# 14 整体式隧道结构

# 本讲内容

- 14.1 概述
- 14.2 半衬砌结构
- 14.3 直墙拱结构
- 14.4 复合衬砌结构
- 14.5 连拱隧道结构

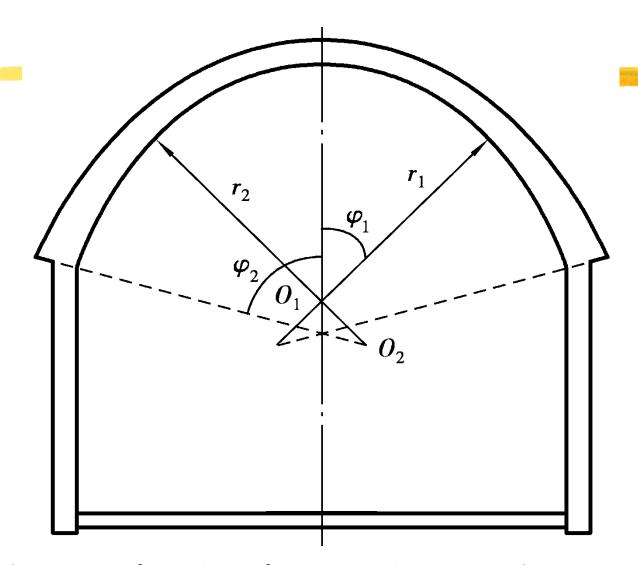


#### 14.1 概述

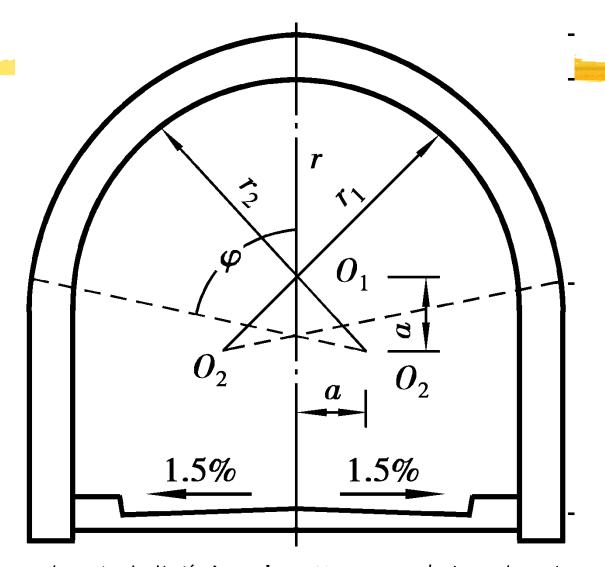
#### 14.1.1 结构形式、受力特点和适用条件

隧道的结构形式可根据地层的类别、使用功能和施工技术水平等进行选择。

按照结构形式的不同,可分为半衬砌结构、厚拱薄壁衬砌结构、直墙拱形衬砌结构、曲墙结构和连拱隧道等形式。

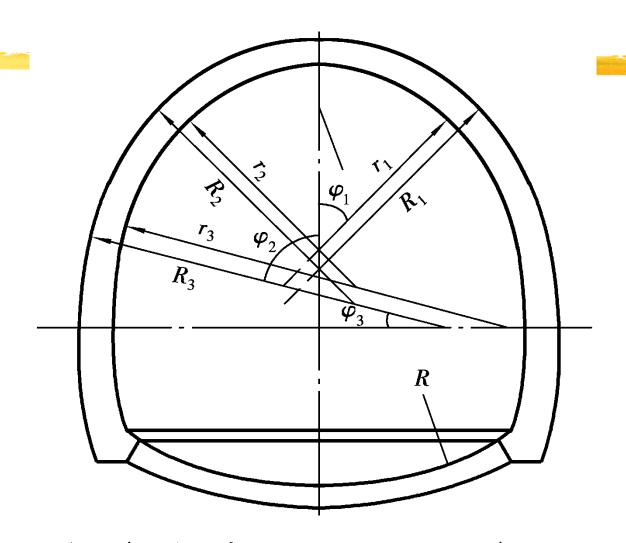


在坚硬或中硬岩层中,利用岩石的强度,拱顶承受主要荷载,边墙受力较小。



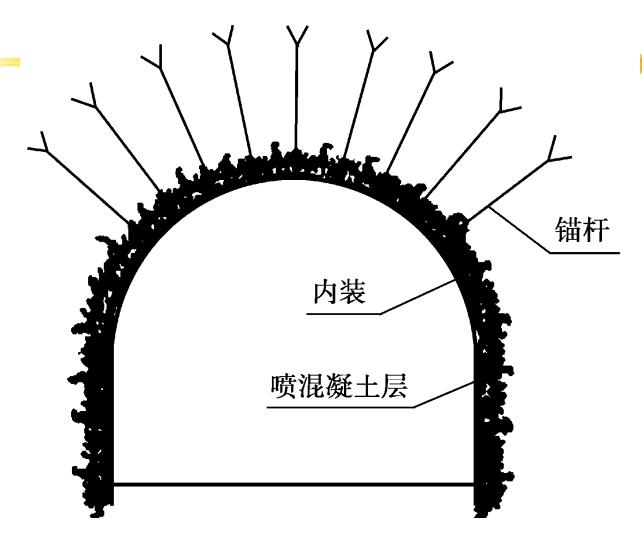
在一般或较差岩层中,拱顶和边墙浇注在一起,形成一个整体结构,共同承受荷载,是常用的结构形式。

#### 曲墙衬砌结构



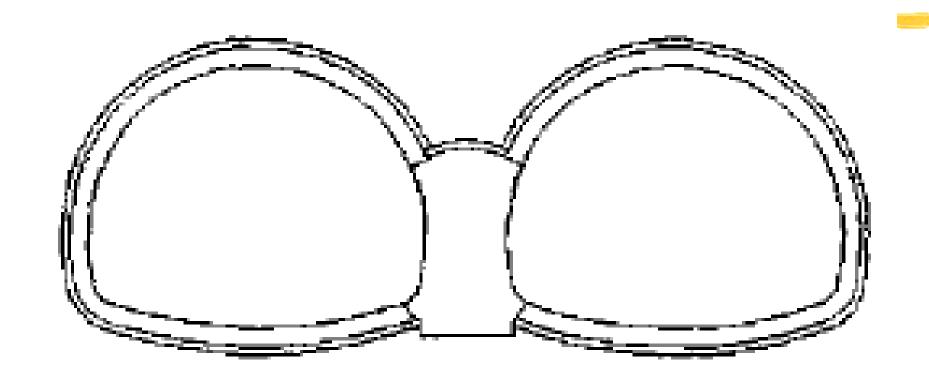
在很差的岩层中,由拱圈、曲线形侧墙和仰拱形板组成,受力性好,施工要求高,也是常用的结构形式。

#### 复合衬砌结构



首先加固围岩,围岩变形趋于稳定后,再施作内衬永久支护。通常由初期支护和二次支护组成。

#### 连拱隧道结构



适用于洞口地形狭窄,或对两洞间距有特殊要求的 中短隧道。

# 14.1.2 隧道结构设计的一般技术要求

A 衬砌截面类型和几何尺寸的确定

类型应根据隧道围岩地质条件、施工条件和使用要求确定;

