文章编号:1674-2974(2024)05-0046-10 DOI:10.16339/j.cnki.hdxbzkb.2024046

基于应变楔模型的堆载下被动斜桩受力变形分析

周德泉 ,朱沁 †,王创业 ,周毅
(长沙理工大学 土木工程学院,湖南 长沙 410114)

摘 要:被动斜桩大多应用于开挖基坑的支护工程中,很少应用于填筑体抗滑工程中,且工程性状尚不清楚.为分析侧向堆载作用下被动斜桩受力变形特性,本文基于应变楔模型(SW模型),结合Boussinesq解进行双重积分及坐标变换,建立了侧向堆载作用下被动斜桩的挠曲微分方程,推导了其相应桩身内力与侧移的有限差分解,并通过与现场试验和室内模型试验对比验证了本文方法的有效性.结果表明:相同荷载作用下,负斜桩的桩顶侧移与桩身弯矩峰值最小、正斜桩次之、直桩最大;正斜桩和负斜桩的桩顶侧移与桩身弯矩峰值均随其倾斜角的增大而减小.侧向堆载下斜桩桩身变形模式为“平移叠加转动”.桩身常规倾斜角范围内(≤20°),坡脚处将桩设置成向堆载中心倾斜、倾斜角较大的负斜桩,可以取得更好的工程效果.

关键词:路基工程;堆载;被动斜桩;应变楔模型
中图分类号:TU473.1 **文献标志码**:A

Analysis on Stress and Deformation of Passive Battered Piles under Surcharge Based on SW Model

ZHOU Dequan,ZHU Qin†,WANG Chuangye,ZHOU Yi
(School of Civil Engineering, Changsha University of Science and Technology, Changsha 410114, China)

Abstract: Passive battered piles are mostly applied in the supporting engineering of the excavation foundation pit but are rarely used in the anti-skid engineering of filling bodies , and the engineering character is not yet clear. To analyze the mechanical deformation characteristics of passive battered piles under lateral surcharge, based on the strain wedge model (SW model) and combined with the Boussinesq solution, this paper establishes the deflection differential equation of passive battered piles under lateral surcharge, derives the finite difference solution of the corresponding internal force and lateral displacement of the piles, and then verifies the effectiveness of this method by comparing the results of field tests and indoor model tests. The results show that under the same surcharge, the top lateral displacement and the bending moment of the straight pile are the largest, followed by the positive battered pile, and the negative battered pile is the smallest. The top lateral displacement and the bending moment of the positive and negative battered pile decrease with the inclination angle increase. Under lateral surcharge, the battered pile undergoes “translating and rotating”. Within the range of conventional pile body inclination angle (≤20°), the

* **收稿日期**:2023-03-27
基金项目:国家自然科学基金资助项目(52278329),National Natural Science Foundation of China(52278329);湖南省交通运输厅科技项目(202019,202247), Scientific Research Fund of Hunan Provincial Department of Transportation (202019,202247);湖南省研究生科研创新项目(CX20200835), Hunan Provincial Innovation Foundation for Postgraduate(CX20200835)
作者简介:周德泉(1967—),男,湖南宁乡人,长沙理工大学教授,博士
† 通信联系人,E-mail:ZhuQin@stu.csust.edu.cn

pile at the foot of the slope set as a negatively battered pile with a larger inclination angle towards the center of the pile load can achieve a better engineering effect.

Key words: roadbed engineering; surcharge; passive battered pile; strain wedge model

工程中,桩体常常直接承受巨大的垂直和水平荷载,或者抵抗岩土侧向移动.根据桩-土相互作用原理,堆载侧面的桩体属于“被动桩”[1],现有理论分析方法主要有土位移法[2-5]和土压力法[6-9].其中,土位移法需进行大量数值模拟或现场实测以确定堆载时土体自由位移,无法在工程中得到广泛应用;土压力法则基于实测数据或塑性理论得到桩侧土压力解析解后,借助已有主动桩分析原理进行计算,更为方便有效.被动直桩方面,Poulos 等[10-11]基于 Mindlin 解推导了均质地基中被动桩的弹性理论解.陈福全等[12]通过引入层状地基中广义 Mindlin 解和堆载作用下土体应力与位移通解对 Poulos 弹性理论解进行改进.上官士青等[13]考虑桩土脱开及土体绕桩流动的情况,提出了水平方向桩-土双位移体系计算模型.李双龙等[14]利用扩展 Koppejan 模型,综合考虑软土主固结效应和蠕变效应,对被动桩-软土时效性相互作用过程进行研究.杨吉新等[15]引入 Pasternak 双参数地基模型,结合 Flamant 解推导的梯形荷载下桩侧土压力计算公式,得到桩身侧向位移的有限差分解.被动斜桩方面,郭景琢等[16]根据斜桩桩侧被动区土体受力特点,对被动区土弹簧进行折减,利用平面杆系有限元推导出斜直组合结构设计计算方法.周海祚等[17]假设倾斜支护桩不发生破坏,采用圆弧条分法分析桩-土整体稳定性,推导其安全系数计算公式.上述方法均对桩周地基采用 Winlker 弹性地基模型,将模型桩简化为 Euler 梁,概念明确便于求解,但未充分考虑桩周土体的连续性和抗剪强度,其计算结果可能存在一定误差.

应变楔模型不仅能充分考虑不同土质条件下模型桩刚度、截面形状、桩身材料非线性等因素,还能分析桩周土层的连续性及液化情况,相较于其他分析方法更具优势[18].Norris[19-20]将抵抗桩身侧移挤压的桩前土体等效为一个三维土楔体,桩侧地基抗力随土楔体三维尺寸及土体内摩擦角发挥值的改变而改变,从而将一维弹性地基梁模型拓展到三维领域.Ashour 等[21-24]在 Norris 的基础上,将应变楔模型推广应用到成层土中的斜坡群桩,并提出了砂土中横向受荷斜桩的桩前地基抗力计算公式.彭文哲等[25]将斜坡地基桩前三维土楔分为上、下两个部分,并对下部应变楔模型进行修正.李忠诚等[26]将堆载下被动桩分为被动侧成拱、主动侧形成应变楔,分别计算被动桩桩侧土压力.倾斜桩的水平承载性能优于直桩[27-28],国内外学者大多聚焦于桩顶直接承担水平拉力的主动斜桩,对土体侧移挤压下的被动斜桩研究相对较少,且研究大多集中在斜桩支护基坑[29-30]和边坡抗滑[31-32]等方面,对于侧向堆载下被动斜桩受力变形分析研究十分有限.

