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既有建筑地下开挖工程中在役桩竖向承载特性分析

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摘要: 如何评价土体开挖条件下在役桩的竖向承载能力, 是桩支承的既有建筑地下开挖工程中亟待解决的关键问题, 围绕上述问题, 明确土体开挖条件下土体应力状态改变、回弹等因素对桩侧和桩端承载特性的影响, 建立考虑土体开挖效应影响的桩侧荷载传递双曲线模型和桩端荷载传递双折线模型, 考虑开挖卸荷效应引起的土体超固结状态提出土体开挖条件下桩侧极限摩阻力的计算方法, 基于有限差分法和荷载传递法形成既有建筑地下开挖条件下在役桩竖向承载特性的计算方法。通过与现有试验结果对比分析, 验证计算方法的合理性。结果表明, 对地下增层开挖条件下单桩进行分析时, 应考虑开挖引起的土体回弹、桩周土超固结状态等因素对桩侧和桩端承载特性的影响, 当计算的归一化土体回弹量较小时(<1), 沉降分析中可不考虑回弹效应。

关键词: 地下开挖; 在役桩; 卸荷效应; 荷载传递法; 承载特性

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Vertical bearing characteristics of in-service pile in underground excavation engineering of existing building

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Abstract: In the project of underground excavation beneath existing building supported by piles, there is a need to evaluate the vertical bearing capacity of the in-service piles under the condition of soil excavation. The influence of variation of soil stress and soil rebound on the bearing characteristics of soil around pile and at pile base was determined. Considering the effect of soil excavation, a hyperbolic model of load transfer along pile shaft and a bilinear model of load transfer at pile end were established. In view of the over-consolidation state of soil induced by the unloading effect of excavation, the calculation method was established to evaluate the ultimate unit skin friction of pile shaft under the condition of excavation. On the basis of the finite difference method and the load transfer method, the calculation method was proposed for predicting the vertical bearing characteristics of in-service pile under the condition of underground excavation beneath existing building. The validity of the proposed method was verified by comparing with the experimental results. Results show that the influence of soil rebound and the over-consolidation state of soil due to excavation on the pile shaft resistance and pile base resistance should be taken into account for the analysis of the pile behavior subject to underground excavation. If the calculated normalized soil rebound is relatively small (e. g. less than 1), the soil rebound can be neglected in the settlement analysis.

Keywords: underground excavation; in-service pile; unloading effect; load transfer method; bearing characteristics

既有建筑地下增层工程是一项综合性很强的复杂工程, 包含既有基础加固、基坑支护结构增设、基础托换、土体开挖、地下室底板浇筑、结构柱和托换

桩截除等工序(以群桩基础支承的既有建筑地下增层开挖工程为例, 见图1)。目前, 国内外已有既有建筑进行地下增层改造的成功案例^[1-5]。桩基础支

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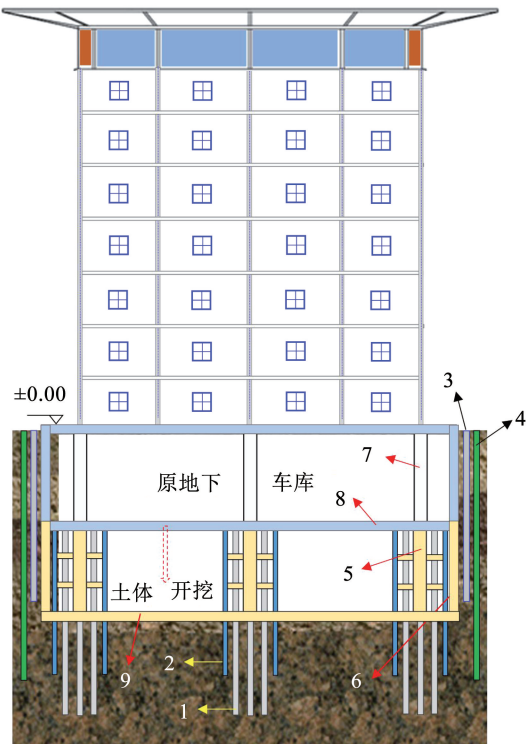
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承的既有建筑地下增层过程中应重点关注土体开挖效应下桩基承载力损失和桩基渐进变形过程,从变形控制角度出发,明确既有建筑地下增层开挖条件下在役桩基竖向承载特性变化过程。鉴于既有建筑地下增层开挖工程的实际情况和复杂性,在役桩基承载特性现场试验很难开展。因此,有必要提出既有建筑地下开挖条件下在役桩基竖向承载特性分析方法。



1—原桩; 2—新补桩; 3—原围护结构; 4—新围护结构;
5—新增框架柱; 6—新增外墙; 7—原柱体结构;
8—原地下车库底板; 9—新增地下车库底板

图 1 群桩支承的既有建筑地下增层开挖示意

Fig. 1 Schematic diagram of underground excavation beneath existing building supported by pile groups

单桩承载特性常用计算方法(如荷载传递法^[6-7]、弹性理论法^[8-9]和数值分析方法^[10-11]等)应用于既有建筑地下开挖工程中,在役桩基承载特性分析时应考虑如下影响因素:1)开挖段桩侧阻力的直接损失;2)开挖卸荷对桩周土应力状态和剪切强度的改变(坑底土体处于超固结状态);3)开挖卸荷引起的桩周土回弹变形。目前已有大量成熟的数值计算软件,结合合理的本构模型和参数取值可用于分析既有建筑地下开挖工程中在役桩基竖向承载特性。然而,既有建筑地下开挖工程中在役桩-土界面的接触模型及其相关参数的确定,仍是数值计算方法中尚需明确的问题。荷载传递法可通过桩-土界面的非线性荷载传递模型较好地模拟桩-土界面的非线性,且计算过程简便,可用于桩基承载特性

