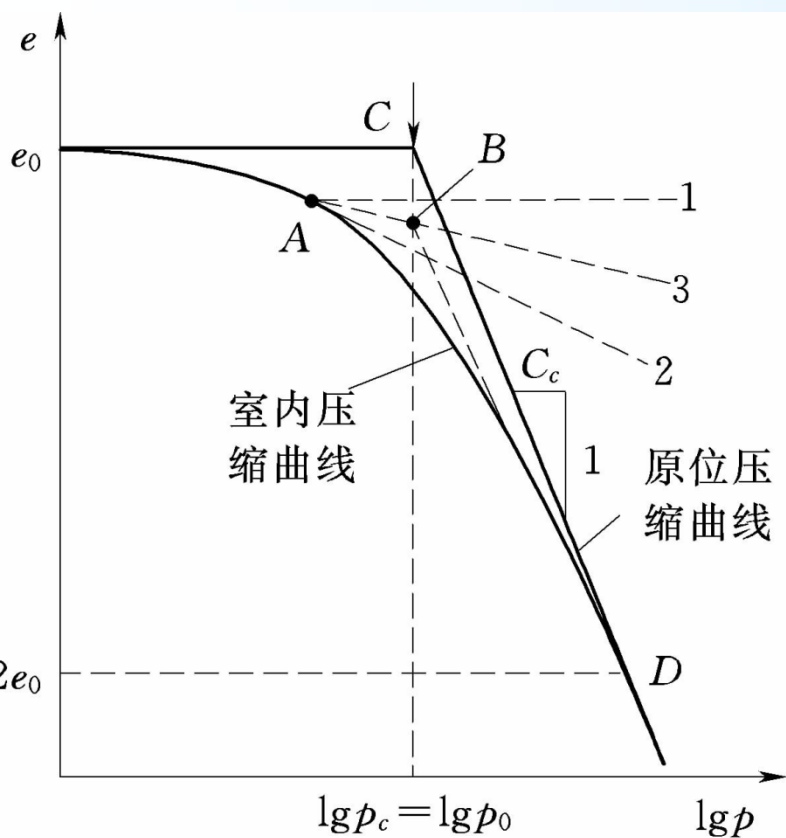


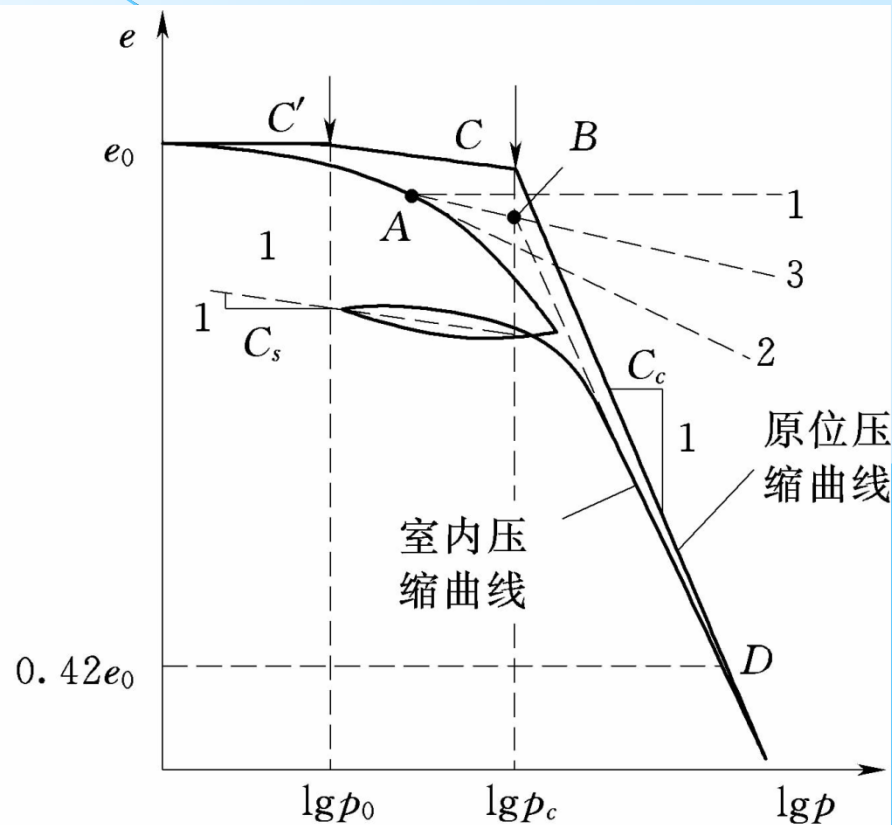
图5-9 作图法确定先期固结压力 p_c

➤ 原位压缩曲线的推求 (图5-10)

Determination of In-situ Compression Curve



(a) 正常固结土



(b) 超固结土

图5-10 原位压缩曲线的推求

➤ 压缩量计算 Calculation of Settlement

$$S = \frac{e_1 - e_2}{1 + e_1} H \quad (5-17)$$

$$S = \frac{a_v(p_2 - p_1)}{1 + e_1} H = \frac{a_v}{1 + e_1} pH \quad (5-18)$$

$$S = \frac{p}{E_s} H = m_v pH \quad (5-19)$$

$$S = \frac{C_c(\lg p_2 - \lg p_1)}{1 + e_1} H = C_c \frac{H}{1 + e_1} \lg \left(\frac{p_2}{p_1} \right) \quad (5-20)$$

5.3.2 单向压缩分层总和法

Layered Summation Method for One-dimensional Compression

- **绘制计算简图** Plot the calculation sketch (图5-13)
- **计算地基中的自重应力和附加应力**
Calculate Gravity Stress and Additional Stress in Foundation
 - 自重应力分布 (Gravity stress distribution)
 - 基底 (有效) 压力 p (或 p') 和 **基底 (有效) 附加压力** $p-\gamma D$ (或 $p'-\gamma D$)
(Effective) Contact Pressure and (Effective) Additional Contact Pressure

➤ 附加应力分布 Increased Stress Distribution

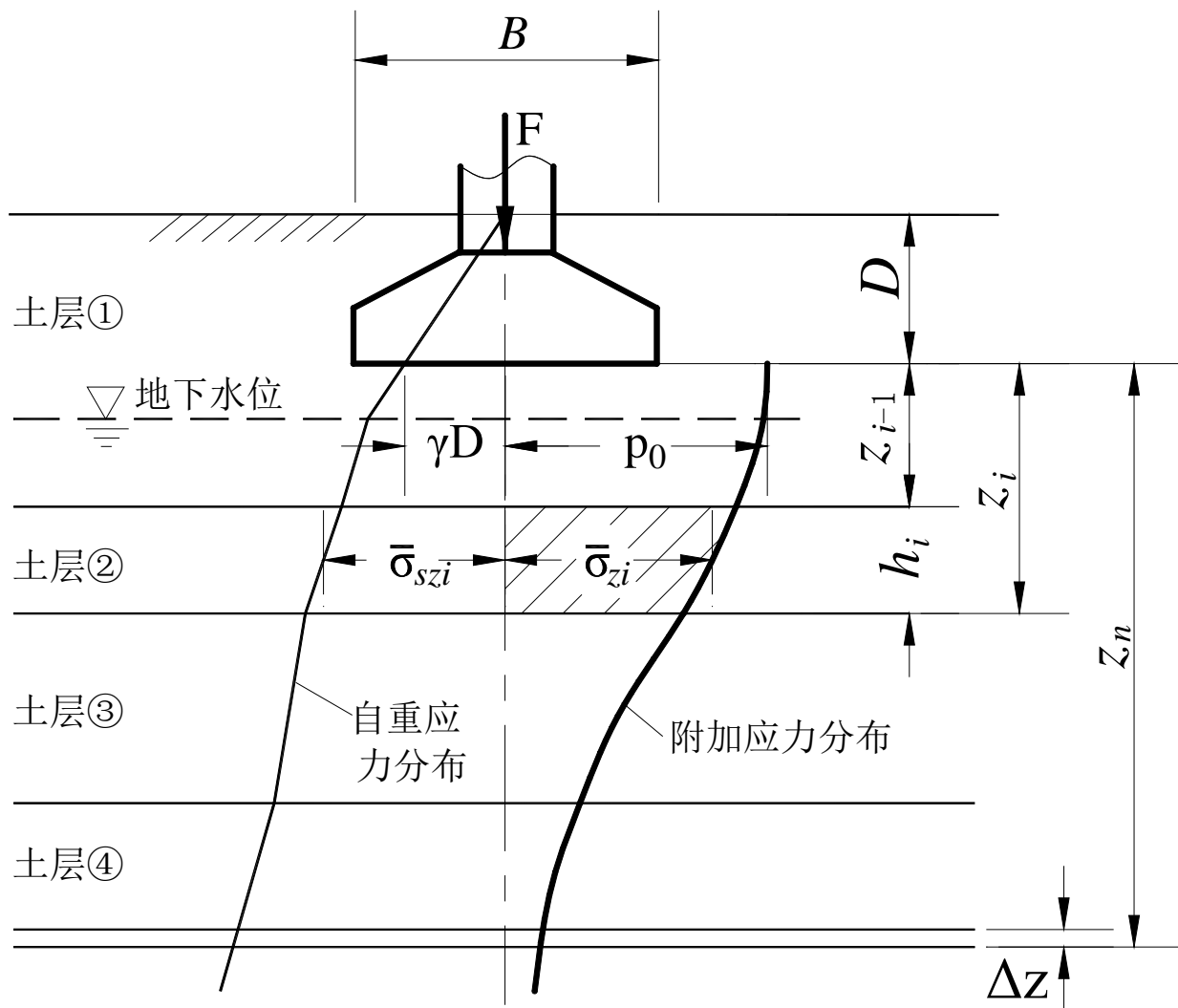


图5-13 自重、附加应力分布及受压层下限

➤ 确定地基分层厚度 Determination of Layer Thickness of Foundation

➤ 分层面 Interface between Layers (包括地下水位线)