本文提出一种适用于侧向堆载作用下被动斜桩桩身内力与侧移的计算方法,引入应变楔模型以充分考虑桩周土体的连续性和抗剪强度.通过对被动斜桩进行受力分析,构建侧向堆载作用下斜桩桩身控制方程;利用应变楔模型对桩前土层地基抗力进行推导;结合 Boussinesq 解进行二重积分及坐标变换得到桩身后侧附加土体压力分布规律;借助有限差分程序求解桩身各深度位置的侧向位移.对比现场试验与室内模型试验结果,验证本文方法,为侧向堆载作用下被动斜桩受力变形分析提供参考,并给出工程建议.

1　基于应变楔模型的简化分析方法

国内外对于正、负斜桩定义尚未统一[33-36].作者[37]定义:侧向卸载或者侧向加载作用下,倾斜角(定义为桩轴线与垂直线间夹角,下同)将增大的桩称为正斜桩,倾斜角将减小的桩称为负斜桩,直桩可视为桩身倾斜角为 0 的特殊斜桩.

桩侧堆载作用下斜桩的计算模型如图 1 所示,模型整体坐标系为 XOZ,以桩顶截面中点 o 为原点,沿桩身轴线方向为 z 轴,垂直于桩身轴线方向为 x 轴,建立局部直角坐标系 xoz.桩侧堆载为 p,桩身长度为 L,桩身倾斜角为 β,斜桩到堆载的最小水平距离为 s.将桩视为弹性地基梁,则桩身挠曲微分方程

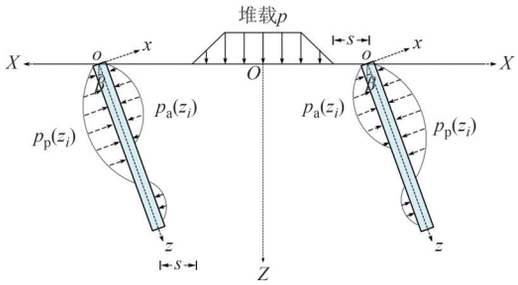
如式(1)所示:

$$EI\frac{\mathrm{d}^4x}{\mathrm{d}z^4}-p_{\mathrm{a}}(z_i)+p_{\mathrm{p}}(z_i)=0 \tag{1}$$

式中:EI为桩身抗弯刚度;$p_{\mathrm{p}}(z_i)$为桩前土体提供的地基抗力;$p_{\mathrm{a}}(z_i)$为堆载导致的桩后附加土压力;x、z分别表示桩身局部坐标下的桩身挠度和桩身深度.

1.1 桩前土体的应变楔模型

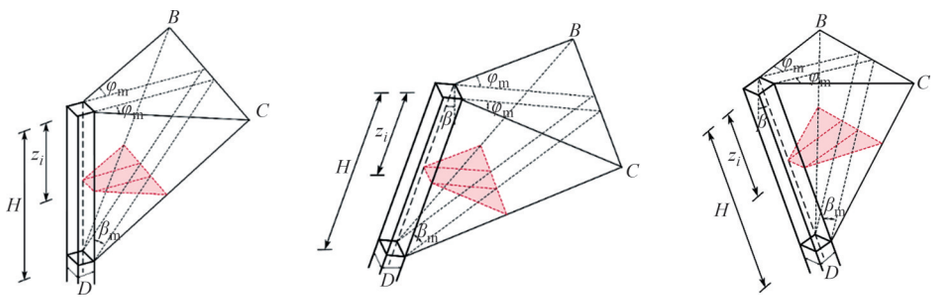
桩前三维应变楔如图2所示,直桩应变楔开展深度为H,斜桩应变楔开展深度为$H\cos\beta$,应变楔伞角为φ_{m},应变楔底角为$\beta_{\mathrm{m}}=\left(45^\circ+\frac{\varphi_{\mathrm{m}}}{2}\right)$,应变楔开展宽度为$\overline{BC}$,方桩边长或圆桩截面内接正方形边长为$D$,直桩第$i$层土楔单元深度为$z_i$,斜桩第$i$层土楔单元深度为$z_i\cos\beta$.



(a)正斜桩 (b)负斜桩

图1 堆载下被动斜桩计算模型

Fig.1 Calculation model of passive battered pile under surcharge



(a)直桩 (b)正斜桩 (c)负斜桩

图2 三维应变楔

Fig.2 Three-dimensional strain wedge

直桩和正斜桩的第i层土楔开展宽度$\overline{BC_i}$为:

$$\overline{BC_i}=2(H-z_i)\tan\beta_{\mathrm{m},i}\tan\varphi_{\mathrm{m},i}+D \tag{2}$$

由于桩身倾斜方向与地面影响,负斜桩第i层土楔开展宽度计算公式与直桩和正斜桩有所不同.

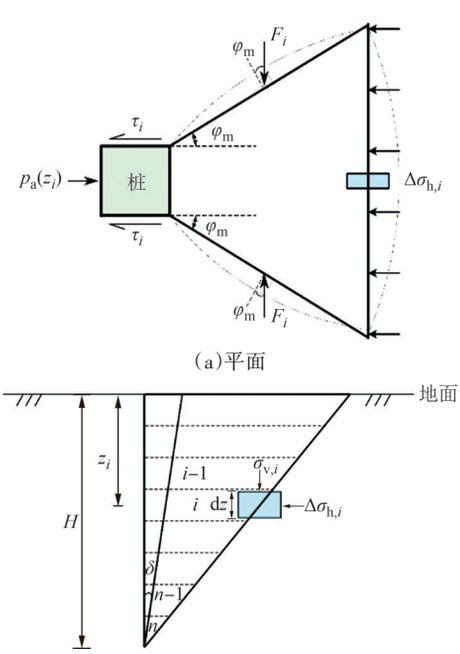
当第i层土楔单元深度$z_i\geqslant\frac{H\tan\beta\tan\beta_{\mathrm{m}}}{1+\tan\beta\tan\beta_{\mathrm{m}}}$时,负斜桩第$i$层土楔开展宽度$\overline{BC}$同样可由式(2)进行计算.

当第i层土楔单元深度$z_i<\frac{H\tan\beta\tan\beta_{\mathrm{m}}}{1+\tan\beta\tan\beta_{\mathrm{m}}}$时,负斜桩第$i$层土楔开展宽度$\overline{BC_i}$为:

$$\overline{BC_i}=2z_i\cot\beta\tan\varphi_{m,i}+D \tag{3}$$

将桩前土楔体离散成n个等厚的土楔单元,直桩、正斜桩和负斜桩的受力分析分别如图3~5所示.其中,dz为各土楔单元厚度,$\Delta\sigma_{\mathrm{h},i}$为第$i$层土楔单元水平应力增量,$\sigma_{\mathrm{v},i}$为第$i$层土楔单元竖向应力,$F_i$为第$i$层土体土楔模型侧壁压力,$\tau_i$为第$i$层土楔单元桩侧剪应力,$\delta$为桩身变形转角,图中虚线部分为真实的应力区.