的快速估算。

荷载传递法用于桩基承载特性分析时能否获得合理的计算结果,关键在于能否选择恰当的荷载传递函数。荷载传递函数可通过试验数据拟合或理论分析获得。目前,国内外学者提出了众多荷载传递模型,如双折线模型^[12]、理想弹塑性模型^[13]、三折线模型^[14]、幂函数模型^[15]、软化模型^[16-17]和双曲线模型^[7,18]等。张乾青^[19]总结了不同桩侧和桩端荷载传递模型,明确了荷载传递模型中参数的意义和取值方法。上述荷载传递模型未考虑开挖引起的土体回弹、应力状态变化对桩基承载特性的影响。为考虑土体开挖对桩基荷载传递特性的影响,龚晓南等^[20-22]提出了考虑土体开挖效应的荷载传递函数。

传统荷载传递函数无法直接用于既有建筑地下开挖工程中在役桩荷载传递特性的分析。针对上述问题,本文明确了土体开挖条件下土体应力状态改变、回弹等因素对桩侧和桩端承载特性的影响,建立了考虑土体开挖效应影响的桩侧荷载传递双曲线模型和桩端荷载传递双折线模型,考虑开挖卸荷效应引起的土体超固结状态提出了土体开挖条件下桩侧极限摩阻力计算方法,基于有限差分法和荷载传递法形成了既有建筑地下增层开挖条件下在役桩基竖向承载特性计算方法。

1 荷载传递模型

1.1 桩侧荷载传递双曲线模型

竖向受荷单桩某一深度 z 处桩身位移 $S_s(z)$ 为桩-土相对位移 $w(z)$ 和土体位移 $w_s(z)$ 之和,即桩身位移 $S_s(z)$ 与桩侧单位摩阻力 $\tau_s(z)$ 关系为^[7]

$$S_s(z) = w(z) + w_s(z) = \frac{a\tau_s(z)}{1 - b\tau_s(z)} + \frac{r_0}{G_0} \ln\left(\frac{r_m}{r_0}\right) \tau_s(z) \quad (1)$$

式中: a 和 b 为双曲线模型参数; G_0 为桩周土体小应变剪切模量; r_0 为桩身半径; r_m 为单桩影响半径, $r_m = 2.5\rho(1 - \nu_s)L$, L 为桩长, ν_s 为桩侧土泊松比, ρ 为桩周土体不均匀系数,对于均质土 $\rho = 1$,对于成层土

$$\rho = \frac{\sum_{k=1}^m G_{sk} L_k}{G_{sm} L}, G_{sk} \text{ 为 } k \text{ 层土中的剪切模量, } G_{sm} \text{ 为土层中剪切模量的最大值, } L_k \text{ 为 } k \text{ 层土的厚度。}$$

既有建筑地下开挖工程中在役单桩某深度 z 处的桩身位移 $S_s(z)$ 除了考虑桩-土相对位移 $w(z)$ 和桩周土体弹性位移 $w_s(z)$ 外,还应考虑开挖土体回弹位移 $w'_s(z)$ ^[23],其中,土体回弹位移 $w'_s(z)$ 可采用式(2)计算,即

$$w'_s(z) = \psi \sum_z^z \frac{\sigma_{re}(h)}{E_{ur}(h)} \Delta h \quad (2)$$

式中: h 为深度; z_m 为开挖土体的影响深度,其值为回弹应力为0时对应的土层深度; ψ 为修正系数,对于土体开挖范围呈长条形的情况,建议取2.0^[24]; $\sigma_{re}(h)$ 为厚度为 Δh 的土层回弹应力; $E_{ur}(h)$ 为厚度为 Δh 的土层回弹模量。

某一深度 z 处土体回弹应力 $\sigma_{re}(z)$ (其值应大于0)可表示为^[24]

$$\sigma_{re}(z) = \alpha_z P_0 - \gamma' z \quad (3)$$

式中: P_0 为开挖范围内土体自重应力; α_z 为附加应力系数,可根据Mindlin应力解计算获得; γ' 为开挖面至深度 z 处范围内土体平均有效重度。

回弹模量可根据Duncan-Chang模型^[25]计算获得,即

$$E_{ur} = K_{ur} p_a (\sigma_3 / p_a)^{n_{ur}} \quad (4)$$

式中: p_a 为大气压力, K_{ur} 和 n_{ur} 为回弹模量参数, σ_3 为土体围压。

由式(1)~(4)可知,土体开挖时竖向受荷桩的桩身位移 $S_s(z)$ 与桩侧单位摩阻力 $\tau_s(z)$ 关系为

$$S_s(z) = \frac{a \tau_s(z)}{1 - b \tau_s(z)} + \frac{r_0}{G_0} \ln \left(\frac{r_m}{r_0} \right) \tau_s(z) - f(z) \quad (5)$$

其中

$$f(z) = \psi \sum_z^z \frac{\Delta \sigma'_v - \gamma' h}{K_{ur} p_a (K_0 \Delta \sigma'_v / p_a)^{n_{ur}}} \Delta h \quad (6)$$