➤ 层厚 $\Delta h_i = 2 \sim 4 \text{ m}$, 且 $\Delta h_i \leq 0.4B$

➤ 确定沉降计算深度 Determination of Depth of Settlement Calculation

➤ 应力控制法 (图5-13) Stress Control Method

一般 $\sigma_z = 0.2\sigma_{sz}$ 软弱地基土 $\sigma_z = 0.1\sigma_{sz}$

➤ 变形控制法 Strain control method

➤ 有相邻荷载影响
$$\Delta S'_n \leq 0.025 \sum_{i=1}^n \Delta S'_i \quad (5-21)$$

$\Delta S'_n$ 对应的计算厚度 Δz 的取值见表5-3

表5-3 土层厚度 Δz 的取值表

基础宽度 B (m)	$B \leq 2$	$2 < B \leq 4$	$4 < B \leq 8$	$8 < B \leq 15$
土层厚度 Δz (m)	0.3	0.6	0.8	1.0

➤ 无相邻荷载影响 $Z_n = B(2.5 - 0.4 \ln B)$ (5-22)

➤ 变形计算 Deformation Calculation (图5-13)

➤ 计算各小分层的应力

$$\bar{\sigma}_{si} = \frac{(\sigma_{si})_{\text{上}} + (\sigma_{si})_{\text{下}}}{2} \quad (5-23)$$

$$\bar{\sigma}_{zi} = \frac{(\sigma_{zi})_{\text{上}} + (\sigma_{zi})_{\text{下}}}{2} \quad (5-24)$$

荷载 p_{1i} 、 p_{2i} 的计算分两种情况：

① 在自重作用下已固结

$$p_{1i} = \sigma_{si}, \quad p_{2i} = \sigma_{si} + \sigma_{zi}$$

② 在自重作用下未固结

$$p_{1i} = p_c \quad p_{2i} = \bar{\sigma}_{si} + \bar{\sigma}_{zi}$$

$$\Delta p = \bar{\sigma}_{si} + \bar{\sigma}_{zi} - p_c$$

➤ 根据荷载 p_{1i} 、 p_{2i} 在 $e \sim p$ 曲线上查得相应的 e_{1i} 、 e_{2i}

➤ 按 $\Delta S_i = \frac{e_{1i} - e_{2i}}{1 + e_{1i}} \Delta h_i$ 计算各分层的变形

➤ 用下式计算地基的最终变形

$$S = \sum_{i=1}^n \Delta S_i \quad (5-25)$$

5.3.1 《建筑地基基础设计规范》推荐方法 Commended Method of Design Code

$$S = \psi_s S' = \psi_s \sum_{i=1}^n \frac{p_0}{E_{si}} (Z_i \bar{\alpha}_i - Z_{i-1} \bar{\alpha}_{i-1}) \quad (5-26)$$

沉降计算经验系数见表5-7

表5-7 沉降计算经验系数 ψ_s 值

\bar{E}_s (MPa)	2.5	4.0	7.0	15.0	20.0
基底附加压力					
$p_0 \geq f_{ak}$	1.4	1.3	1.0	0.4	0.2
$p_0 \leq 0.75 f_{ak}$	1.1	1.0	0.7	0.4	0.2

表中

$$\bar{E}_s = \frac{\sum \Delta A_i}{\sum \frac{\Delta A_i}{E_{si}}} = \frac{p_0 \sum_{i=1}^n (z_i \bar{\alpha}_i - z_{i-1} \bar{\alpha}_{i-1})}{p_0 \sum_{i=1}^n \frac{(z_i \bar{\alpha}_i - z_{i-1} \bar{\alpha}_{i-1})}{E_{si}}} = \frac{\sum_{i=1}^n (z_i \bar{\alpha}_i - z_{i-1} \bar{\alpha}_{i-1})}{\sum_{i=1}^n \frac{(z_i \bar{\alpha}_i - z_{i-1} \bar{\alpha}_{i-1})}{E_{si}}} \quad (5-31)$$

式中的 ΔA_i 见[图5-16](#)中阴影所示

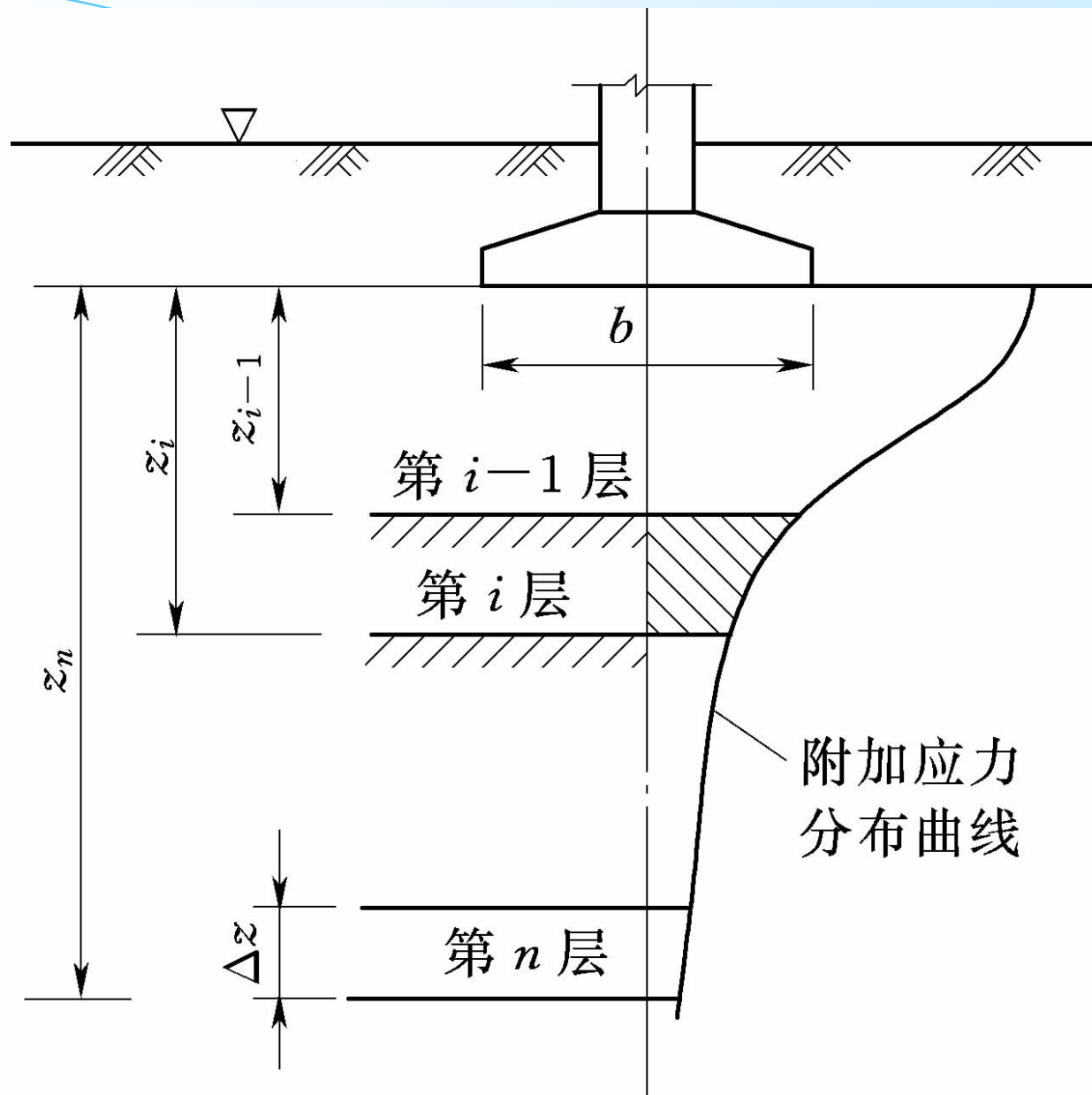


图5-16 基础沉降计算分层示意

5.3.3 考虑应力历史的地基最终变形计算

Final deformation Calculation of Foundation Considering Stress History

➤ 正常固结土 (图5-18)

Normally Consolidated Soil

$$\Delta e = e_0 - e_1 = C_{ci} \lg \left(\frac{p_0 + \Delta p}{p_0} \right) \quad (5-32)$$

$$S = \frac{e_0 - e_1}{1 + e_0} H$$

$$S = \frac{C_c}{1 + e_0} H \lg \left(\frac{p_0 + \Delta p}{p_0} \right) \quad (5-33)$$