引入应力水平SL,第i层土楔单元应力水平SL_i可通过三轴试验或经验公式得到:



(a)平面 (b)剖面

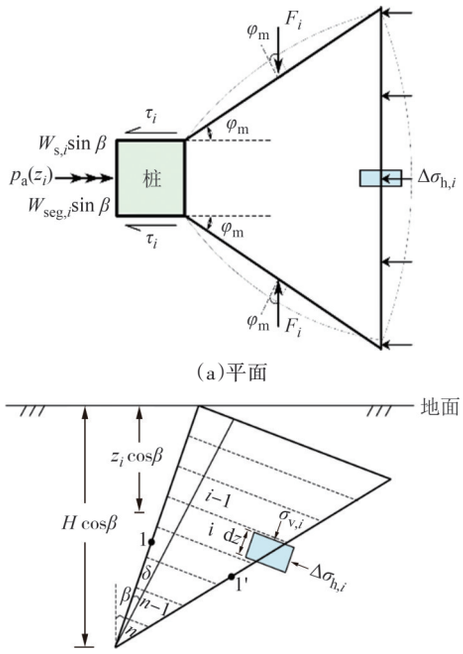
图3 直桩应变楔模型

Fig.3 Strain wedge model of straight pile

单桩第i层土楔单元水平应力增量$\Delta\sigma_{\mathrm{h},i}$为[22]:

$$\Delta\sigma_{\mathrm{h},i}=\mathrm{SL}_i\Delta\sigma_{\mathrm{hf},i} \tag{4}$$

第i层土楔单元水平应力极限增量$\Delta\sigma_{\mathrm{hf},i}$为[23]:

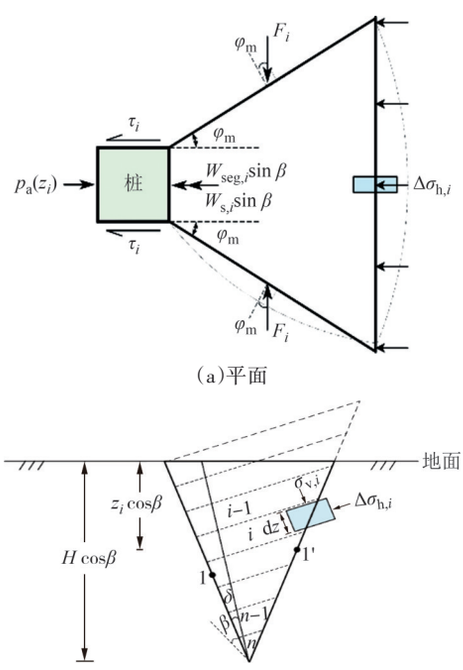


(a)平面

(b)剖面

图 4　正斜桩应变楔模型

Fig.4　Strain wedge model of positive battered pile



(a)平面

(b)剖面

图 5　负斜桩应变楔模型

Fig.5　Strain wedge model of negative battered pile

$$\Delta\sigma_{hf,i}=\begin{cases}\overline{\sigma}_{v0,i}\left[\tan^2\left(45^\circ+\dfrac{\varphi}{2}\right)-1\right];\ c=0,\ \varphi\neq 0\\ \left(\dfrac{c}{\tan\varphi}+\overline{\sigma}_{v0,i}\right)\left[\tan^2\left(45^\circ+\dfrac{\varphi}{2}\right)-1\right];\ c\neq 0,\ \varphi\neq 0\end{cases}\tag{5}$$

其中,$\overline{\sigma}_{v0,i}$为第i层土楔单元竖向有效应力,对于直桩:$\overline{\sigma}_{v0,i}=\sigma_1$,对于正(负)斜桩:$\overline{\sigma}_{v0,i}=\dfrac{\sigma_1+\sigma_1'}{2}$.

各土楔单元应力均满足应力平衡方程,故桩前土体提供的地基抗力$p_p(z_i)$为:

$$p_p(z_i)=\begin{cases}\Delta\sigma_{h,i}\overline{BC}_iS_1+2\tau_iDS_2,\beta=0;\\ (\Delta\sigma_{h,i}\overline{BC}_i-W_{seg,i}\sin\beta-W_{s,i}\sin\beta)S_1+\\ \qquad 2\tau_iDS_2,\beta>0;\\ (\Delta\sigma_{h,i}\overline{BC}_i+W_{seg,i}\sin\beta+W_{s,i}\sin\beta)S_1+\\ \qquad 2\tau_iDS_2,\beta<0\end{cases}\tag{6}$$

式中:S_1、S_2为桩形系数,方桩截面S_1、S_2均为1.0,圆桩截面S_1、S_2分别为0.75和0.50;$W_{s,i}$表示第i层土楔单元对应桩段所承担的上部土条重力;$W_{seg,i}$表示第i层土楔单元对应桩段的重力.当模型桩桩身倾斜角β=0时,选用式(6)中的第一个公式进行计算;当模型桩桩身倾斜角$\beta>0$时,选用式(6)中的第二个公式进行计算;当模型桩桩身倾斜角$\beta<0$时,选用式(6)中的第三个公式进行计算.

非极限状态桩侧剪应力τ_i为[25]:

$$\tau_i=\begin{cases}\overline{\sigma}_{v0,i}\tan\varphi_{s,i},\tan\varphi_{s,i}=2\tan\varphi_{m,i},\tan\varphi_{s,i}\leqslant\tan\varphi_i;\\ \overline{\sigma}_{v0,i}\tan\varphi_{s,i}+2C_s,\tan\varphi_{s,i}=2\tan\varphi_{m,i},C_s=2C_m\end{cases}\tag{7}$$

式中:$\varphi_{s,i}$和C_s分别为第i层土楔单元桩-土界面摩擦角和黏聚力;C_m为基于摩尔库伦破坏准则的桩侧土体内摩擦角发挥值对应截距.当桩周土层为砂土时,应选用式(7)中的第一个公式进行计算;当桩周土层为一般黏性土时,应选用式(7)中的第二个公式进行计算.

由摩尔应变圆原理可知,第i层土楔单元桩身转角δ_i与水平位移X_i关系为:

$$x_i=\sum\delta_i\mathrm{d}z\tag{8}$$

$$X_i=x_i\cos\beta\tag{9}$$

其中,δ_i可由桩土变形协调条件$\delta_i=\dfrac{\varepsilon_i}{\Psi_s}$求得,桩土连接参数$\Psi_s=\dfrac{2}{(1+\nu)\sin 2\Theta_m}$,土楔单元泊松比为$\nu$,$\Theta_m=45^\circ-\dfrac{\varphi_m}{2}$.