式中 $\Delta \sigma'_v$ 为开挖土体引起深度 z 处的竖向附加应力。

1.2 桩侧荷载传递模型参数确定

式(1)中参数 a 为桩-土界面初始剪切刚度 k_{s0} 的倒数, b 的倒数为桩-土相对位移无穷大时对应

$$\begin{aligned} \Delta \sigma'_v = & \frac{\gamma_1}{\pi} \left[h \arctan \frac{a}{z_1} - \frac{a}{2} \ln(r_1^2) + z \arctan \frac{z_1}{a} + h \arctan \frac{a}{z_2} + \frac{a}{2} \ln(r_2^2) - z \arctan \frac{z_2}{a} \right] + \\ & \frac{\gamma_1}{2\pi(1-\nu)} \left[\frac{a}{2} \ln(r_2^2) - \frac{a}{2} \ln(r_1^2) + 2z(1-2\nu) \left(\arctan \frac{z_2}{a} - \arctan \frac{z}{a} \right) - \frac{2ahz}{r_2^2} \right] \end{aligned} \quad (12)$$

式中: ν 为土体泊松比, $z_1 = z - h, z_2 = z + h, r_1^2 = a^2 + z_1^2, r_2^2 = a^2 + z_2^2$ 。

地面下深度 h 处的超载引起 z 处的土体竖向有效应力增量 $\Delta \sigma'_{v0}$ 为

$$\begin{aligned} \Delta \sigma'_{v0} = & \frac{q_0}{\pi} \left(\arctan \frac{a}{z_1} + \arctan \frac{a}{z_2} \right) + \\ & \frac{q_0}{2\pi(1-\nu)} \left\{ \frac{az_1}{r_1^2} + \frac{a[h + (3-4\nu)z]}{r_2^2} + \frac{4ahzz_2}{r_2^4} \right\} \end{aligned} \quad (13)$$

由式(11)~(13)可知,地表下深度 z 处土体超固结比 R_{OC} 为

$$R_{OC} = \frac{\gamma_1 z + \Delta \sigma'_{v0} - \Delta \sigma'_v(h_1)}{\gamma_2 z - \Delta \sigma'_v(h_2)} \quad (14)$$

的单位侧摩阻力,可表示为^[7,18,26]

$$\begin{cases} a = 1/k_{s0} \\ b = R_s/\tau_{su} \end{cases} \quad (7)$$

式中: R_s 为桩侧摩阻力破坏比,为0.85~0.95; τ_{su} 为桩侧极限单位摩阻力。

桩侧初始承载刚度 k_{s0} 可根据Randolph和Wroth^[27]的弹性理论求得,即

$$k_{s0} = \frac{G_0}{r_0 \ln(r_m/r_0)} \quad (8)$$

对于非剪胀性土,如正常固结黏土,土体开挖前桩侧单位极限摩阻力 τ_{su} 为

$$\tau_{su} = \sigma'_n \tan \delta = [(1 - \sin \varphi') \sigma'_v] \tan \delta \quad (9)$$

式中: φ' 为土体有效内摩擦角; σ'_v 为土体竖向有效应力; δ 为桩-土界面摩擦角,通常取 $\delta = (0.75 \sim 1) \varphi'^{[28]}$,对于钻孔灌注桩(因施工因素,桩身粗糙度较大),可近似取 $\delta = \varphi'^{[29-31]}$ 。

非剪胀性土中,土体开挖后考虑土体超固结状态,桩侧单位极限摩阻力 τ_{su} 为

$$\tau_{su} = [(1 - \sin \varphi') R_{OC}^{\sin \varphi} \sigma'_v] \tan \delta \quad (10)$$

式中 R_{OC} 为增层开挖前、后竖向有效应力之比,即

$$R_{OC} = \frac{\bar{\gamma}_1(z - h_1) + q_0}{\bar{\gamma}_2(z - h_2)} \quad (11)$$

式中: $\bar{\gamma}_1$ 和 $\bar{\gamma}_2$ 分别为土体开挖前、后土层平均有效重度, h_1 和 h_2 为开挖前、后土体深度(从开挖起始面计算), q_0 为土体开挖前地面荷载。

以图2中开挖宽度为 $2a$ 的情况为例,地面下深度 h 范围内土体开挖导致深度 z 处竖向有效应力改变量 $\Delta \sigma'_v$ 可计算为^[21]

$$\Delta \sigma'_v = \frac{\gamma_1}{\pi} \left[h \arctan \frac{a}{z_1} - \frac{a}{2} \ln(r_1^2) + z \arctan \frac{z_1}{a} + h \arctan \frac{a}{z_2} + \frac{a}{2} \ln(r_2^2) - z \arctan \frac{z_2}{a} \right] + \frac{\gamma_1}{2\pi(1-\nu)} \left[\frac{a}{2} \ln(r_2^2) - \frac{a}{2} \ln(r_1^2) + 2z(1-2\nu) \left(\arctan \frac{z_2}{a} - \arctan \frac{z}{a} \right) - \frac{2ahz}{r_2^2} \right] \quad (12)$$

对于剪胀性土,如砂土、砾石土及超固结黏土,土体开挖前桩侧单位极限摩阻力 τ_{su} 可假定为柱孔扩张问题进行求解^[32],即

$$\tau_{su} = \left[(1 - \sin \varphi') \sigma'_v + \frac{4G_s}{D} u_{cs} \right] \tan \delta \quad (15)$$

式中: D 为桩身直径; G_s 为桩周土体剪切模量, $G_s = \alpha G_0$, α 为折减系数; u_{cs} 为桩-土界面极限剪胀量。

剪胀性土中,土体开挖后考虑土体超固结状态,桩侧单位极限摩阻力 τ_{su} 为

$$\tau_{su} = \left[(1 - \sin \varphi') R_{OC}^{\sin \varphi} \sigma'_v + \frac{4G_s}{D} u_{cs} \right] \tan \delta \quad (16)$$