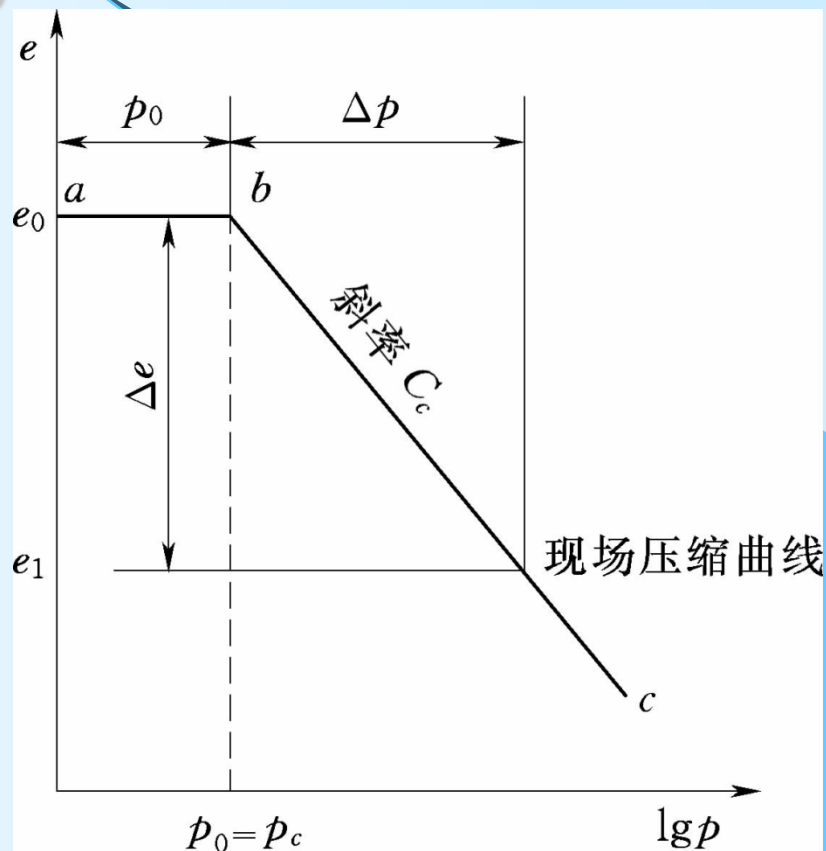


图5-18 正常固结土的现场压缩 $e - \lg p$ 曲线

欠固结土 (图5-19)

Underconsolidated Soil

(1) 由自重应力产生的变形 S_1

(2) 由附加应力产生的变形 S_2

$$S = S_1 + S_2$$

$$= \frac{\Delta e''}{1 + e_c} H + \frac{\Delta e'}{1 + e_0} H_0 \quad (5-34)$$

$$= \frac{H}{1 + e_c} C_c \lg \frac{p_0}{p_c} \quad (5-35)$$

$$+ \frac{H_0}{1 + e_0} C_c \lg \left(\frac{p_0 + \Delta p}{p_0} \right)$$

$$S = \frac{H}{1 + e_c} C_c \lg \left(\frac{p_0 + \Delta p}{p_c} \right)$$

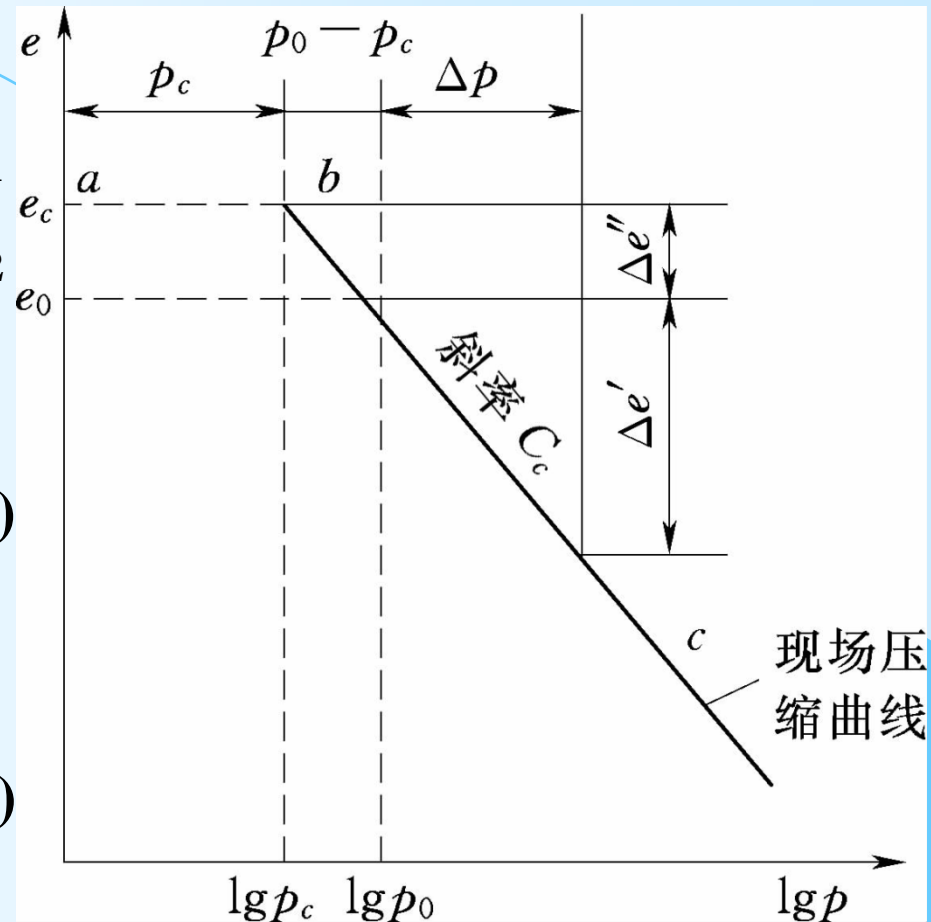


图5-19 欠固结土的现场压缩 $e - \lg p$ 曲线

➤ **超固结土 (Overconsolidated soil)** (图5-20)

➤ 当 $\Delta p > p_c - p_0$ 时

$$\text{超固结段 } \Delta e' = C_s \lg \left(\frac{p_c}{p_0} \right) \quad (5-36)$$

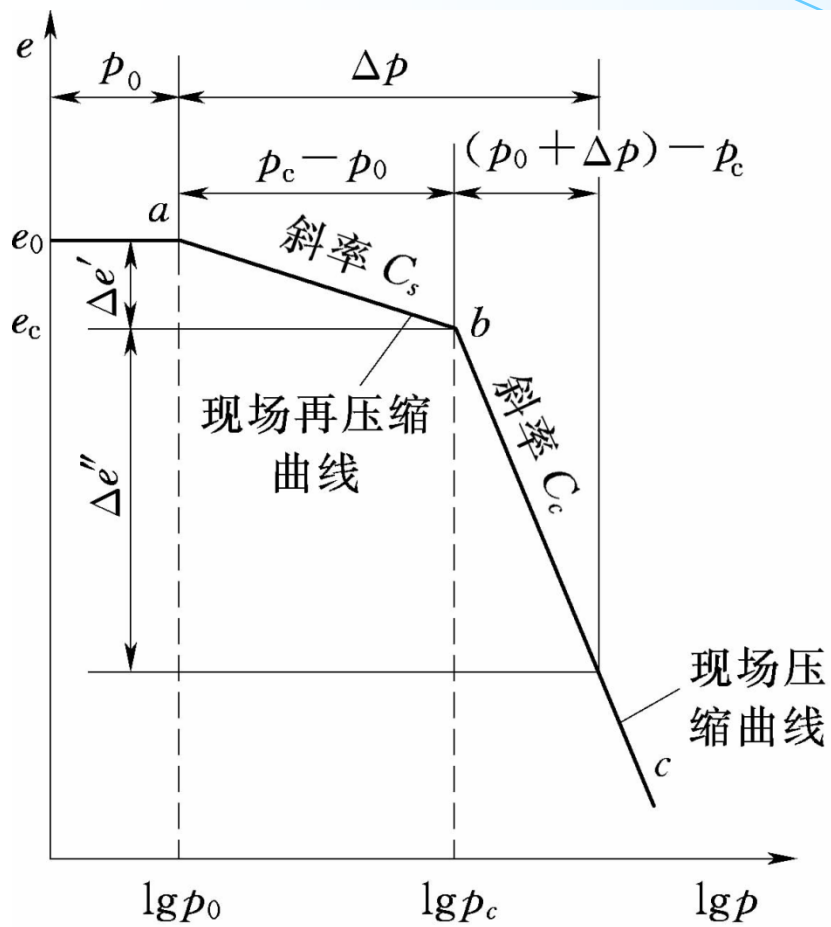
$$\text{正常固结段 } \Delta e'' = C_c \lg \left(\frac{p_0 + \Delta p}{p_c} \right) \quad (5-37)$$

$$\begin{aligned} S &= S_1 + S_2 = \frac{\Delta e'}{1 + e_0} H + \frac{\Delta e''}{1 + e_c} H_c \\ &= \frac{H}{1 + e_0} C_s \lg \frac{p_c}{p_0} + \frac{H_c}{1 + e_c} C_c \lg \left(\frac{p_0 + \Delta p}{p_c} \right) \end{aligned} \quad (5-38)$$