几何尺寸应根据内部净跨、净高、墙高以及拱轴形状、厚度及其变化规律确定。

# B衬砌材料的选择

村砌材料应具有足够的强度、耐久性和防水性; 在特殊 条件下还要具有抗侵蚀性和抗冻性。

常用材料主要有混凝土、喷射混凝土、钢筋混凝土及石材等。其中混凝土和钢筋混凝土比较常用。

# C衬砌结构的一般构造要求

#### C.1 混凝土保护层

最小厚度一般装配式衬砌为20mm, 现浇衬砌内层为25mm, 外层为30mm; 钢筋网喷混凝土一般为20mm。

随着截面厚度的增加,保护层厚度也应适当增加。

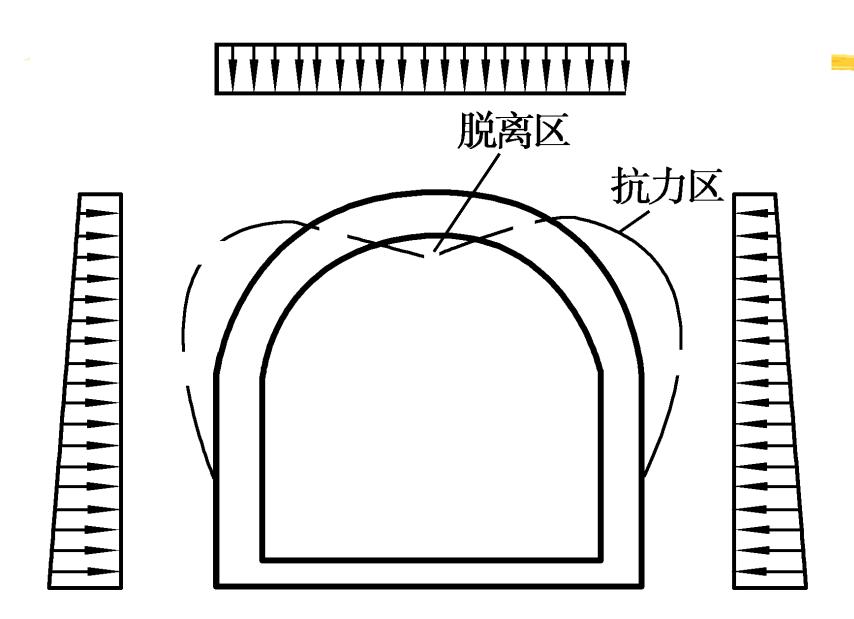
#### C.2 衬砌的超挖和欠挖

现浇混凝土衬砌一般不允许欠挖,个别欠挖部分深度不得超过衬砌截面厚度的1/4,并不得大于15cm。

超挖允许值一般也不宜超过15cm。

#### C.3 变形缝的设置

沉降缝和伸缩缝。宽度应大于20mm,缝内可夹沥青木板和沥青麻丝。



# 设计计算方法

| <u> </u> | <b>*</b> ***                                      |   |  |
|----------|---|---|--|
| 种类国家     | 盾构开挖的软土质隧道  | 喷锚钢支撑的软土质隧道                                       | 中硬石质深埋隧道                                   |
| 奥地利      | 弹性地基圆环  | 弹性地基圆环、有限元法、<br>收敛一约束法                            | 经验法  |
| 德国       | 覆盖层厚小于 2D, 顶部无约束的弹性地基圆环;覆盖层厚大于 3D, 全支承弹性地基圆环、有限元法 | 覆盖层厚小于 2D, 顶部无约束的弹性地基圆环;覆盖层厚大于 3D, 全支承弹性地基圆环、有限元法 | 全支承弹性地基圆环、有<br>限元法、连续介质或收敛—<br>约束法         |
| 法国       | 弹性地基圆环有限元法  | 有限元法、作用—反作用<br>模型、经验法                             | 连续介质模型、收敛—约<br>束法、经验法                      |
| 日本       | 局部支承弹性地基圆环  | 局部支承弹性地基圆环、<br>经验加测试有限元法                          | 弹性地基框架、有限元法、<br>特性曲线法                      |
| 中国       | 自由变形或弹性地基圆环                                       | 初期支护:有限元法<br>收敛一约束法<br>二期支护:弹性地基圆环                | 初期支护:经验法<br>永久支护:作用和反作用<br>模型<br>大型洞室:有限元法 |
| 瑞士       |   | 作用—反作用模型  | 有限元法、有时用收敛—约<br>束法                         |
| 英国       | 弹性地基圆环缪尔伍德法                                       | 收敛一约束法、经验法  | 有限元法、收敛—约束法、<br>经验法                        |
| 美国       | 弹性地基圆环  | 弹性地基圆环、作用一反<br>作用模型                               | 弹性地基圆环、有限元法、<br>锚杆经验法                      |

# 作用在隧道结构上的荷载

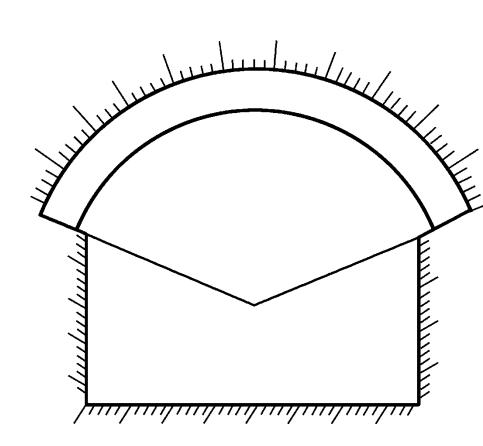
| 编号 | 荷载类型     |             | 荷载名称                  |  |
|----|----------|-------------|-----------------------|--|
| 1  | 永久荷载(恒载) |             | 围岩压力                  |  |
| 2  |          |             | 结构自重力                 |  |
| 3  |          |             | 填土压力                  |  |
| 4  |          |             | 混凝土收缩和徐变影响力           |  |
| 5  |          | 基本可         | 公路车辆荷载,人群荷载           |  |
| 6  |          | 整本的<br>变荷载  | 立交公路车辆荷载及其所产生的冲击力和土压力 |  |
| 7  | 可变荷载     | 文 例 報       | 立交铁路列车活载及其所产生的冲击力和土压力 |  |
| 8  |          | 其他可 — 变荷载 — | 立交渡槽流水压力              |  |
| 9  |          |             | 温度变化的影响力              |  |
| 10 |          |             | 冻胀力                   |  |
| 11 | 偶然荷载     |             | 落石冲击力                 |  |
| 12 |          |             | 地震力                   |  |
| 13 |          |             | 施工荷载                  |  |

#### 14.2 半衬砌结构

### 14.2.1 半衬砌结构的形式

只在拱部构筑拱圈,而侧壁不构筑侧墙(或仅构筑构造墙)的 结构。

关键部位就是拱座,通常 采用斜拱座和折线型拱座(图 14-2)。



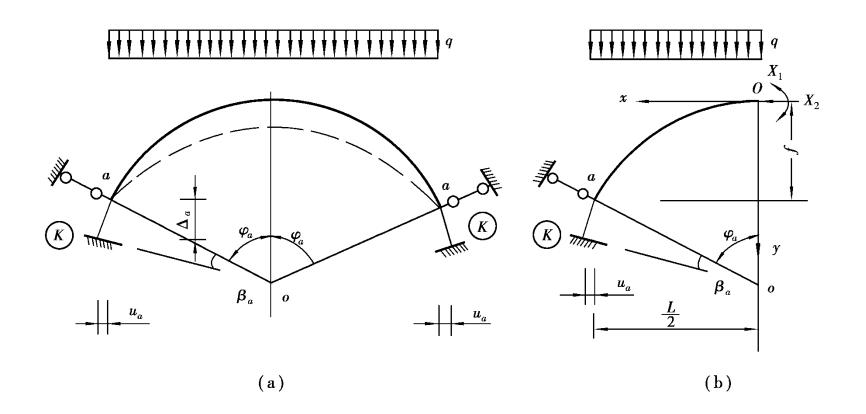
# 14.2.2 半衬砌结构的内力计算方法

## 基本假定

- 1. 忽略拱圈和薄墙的相互影响;
- 2. 拱脚处的约束为"弹性固定",即只能产生转动和沿 拱轴切线方向的位移,且岩层将随拱脚一起变形,符 合文克尔假设。
- 3.拱圈部位忽略弹性抗力的影响,偏于安全。
- 4.按平面问题处理,偏于安全。

# 计算简图

该力学模型为弹性固定无铰拱三次超静定结构。

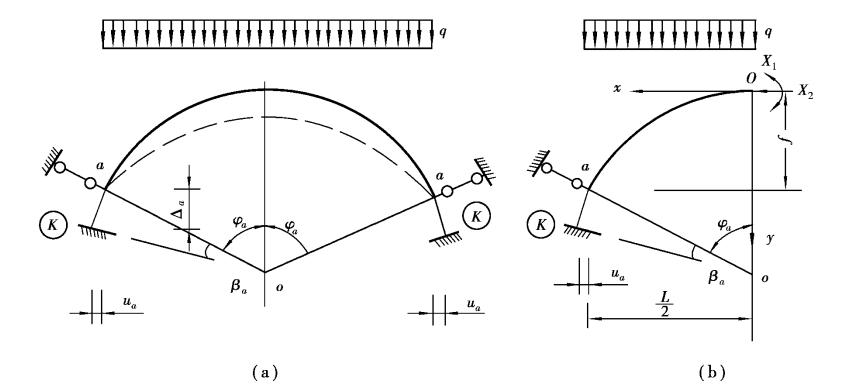


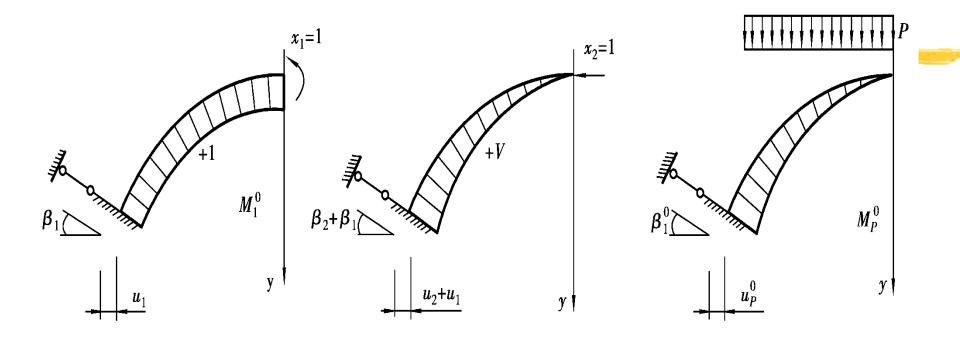
# 半衬砌的计算

#### 计算图式、基本结构及正则方程

$$X_{1}\delta_{11} + X_{2}\delta_{12} + \Delta_{1p} + \beta_{a} = 0$$

$$X_{1}\delta_{21} + X_{2}\delta_{22} + \Delta_{2p} + f\beta_{a} + u_{a} = 0$$





$$\beta_{a} = X_{1}\overline{\beta}_{1} + X_{2}(\overline{\beta}_{2} + f\overline{\beta}_{1}) + \overline{\beta}_{ap}^{0} 
u_{a} = X_{1}\overline{u}_{1} + X_{2}(\overline{u}_{2} + f\overline{u}_{1}) + u_{ap}^{0}$$

$$X_{1}\delta_{11} + X_{2}\delta_{12} + \Delta_{1p} + \beta_{a} = 0$$

$$X_{1}\delta_{21} + X_{2}\delta_{22} + \Delta_{2p} + f\beta_{a} + u_{a} = 0$$

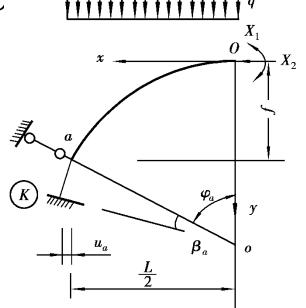
$$\beta_0 = X_1 \beta_1 + X_2 (\beta_2 + f \beta_1) + \beta_P$$

$$\mu_0 = X_1 \mu_1 + X_2 (\mu_2 + f \mu_1) + \mu_P$$

这里的6个系数均称为弹性固定 系数。

联立上面2个方程组,经过化简可得求解X1X2

的方程组。



14-2

 $a_{11}X_1 + a_{12}X_2 + a_{10} = 0$   $a_{21}X_1 + a_{22}X_2 + a_{20} = 0$ 14-3

₩ 求解上面的方程组,可以得到:

$$X_{1} = \frac{\begin{vmatrix} a_{11} & a_{10} \\ a_{21} & a_{20} \end{vmatrix}}{\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}} \qquad X_{2} = \frac{\begin{vmatrix} a_{12} & a_{10} \\ a_{22} & a_{20} \end{vmatrix}}{\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}}$$
14-4