G_0 可根据室内试验和原位试验结果确定,无试验数据时可采用式(17)近似计算获得^[33],即

乏试桩现场试验数据时,可采用桩端位移为 10% D 时对应的极限桩端承载力 $q_{b0.1}$ 进行估算, k_2 可表示为^[42]

$$k_2 = \frac{0.3q_{bu} - k_1 S_{bu}}{0.1D - S_{bu}} \tag{24}$$

式中 q_{bu} 为极限桩端阻力。

黏土中单桩的桩端极限承载力 q_{bu} 为^[43]

$$q_{bu} = 9S_u \tag{25}$$

式中 S_u 为桩端土的不排水强度。

砂土中单桩的桩端极限承载力 q_{bu} 为^[42]

$$q_{bu} = N_q \sigma'_v \tag{26}$$

$$N_q = \frac{A}{1 - \sin \varphi'_{cv}} \left[\frac{G_b / \sigma'_v}{B + D (G_b / \sigma'_v)^{-0.8}} \right]^C \tag{27}$$

式中参数 A, B, C 和 D 可通过式(28)进行计算。

$$A = \frac{3(1 + \sin \varphi'_{cv})}{3 - \sin \varphi'_{cv}} \left(\frac{1 + 2K_0}{3} \right) \tag{28a}$$

$$B = \left(\frac{1 + 2K_0}{3} \right) \tan \varphi'_{cv} \tag{28b}$$

$$C = \frac{4 \sin \varphi'_{cv}}{3(1 + \sin \varphi'_{cv})} \tag{28c}$$

$$D = 50 \left[\frac{(1 + 2K_0)}{3} \tan \varphi'_{cv} \right]^{1.8} \tag{28d}$$

式中 K_0 为土体静止土压力系数。

2 单桩荷载 - 沉降计算方法

竖向荷载作用下单桩桩身位移 $S_s(z)$ 与桩侧单位侧摩阻力 $\tau_s(z)$ 间的荷载传递微分方程为

$$\frac{d^2 S_s(z)}{dz^2} = \frac{\pi D \tau_s(z)}{E_p A_p} \tag{29}$$

式中: E_p 为桩身弹性模量, A_p 为桩身横截面积。

对于形式简单的荷载传递函数,可通过求解式(29)获得解析解。对于形式较复杂的荷载传递函数,则无法获得式(29)的解析解,可通过泰勒级数法^[44]、龙格 - 库塔法^[45]和有限差分法等数值分析方法将式(29)转换为代数形式进行求解。本文采用有限差分法计算既有建筑土体开挖前、后在役单桩的承载特性。

计算前先将全桩分成若干桩段,对桩身控制方程差分离散后转换成代数方程(式(30))逐段求解桩身轴力 - 位移关系,即

$$S_s^{i+1} = \left(\frac{L}{n} \right)^2 \left(- \frac{2\pi r_0}{E_p A_p} \tau^i \right) + 2S_s^i - S_s^{i-1} \tag{30}$$

土体开挖前、后竖向受荷单桩承载特性计算步骤如下:

1) 将单桩从桩顶至桩端分成 n 个桩段,桩顶处桩段编号为 1,桩端处桩段编号为 n 。

2) 假定桩顶荷载 Q 。

3) 假设桩段 1 顶面和底面处的位移, S_s^1 和 S_s^2 (其值假定较小)。

4) 根据式(1)或(5)(土体开挖前、后)计算桩段 1 顶面和底面处的桩侧单位摩阻力 τ_s^1 和 τ_s^2 。

5) 假设桩身轴力线性变化,桩段 1 底面处的桩身位移修正值可由式(31)计算获得,即

$$S_s^{2'} = S_s^1 - S_c^1 \tag{31}$$

式中: S_c^1 为桩段 1 的桩身压缩量,可根据式(32)计算获得,即

$$S_c^1 = \frac{\Delta l \left\{ Q + \left[Q - \frac{\pi D \Delta l (\tau_s^1 + \tau_s^2)}{2} \right] \right\}}{2E_p A_p} \tag{32}$$

6) 比较式(31)中计算获得的 $S_s^{2'}$ 与步骤(3)中假定的 S_s^2 值。若 $|S_s^2 - S_s^{2'}| \leq 1 \times 10^{-6}$ m,则桩段 1 底面处的桩身位移可取为 S_s^2 ;若 $|S_s^2 - S_s^{2'}| > 1 \times 10^{-6}$ m,需重新假定步骤(3)中的 S_s^2 值,直至 $|S_s^2 - S_s^{2'}| \leq 1 \times 10^{-6}$ m 为止。

7) 采用式(30)计算其他桩段的桩身位移。

8) 由式(33)计算单桩总侧摩阻力 Q_s ,即

$$Q_s = \sum_1^{n+1} \pi D \Delta l \frac{(\tau_s^i + \tau_s^{i+1})}{2} \tag{33}$$

9) 根据计算获得的桩段 n 底面位移 S_s^{n+1} 和式(21)或(22)(土体开挖前、后)计算桩端阻力 Q_b (考虑桩端面积)。

10) 根据式(34)计算单桩总承载力 Q' ,即

$$Q' = Q_s + Q_b \tag{34}$$

11) 比较式(34)中计算获得的 Q' 与步骤(2)中假定的 Q 值。若 $|Q - Q'|$ 小于一给定的容许误差值,如 1 N,则桩段 1 顶面处位移可取为 S_s^1 ;若 $|Q - Q'|$ 大于该容许误差值,需重新假定步骤(3)中的 S_s^1 值,直至 $|Q - Q'|$ 小于给定的容许误差值为止。