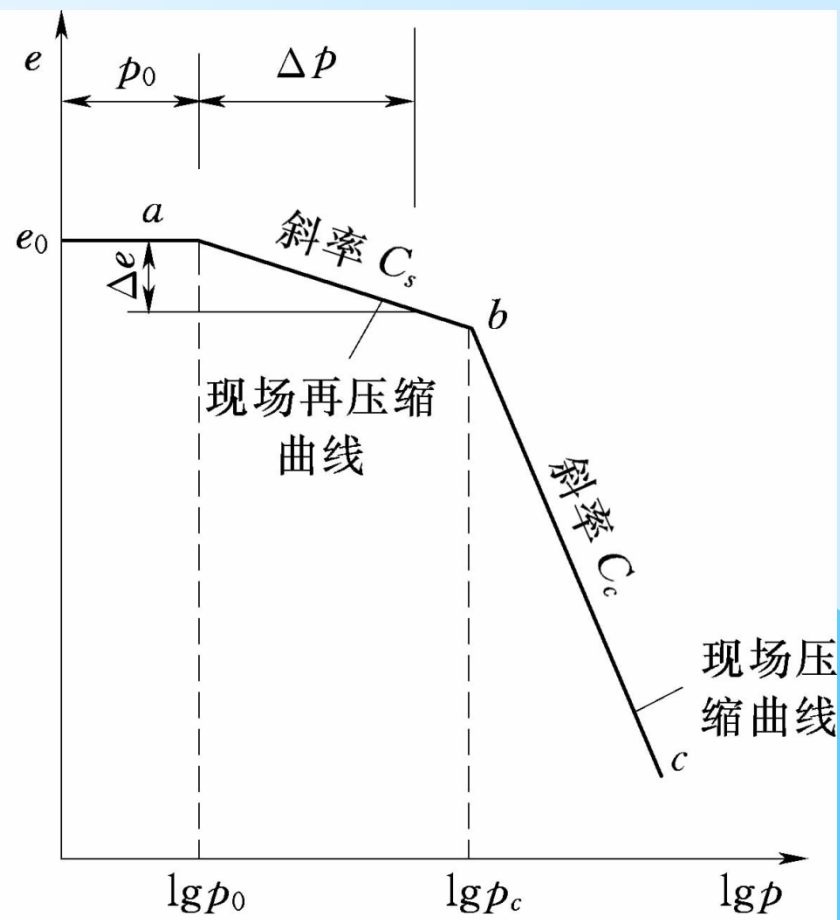
➤ 当 $\Delta p < p_{ci} - p_{0i}$ 时

$$S = \frac{\Delta e}{1 + e_0} = \frac{H}{1 + e_0} C_s \lg \left(\frac{p_0 + \Delta p}{p_0} \right) \quad (5-39)$$





(a) $\Delta p > p_c - p_0$



(b) $\Delta p \leq p_c - p_0$

图5-20 超固结土在现场压缩 $e - \lg p$ 曲线

5.4 饱和粘土的一维固结理论

5.4 One-dimensional Consolidation Theory for Saturated Cohesive Soil

5.4.1 饱和土的单向固结模型

One-dimensional Consolidation Model for Saturated Soil

➤ **模型组成** (Model Composition)

- (1) 弹簧 (Spring)—土骨架 (Soil Skeleton)
- (2) 水(Water)—土中水(Water in Soil)
- (3) 开孔活塞板 (Piston with Hole) —土的排水条件 (Drainage Condition of Soil)
- (4) 容器 (Container) —侧限条件 (Confining Condition)

➤ **固结过程 (Consolidation Process)**

$$t = 0, u = \Delta p, \sigma' = 0$$

$$0 < t < \infty, u \neq 0, \sigma' \neq 0, u + \sigma' = \Delta p$$

$$t \rightarrow \infty, u = 0, \sigma' = \Delta p$$

➤ **超静水压力 u**

Excess pore water pressure

➤ **超静水头 Δh**

$$\Delta h = \frac{u}{\gamma_w} = \frac{\Delta p}{\gamma_w}$$

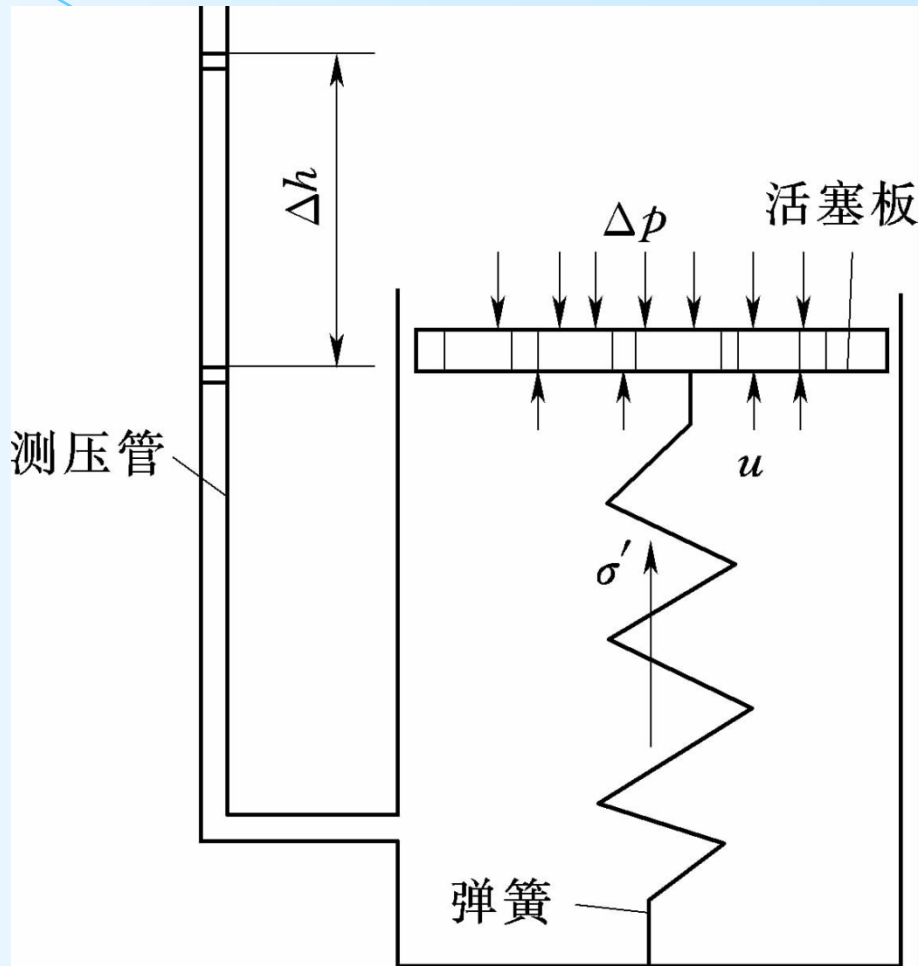


图5-22 太沙基饱和土单向固结模型

5.4.3 单向固结微分方程的建立及其解答

Establish and solution of one-dimensional consolidation differential equation

➤ 基本假定 (Basic assumption)

- (1) 土体是均质饱和的；
- (2) 土颗粒和孔隙水不可压缩；
- (3) 土中的渗流和变形是一维的；
- (4) 土中的渗流符合达西定律；
- (5) 固结过程中的土的渗透系数和压缩系数为常数；
- (6) 外部荷载连续均布且一次性施加；
- (7) 土体的固结变形是微小的。

一维渗流固结微分方程的建立(图5-23)

孔隙体积 Void Volume

土颗粒体积 Soil Particle Volume

$$V_v = \frac{e}{1+e_0} dx dy dz$$

$$V_s = \frac{1}{1+e_0} dx dy dz$$

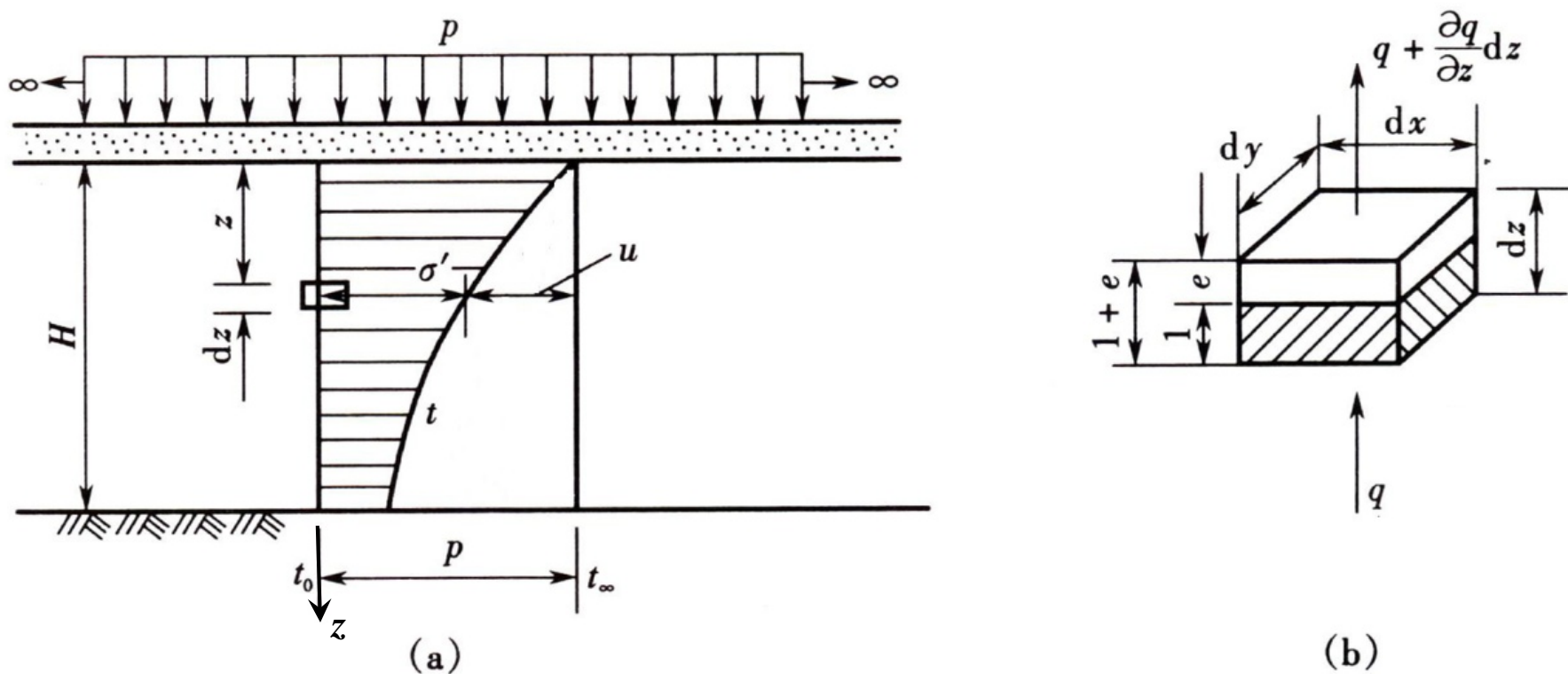


图5-23 饱和土的单向固结过程

(a) 土层情况及时刻 t 有效应力和孔隙水压力分布； (b) 深度 z 处的微元体

(1) 微分体中水量变化 Water Volume Change in Micro-element

$$dQ = \left[\left(q + \frac{\partial q}{\partial z} dz \right) - q \right] dt = \frac{\partial q}{\partial z} dz dt \quad (5-41)$$