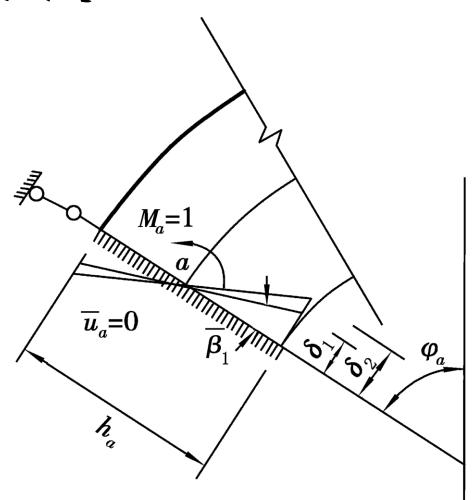
# 14.2.3 拱脚弹性固定系数的确定

(1)单位力矩作用时

$$\sigma_{1} = \frac{\overline{M}_{a}}{W_{a}} = \frac{6}{bh_{a}^{2}}; \delta_{1} = \frac{\sigma_{1}}{k_{a}} = \frac{6}{k_{a}bh_{a}^{2}}$$

$$\overline{\beta}_{1} = \frac{\delta_{2}}{\frac{h_{a}}{2}} = \frac{12}{k_{a}bh_{a}} = \frac{1}{k_{a}J_{a}}; \overline{u}_{a} = 0$$

U=v=0



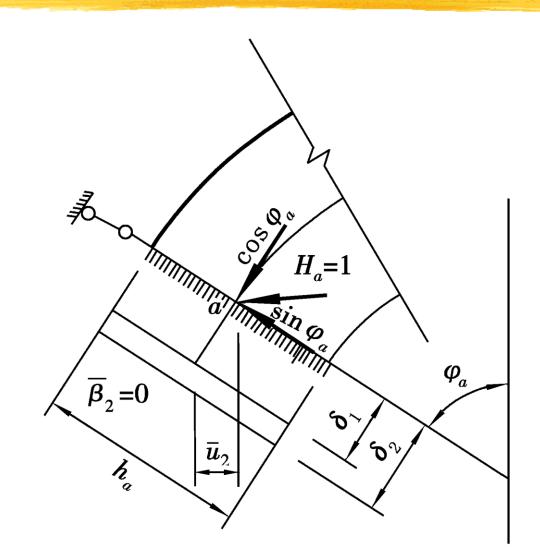
#### (2)单位水平力作用时

根据局部变形理论

$$\mu = \frac{\cos \varphi_j}{Kbd_j}$$

$$v = \frac{\sin \varphi_j}{Kbd_j}$$

$$\beta = 0$$



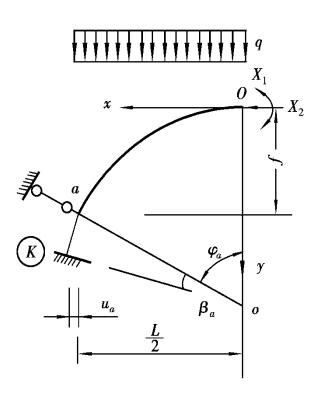
#### (3)外荷载作用时

$$\beta_{ap}^{0} = M_{ap}^{0} \overline{\beta}_{1} + H_{ap}^{0} \overline{\beta}_{2} = M_{ap}^{0} \overline{\beta}_{1};$$

$$u_{ap}^{0} = M_{ap}^{0} \overline{u}_{1} + H_{ap}^{0} \overline{u}_{2} = N_{ap}^{0} \frac{\cos \varphi_{a}}{k_{a} b h_{a}}$$

$$v_{P} = \frac{N_{P}^{0} \sin \varphi_{j}}{K d_{j}}$$

# 14.2.4 拱图变估计算 $pprox \frac{\Delta S}{E} \sum \frac{1}{J}$



$$\delta_{12} \approx \frac{\Delta S}{E} \sum \frac{y}{J}$$

$$\delta_{22} \approx \frac{\Delta S}{E} \sum \frac{y^2}{J}$$

$$\Delta_{1p} \approx \frac{\Delta S}{E} \sum \frac{M_p^0}{EJ}$$

$$\Delta_{2p} \approx \frac{\Delta S}{E} \sum \frac{y M_p^0}{E J}$$

同14-17

#### 拱圈截面内力 (确定方程14-4的系数)

$$a_{11}X_{1} + a_{12}X_{2} + a_{10} = 0$$

$$a_{21}X_{1} + a_{22}X_{2} + a_{20} = 0$$

$$a_{11} = \delta_{11} + \overline{\beta}_{1}$$

$$a_{22} = \delta_{22} + \overline{u}_{2} + f\overline{u}_{1} + f\overline{\beta}_{2} + f^{2}\overline{\beta}_{1}$$

$$a_{12} = a_{21} = \delta_{12} + \overline{\beta}_{2} + f\overline{\beta}_{1} = \delta_{21} + \overline{u}_{1} + f\overline{\beta}_{1}$$

$$a_{10} = \Delta_{1p} + \beta_{ap}^{0}$$

$$a_{20} = \Delta_{2p} + f\beta_{ap}^{0} + u_{ap}^{0}$$

#### 最后可求出半衬砌的各截面内力

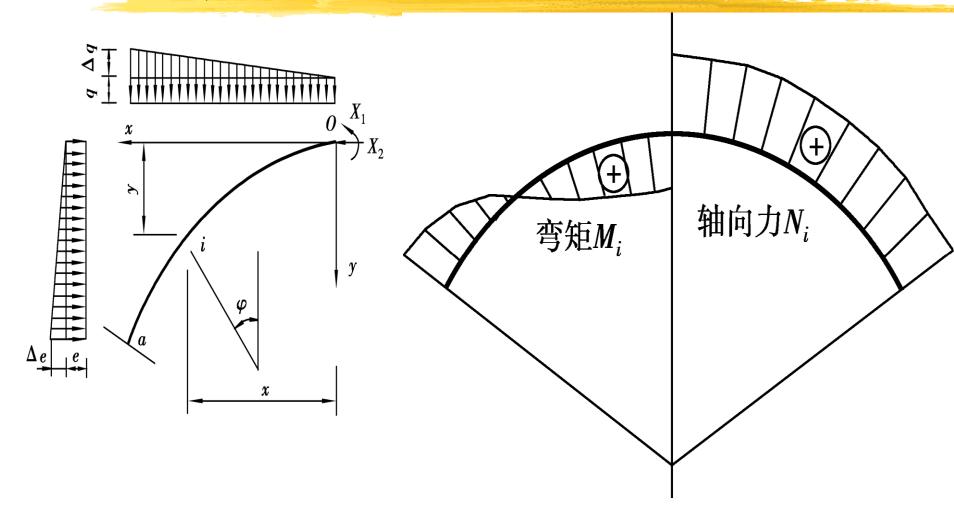
$$X_{1} = \frac{a_{22}a_{10} - a_{12}a_{20}}{a_{12}^{2} - a_{11}a_{22}}$$