12) 假定一系列不同的桩顶荷载值 Q ,重复步骤 3) ~ 11),直至得到桩顶荷载 - 位移关系曲线。

3 算例分析

3.1 算例 1

此算例来自文献[46]中桩基足尺载荷试验,选用桩长为 6 m、桩径为 0.6 m、桩身弹性模量约为 30 GPa 的钻孔灌注桩静载试验结果进行相关分析。现场测试表明,地表下存在约 20 m 的花岗岩残积土,地下水位位于地表以下约 10 m 处(即地下水位在桩端以下)。根据现场静力触探试验和 Mascarucci^[34]、Bolton^[36]、Rowe^[37]、Viana^[46] 和 Jamiolkowski 等^[47]研究结果可知,该场地土层临界状态摩擦角约为 32°,剪切带厚度 t_s 约为 4 mm,剪切

模量折减系数 α 取其平均值 0.75, q_c 实测值、 D_r 估算值、 φ_p 估算值和 ψ_p 估算值见图 3。

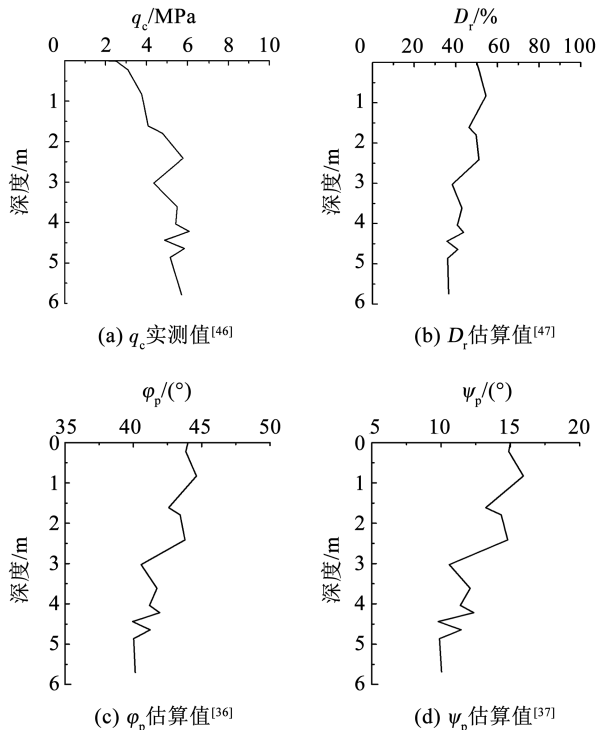


图 3 土层物理力学特性

Fig. 3 Physical and mechanical properties of soil layer

单桩实测荷载-位移曲线和本文计算方法获得的单桩荷载-位移曲线见图 4。可以看出,本文方法计算得到的预测结果与实测结果较吻合。

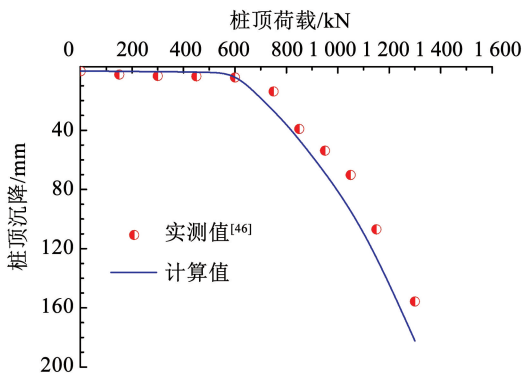


图 4 桩顶荷载-沉降曲线的计算值和实测值

Fig. 4 Calculated and measured load-settlement curve at pile head

3.2 算例 2

该算例来自冯若峰等^[48]开展的既有建筑地下土体开挖条件下在役桩承载特性模型试验。为模拟实际工程中的开挖过程,模型实验中桩基始终在承担上部荷载的条件下进行桩周土体的开挖。每层土体开挖后待在役桩变形稳定后方可进行下一层土体开挖。该模型试验中模型桩由铝管打磨制成,桩径为 0.03 m,桩长为 1.0 m,桩身弹性模量为 25.9 GPa。试验中所用砂土的平均相对密实度、内摩擦角等参

数见文献[48],不同开挖深度时砂土的剪切模量可根据经验公式(17)计算求得。既有建筑地下土体开挖条件下在役单桩实测荷载-归一化沉降(w_i/D ,即桩顶沉降/桩径)曲线和本文计算方法获得的单桩荷载-归一化沉降曲线见图 5。可以看出,对于地下增层开挖条件下的在役单桩,考虑和不考虑开挖卸荷效应计算得到的极限承载力相近,但考虑开挖效应计算结果要略高于不考虑开挖效应计算结果。对于桩顶刚度,考虑开挖土体回弹计算结果要低于不考虑土体回弹计算结果。考虑开挖卸荷回弹效应的计算结果与试验结果更为吻合。

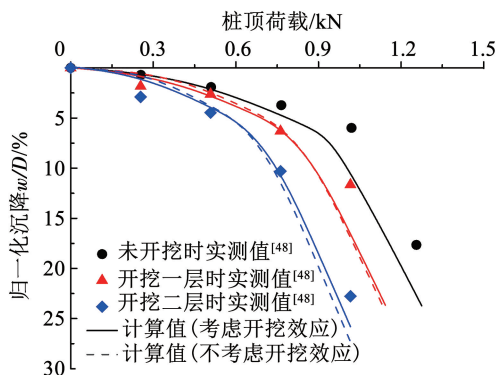


图 5 在役桩顶荷载-归一化沉降曲线的计算值和实测值

Fig. 5 Calculated and measured load-normalized settlement curve at head of in-service pile