联立式(6)、式(8)可得,桩前土体地基反力模量为:

$$E_{s,i}=\frac{p_p(z_i)}{x_i}\tag{10}$$

1.2 桩后土压力

如图6所示,为求解堆载作用下桩后水平附加土压力$p_a(z_i)$,假定地基土体为半无限弹性体,对Boussinesq解进行二重积分及坐标变换,梯形分布荷载作用下,模型整体坐标系XOZ内任意一点$M(X,Z)$($X \geqslant b+l$)处的附加竖向应力σ_Z和水平应力σ_X分别为[38]:

$$\begin{aligned}\sigma_Z = {} & \frac{p}{\pi}\left\{\frac{X+l+b}{l}\left[\arctan\left(\frac{X+l+b}{Z}\right)-\arctan\left(\frac{X-b}{Z}\right)\right]-\frac{Z(X+b)}{Z^2+(X+b)^2}\right\}+\\ & \frac{p}{\pi}\left\{\frac{X-l-b}{l}\left[\arctan\left(\frac{X-l-b}{Z}\right)-\arctan\left(\frac{X-b}{Z}\right)\right]+\frac{Z(X-b)}{Z^2+(X-b)^2}\right\}+\\ & \frac{p}{\pi}\left\{\arctan\left(\frac{X+b}{Z}\right)-\operatorname{arcta}\left(\frac{X-b}{Z}\right)+\frac{2bZ\left(b^2+Z^2-X^2\right)}{\left[Z^2+(X+b)^2\right]\left[Z^2+(X-b)^2\right]}\right\}\end{aligned} \tag{11}$$

$$\begin{aligned}\sigma_X = {} & \frac{p}{\pi}\left\{\frac{X+l+b}{l}\left[\arctan\left(\frac{X+l+b}{Z}\right)-\arctan\left(\frac{X-b}{Z}\right)\right]+\frac{Z(X+b)}{Z^2+(X+b)^2}+\frac{Z}{l}\ln\frac{Z^2+(X+b)^2}{Z^2+(X+l+b)^2}\right\}+\\ & \frac{p}{\pi}\left\{\frac{X-l-b}{l}\left[\arctan\left(\frac{X-l-b}{Z}\right)-\arctan\left(\frac{X-b}{Z}\right)\right]-\frac{Z(X-b)}{Z^2+(X-b)^2}-\frac{Z}{l}\ln\frac{Z^2+(X-l-b)^2}{Z^2+(X-b)^2}\right\}+\\ & \frac{p}{\pi}\left\{\arctan\left(\frac{X+b}{Z}\right)-\arctan\left(\frac{X-b}{Z}\right)-\frac{2bZ(b^2+Z^2-X^2)}{\left[Z^2+(X+b)^2\right]\left[Z^2+(X-b)^2\right]}\right\}\end{aligned} \tag{12}$$

式中:$2b$为均布条形荷载长度;l为三角形分布荷载长度.

堆载作用下桩后水平附加土压力应为Boussinesq积分解的2倍[39],故垂直于桩身的桩后土压力$P_a(z_i)$为:

$$p_a(z_i)=\begin{cases}2\sigma_x, & \beta=0;\\ 2(\sigma_x\cos\beta+\sigma_z\sin\beta), & \beta>0;\\ 2(\sigma_x\cos\beta-\sigma_z\sin\beta), & \beta<0\end{cases} \tag{13}$$

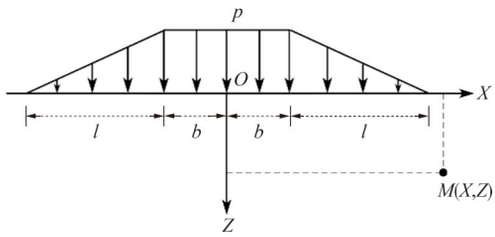


图6 梯形荷载分布示意图

Fig.6 Schematic of trapezoidal distributed load

1.3 有限差分法求解桩身挠曲微分方程

当土层性质差异不大时,可将天然土层视为成层土所组成的多层均质土,此时宜采用有限差分法进行求解.基于传统弹性地基梁法(即BEF法)与局部变形理论,结合桩、土物理力学性质参数,将斜桩沿桩身方向划分成n个厚度为dz的桩段单元,将四阶差分公式代入式(1),化简可得斜桩挠曲线微分方程的差分格式为:

$$x_{i-2}-4x_{i-1}+\left[(\mathrm{d}z)^4\frac{E_{s,i}}{EI}+6\right]x_i-4x_{i+1}+x_{i+2}=\frac{(\mathrm{d}z)^4}{EI}p_a(z_i) \tag{14}$$

桩顶自由、桩顶弯矩M_0、剪力Q_0已知条件下,两个补充方程为:

$$\begin{cases}x_{-1}-2x_0+x_1=\dfrac{M_0(\mathrm{d}z)^2}{EI},\\ -x_{-2}-2x_{-1}-2x_1+x_2=\dfrac{2Q_0(\mathrm{d}z)^3}{EI}\end{cases} \tag{15}$$

桩端自由,桩底剪力、弯矩均可视为零,两个补充方程为:

$$\begin{cases}-x_{n-2}+2x_{n-1}-2x_{n+1}+x_{n+2}=0,\\ x_{n-1}-2x_n+x_{n+1}=0\end{cases} \tag{16}$$

基于层间完全接触理论,联立对应边界条件补充方程,将桩段各节点刚度矩阵合并为整体刚度矩阵[$\boldsymbol{K}$],桩身转角、弯矩及剪力的具体差分格式由参考文献[40]可得,具体迭代计算过程如下:

1)综合考虑桩-土系统相关尺寸与物理力学参数,将斜桩及桩周土层分别离散成n个厚度为dz的单元段.

2)令桩前应变楔开展深度为H、初始应变为ε,由式(9)计算桩顶侧移$(x_0)_{SWM}$;联立式(8)和式(10)求出桩前土体地基反力模量$E_{s,i}$,由式(13)计算得到桩后土压力$p_a(z_i)$,代入式(14)即可计算桩顶侧移$(x_0)_{BEF}$.

3)比较$(x_0)_{SWM}$和$(x_0)_{BEF}$,当$(x_0)_{SWM}-(x_0)_{BEF}\leqslant 0.001$时,即可认为二者相等,结束循环;否则,修正$H$和$\varepsilon$,返回步骤2).

2　试验验证

2.1　实体工程测试

邓会元[41]依托甬台温复线围垦区温州段实体工程,对侧向非对称堆载下临近直桩进行现场试验研究.试验参数如下:桩长 L=75 m,桩径 D=1.8 m,桩身混凝土标号为C35,堆载体为重度 19 kN/m^{3}的粉质黏土,堆载顶面及底面尺寸分别为 10 m×10 m 和 19 m×19 m,堆载高度为 2.8 m,桩侧到堆载的距离为 3 m,土层参数见表 1.