(2) 孔隙体积变化为(Change of void volume)

$$dV = dV_v = \frac{\partial V_v}{\partial t} dt = \frac{\partial}{\partial t} \left(\frac{e}{1+e_0} dz \right) dt = \frac{1}{1+e_0} \frac{\partial e}{\partial t} dz dt \quad (5-42)$$

(3) 水量与孔隙体积变化相等

$$\frac{\partial q}{\partial z} dz dt = \frac{1}{1+e_0} \frac{\partial e}{\partial t} dz dt \quad \longrightarrow \quad \frac{\partial q}{\partial z} = \frac{1}{1+e_0} \frac{\partial e}{\partial t}$$

$$\text{由 } de = -a_v d\sigma' \quad \text{得} \quad \frac{\partial e}{\partial t} = -a_v \frac{\partial \sigma'}{\partial t}$$

$$\frac{\partial e}{\partial t} = -a_v \frac{\partial(\sigma - u)}{\partial t} = a_v \frac{\partial u}{\partial t}$$

将上式代入式 (5-33)，得

$$\frac{\partial q}{\partial z} = \frac{a_v}{1 + e_0} \frac{\partial u}{\partial t} \quad (5-44)$$

由达西定律，得

$$v = ki = \frac{k}{\gamma_w} \frac{\partial u}{\partial z} \quad (5-45)$$

将上式代入式 (5-36) ($A = dx dy = 1$, 则 $q = v$), 得

$$\frac{k}{\gamma_w} \frac{\partial^2 u}{\partial z^2} = \frac{a_v}{1 + e_0} \frac{\partial u}{\partial t} \quad (5-46)$$

$$\frac{k(1 + e)}{\gamma_w a_v} \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \quad (5-47)$$

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \quad (5-48)$$

式中, $C_v = \frac{k(1+e)}{\gamma_w a_v}$ 为固结系数, cm^2/yr ,

Coefficient of Consolidation

➤ **微分方程的解**

Solution of the Differential Equation

初始条件: $t = 0$, $0 \leq z \leq H$, $u_0 = p$

边界条件 透水边界: $z = 0$, $u = 0 (0 \leq t < \infty)$;

不透水边界: $z = H$, $\frac{\partial u}{\partial z} = 0 (0 \leq t < \infty)$

$$u = \frac{4p}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin \frac{n\pi z}{2H} e^{-\frac{n^2 \pi^2}{4} T_v} \quad (5-49)$$

式中, $T_v = \frac{C_v t}{H^2}$ 为无因次时间因素 (Time Factor)

5.4.4 固结度及其应用

Degree of Consolidation and Application

➤ 固结度 U_t 的概念及求解

Concept of Degree of Consolidation and Solution

➤ 概念 Conception

$$U_{zt} = \frac{\sigma'}{p} = \frac{p-u}{u_0} = 1 - \frac{u}{u_0} \quad (5-50)$$

$$U_t = 1 - \frac{\int_0^H u dz}{\int_0^H p dz} = \frac{\int_0^H \sigma'_t dz}{pH} = \frac{m_v \int_0^H \sigma'_t dz}{m_v pH} = \frac{S_t}{S} \quad (5-51)$$

固结度：地基在一定压力作用下，经某段时间产生的变形量 S_t 与地基最终变形量 S 的比值

将式 (5-49) 代入式 (5-51) 中, 积分后得

$$U_t = 1 - \frac{8}{\pi^2} \left(e^{-\frac{\pi^2}{4}T_v} + \frac{1}{9}e^{-9\frac{\pi^2}{4}T_v} + \frac{1}{25}e^{-25\frac{\pi^2}{4}T_v} + \dots \right) = 1 - \frac{8}{\pi^2} \sum_{m=1}^{\infty} \frac{1}{m^2} e^{-m^2\frac{\pi^2}{4}T_v} \quad (5-52)$$

实用上常取无穷级数的第1项即可满足要求, 则有

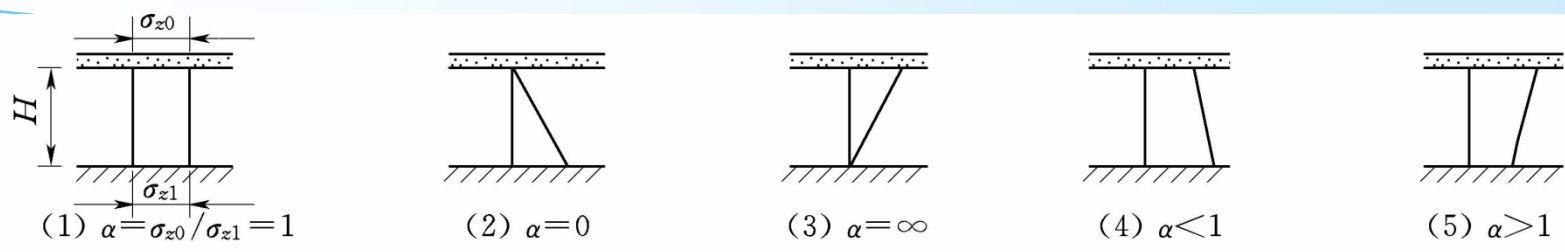
$$U_t = 1 - \frac{8}{\pi^2} e^{-\frac{\pi^2}{4}T_v} = f(T_v) = f(C_v, t, H^2) \quad (5-53)$$

不同应力分布下 U_t-T_v 关系曲线如图5-24

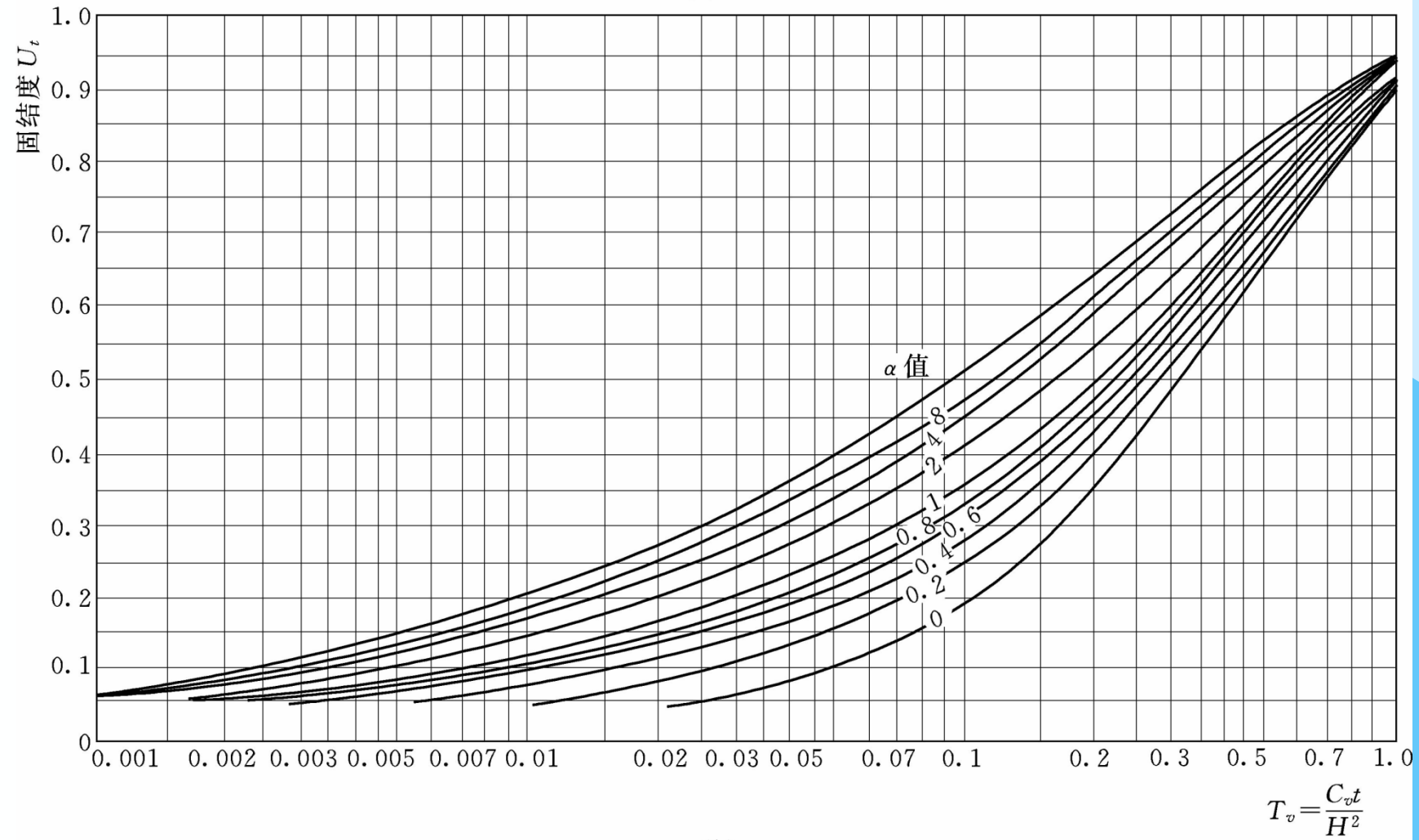
For Half-closed layer

$$\alpha = \frac{\text{透水面处的应力 } \sigma_{z0}}{\text{不透水面处的应力 } \sigma_{z1}}$$

For two-way drainage (Open layer), $\alpha = 1.0$



(a)