需要指出的是,该算例涉及的是小尺度模型试验,开挖规模较小,土体应力状态变化不显著。对于原位条件下的增层开挖工程,考虑开挖卸荷效应,其计算值的差异可能会更加明显。

为研究坑底土回弹效应对于在役桩承载性能的影响,分析了土体回弹量大小对于荷载传递曲线的影响。分析中采用无量纲化参数减小参数取值对于结果的影响。选取了一系列归一化土体回弹量值 w_r/w_{ref} (w_r 为土体回弹量, w_{ref} 为参考土体位移),并计算其对应的荷载传递曲线以及该曲线与不考虑土体回弹荷载传递曲线的偏差。该偏差由正规化方均根差表示,其中,参考土体位移 w_{ref} 由桩侧极限阻力 τ_{su} 和桩侧初始承载刚度值 k_{s0} 计算得到:

$$w_{ref} = \frac{\tau_{su}}{k_{s0}} \quad (35)$$

敏感性分析表明,采用无量纲化分析使得参数取值大小对结果不产生影响。计算的正规化方均根差与归一化回弹量的关系见图 6。可以看出,当归一化土体回弹量 $w_r/w_{ref} < 1$ 时,荷载传递曲线计算偏差小于 5%,此时是否考虑土体回弹对于计算结果影响不大,实际分析中可略去回弹效应;当 $w_r/w_{ref} > 3$ 时,计算误差已经超过了 10%,沉降计算中需考虑土体回弹的影响。

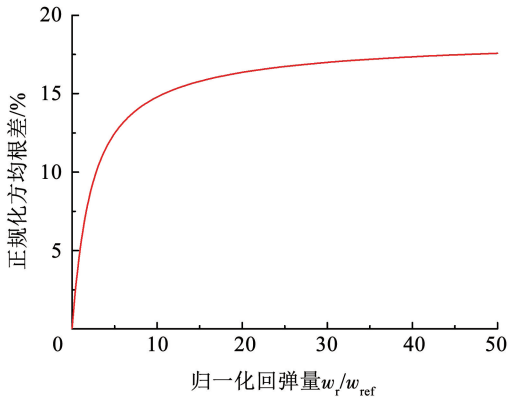


图6 土体回弹量对于荷载传递关系的影响

Fig. 6 Influence of soil rebounding on load transfer relationship of pile

4 结 论

围绕既有建筑地下土体开挖条件下在役桩竖向承载能力评价等问题展开研究,提出了既有建筑地下土体开挖条件下在役桩基竖向承载特性的计算方法,并通过算例分析验证了本文计算方法的合理性。结论如下:

- 1) 地下增层在役桩基开挖效应包括开挖段侧阻力的直接损失、开挖卸荷引起的桩周土体应力状态变化及土体回弹引起的桩顶刚度降低。
- 2) 可采用双曲线模型模拟桩侧单位摩阻力和桩-土相对位移间的关系,可采用双折线模型模拟桩端位移和桩端阻力间的关系。
- 3) 对于较复杂的荷载传递函数,无法获得竖向荷载作用下单桩荷载传递微分方程的解析解时,可采用有限差分法,结合荷载传递法建立既有建筑地下土体开挖条件下在役桩基竖向承载特性的计算方法。
- 4) 对地下增层开挖条件下单桩进行分析时,应考虑开挖引起的土体回弹、桩周土超固结状态等因素对桩侧和桩端承载特性的影响。
- 5) 当归一化土体回弹量小于1时,荷载传递曲线计算偏差小于5%,沉降分析中可不考虑回弹效应。

参考文献

[1] 李志勇. 老旧小区停车难题怎么破? [N]. 经济参考报, 2020-07-03(5)

[2] 贾强, 张鑫, 刘磊. 既有建筑地下增层技术的发展与展望[J]. 施工技术, 2018, 47(6): 84

JIA Qiang, ZHANG Xin, LIU Lei. Development and expectation of basement-addition technology in existing building[J]. Construction Technology, 2018, 47(6): 84. DOI:10.7672/sqjs2018060084

[3] 汤永净. 蒙特利尔地下空间扩建中的古建筑保护技术[J]. 地下空间与工程学报, 2010, 6(4): 672

TANG Yongjing. Montreal underground pedestrian network and protection of ancient church[J]. Chinese Journal of Underground Space and Engineering, 2010, 6(4): 672. DOI: 10.3969/j. issn. 1673-0836. 2010. 04. 003

[4] 文颖文, 刘松玉, 胡明亮, 等. 地下增层工程中既有结构变形控制技术[J]. 岩土工程学报, 2013, 35(10): 1914

WEN Yingwen, LIU Songyu, HU Mingliang, et al. Deformation control techniques for existing buildings during construction process of basement[J]. Chinese Journal of Geotechnical Engineering, 2013, 35(10): 1914

[5] SHAN H, YU F, XIA T, et al. Performance of the underpinning piles for basement-supplementing retrofit of a constructed building[J]. Journal of Performance of Constructed Facilities, 2017, 31(4): 4017017. DOI: 10.1061/(asce)cf.1943-5509.0001008

[6] KRAFT L M, RAY R P, KAGAWA T. Theoretical t - z curves[J]. Journal of the Geotechnical Engineering Division, 1981, 107(11): 1543

[7] ZHANG Q Q, LIU S W, ZHANG S M, et al. Simplified non-linear approaches for response of a single pile and pile groups considering progressive deformation of pile-soil system[J]. Soils and Foundations, 2016, 56(3): 473. DOI: 10.1016/j. sandf. 2016. 04. 013

[8] XU K J, POULOS H G. General elastic analysis of piles and pile groups[J]. International Journal for Numerical and Analytical Methods in Geomechanics, 2000, 24(15): 1109

[9] 王伟, 杨敏. 竖向荷载下桩基础弹性分析的改进计算方法[J]. 岩土力学, 2006, 27(8): 1403

WANG Wei, YANG Min. An improved elastic analysis method of pile foundation under vertical loading[J]. Rock and Soil Mechanics, 2006, 27(8): 1403. DOI: 10.3969/j. issn. 1000-7598. 2006. 08. 036