表 1　土层物理力学参数

Tab.1　Physical and mechanical parameters of soil

土层	厚度/m	重度 γ/(kN·m^{-3})	压缩模量 E_s/MPa	黏聚力 c/kPa	内摩擦角 φ/(°)	泊松比 ν
粉质黏土	1.6	19	4.5	22	6.7	0.32
淤泥 1	7.9	17.1	1.99	5.5	1.25	0.4
淤泥 2	20.8	16.4	1.83	8.4	2.18	0.4
淤泥质黏土	6.4	17	2.17	15	3.85	0.4
黏土 1	17.5	17.3	2.73	19.25	5.83	0.35
黏土 2	11.9	17.6	2.98	23	7.7	0.3
圆砾	4.4	18.2	30	2	32	0.25
卵石	14.4	18.7	42	1	35	0.2

将本文计算方法得到的桩身侧移与文献[41]现场监测结果进行对比,结果如图 7 所示.由图 7 可知,本文计算结果与现场监测数据接近,桩身侧移计算值稍大于现场监测结果,这是因为现场工程桩桩顶附近存在钢护筒约束.

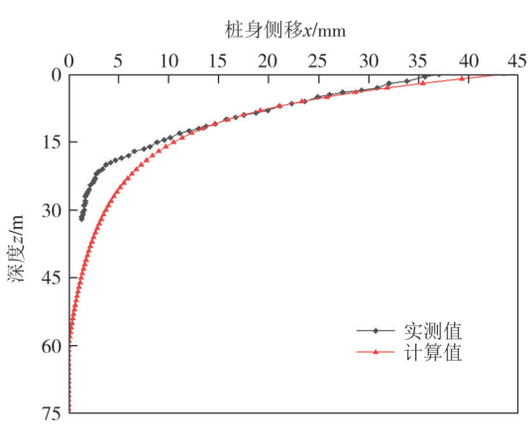


图 7　桩身位移对比

Fig.7　Comparison of pile displacement

2.2　模型试验

为进一步探讨侧向堆载下砂土中被动斜桩桩身变形响应规律及其理论计算方法的合理性,以砂土中被动斜桩室内模型试验为例(见图 8),对其进行对比分析.本次试验模型桩桩长 800 mm,桩身计算宽度 40 mm,桩身弹性模量 34 GPa,桩身倾斜角 β=−20°、−10°、0°、+10°、+20°;通过室内土工试验获得模型砂土物理力学性质指标为:含水率 2 %,内摩擦角 39.8°,重度 18 kN/m^3,曲率系数 C_c=2.7,不均匀系数 C_u=5.5,相对密实度 D_r=0.66.模型箱内壁涂抹凡士林,并覆盖 20 mm 厚的聚乙烯泡沫层,以减弱边界效应[42].

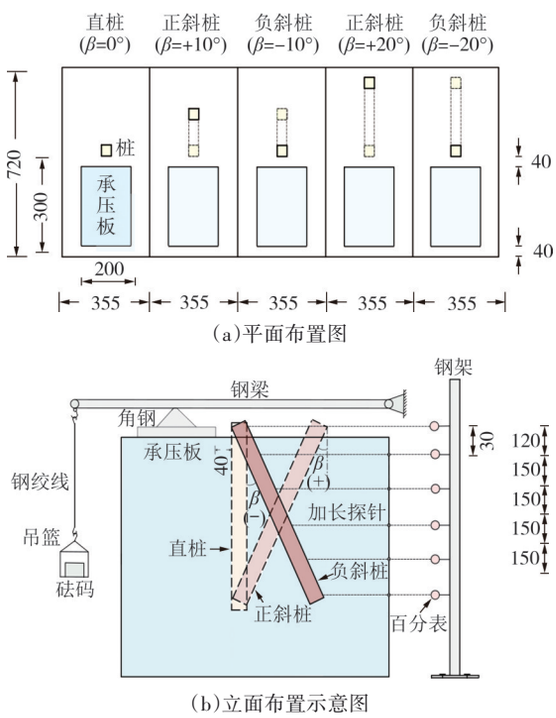


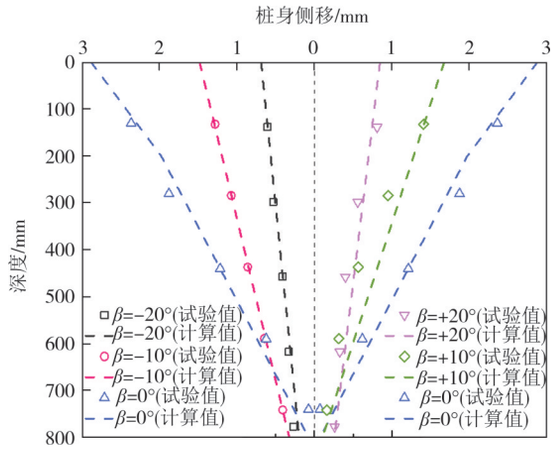
图 8　模型试验方案(单位:mm)

Fig.8　Layout of model test scheme(unit:mm)

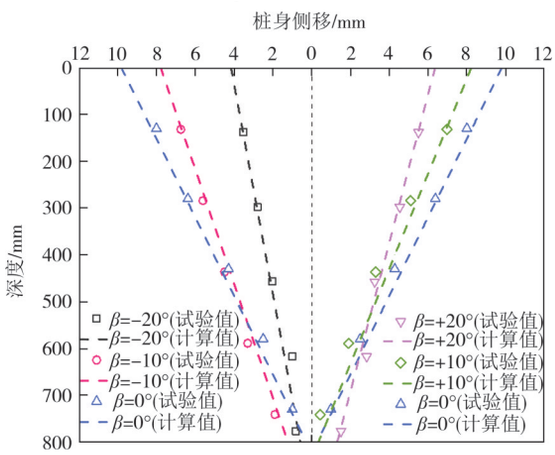
模型试验加载系统主要包括工字梁、角钢、承压板、砝码和吊篮,通过依次向吊篮中添加砝码进行加载,换算可得模型试验第一、第二级桩侧堆载值分别为 p_1=84.375 kPa 和 p_2=184.375 kPa.模型桩桩身同一截面应变片数据由应变仪采集,其换算公式可参考文献[43].