$$X_{2} = \frac{a_{11}a_{20} - a_{12}a_{10}}{a_{12}^{2} - a_{11}a_{22}}$$

$$M_{i} = X_{1} + X_{2}y_{i} + M_{ip}^{0}$$

$$N_{i} = X_{2}\cos\varphi_{i} + N_{ip}^{0}$$

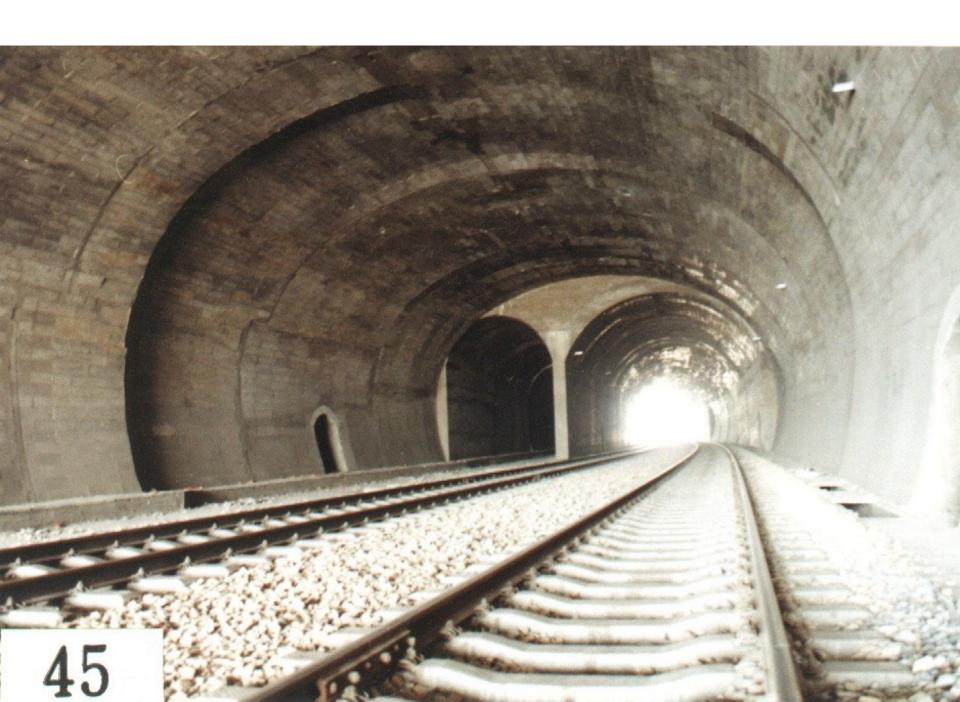
# 计算实例



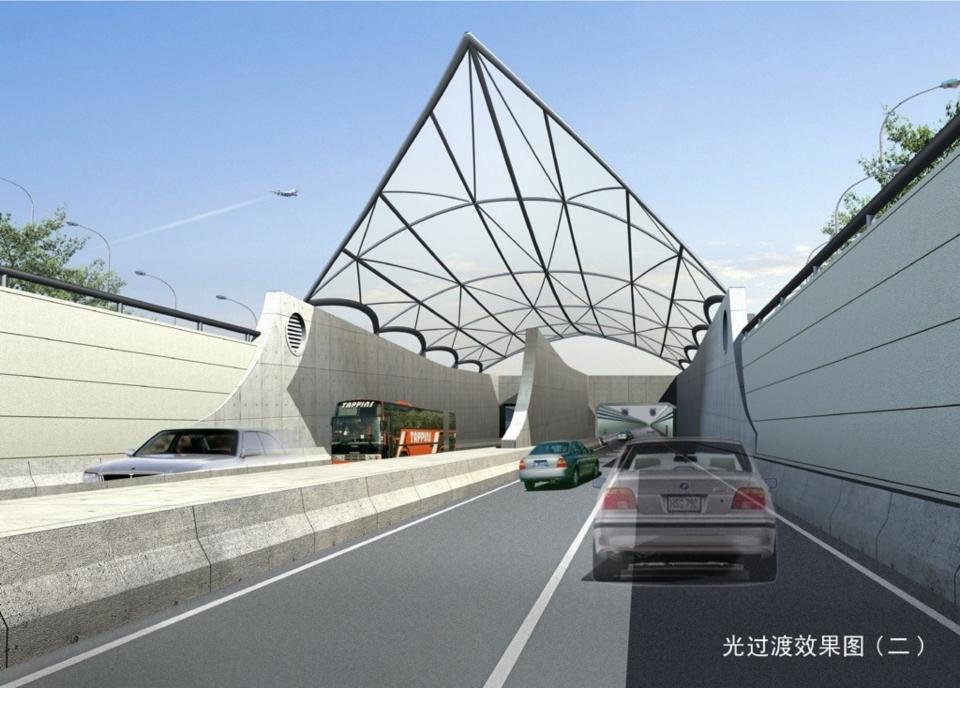


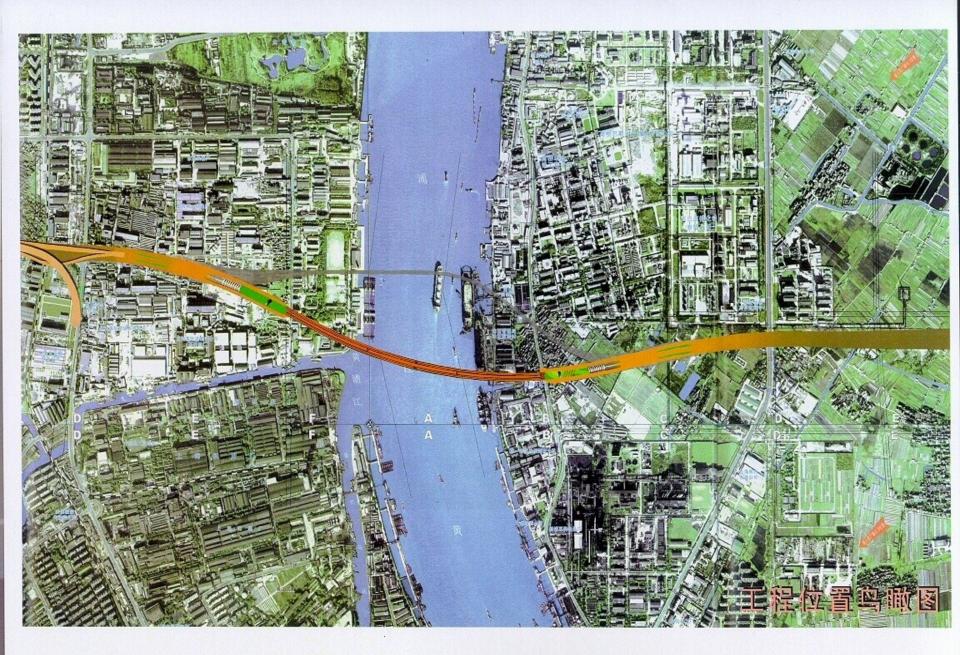






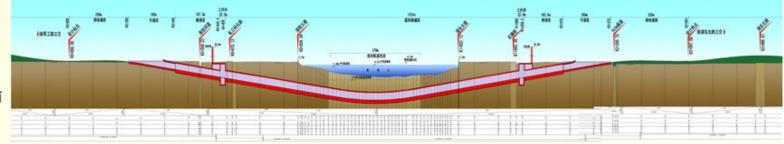












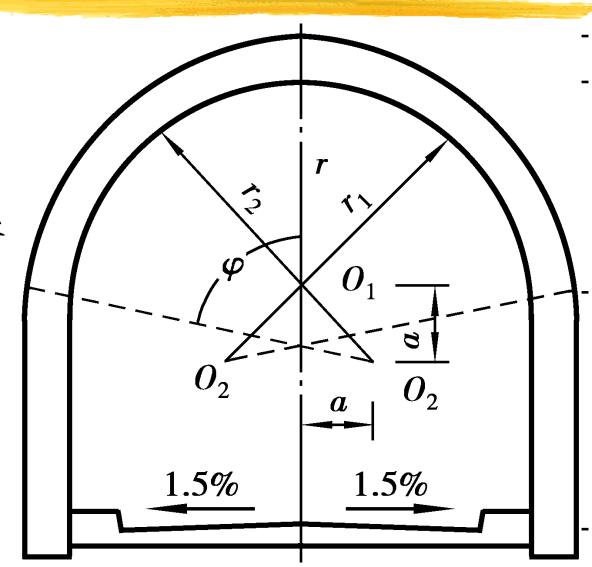


#### 14.3 直墙拱结构

## 14.3.1 计算简图

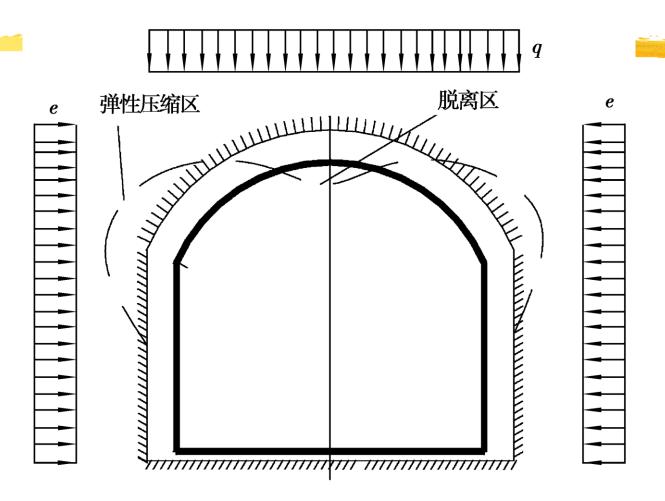
一般由拱圈、竖直侧墙 和底板组成。

底板不是受力构件,由 拱圈和侧墙共同承受 外力。

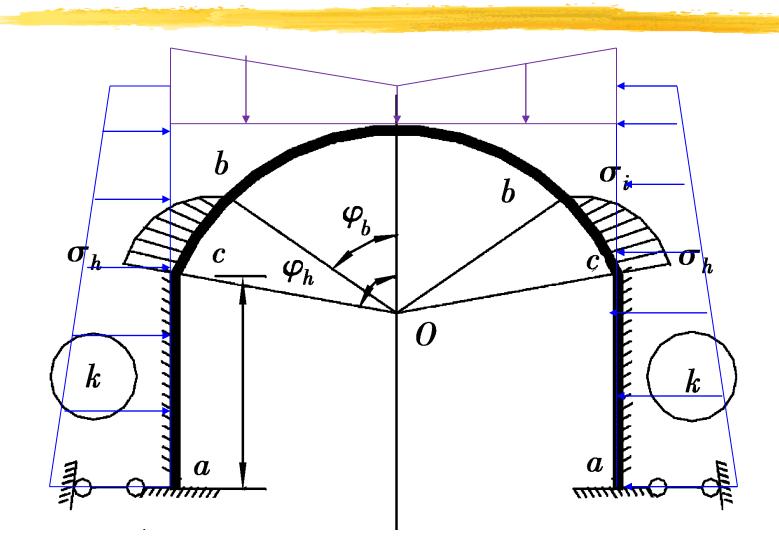


## 基本假定

- 1. 按平面问题处理;
- 2. 拱圈与边墙整体连接,地层压力、结构自重等以梯形分布,拱圈抗力假定为二次抛物线规律或不考虑(回填不密实时);
- 3.边墙视为弹性地基梁;
- 4.墙底与基岩间不产生水平位移,边墙视为绝对刚性的地基梁;
- 5.实际工程中边墙与底板通常分别浇注,计算中按统一浇注考虑。