[10] SAID I, DE GENNARO V, FRANK R. Axisymmetric finite element analysis of pile loading tests[J]. Computers and Geotechnics, 2009, 36(1/2): 6. DOI: 10.1016/j. compgeo. 2008. 02. 011

[11] ZHANG Q Q, LIU S W, FENG R F, et al. Finite element prediction on the response of non-uniformly arranged pile groups considering progressive failure of pile-soil system[J]. Frontiers of Structural and Civil Engineering, 2020, 14(4): 961. DOI: 10.1007/s11709-020-0632-5

[12] ZHANG Q Q, ZHANG Z M, HE J Y. A simplified approach for settlement analysis of single pile and pile groups considering interaction between identical piles in multilayered soils[J]. Computers and Geotechnics, 2010, 37(7/8): 969. DOI: 10.1016/j. compgeo. 2010. 08. 003

[13] ERNESTO M. Approximate elastic-plastic solution for axially loaded piles[J]. Journal of Geotechnical Engineering, 1994, 120(9): 1616. DOI: 10.1061/(asce)0733-9410(1994)120:9(1616)

[14] ZHAO M H, YANG M H, ZOU J J. Vertical bearing capacity of pile based on load transfer model[J]. Journal of Central South University of Technology (English Edition), 2005, 12(4): 488. DOI: 10.4324/9780203880876-11

[15] WANG Z J, XIE X Y, WANG J C. A new nonlinear method for vertical settlement prediction of a single pile and pile groups in layered soils[J]. Computers and Geotechnics, 2012, 45(9): 118. DOI: 10.1016/j. compgeo. 2012. 05. 011

[16] 邹健, 张忠苗, 刘俊伟, 等. 一种考虑桩侧土应变软化的荷载传递函数[J]. 岩土工程学报, 2010, 32(7): 1109

ZOU Jian, ZHANG Zhongmiao, LIU Junwei, et al. A load transfer model considering stain softening of soils[J]. Chinese Journal of Geotechnical Engineering, 2010, 32(7): 1109

[17] 林春金, 张乾青, 梁发云, 等. 考虑桩-土体系渐进破坏的单桩承载特性研究[J]. 岩土力学, 2014, 35(4): 1131

LIN Chunjin, ZHANG Qianqing, LIANG Fayun, et al. Analysis of bearing behavior of a single pile considering progressive failure of pile-soil system[J]. Rock and Soil Mechanics, 2014, 35(4): 1131

[18] ZHANG Q Q, LIU S W, FENG R F, et al. Analytical method for prediction of progressive deformation mechanism of existing piles due to excavation beneath a pile-supported building[J]. International Journal of Civil Engineering, 2019, 17(6): 751. DOI: 10.1007/s40999-018-0309-9