图 9 为不同倾斜角斜桩桩身侧移变化规律,图 10 为不同倾斜角斜桩桩身弯矩变化规律.分析可知:

1) 本文建立的侧向堆载下被动斜桩桩身受力



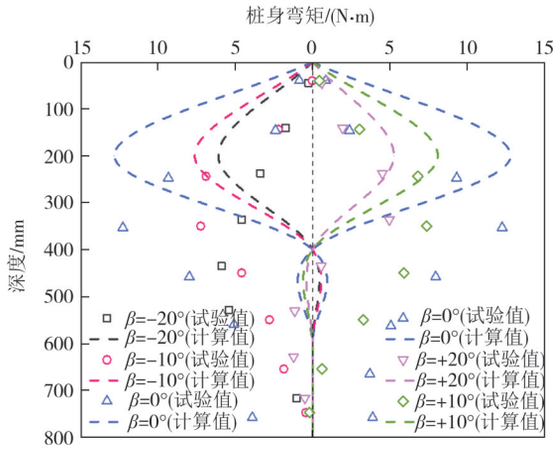
(a)p=84.375 kPa



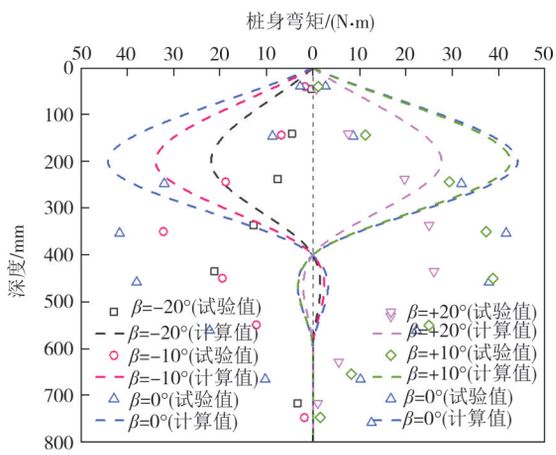
(b)p=184.375 kPa

图 9 不同倾斜角斜桩桩身侧移

Fig.9 Lateral displacement of battered piles with different inclination angles



(a)p=84.375 kPa



(b)p=184.375 kPa

图 10 不同倾斜角斜桩桩身弯矩

Fig.10 Bending moment of battered piles with different inclination angles

变形的有限差分解与室内模型试验结果吻合较好.对比表2、表3中模型桩桩顶侧移与桩身弯矩峰值可以发现,计算结果与试验结果相差不大.例如,对应于桩侧堆载值p=84.375 kPa、桩身倾斜角β=+20°的模型桩,其对应桩顶侧移最大计算误差为−4.6%(负号表示计算结果小于试验结果),对应桩身倾斜角β=+10°的模型桩,其对应桩身弯矩峰值M_{max}的计算误差为8.9%,这是因为试验砂土静置沉降过程中,斜桩会与其倾斜方向一侧试验砂发生挤压,另一侧桩−砂之间存在微小缝隙,影响桩侧试验砂所能提供的水平抗力[24].

2)模型桩桩身侧移沿桩顶至桩底方向呈线性递减,侧移峰值出现在桩顶位置;加载过程中,直桩桩顶侧移远大于桩底侧移,桩底侧移很小,桩顶与桩底的侧移差值随荷载的增大而显著增大,位移模式为“平移叠加转动”.堆载相同时,斜桩桩身位移峰值随桩身倾斜角增大而减小.堆载和倾斜角相同时,负斜桩位移峰值小于正斜桩[44-45].

3)模型桩桩身弯矩随桩身深度增加先增大后减小再稍增大,桩身弯矩峰值位于土层中上部,堆载下被动斜桩破坏模式为弯曲破坏.堆载相同时,斜桩桩身弯矩峰值随桩身倾斜角增大而减小.堆载和倾斜角相同时,负斜桩弯矩峰值小于正斜桩.

表 2 试验与理论计算结果对比(p=84.375 kPa)

Tab.2 Comparison of test and calculated results

p=84.375 kPa

桩身倾斜角β/(°)	桩顶侧移x_0			桩身弯矩峰值M_{max}		
	试验值/mm	计算值/mm	误差/%	试验值/(N·m)	计算值/(N·m)	误差/%
−20	0.68	0.69	0.7	5.9	6.1	3.4
−10	1.47	1.48	0.3	7.2	7.6	5.1
0	2.89	2.88	−0.5	12.3	12.8	4.3
+10	1.61	1.67	3.6	7.4	8.1	8.9
+20	0.89	0.85	−4.6	5	5.3	5.6

表 3　试验与理论计算结果对比(p=184.375 kPa)

Tab.3　Comparison of test and calculated results

p=184.375 kPa

桩身倾斜角β/(°)	桩顶侧移x_0			桩身弯矩峰值M_{max}		
	试验值/mm	计算值/mm	误差/%	试验值/(N·m)	计算值/(N·m)	误差/%
−20	4.20	4.20	0.01	21.2	21.9	3.3
−10	7.90	7.90	0.01	32.2	33.9	5.0
0	9.79	9.81	0.30	41.6	44.1	5.7
+10	8.20	8.20	0.01	38.8	42.5	8.8
+20	6.40	6.40	−0.01	26.1	27.7	5.9

3　结 论

本文基于应变楔模型求得桩前土层地基抗力,结合Boussinesq解进行双重积分及坐标变换得到桩后土体压力分布形式,推导了侧向堆载作用下被动斜桩桩身挠曲微分方程,获得了相应的桩身内力位移分析有限差分解,并与现场试验和室内模型试验进行对比分析,得到以下结论:

1) 侧向堆载下,直桩和斜桩的桩身侧移均随桩身深度的增加而减小,桩身侧移峰值出现在桩顶附近.堆载相同时,常规倾斜角($\beta \leqslant 20°$)的斜桩桩身位移峰值随桩身倾斜角增大而减小.堆载和倾斜角相同时,负斜桩位移峰值小于正斜桩.

2) 堆载作用下,直桩和斜桩的桩身弯矩均随桩身深度的增加呈先增大后减小再稍增大趋势,桩身弯矩峰值出现在土层中上部.堆载相同时,常规倾斜角($\beta \leqslant 20°$)的斜桩桩身弯矩峰值随桩身倾斜角增大而减小.堆载和倾斜角相同时,负斜桩弯矩峰值小于正斜桩.

3) 工程中,建议采用负斜桩代替直桩,能更有效提高桩体的抗滑移能力.

参考文献

[1] DE BEER E E. The effects of horizontal loads on piles due to surcharge or seismic effects [C]//BRUNI R, CORRADINI A, LAFUENTE A L, et al. Proceedings of the Ninth International Conference on Soil Mechanics and Foundation Engineering. Tokyo: ICSMFE, 1977:547-558.

[2] 竺明星, 龚维明, 徐国平,等. 大面积堆载作用下轴向受力隔离桩的承载机制分析[J]. 岩石力学与工程学报, 2014, 33(2): 421-432.
ZHU M X, GONG W M, XU G P, et al. Analysis of bearing mechanism of axially loaded isolation piles under larger-scale surcharge loading [J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(2):421-432. (in Chinese)

[3] 冯国辉, 窦炳珺, 黄展军,等. 盾构开挖引起的临近桩基水平位移的简化计算方法[J]. 湖南大学学报(自然科学版),2022, 49(9):136-144.
FENG G H, DOU B J, HUANG Z J, et al. Simplified calculation method for lateral displacement of adjacent pile due to tunneling [J]. Journal of Hunan University (Natural Sciences), 2022, 49(9):136-144. (in Chinese)

[4] ZHANG A J, MO H H, ZHU Z D. Theoretical elastio-plastic solution for piles subject to lateral soil movement [J]. Procedia Earth and Planetary Science, 2012, 5:58-63.