# 计算简图



# 14.3.2 直墙式衬砌内力计算方法

## 计算原理

- 拱顶的计算方法与半衬砌即结构相同(考虑拱顶受到的弹性抗力);
- 边墙按照弹性地基梁计算(按类型分为长梁、短梁 和刚性梁分别计算)。

## 拱圈的计算

与半衬砌即结构相同(考虑弹性抗力)

$$\sigma_i = \frac{\cos^2 \varphi_b - \cos^2 \varphi_i}{\cos^2 \varphi_b - \cos^2 \varphi_h} \sigma_h$$

$$\sigma_i = (1 - 2\cos^2 \varphi_i) \sigma_h$$

边墙的计算

(1)边墙为短梁(1 < αh < 2.75)

$$\overline{\beta}_{1} = \frac{4\alpha^{3}}{c}(\varphi_{11} + \varphi_{12}A)$$

$$\overline{u}_{1} = \frac{2\alpha^{2}}{c}(\varphi_{13} + \varphi_{11}A)$$

$$\begin{aligned} \overline{\beta}_2 &= \overline{u}_1 = \frac{2\alpha^2}{c} (\varphi_{13} + \varphi_{11}A) \\ \overline{u}_2 &= \frac{2\alpha}{c} (\varphi_{10} + \varphi_{13}A) \\ \beta_e &= -\frac{\alpha}{c} (\varphi_4 + \varphi_3 A) e - \frac{\alpha}{c} \left[ \left( \varphi_4 - \frac{\varphi_{14}}{\alpha h} \right) + \left( \varphi_3 - \frac{\varphi_{10}}{\alpha h} \right) A \right] \Delta e \\ u_e &= -\frac{1}{c} (\varphi_{14} + \varphi_{15}A) e - \frac{1}{c} \left( \frac{\varphi_2}{2\alpha h} - \varphi_1 + \frac{\varphi_4}{2} A \right) \Delta e \end{aligned}$$

$$\varphi_1 = \operatorname{ch}\alpha x \operatorname{cos}\alpha x; \quad \varphi_2 = \operatorname{ch}\alpha x \sin\alpha x + \operatorname{sh}\alpha x \operatorname{cos}\alpha x$$

$$\varphi_3 = \operatorname{sh}\alpha x \sin\alpha x; \quad \varphi_4 = \operatorname{ch}\alpha x \sin\alpha x - \operatorname{sh}\alpha x \operatorname{cos}\alpha x$$

$$\varphi_5 = (\operatorname{ch}\alpha x - \operatorname{sh}\alpha x)(\operatorname{cos}\alpha x - \sin\alpha x); \quad \varphi_6 = \operatorname{cos}\alpha x(\operatorname{ch}\alpha x - \operatorname{sh}\alpha x)$$

$$\varphi_7 = (\operatorname{ch}\alpha x - \operatorname{sh}\alpha x)(\operatorname{cos}\alpha x + \sin\alpha x); \quad \varphi_8 = \sin\alpha x(\operatorname{ch}\alpha x - \operatorname{sh}\alpha x)$$

$$\varphi_{9} = \frac{1}{2}(\cosh^{2}\alpha x + \cos^{2}\alpha x); \quad \varphi_{10} = \frac{1}{2}(\sh\alpha x \cosh\alpha x - \sin\alpha x \cos\alpha x)$$

$$\varphi_{11} = \frac{1}{2}(\sh\alpha x \cosh\alpha x + \sin\alpha x \cos\alpha x); \quad \varphi_{12} = \frac{1}{2}(\sh^{2}\alpha x - \sin^{2}\alpha x)$$

$$\varphi_{13} = \frac{1}{2}(\cosh^{2}\alpha x + \sin^{2}\alpha x); \quad \varphi_{14} = \frac{1}{2}(\cosh\alpha x - \cos\alpha x)^{2}$$

$$\varphi_{15} = \frac{1}{2}(\sh\alpha x + \sin\alpha x)(\cosh\alpha x - \cos\alpha x)$$

$$\beta_{cp}^{0} = M_{cp}^{0} \overline{\beta}_{1} + H_{cp}^{0} \overline{\beta}_{2} + e \overline{\beta}_{e} = 0$$

$$u_{cp}^{0} = M_{cp}^{0} \overline{u}_{1} + H_{cp}^{0} \overline{u}_{2} + e \overline{u}_{e} = 0$$

$$M_{c} = M_{cp}^{0} + X_{1} + X_{2} f$$

$$H_{c} = H_{cp}^{0} + X_{2}$$

$$\beta_{c} = X_{1} \overline{\beta_{1}} + X_{2} (\overline{\beta_{2}} + f \overline{\beta_{1}}) + \beta_{cp}^{0}$$

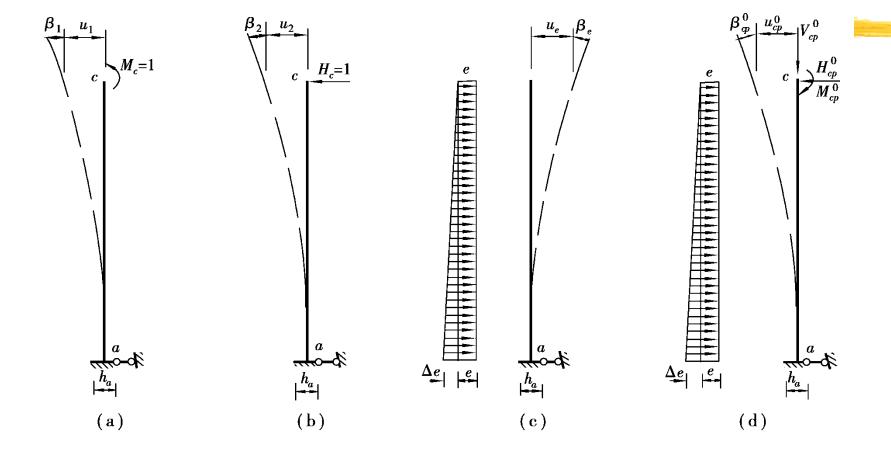
$$u_{c} = X_{1} \overline{u_{1}} + X_{2} (\overline{u_{2}} + f \overline{u_{1}}) + u_{cp}^{0}$$

$$M = -u_c \frac{k}{2\alpha^2} \varphi_3 + \beta_c \frac{k}{4\alpha^3} \varphi_4 + M_c \varphi_1 + H_c \frac{1}{2\alpha} \varphi_2$$

$$H = -u_c \frac{k}{2\alpha} \varphi_2 + \beta_c \frac{k}{2\alpha^2} \varphi_3 - M_c \alpha \varphi_4 + H_c \varphi_1$$

$$\beta = u_c \alpha \varphi_4 + \beta_c \varphi_1 - M_c \frac{2\alpha^3}{k} \varphi_2 - H_c \frac{2\alpha^2}{k} \varphi_3$$

$$u = u_c \varphi_1 - \beta_c \frac{1}{2\alpha} \varphi_2 + M_c \frac{2\alpha^2}{k} \varphi_3 + H_c \frac{\alpha}{k} \varphi_4$$



### (2)墙边为长梁(αh≥2.75)

$$\overline{\beta}_{1} = \frac{4\alpha^{3}}{k}$$

$$\overline{u}_{1} = \overline{\beta}_{2} = \frac{2\alpha^{2}}{k}$$

$$\overline{u}_{2} = \frac{2\alpha}{k}$$

$$\beta_{e} = -\frac{\alpha}{c}(\varphi_{4} + \varphi_{3}A)$$

$$u_{e} = -\frac{1}{c}(\varphi_{14} + \varphi_{15}A)$$

(3)边墙为刚性梁(αh≤1)

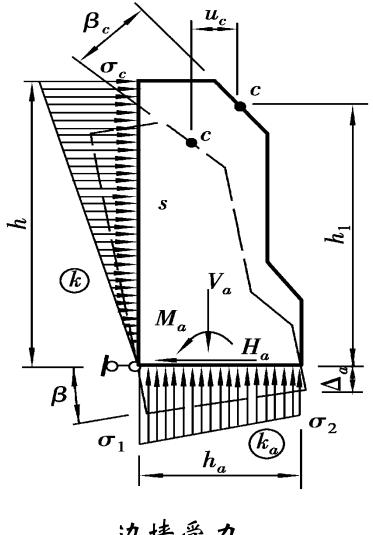
$$M_a - \left[\frac{\sigma_h h^2}{3} + \frac{(\sigma_1 - \sigma_2)h_a^2}{12} + \frac{sh_a}{2}\right] = 0$$

$$\beta = \frac{\sigma_1 - \sigma_2}{k_a h_a} = \frac{\sigma_h}{kh}$$

$$\sigma_1 - \sigma_2 = n\sigma_h \frac{h_a}{h}$$

$$\sigma_h = \frac{12M_a h}{4h^3 nh_a^3 + 3\mu h_a h^2} = \frac{M_a h}{J_a'}$$

$$\beta = \frac{\sigma_h}{kh} = \frac{Ma}{kJ_a'}$$



边墙受力

$$\begin{vmatrix}
\bar{\beta}_1 &= \frac{1}{kJ'_a} \\
\bar{u}_1 &= \bar{\beta}_1 h_1 &= \frac{h_1}{kJ'_a}
\end{vmatrix}$$

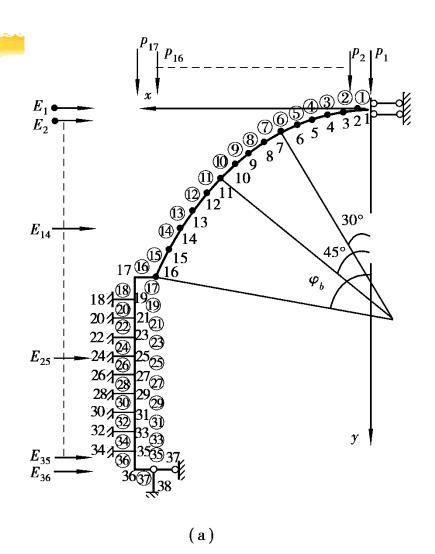
$$\bar{\beta}_{2} = \frac{h_{1}}{kJ'_{a}} = \bar{\beta}_{1}h_{1}$$

$$\bar{u}_{2} = \bar{\beta}_{2}h_{1} = \frac{h_{1}^{2}}{kJ'_{a}} = \bar{\beta}_{1}h_{1}^{2}$$