- [19] 张乾青. 竖向抗压桩承载机理与受力特性分析方法[J]. 山东科技大学学报(自然科学版), 2020, 39(4): 93
ZHANG Qianqing. Bearing mechanism and response analysis method of vertically loaded piles[J]. Journal of Shandong University of Science and Technology (Nature Science), 2020, 39(4): 93
- [20] 龚晓南, 伍程杰, 俞峰, 等. 既有地下室增层开挖引起的桩基侧摩阻力损失分析[J]. 岩土工程学报, 2013, 35(11): 1957
GONG Xiaonan, WU Chengjie, YU Feng, et al. Shaft resistance loss of piles due to excavation beneath existing basements[J]. Chinese Journal of Geotechnical Engineering, 2013, 35(11): 1957
- [21] 伍程杰, 龚晓南, 房凯, 等. 增层开挖对既有建筑物桩基承载刚度影响分析[J]. 岩石力学与工程学报, 2014, 33(8): 1526
WU Chengjie, GONG Xiaonan, FANG Kai, et al. Effect of excavation beneath existing buildings on loading stiffness of piles[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(8): 1526. DOI: 10.13722/j.cnki.jrme.2014.08.003
- [22] 曹平, 张敬一, 梁发云. 地下增层开挖时单桩竖向沉降的近似解析方法[J]. 结构工程师, 2019, 35(3): 216
CAO Ping, ZHANG Jingyi, LIANG Fayun. Theoretical analysis about influence of excavation under existing building to vertical settlement of piles[J]. Structural Engineers, 2019, 35(3): 216. DOI: 10.3969/j.issn.1005-0159.2019.03.030
- [23] 纠永志, 祝彦知. 开挖条件下非均质地基中单桩竖向承载特性非线性分析[J]. 岩土力学, 2017, 38(6): 1666
JIU Yongzhi, ZHU Yanzhi. Nonlinear analysis for bearing characteristics of vertically loaded single pile in non-homogeneous soil under excavation[J]. Rock and Soil Mechanics, 2017, 38(6): 1666. DOI: 10.16285/j.rsm.2017.06.015
- [24] 楼晓明, 李德宁, 刘建航. 深基坑坑底地基的回弹应力与回弹变形[J]. 土木工程学报, 2012, 45(4): 134
LOU Xiaoming, LI Dening, LIU Jianhang. Rebound stress and deformation below the bottom of deep excavations[J]. China Civil Engineering Journal, 2012, 45(4): 134
- [25] 杨建民, 李嘉. 基坑底分层回弹量的实用计算方法[J]. 岩土力学, 2014, 35(5): 1413
YANG Jianmin, LI Jia. A practical method for calculating layerwise rebound at the bottom of foundation pit[J]. Rock and Soil Mechanics, 2014, 35(5): 1413
- [26] 陈明, 李镜培. 开挖卸荷桩土界面荷载传递模型的修正与验证[J]. 哈尔滨工业大学学报, 2014, 46(10): 75
CHEN Ming, LI Jingpei. Improved hyperbolic model of load-transfer for pile-soil interface and its verification considering deep excavation[J]. Journal of Harbin Institute of Technology, 2014, 46(10): 75. DOI: 10.11918/j.issn.0367-6234.2014.10.013
- [27] RANDOLPH M F, WROTH C P. Analysis of deformation of vertically loaded piles[J]. Journal of Geotechnical Engineering, 1978, 104(12): 1465. DOI: 10.1061/ajgeb6.0000729
- [28] KISHIDA H, UESUGI M. Tests of the interface between sand and steel in the simple shear apparatus[J]. Géotechnique, 1987, 37(1): 45. DOI: 10.1680/geot.1987.37.1.45
- [29] LOUKIDIS D, SALGADO R. Analysis of the shaft resistance of non-displacement piles in sand[J]. Géotechnique, 2008, 58(4): 283. DOI: 10.1680/geot.2008.58.4.283
- [30] LEHANE B M. Scale effects on tension capacity for rough piles buried in dense sand[J]. Géotechnique, 2005, 55(10): 709. DOI: 10.1680/geot.2005.55.10.709
- [31] ZHANG Q Q, ZHANG Z M. A simplified nonlinear approach for single pile settlement analysis[J]. Canadian Geotechnical Journal, 2012, 49(11): 1256. DOI: 10.1139/cgj-2013-0022
- [32] FENG R F, ZHANG Q Q, LIU S W. Experimental study of the effect of excavation on existing loaded piles[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2020, 146(9): 04020091. DOI: 10.1061/(asce)gt.1943-5606.0002336
- [33] HARDIN B O, DRNEVICH V P. Shear modulus and damping in soils: design equations and curves[J]. Journal of Soil Mechanics and Foundations Division, 1972, 98(7): 667. DOI: 10.1061/jsfeaq.0001760
- [34] MASARUCCI Y, MILIZIANO S, MANDOLINI A. 3M analytical method: evaluation of shaft friction of bored piles in sands[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2015, 142(3): 4015086. DOI: 10.1061/(asce)gt.1943-5606.0001392
- [35] WERNICK E. Skin friction of cylindrical anchors in non-cohesive soils[C]//Proceedings Symposium on Soil Reinforcing and Stabilising Techniques in Engineering Practice. Sydney: [s. n.], 1978: 201
- [36] BOLTON M D. Strength and dilatancy of sands[J]. Geotechnique, 1986, 36(1): 65. DOI: 10.1680/geot.1986.36.1.65
- [37] ROWE P W. The stress-dilatancy relation for static equilibrium of an assembly of particles in contact[J]. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 1962, 269: 500
- [38] 张乾青. 软土地基桩基受力性状和沉降特性试验与理论研究[D]. 杭州: 浙江大学, 2012
ZHANG Qianqing. Test and theoretical study on bearing capacity behavior and settlement of pile in soft soils[D]. Hangzhou: Zhejiang University, 2012
- [39] ZHANG Q Q, ZHANG Z M. Simplified calculation approach for settlement of single pile and pile groups[J]. Journal of Computing in Civil Engineering, 2012, 26(6): 750. DOI: 10.1061/(asce)cp.1943-5487.0000167
- [40] ZHANG Q Q, LI L P, CHEN Y J. Analysis of compression pile response using a softening model, a hyperbolic model of skin friction, and a bilinear model of end resistance[J]. Journal of Engineering Mechanics, 2014, 140(1): 102. DOI: 10.1061/(asce)em.1943-7889.0000640
- [41] 张乾青, 李术才, 李利平, 等. 考虑侧阻软化和端阻硬化的群桩沉降简化算法[J]. 岩石力学与工程学报, 2013, 32(3): 615
ZHANG Qianqing, LI Shucai, LI Liping, et al. Simplified method for settlement prediction of pile groups considering skin friction softening and end resistance hardening[J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(3): 615
- [42] YASUFUKU N, OCHIAI H, OHNO S. Pile end-bearing capacity of sand related to soil compressibility[J]. Soils and Foundations, 2001, 41(4): 59. DOI: 10.3208/sandf.41.4_59
- [43] SHEIL B B, MCCABE B A. An analytical approach for the prediction of single pile and pile group behavior in clay[J]. Computers and Geotechnics, 2016, 75: 145. DOI: 10.1016/j.compgeo.2017.01.008
- [44] CHENG S, ZHANG Q Q, LI S C, et al. Nonlinear analysis of the response of a single pile subjected to tension load using a hyperbolic model[J]. European Journal of Environmental and Civil Engineering, 2018, 22(2): 181. DOI: 10.1080/19648189.2016.1185969
- [45] PAN D D, ZHANG Q Q, LIU S W, et al. Analysis on response prediction of a single pile and pile groups based on the Runge-Kutta method[J]. KSCE Journal of Civil Engineering, 2018, 22(1): 92. DOI: 10.1007/s12205-017-0578-x
- [46] FONSECA A V D, SANTOS J A. International prediction event. Behaviour of CFA, driven and bored piles in residual soil. ISC 2 experimental site[R]. Lisboa: FEUP, 2008
- [47] JAMIOLKOWSKI M, LO PRESTI D C F, MANASSERO M. Evaluation of relative density and shear strength of sands from CPT and DMT[C]//Symposium on Soil Behavior and Soft Ground Construction. Cambridge: American Society of Civil Engineers, 2003: 201
- [48] FENG R F, ZHANG Q Q, LIU S W. Experimental study of the effect of excavation on existing loaded piles[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2020, 146(9): 04020091. DOI: 10.1061/(asce)gt.1943-5606.0002336