[5] 杨敏, 周红波. 承受侧向土体位移桩基的一种耦合算法[J]. 岩石力学与工程学报, 2005, 24(24):4491-4497.
YANG M, ZHOU H B. A coupling analytical solution of piles subjected to lateral soil movements [J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(24): 4491-4497. (in Chinese)

[6] 胡建荣, 王昌金, 朱向荣. 滑动土体与邻近桩基相互作用的弹塑性解[J]. 岩土力学, 2011, 32(11):3414-3419, 3426.
HU J R, WANG C J, ZHU X R. Elastoplastic solution for interaction between slipping soil and adjacent piles [J]. Rock and Soil Mechanics, 2011, 32(11):3414-3419, 3426. (in Chinese)

[7] 张浩, 石明磊, 郭院成. 土体侧移作用下被动桩受力变形的简化解析计算[J]. 东南大学学报(自然科学版), 2016, 46(2): 392-399.
ZHANG H, SHI M L, GUO Y C. Simplified analytical calculation for forced deformation of passive pile subjected to lateral soil displacement [J]. Journal of Southeast University (Natural Science Edition), 2016, 46(2):392-399. (in Chinese)

[8] 张浩, 孙凯, 杨玲,等. 被动桩-侧移软土相互作用于桩身被动荷载分析[J]. 土木工程与管理学报, 2020, 37(3):45-51.
ZHANG H, SUN K, YANG L, et al. Analysis of passive pile-lateral soft soil interaction and passive loading on pile [J]. Journal of Civil Engineering and Management, 2020, 37(3): 45-51. (in Chinese)

[9] 梁发云, 李彦初, 黄茂松. 基于Pasternak双参数地基模型水平桩简化分析方法[J]. 岩土工程学报, 2013, 35(增刊1): 300-304.
LIANG F Y, LI Y C, HUANG M S. Simplified method for laterally loaded piles based on Pasternak double-parameter spring model for foundations [J]. Chinese Journal of Geotechnical Engineering, 2013, 35(Sup.1):300-304. (in Chinese)

[10] POULOS H G. Analysis of piles in soil undergoing lateral movement[J]. JSMFD, ASCE, 1973, 99(SM5):391-406.

[11] POULOS H G, DAVIS E H. Pile foundation analysis and design [M]. New York: John Wiley & Sons, 1980.

[12] 陈福全, 黄伟达. 基于Poulos弹性理论的被动桩改进算法[J]. 岩土力学, 2008, 29(4):905-910.
CHEN F Q, HUANG W D. A modified analysis method for passive pile based on Poulos's elastic theory [J]. Rock and Soil Mechanics, 2008, 29(4):905-910. (in Chinese)

[13] 上官士青, 杨敏, 李卫超. 分别考虑桩和土水平向位移的被动桩简化算法[J]. 建筑结构学报, 2018, 39(1):162-172.
SHANGGUAN S Q, YANG M, LI W C. Simplified method of passive piles with independent lateral displacement of piles and soil[J]. Journal of Building Structures, 2018, 39(1):162-172. (in Chinese)

[14] 李双龙, 魏丽敏, 冯胜洋,等. 基于扩展Koppejan模型的被动桩-软土时效性相互作用研究[J]. 岩土力学, 2022, 43(9):2602-2614.
LI S L, WEI L M, FENG S Y, et al. Time-dependent interactions between passive piles and soft soils based on the extended Koppejan model[J]. Rock and Soil Mechanics, 2022, 43(9):2602-2614. (in Chinese)

[15] 杨吉新, 王金川, 陈天驰,等. 一种单侧堆载作用下桩基侧向位移计算方法[J]. 武汉理工大学学报(交通科学与工程版), 2023,47(3):556-567.
YANG J X, WANG J C, CHEN T C, et al. A method of calculating lateral displacement of pile under single-side surcharge load[J]. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2023, 47(3):556-567. (in Chinese)

[16] 郭景琢, 李昕昊, 程雪松,等. 基坑斜直组合倾斜桩支护结构设计计算方法研究[J]. 土木工程学报,2023,56(8):153-163.
GUO J Z, LI X H, CHENG X S, et al. Study on design and calculation method of vertical and inward-inclined piles retaining structure of excavation[J]. China Civil Engineering Journal, 2023, 56(8):153-163.(in Chinese)

[17] 周海祚, 郑刚, 何晓佩,等. 基坑倾斜桩支护稳定特性及分析方法研究[J]. 岩土工程学报, 2022, 44(2):271-277.
ZHOU H Z, ZHENG G, HE X P, et al. Stability characteristics and analysis method for inclined retaining walls in excavations[J]. Chinese Journal of Geotechnical Engineering, 2022, 44(2):271-277. (in Chinese)

[18] 赵明华, 李帅超, 彭文哲. 基于有限元分析的横向受荷刚性桩应变楔模型形体参数研究[J]. 铁道科学与工程学报, 2019, 16(3):674-683.
ZHAO M H, LI S C, PENG W Z. Study of laterally-loaded rigid pile strain wedge model shape parameters base on finite element analysis[J]. Journal of Railway Science and Engineering, 2019, 16(3):674-683. (in Chinese)

[19] NORRIS G M. The drained shear strength of uniform quartz sand as related to particle size and natural variation in particle shape and surface roughness[D]. Berkeley: University of California, 1977:210-262.

[20] NORRIS G M. Theoretically based BEF laterally loaded pile analysis[C]// Proceedings of the 3rd International Conference on Numerical Methods in Offshore Piling. Paris: Technip, 1986: 361-386.

[21] ASHOUR M, NORRIS G M, PILLING P. Lateral loading of a pile in layered soil using the strain wedge model[J]. Journal of Geotechnical and Geoenvironmental Engineering, 1998, 124(4): 303-315.

[22] ASHOUR M, PILLING P, NORRIS G M. Lateral behavior of pile groups in layered soils [J]. Journal of Geotechnical and Geoenvironmental Engineering, 2004, 130(6):580-592.

[23] ASHOUR M, ARDALAN H. Analysis of pile stabilized slopes based on soil-pile interaction[J]. Computers and Geotechnics, 2012, 39:85-97.

[24] ASHOUR M, ALAAELDIN A, ARAB M G. Laterally loaded battered piles in sandy soils[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2020, 146(1):06019017.

[25] 彭文哲, 赵明华, 杨超炜,等. 斜坡地基桩前土抗力的应变楔模型修正[J]. 中南大学学报(自然科学版), 2020, 51(7):1936-1945.
PENG W Z, ZHAO M H, YANG C W, et al. Modification of strain wedge model for soil resistance in front of piles in sloping ground[J]. Journal of Central South University (Science and Technology), 2020, 51(7):1936-1945. (in Chinese)

[26] 李忠诚, 杨敏. 被动桩土压力计算的被动拱-主动楔模型[J]. 岩石力学与工程学报, 2006, 25(增刊2):4241-4247.
LI Z C, YANG M. Passive arching-active wedge model of soil pressure calculation in passive piles[J]. Chinese Journal of Rock Mechanics and Engineering, 2006, 25(Sup.2):4241-4247. (in Chinese)

[27] PRAKASH S, SUBRAMANYAM G. Behaviour of battered piles under lateral loads[J]. Journal Indian Nature Social of Soil Mechanical and Foundation Engineering, 1965(4):177-196.