(b)

图5-22 典型简化附加应力分布下固结度 U_t 与时间因数 T_v 的关系曲线

➤ 地基变形与时间的关系

➤ 求某特定时刻 t 的变形 S_t

先求 S ，然后

$$C_v = \frac{k(1+e)}{\gamma_w a} = \frac{k}{\gamma_w} E_s$$

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

$k, a, e \longrightarrow C_v \longrightarrow T_v$

$U_t \sim T_v$ 曲线

$\longrightarrow U_t \longrightarrow S_t = U_t S \quad (5-54)$

➤ 求土层达到一定变形 S_t 时所需时间 t

$$U_t = \frac{S_t}{S}$$

$S, S_t \longrightarrow U_t \xrightarrow{U_t \sim T_v \text{ 曲线}} T_v \longrightarrow t = \frac{H^2 T_v}{C_v}$

(5-55)

► 等速逐渐加载的一维固结问题的修正方法

① 绘制一次瞬时加载的 U_t-t 关系曲线 a 线

② 在 $0 < t < t_0$ 段,

$$U_t = U_{\frac{t}{2}} \frac{p_t}{p}$$

③ 在 $t > t_0$ 段,

$$U'_t = U_{(t-t_0)/2}$$

上述修正采用的

假设见 **P119-120**

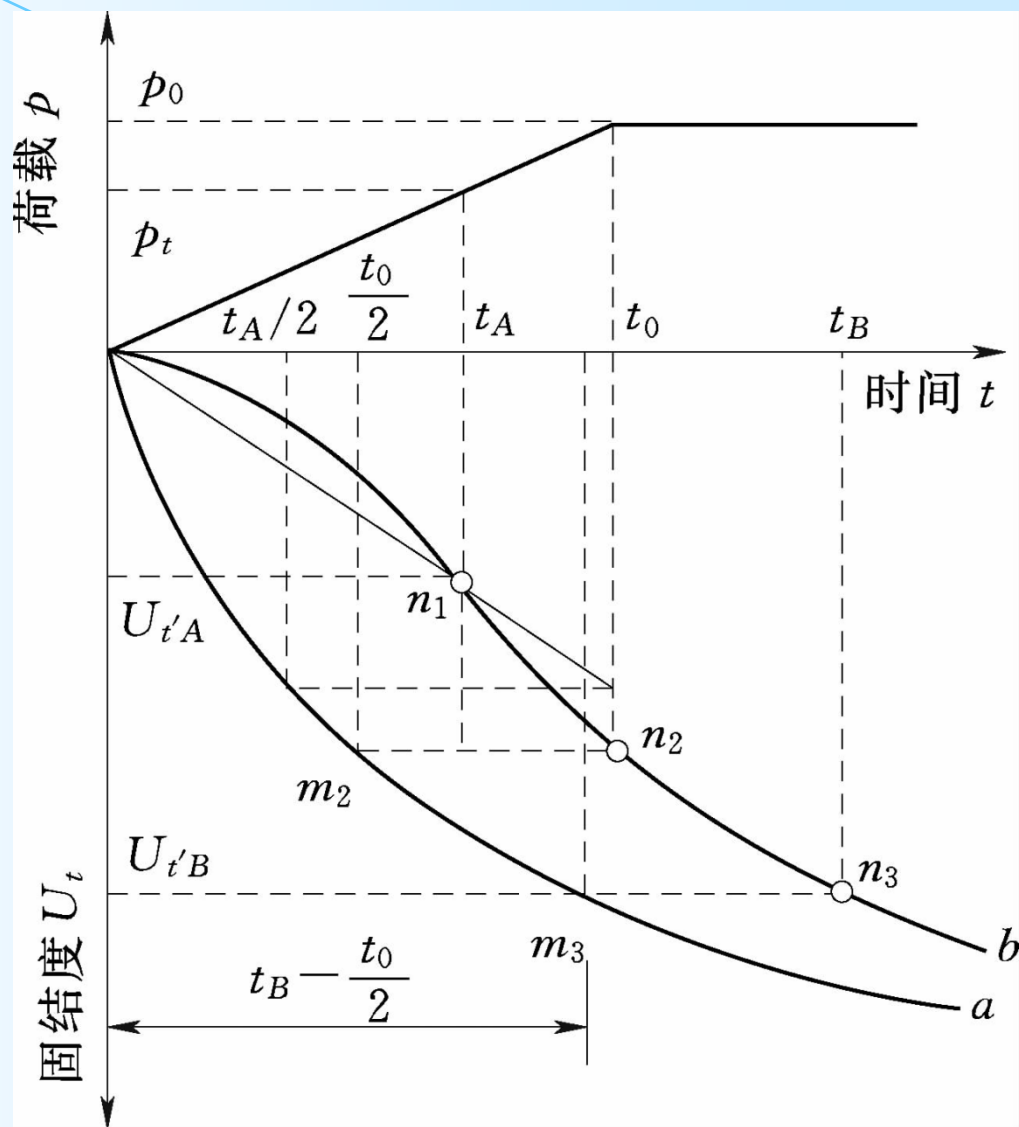


图5-26 单向逐渐等速加荷固结曲线的绘制

➤ 固结系数 C_v 的确定

Determination of Coefficient of Consolidation

➤ 时间平方根法 (The Root Time Method) (图5-27)