# 14.3.3 设计计算步骤及算例

- 1. 拱顶的计算
  - (1) 用力法方程式 (14-20) 求解多余力x1、x2
  - (2) 将x1、x2代入式 (14-19) 的第二式求出u0.其中有:
    σn=Ku0sinφn
  - (3) 求出x1、x2后,利用静力平衡条件计算拱顶各截面的内力;
- 2. 边墙的计算(初参数法)
- 由式 (14-19) 确定出初参数后按类型分为长梁、短梁和刚性梁分别计算。

### 有限单元法简介



直墙式衬砌计算的基本结构图式

#### 直接刚度法的求解

$$\{P\} = [K] \{\Delta\}$$

$$\left[\Delta \frac{P_{\alpha}}{P_{\beta}}\Delta\right] = \Delta \left[\frac{K_{\alpha\alpha}}{K_{\beta\alpha}} \frac{K_{\alpha\beta}}{K_{\beta\beta}}\right] \left[\Delta \frac{\Delta_{\alpha}}{\Delta_{\beta}}\Delta\right] \qquad (6.8.8)$$

$$\{P_{\alpha}\} = [K_{\alpha\alpha}] \{\Delta_{\alpha}\} + [K_{\alpha\beta}] \{\Delta_{\beta}\} \qquad (6.8.9)$$

$$\{P_{\beta}\} = [K_{\beta\alpha}] \{\Delta_{\alpha}\} + [K_{\beta\beta}] \{\Delta_{\beta}\} \qquad (6.8.10)$$

$$\{\Delta_{\alpha}\} = [K_{\alpha\alpha}]^{-1} (\{P_{\alpha}\} - [K_{\alpha\beta}] \{\Delta_{\beta}\}) \qquad (6.8.11)$$

$$\{\Delta_{\alpha}\} = [K_{\alpha\alpha}]^{-1} \{P_{\alpha}\} \qquad (6.8.12)$$

$$\{P_{\beta}\} = [K_{\beta\alpha}] [K_{\alpha\alpha}]^{-1} \{P_{\alpha}\} - [K_{\alpha\beta}] \{\Delta_{\beta}\}) + [K_{\beta\beta}] \{\Delta_{\beta}\}$$

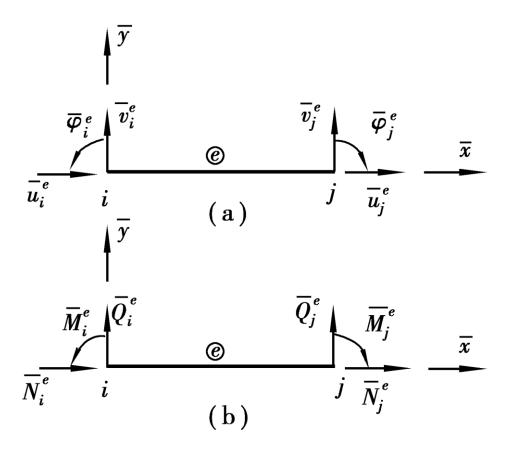
$$= [K_{\beta\alpha}] [K_{\alpha\alpha}]^{-1} \{P_{\alpha}\} \qquad (6.8.13)$$

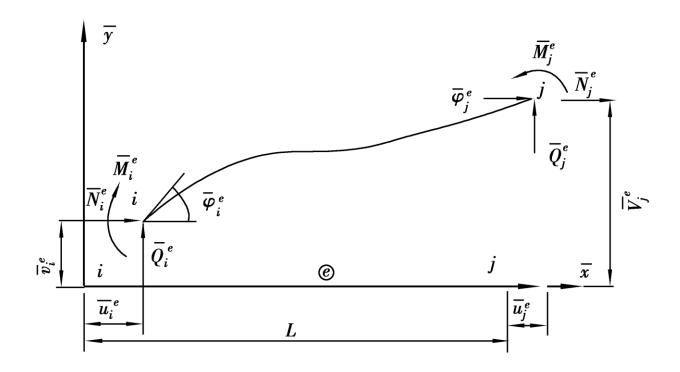
# 单元刚度矩阵

#### 1. 衬砌单元刚度矩阵

$$\{ar{oldsymbol{\delta}_{j}^{e}}\} = egin{pmatrix} \overline{v}_{j}^{e} \ \overline{oldsymbol{arphi}_{j}^{e}} \end{pmatrix} \qquad \{ar{oldsymbol{\delta}_{i}^{e}}\} = egin{pmatrix} \overline{v}_{i}^{e} \ \overline{oldsymbol{arphi}_{i}^{e}} \end{pmatrix}$$

$$\{\,\overline{S}_{i}^{e}\,\} = egin{pmatrix} \overline{N}_{i}^{e} \ \overline{\overline{Q}}_{i}^{e} \ \overline{M}_{i}^{e} \end{pmatrix} \qquad \{\,\overline{S}_{j}^{e}\,\} = egin{pmatrix} \overline{N}_{j}^{e} \ \overline{\overline{Q}}_{j}^{e} \ \overline{M}_{j}^{e} \end{pmatrix}$$





$$\begin{split} \overline{Q}_{i}^{e} &= \frac{12EI}{l^{3}} \overline{v}_{i}^{e} + \frac{6EI}{l^{2}} \overline{\varphi}_{i}^{e} - \frac{12EI}{l^{3}} \overline{v}_{j}^{e} + \frac{6EI}{l^{2}} \overline{\varphi}_{j}^{e} \\ \overline{Q}_{j}^{e} &= -\frac{12EI}{l^{3}} \overline{v}_{i}^{e} - \frac{6EI}{l^{2}} \overline{\varphi}_{i}^{e} + \frac{12EI}{l^{3}} \overline{v}_{j}^{e} - \frac{6EI}{l^{2}} \overline{\varphi}_{j}^{e} \\ \overline{N}_{i}^{e} &= \frac{EF}{l} \overline{u}_{i}^{e} - \frac{EF}{l} \overline{u}_{j}^{e} \\ \overline{Q}_{i}^{e} &= \frac{12EI}{l^{3}} \overline{v}_{i}^{e} + \frac{6EI}{l^{2}} \overline{\varphi}_{i}^{e} - \frac{12EI}{l^{3}} \overline{v}_{j}^{e} + \frac{6EI}{l^{2}} \overline{\varphi}_{j}^{e} \\ \overline{M}_{j}^{e} &= \frac{6EI}{l^{2}} \overline{v}_{i}^{e} + \frac{4EI}{l} \overline{\varphi}_{i}^{e} - \frac{6EI}{l^{2}} \overline{v}_{j}^{e} + \frac{2EI}{l^{2}} \overline{\varphi}_{j}^{e} \\ \overline{N}_{i}^{e} &= -\frac{EF}{l} \overline{u}_{i}^{e} + \frac{EF}{l} \overline{u}_{j}^{e} \\ \overline{Q}_{j}^{e} &= -\frac{12EI}{l^{3}} \overline{v}_{i}^{e} - \frac{6EI}{l^{2}} \overline{\varphi}_{i}^{e} + \frac{12EI}{l^{3}} \overline{v}_{j}^{e} - \frac{6EI}{l^{2}} \overline{\varphi}_{j}^{e} \\ \overline{M}_{j}^{e} &= \frac{6EI}{l^{2}} \overline{v}_{i}^{e} + \frac{2EI}{l} \overline{\varphi}_{i}^{e} - \frac{6EI}{l^{2}} \overline{\varphi}_{j}^{e} + \frac{4EI}{l} \overline{\varphi}_{j}^{e} \\ \overline{M}_{j}^{e} &= \frac{6EI}{l^{2}} \overline{v}_{i}^{e} + \frac{2EI}{l} \overline{\varphi}_{i}^{e} - \frac{6EI}{l^{2}} \overline{v}_{j}^{e} + \frac{4EI}{l} \overline{\varphi}_{j}^{e} \end{split}$$

$$\begin{bmatrix} \overline{N}_{i}^{e} \\ \overline{Q}_{i}^{e} \\ \overline{M}_{i}^{e} \\ \overline{N}_{j}^{e} \\ \overline{Q}_{j}^{e} \\ \overline{M}_{j}^{e} \end{bmatrix} = \begin{bmatrix} \frac{EF}{l} & 0 & 0 & -\frac{EF}{l} & 0 & 0 \\ 0 & \frac{12EI}{l^{3}} & \frac{6EI}{l^{2}} & 0 & -\frac{12EI}{l^{3}} & \frac{6EI}{l^{2}} \\ 0 & \frac{6EI}{l^{2}} & \frac{4EI}{l} & 0 & -\frac{6EI}{l^{2}} & \frac{2EI}{l} \\ -\frac{EF}{l} & 0 & 0 & \frac{EF}{l} & 0 & 0 \\ 0 & -\frac{12EI}{l^{3}} & -\frac{6EI}{l^{2}} & 0 & \frac{12EI}{l^{3}} & -\frac{6EI}{l^{2}} \\ 0 & \frac{6EI}{l^{2}} & \frac{2EI}{l} & 0 & -\frac{6EI}{l^{2}} & \frac{4EI}{l} \end{bmatrix} \begin{bmatrix} \overline{u}_{i}^{e} \\ \overline{\psi}_{i}^{e} \\ \overline{\psi}_{j}^{e} \\ \overline{\psi}_{j}^{e} \end{bmatrix}$$

- $\mathbb{H}$  刚度矩阵[ $K^e$ 有两个重要性质:
- $\mathbb{H}$  ①刚度矩阵 $[K^e]$ 是一个对称矩阵,这是因为在刚度矩阵 $[K^e]$ 中位于斜对 $K^e$ 线两边处于对称位置的两个元素是相等的。
- $\mathbb{H}$  ②刚度矩阵 $|K^e|$ 是奇异矩阵,显然,在 $|K^e|$ 中若将第4行的元素与第1行的元素相加,则等于零,因此,根据行列式的性质可知,与矩阵 $|K^e|$ 相应的行列式等于零,故刚度矩阵 $|K^e|$ 是奇异的。