[28] RANJAN G, RAMASAMY G, TYAGI R P. Lateral response of batter piles and pile bents in clay[J]. Indian Geotechnical Journal, 1980, 10(2):135-142.

[29] 郑刚, 王玉萍, 程雪松,等. 倾斜桩支护结构的工作性能和基坑稳定性[J]. 厦门大学学报(自然科学版), 2021, 60(1):115-124.
ZHENG G, WANG Y P, CHENG X S, et al. Working performance and stability of excavation retained by inclined retaining structures[J]. Journal of Xiamen University (Nature Science), 2021, 60(1):115-124. (in Chinese)

[30] 叶金铋, 周先齐, 王晨飞,等. 基坑双排斜桩模型试验研究[J]. 地下空间与工程学报, 2021, 17(2):398-404, 519.
YE J B, ZHOU X Q, WANG C F, et al. Model test of double-row inclined piles in foundation pit [J]. Chinese Journal of Underground Space and Engineering, 2021, 17(2):398-404, 519. (in Chinese)

[31] YE J, HE X. Performance of batter pile walls in deep excavation: laboratory test and numerical analysis[J]. Mechanics of Advanced Materials and Structures, 2021, 28(14):1-10.

[32] 胡明, 雷用, 赵晓柯. 倾斜微型桩桩身参数敏感性有限元分析[J]. 后勤工程学院学报, 2014, 30(1):12-16, 68.
HU M, LEI Y, ZHAO X K. The finite element analysis of inclined micropiles parameter sensitivity [J]. Journal of Logistical Engineering University, 2014, 30(1):12-16, 68. (in Chinese)

[33] 凌道胜, 任涛, 王云岗. 砂土地基斜桩水平承载特性p-y曲线法[J]. 岩土力学, 2013, 34(1): 155-162.

LING D S, REN T, WANG Y G. A *p*–*y* curve method for horizontal bearing characteristics of single batter pile in sands[J]. Rock and Soil Mechanics, 2013, 34(1):155–162. (in Chinese)

[34] 周德泉,颜超,邓超. 堆载作用下桩体工程特性研究[J].中外公路,2015,35(1):5–8.
ZHOU D Q, YAN C, DEDG C. Study on engineering characteristics of pile under surcharge load[J]. Journal of China & Foreign Highway,2015,35(1):5–8.(in Chinese)

[35] 周德泉,杨帆,谭焕杰.土体中倾斜桩工程性状研究[J].中外公路,2012,32(3):14–18.
ZHOU D Q, YANG F,TAN H J.Study on engineering behavior of inclined pile in soil[J]. Journal of China & Foreign Highway, 2012,32(3):14–18.(in Chinese)

[36] ZHANG L M, MCVAY M C, LAI P W. Centrifuge modelling of laterally loaded single battered piles in sands [J]. Canadian Geotechnical Journal, 1999, 36(6):1074–1084.

[37] 周德泉,王创业,周毅,等.被动倾斜桩应用研究与展望[J].中外公路, 2023,43(2):1–10.
ZHOU D Q, WANG C Y, ZHOU Y, et.al. Application research and prospect of passive battered pile [J]. Journal of China & Foreign Highway,2023,43(2):1–10. (in Chinese)

[38] 刘光秀, 李玉根, 曹艳妮. 路堤荷载下地基的侧向变形计算分析[J]. 岩土力学, 2018, 39(12):4517–4536.
LIU G X, LI Y G, CAO Y N. Calculation and analysis of lateral deformation of ground under embankment load[J]. Rock and Soil Mechanics, 2018, 39(12):4517–4536. (in Chinese)

[39] 张浩, 石名磊, 郭院成,等. 不平衡堆载作用下临近结构桩的侧向受力机制[J]. 岩土工程学报, 2016, 38(12):2226–2236.
ZHANG H, SHI M L, GUO Y C, et al. Lateral mechanical behaviors of structural piles adjacent to imbalanced surcharge loads [J]. Chinese Journal of Geotechnical Engineering, 2016, 38(12): 2226–2236. (in Chinese)

[40] 尹平保, 聂道流, 杨朝晖,等. 斜坡基桩*p*–*y*曲线及水平承载计算方法研究[J]. 岩石力学与工程学报, 2018, 37(4):996–1003.
YIN P B, NIE D L, YANG Z H, et al. The *p*–*y* curve and computation method of the horizontal bearing capacity of piles in sloping ground [J]. Chinese Journal of Rock Mechanics and Engineering, 2018, 37(4): 996–1003. (in Chinese)

[41] 邓会元. 滨海吹填围垦区堆载作用下桩基承载特性研究[D]. 南京: 东南大学, 2021:189–203.
DENG H Y. Study on bearing characterics of pile foundation under surcharge load in coastal reclamation area[D]. Nanjing: Southeast University, 2021:189–203. (in Chinese)

[42] 周德泉, 冯晨曦, 肖灿,等. 倾斜软基上斜直桩组合结构单侧受力破坏模式试验[J]. 中国公路学报, 2021, 34(7):201–214.
ZHOU D Q, FENG C X, XIAO C, et al. Experimental study on the failure mode of inclined–straight pile composite structure on declining soft foundation under single side load[J]. China Journal of Highway and Transport, 2021, 34(7):201–214. (in Chinese)

[43] 曹卫平, 夏冰, 赵敏,等. 砂土中水平受荷斜桩的*p*–*y*曲线及其应用[J]. 岩石力学与工程学报, 2018, 37(3):743–753.
CAO W P, XIA B, ZHAO M, et al. *p*–*y* curves of laterally loaded batter piles in sand and its application [J]. Chinese Journal of Rock Mechanics and Engineering, 2018, 37(3): 743–753. (in Chinese)

[44] 谢旭. 坡脚斜直双排桩被动受力响应研究[D]. 长沙: 长沙理工大学, 2021:24–28.
XIE X. Study on passive force response of oblique straight double row piles at slopes foot [D]. Changsha: Changsha University of Science and Technology, 2021:24–28. (in Chinese)

[45] 王创业. 负斜被动桩受力响应与*p*–*y*曲线试验研究[D]. 长沙: 长沙理工大学, 2021:35–40.
WANG C Y. Experimental study on the lateral response and *p*–*y* curve of negative batter passive piles [D]. Changsha: Changsha University of Science and Technology, 2021:35–40. (in Chinese)