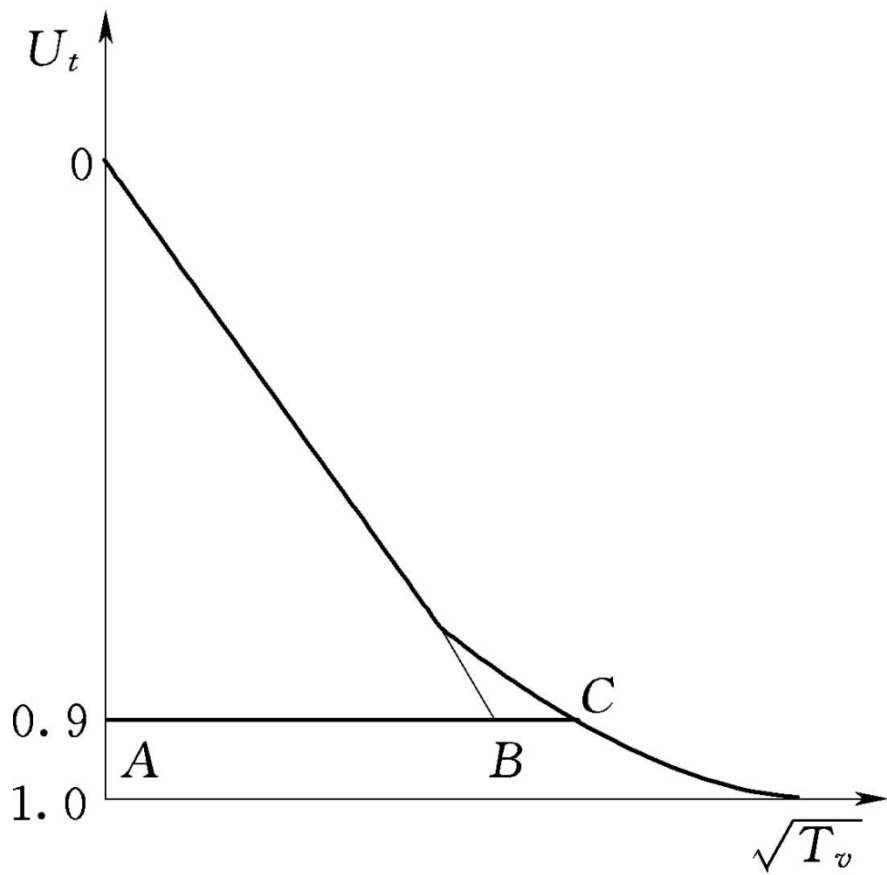
➤ 绘制变形量与时间平方根的关系曲线

➤ 延长直线段交纵轴于 R_0 ，作与 R_0b 的横坐标之比为 1.15 的直线 R_0c 交原固结曲线于 c 点

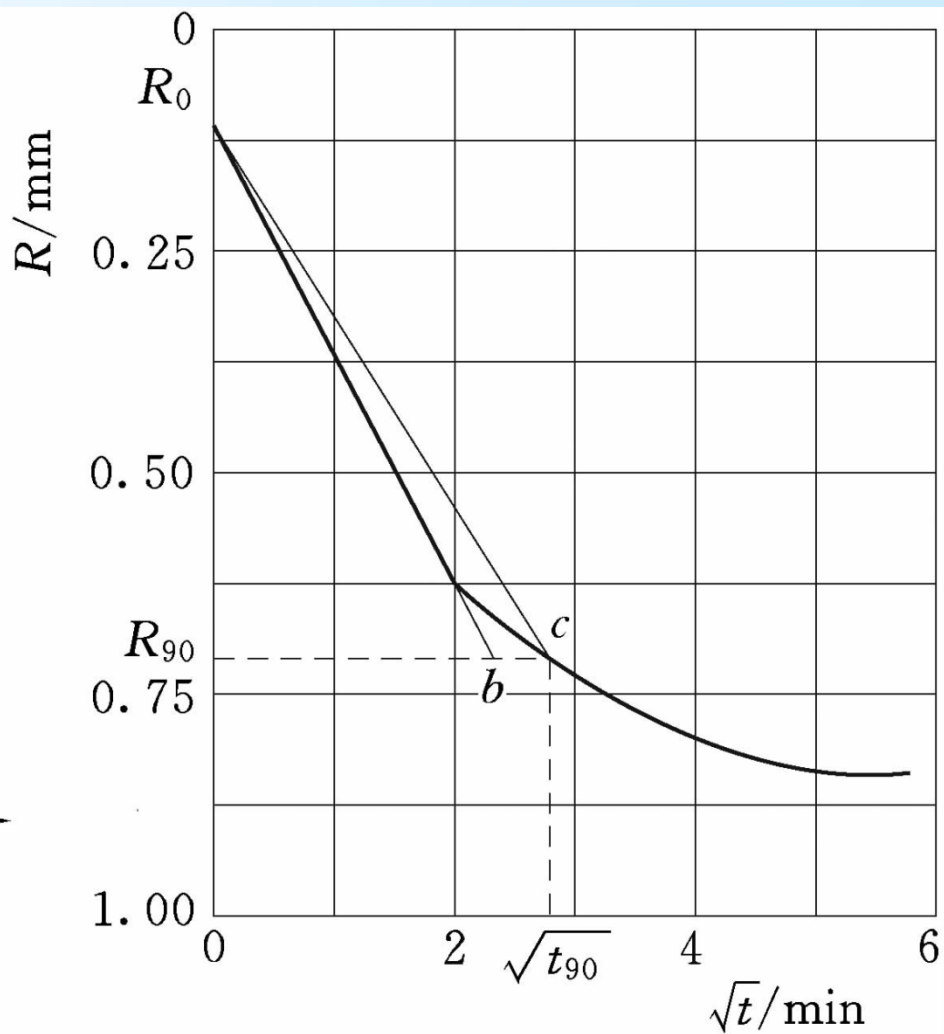
➤ C 点对应的横坐标为 t_{90} 的平方根，纵坐标为 R_{90} ，对应固结度 $U_t=90\%$ ，进而可以求得相应 $T_v=0.848$ ，则有

$$C_v = \frac{0.848H^2}{t_{90}} \quad (5-56)$$





(a)

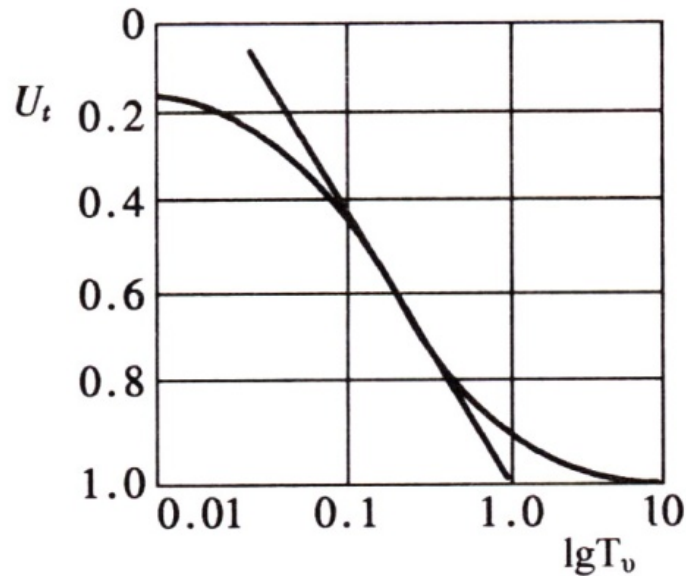


(b)

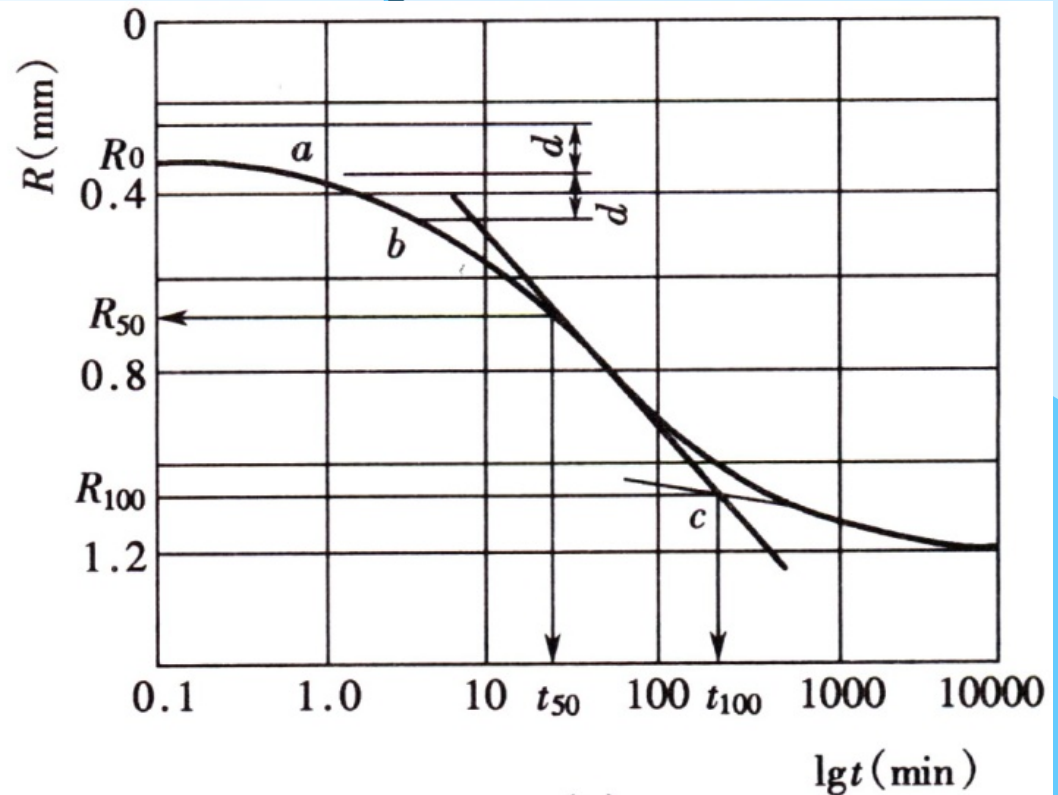
图5-27 时间平方根法求 C_v
 (a) 理论固结曲线； (b) 试验曲线

➤ 时间对数法 (The Log Time Method) (图5-28)

$$C_v = \frac{0.196H^2}{t_{50}} \quad (5-49)$$



(a)



(b)

图5-28 时间对数法求 C_v
 (a) 理论固结曲线; (b) 试验曲线

5.5 土的多维变形与固结

5.5 Three-dimensional Deformation and Consolidation

5.5.1 地基总变形的组成 (图5-29)