#### 2. 链杆单元刚度矩阵

$$R_i = K l_i u_i$$

$$\begin{bmatrix} R_i \\ q_i \\ m \end{bmatrix} = \begin{bmatrix} Kl_i & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_i \\ v_i \\ \varphi_i \end{bmatrix}$$

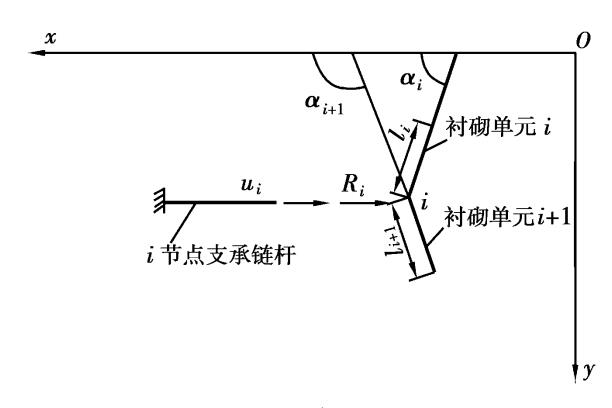
#### 3. 墙底弹性支座单元刚度矩阵

$$N_{B} = B\sigma_{0}$$

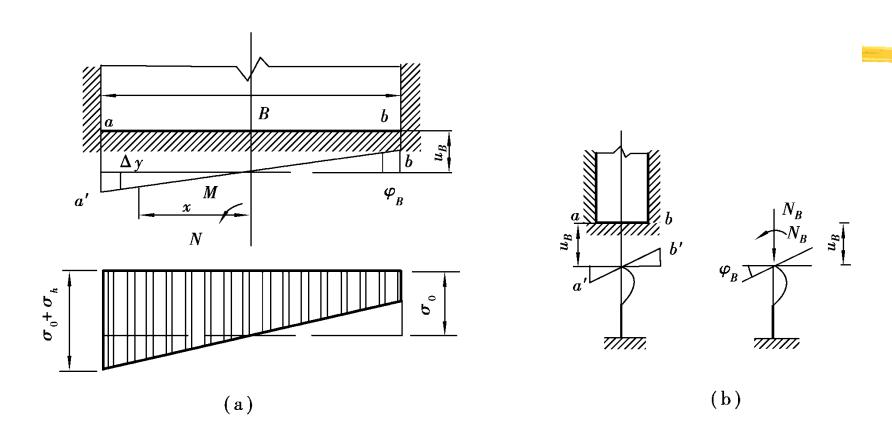
$$M_{B} = \int_{-\frac{B}{2}}^{\frac{B}{2}} \sigma_{x} x dx$$

$$\sigma_{x} = \Delta y K_{B} = x \varphi_{B} K_{B}$$

$$\sigma_{0} = u_{B} K_{B}$$



链杆单元



弹性支承单元

$$N_B = BK_B u_B$$

$$M_B = \frac{1}{12} B^3 K_B \varphi_B$$

$$\begin{bmatrix} N_B \\ M_B \end{bmatrix} = \begin{bmatrix} K_B B & 0 \\ 0 & \frac{K_B B^3}{12} \end{bmatrix} \begin{bmatrix} u_b \\ \varphi_B \end{bmatrix}$$

$$\begin{bmatrix} N_B \\ Q_B \\ M_B \end{bmatrix} = \begin{bmatrix} K_B B & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{K_B B^3}{12} \end{bmatrix} \begin{pmatrix} u_B \\ v_B \\ \varphi_B \end{pmatrix}$$

$$\{S_B\} = [K_{rB}] \{\Delta_B\}$$

$$[K_{rB}] = \begin{pmatrix} K_B B & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{K_B B^3}{12} \end{pmatrix}$$

$$N_{B} = \frac{E_{B}F_{B}}{l_{B}}u$$

$$M_{B} = \frac{4E_{B}I_{B}}{l_{B}}\varphi_{B}$$

$$K_{B} = \frac{E_{B}}{l_{B}}$$

$$I_{B} = \frac{1}{48}B^{3}$$

$$E_{B} = K_{B}$$

$$E_{B} = K_{B}$$

$$I_{B} = \frac{1}{48}B^{3}$$

#### 4. 刚性单元

结构刚度方程 的形成

$$\left\{ \begin{array}{l} S_{1}^{1} \right\} &= \left[ \begin{array}{c} K_{11}^{1} \right] \left\{ \begin{array}{c} \delta_{1}^{1} \right\} \\ + \left[ \begin{array}{c} K_{12}^{1} \right] \left\{ \begin{array}{c} \delta_{2}^{1} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{2}^{1} \right\} &= \left[ \begin{array}{c} K_{21}^{1} \right] \left\{ \begin{array}{c} \delta_{1}^{1} \right\} \\ + \left[ \begin{array}{c} K_{22}^{1} \right] \left\{ \begin{array}{c} \delta_{2}^{1} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{2}^{2} \right\} &= \left[ \begin{array}{c} K_{22}^{2} \right] \left\{ \begin{array}{c} \delta_{2}^{2} \right\} \\ + \left[ \begin{array}{c} K_{23}^{2} \right] \left\{ \begin{array}{c} \delta_{3}^{2} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{3}^{2} \right\} &= \left[ \begin{array}{c} K_{32}^{2} \right] \left\{ \begin{array}{c} \delta_{2}^{2} \right\} \\ + \left[ \begin{array}{c} K_{33}^{2} \right] \left\{ \begin{array}{c} \delta_{3}^{2} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{3}^{3} \right\} &= \left[ \begin{array}{c} K_{33}^{3} \right] \left\{ \begin{array}{c} \delta_{3}^{3} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{3}^{3} \right\} &= \left[ \begin{array}{c} K_{33}^{3} \right] \left\{ \begin{array}{c} \delta_{33}^{3} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{33}^{33} \right\} &= \left[ \begin{array}{c} K_{333}^{33} \right] \left\{ \begin{array}{c} \delta_{33}^{33} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{33}^{33} \right\} &= \left[ \begin{array}{c} K_{3533}^{33} \right] \left\{ \begin{array}{c} \delta_{33}^{33} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{35}^{35} \right\} &= \left[ \begin{array}{c} K_{3533}^{35} \right] \left\{ \begin{array}{c} \delta_{35}^{35} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{35} \right\} &= \left[ \begin{array}{c} K_{3535}^{35} \right] \left\{ \begin{array}{c} \delta_{35}^{35} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{3636}^{36} \right] \left\{ \begin{array}{c} \delta_{36}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{3636}^{36} \right] \left\{ \begin{array}{c} \delta_{36}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{3636}^{36} \right] \left\{ \begin{array}{c} \delta_{36}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{3636}^{36} \right] \left\{ \begin{array}{c} \delta_{36}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{3636}^{36} \right] \left\{ \begin{array}{c} \delta_{36}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{3636}^{36} \right] \left\{ \begin{array}{c} \delta_{36}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} S_{36}^{36} \right\} &= \left[ \begin{array}{c} K_{366}^{36} \right] \left\{ \begin{array}{c} S_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \end{array} \right\} \\ \left\{ \begin{array}{c} K_{366}^{36} \right\} \\ \left\{ \begin{array}{c$$

$$\{R_{19}^{18}\} = [K_{r19}^{18}] \{\Delta_{19}\}$$
 $\{R_{21}^{20}\} = [K_{r21}^{20}] \{\Delta_{21}\}$ 
 $\vdots$ 
 $\{R_{35}^{34}\} = [K_{r35}^{34}] \{\Delta_{35}\}$ 
 $\{\delta_{1}^{1}\} = \{\Delta_{1}\}$ 
 $\{\delta_{2}^{1}\} = \{\delta_{2}^{2}\} = \{\Delta_{2}\}$ 
 $\{\delta_{3}^{2}\} = \{\delta_{3}^{3}\} = \{\Delta_{3}\}$ 
 $\{\delta_{32}^{3}\} = \{\delta_{33}^{33}\} = \{\Delta_{4}\}$ 
 $\vdots$ 
 $\{\delta_{35}^{31}\} = \{\delta_{35}^{33}\} = \{\Delta_{35}\}$ 
 $\{\delta_{35}^{33}\} = \{\delta_{35}^{35}\} = \{\Delta_{35}\}$ 
 $\{\delta_{36}^{35}\} = \{\delta_{36}^{36}\} = \{\Delta_{36}\}$ 
 $\{\delta_{37}^{36}\} = \{\Delta_{37}\}$ 

```
\{P_1\} = \{S_1^1\}
\{P_2\} = \{S_2^1\} = \{S_2^2\}
\{P_3\} = \{S_3^2\} = \{S_3^3\}
\{P_{35}\} = \{S_{35}^{33}\} + \{S_{35}^{35}\} + \{R_{35}^{34}\}
\{P_{36}\} = \{S_{36}^{35}\} + \{S_{36}^{36}\}
\{P_{37}\} = \{S_{37}^{36}\} + \{S_{37}^{37}\}
```

$$\{P_{1}\} = [K_{11}^{1}] \{\Delta_{1}\} + [K_{12}^{1}] \{\Delta_{2}\}$$

$$\{P_{2}\} = [K_{21}^{1}] \{\Delta_{1}\} + [K_{22}^{1}] \{\Delta_{2}\} + [K_{22}^{2}] \{\Delta_{2}\} + [K_{23}^{2}] \{\Delta_{3}\}$$

$$= [K_{21}^{1}] \{\Delta_{1}\} + ([K_{22}^{1}] + [K_{22}^{2}]) \{\Delta_{2}\} + [K_{23}^{2}] \{\Delta_{3}\}$$

$$\{P_{3}\} = [K_{32}^{2}] \{\Delta_{2}\} + [K_{33}^{2}] \{\Delta_{3}\} + [K_{33}^{3}] \{\Delta_{3}\} + [K_{34}^{3}] \{\Delta_{4}\}$$