Composition of Total Deformation

$$S = S_d + S_c + S_s \quad (5-58)$$

5.5.2 瞬时变形 S_d 的计算

Calculation of Immediate Deformation

$$S_d = pB \left(\frac{1 - \mu^2}{E} \right) C_d \quad (5-59)$$

C_d 为形状系数 (Shape Coefficient), 见表5-11

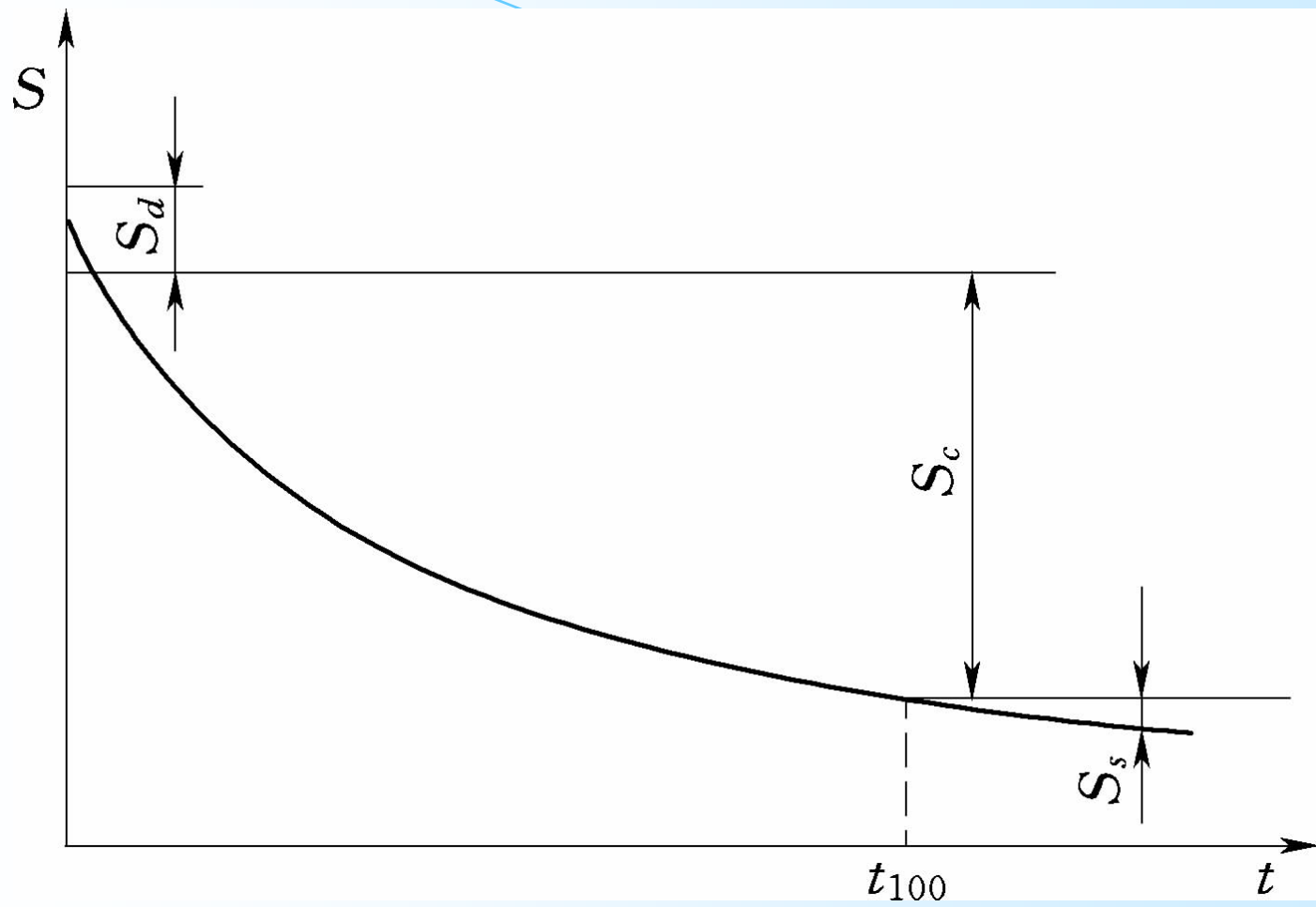


图5-29 地基受荷历时与变形关系曲线

表 5-11

地基表面荷载面积内若干点处的沉降系数

形状 \ 位置		中心	角点	短边中心	长边中心	平均值
圆		1.00	0.64	0.64	0.64	0.85
圆 (刚性的)		0.79	0.79	0.79	0.79	0.79
正方形		1.12	0.56	0.76	0.76	0.95
正方形 (刚性的)		0.89	0.89	0.89	0.89	0.89
矩形 (长边/短边)	1.5	1.36	0.67	0.89	0.97	1.15
	2	1.52	0.76	0.98	1.12	1.30
	3	1.78	0.88	1.11	1.35	1.52
	5	2.10	1.05	1.27	1.68	1.83
	10	2.53	1.26	1.49	2.12	2.25
	100	4.00	2.00	2.20	3.60	3.70
	1000	5.47	2.75	2.94	5.03	5.15
	10000	6.90	3.50	3.70	6.50	6.60

5.5.3 多维压缩条件下的固结变形计算（自学）

5.5.4 次固结变形 S_s （图5-32）

Secondary consolidation deformation

$$\Delta e = -C_\alpha \lg \frac{t}{t_1}$$

(5-65)

$$S_s = \frac{H}{1+e_0} C_\alpha \lg \frac{t_2}{t_1}$$

(5-66)

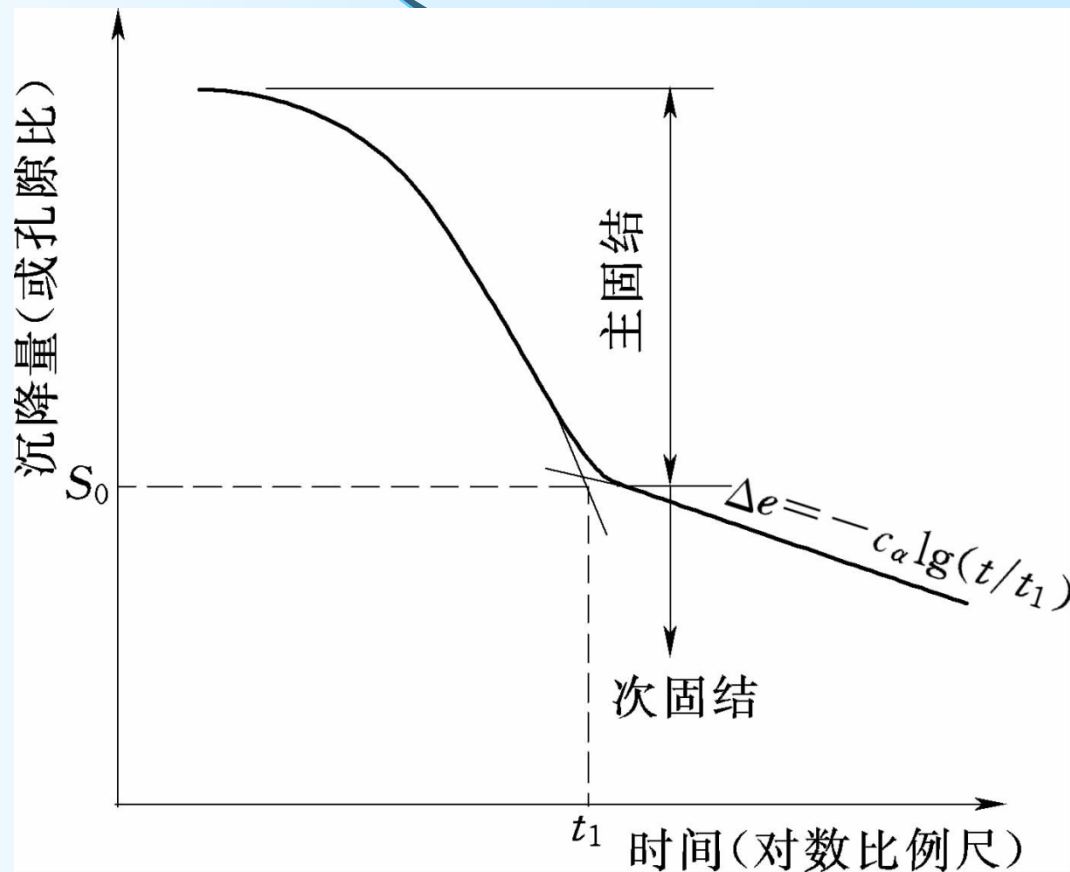


图5-30 次固结沉降量（或孔隙比）与时间的关系曲线

5.6 地基变形控制

5.6 Deformation Control of Foundation

5.6.1 地基的变形控制指标

Control Parameter of Foundation Deformation

➤ **沉降量 Settlement**

指建筑物基础底面某点的绝对竖向变形量

➤ **沉降差 Settlement Difference**

指建筑物基础底面某两点或同一建筑物中相邻两个基础的沉降量之差。

➤ **倾斜 Inclination:** 指单独基础倾斜方向两端点的沉降差与其距离的比值，以‰表示

➤ **局部倾斜 Local Inclination:** 指砖石砌体承重结构沿纵墙6~10m内基础两点的沉降差与其距离的比值，以‰表示

5.6.1 地基的允许变形量

Allowable Deformation of Foundation

- 房屋和构筑物的地基允许变形 (表5-12)

Foundation Allowable Deformation for Building

- 土坝和土堤: $[S]=(0.5\% \sim 1.0\%)H$

- 港口工程重力式码头

方块码头和扶壁式码头为150~200 mm; 沉箱码头为200~250 mm

- 水闸地基

最大沉降量不宜超过15 cm, 相邻部位的最大沉降差不宜超过5 cm



表 5-12

建筑物的地基变形允许值

变形特征		地基土类型	中、低压缩性土	高压缩性土
		砌体承重结构基础的局部倾斜		
工业与民用建筑 相邻柱基的沉降差	框架结构		0.0021	0.0031
	砌体墙填充的边排柱		0.00071	0.0011
	当基础不均匀沉降时不产生附加应力的结构		0.0051	0.0051
单层排架结构（柱距为 6m）柱基的沉降量/mm			(120)	200
桥式吊车轨面的倾斜（按不 调整轨道考虑）	纵向		0.004	
	横向		0.003	
多层和高层建筑的 整体倾斜	$H_g \leq 24$		0.004	
	$24 < H_g \leq 60$		0.003	
	$60 < H_g \leq 100$		0.0025	
	$H_g > 100$		0.002	
体型简单的高层建筑基础的平均沉降量/mm			200	
高耸结构基础的 倾斜	$H_g \leq 20$		0.008	
	$20 < H_g \leq 50$		0.006	
	$50 < H_g \leq 100$		0.005	
	$100 < H_g \leq 150$		0.004	
	$150 < H_g \leq 200$		0.003	
	$200 < H_g \leq 250$		0.002	
高耸结构基础的 沉降量/mm	$H_g \leq 100$		400	
	$100 < H_g \leq 200$		300	
	$200 < H_g \leq 250$		200	

5.6.1 减小地基沉降的措施（自学）

Measure to Decrease Settlement of Foundation

- **上部结构设计 Design of Upper Structure**
- **基础设计 Design of Footing**
- **地基处理 Improvement of Foundation**