$$= [K_{32}^{2}] \{\Delta_{2}\} + ([K_{33}^{2}] + [K_{33}^{3}]) \{\Delta_{3}\} + [K_{34}^{3}] \{\Delta_{4}\}$$

$$\{P_{35}\} = [K_{3533}^{3}] \{\Delta_{33}\} + [K_{3535}^{3}] \{\Delta_{35}\} + [K_{3535}^{35}] \{\Delta_{35}\} + [K_{3636}^{35}] \{\Delta_{35}\} [K_{3636}^{35}] \{\Delta_{36}\}$$

$$= [K_{3533}^{3}] \{\Delta_{33}\} + ([K_{3535}^{35}] + [K_{3535}^{35}] + [K_{3536}^{35}]) \{\Delta_{35}\} + [K_{3636}^{35}] \{\Delta_{36}\}$$

$$\{P_{36}\} = [K_{3635}^{35}] \{\Delta_{35}\} + [K_{3636}^{35}] \{\Delta_{36}\} + [K_{3636}^{37}] \{\Delta_{36}\} + [K_{3737}^{37}] \} \{\Delta_{36}\} + [K_{3737}^{36}] \{\Delta_{36}\} + [K_{3737}^{36}] \{\Delta_{36}\} + [K_{3737}^{36}] \{\Delta_{36}\} + [K_{3737}^{36}] \{\Delta_{37}\}$$

$$= [K_{366}^{36}] \{\Delta_{36}\} + [K_{3737}^{36}] \{\Delta_{37}\} + [K_{3737}^{37}] \{\Delta_{37}\}$$

$$= [K_{3726}^{36}] \{\Delta_{26}\} [K_{3737}^{36}] + [K_{3737}^{37}] \{\Delta_{37}\}$$

$$= [K_{3736}^{36}] \{\Delta_{26}\} [K_{3737}^{36}] + [K_{3737}^{37}] \{\Delta_{37}\}$$

$$\begin{bmatrix}
 K_{11} \end{bmatrix} = \begin{bmatrix}
 K_{11}^{1} \end{bmatrix} \\
 \begin{bmatrix}
 K_{22} \end{bmatrix} = \begin{bmatrix}
 K_{22}^{1} \end{bmatrix} + \begin{bmatrix}
 K_{22}^{2} \end{bmatrix} \\
 \begin{bmatrix}
 K_{33} \end{bmatrix} = \begin{bmatrix}
 K_{33}^{2} \end{bmatrix} + \begin{bmatrix}
 K_{33}^{3} \end{bmatrix}$$

$$\begin{bmatrix} K_{3535} \end{bmatrix} = \begin{bmatrix} K_{3535}^{33} \end{bmatrix} + \begin{bmatrix} K_{3535}^{35} \end{bmatrix} + \begin{bmatrix} K_{3535}^{34} \end{bmatrix}$$

$$\begin{bmatrix} K_{3636} \end{bmatrix} = \begin{bmatrix} K_{3636}^{35} \end{bmatrix} + \begin{bmatrix} K_{3636}^{36} \end{bmatrix}$$

$$\begin{bmatrix} K_{3737} \end{bmatrix} = \begin{bmatrix} K_{3737}^{36} \end{bmatrix} + \begin{bmatrix} K_{3737}^{37} \end{bmatrix}$$

$$\begin{bmatrix} P_{1} \\ P_{2} \\ P_{3} \\ \vdots \\ P_{35} \\ P_{36} \\ P_{37} \end{bmatrix} = \begin{bmatrix} [K_{11}][K_{12}] \\ [K_{21}][K_{22}][K_{23}] \\ [K_{32}][K_{33}][K_{34}] \\ \vdots \\ 0 \\ [K_{34}] \end{bmatrix}$$

$$\vdots \\ [K_{35}][K_{3533}][K_{3535}][K_{3535}] \begin{bmatrix} K_{355} \\ K_{3535} \end{bmatrix} \begin{bmatrix} K_{355} \\ K_{3635} \end{bmatrix} \begin{bmatrix} K_{3637} \\ K_{3736} \end{bmatrix} \begin{bmatrix} K_{363} \\ K_{3737} \end{bmatrix}$$

$$\{P\} = [K]\{\Delta\}$$

# 衬砌截面强度验算

$$K = \frac{N_{jx}}{N} \gg K_{gf}$$

表 6.3 混凝土和砌体结构的强度安全系数

| 圬工种类    | 混凝土    |         | 砌           | 体       |
|---------|--------|---------|-------------|---------|
|         | 永久荷载+基 | 永久荷载+基  | 永久荷载+基      | 永久荷载+基  |
| 荷载组合    | 本可变荷载  | 本可变荷载+其 | 本可变荷载       | 本可变荷载+其 |
|         |        | 他可变荷载   |             | 他可变荷载   |
| 混凝土或砌体达 | 2. 4   | 2. 0    | 2. 7        | 2.3     |
| 到抗压极限强度 | 2.4    | 2. 0    | <b>2.</b> I | 2. 3    |
| 混凝土达到抗  | 3. 6   | 3. 0    |             |         |
| 拉极限强度   |        |         |             |         |

表 6.4 钢筋混凝土结构的强度安全系数

| 荷载组合                        | 永久荷载 + 基本可变荷载 | 永久荷载 + 基本可变荷载 + 其他可变荷载 |
|-----------------------------|---------------|------------------------|
| 钢筋达到设计强度或混凝土达<br>到抗压或抗剪极限强度 | 2. 0          | 1. 7                   |
| 混凝土达到抗拉极限强度                 | 2. 4          | 2. 0                   |

$$KN \leq \varphi \alpha R_a b d$$

$$KN \leqslant \varphi \, \frac{1.\,75 R_l b d}{\frac{6e_0}{d} - 1}$$

#### 14.4 复合衬砌结构

## 定义:

复合衬砌常由初期支护和二次支护组成,防水要求高时增设防水层。

#### 初期支护

常为喷射混凝土支护,必要时用锚喷支护。

#### 二次支护

- 常为整体式现浇混凝土衬砌, 或喷射混凝土衬砌, 必要时设置钢筋增强 截面。
- 二次支护的厚度和配筋量主要取决于洞形、净空尺寸、土层地质条件和 施作时机。

在确定开挖断面时,除应满足隧道净空和结构尺寸外,还应考虑初期支护并预留适当的变形量。

#### 承载机理:

围岩破坏一般首先是张性破坏,接着是塑性剪切流动破坏,如能及时支护,使在洞周形成处于稳定状态的承载环,洞室围岩即可保持稳定。

### 受力变形特点:

在约束围岩的同时允许围岩产生适当的变形,充分发挥围岩的自支撑能力,以及借助调整支护结构层的施作时间改善结构层受力的分布,使其承载力提高。

# 复合结构的计算(公路隧道设计规范)

通常采用荷载结构法和地层结构法。一不能反映复合支护的施作过程对结构受力变形的影响。

目前建立了粘弹性分析法和粘弹粘塑性分析法。

9.2.5 I~V级围岩中,复合式衬砌的初期支护应主要按工程类比法设计。其中 IV、V级围岩的支护参数应通过计算确定,计算方法为地层结构法。地层结构法的计算原理可

- 9.2.6 复合式衬砌中的二次衬砌, I~Ⅲ级围岩中为安全储备, 并按构造要求设计; IV、V级围岩中为承载结构, 可采用地层结构法计算内力和变形。
- 9.2.7 进行衬砌计算时,围岩地层的特性参数值应按地质资料选用,无资料时可按附录 A 中表 A.0.4-1 选用。隧道开挖后,应按监控量测结果对其修正。

## 14.5 连拱隧道结构

# 定义

是洞体衬砌结构相连的一种特殊双洞结构形式即侧墙相连.

# 特点

双洞轴线间距小,占地少,便于洞外接线.

施工复杂,造价高,工期长.

一般用于地形困难地区,一般为短隧道.

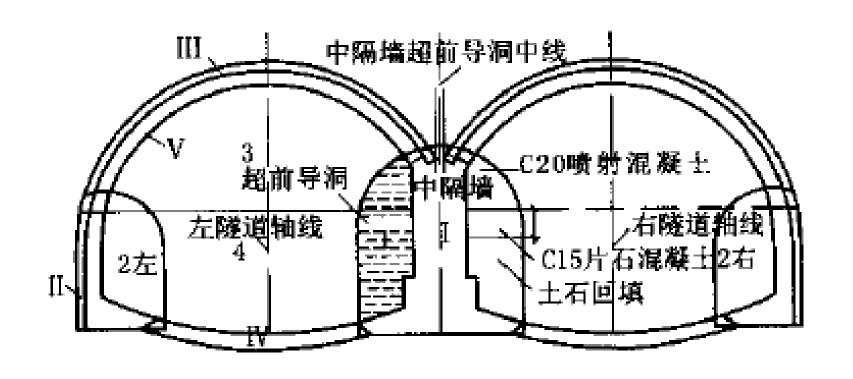


图 1 双连拱隧道结构

连拱隧道的主要部位为中隔墙,中导洞位置

近年来,我国高速公路建设发展异常迅猛。许 多路段穿插在崇山峻岭之间,因此隧道构造物越来 越多和越来越长。由于受地形限制和设计要求,有 些地段布线十分困难,采用双连拱隧道的形式是一 种解决问题的有效手段。双连拱隧道与分离式隧道 相比有很多优点:① 避免了洞口分幅路基,减少了 占地,与洞外路线连接方便;② 在傍山或土垭口地 形利于洞口位置选择,并可减少隧道长度;③ 避免 了隧道洞口特大桥分幅; ④ 可保持路线线形流畅, 且断面造型美观;⑤ 城市中双连拱隧道可以大大 减少拆迁,降低工程费用。

# 14.5.2 连拱隧道的设计和计算方法

力学条件复杂,一般用有限元方法计算.

e v

e u

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