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水平动荷载作用下海洋大直径管桩动力响应解析解

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摘要: 考虑桩-土-流体耦合振动, 研究了谐和激振水平动荷载作用下的海洋大直径管桩振动响应问题。将桩周和桩芯海水考虑为无黏性不可压缩流体建立其控制方程求得海水速度势解析表达式, 继而得到作用于桩身动水压力表达式。将土体看作黏弹性介质建立桩周土和桩芯土控制方程, 对土体方程直接解耦求解, 得到桩周土和桩芯土位移和抗力表达式。利用桩-土体位移连续条件、桩-流体速度连续条件以及桩身边界条件, 求解得到了水平谐振荷载下海洋大直径管桩位移解析解, 并提出了桩顶水平动力柔度因子概念。将理论解所得结果与有限元结果对比, 验证了本文解的正确性。分析了海水动水压力、埋入海水段桩长、管桩内外半径、桩身模量、土体模量等参数对海洋大直径管桩水平动力响应特性的影响。

关键词: 海洋工程; 大直径管桩; 水平振动; 动水压力; 柔度因子

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Analytical solution for dynamic response of offshore large-diameter pipe piles subjected to horizontal dynamic loads

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Abstract: The vibration response of offshore large-diameter pipe piles subjected to harmonic horizontal dynamic loads is studied by considering the pile-soil-seawater coupled vibration. The governing equations for the outer and inner seawater are established, and the analytical expressions for the velocity potential of the seawater are obtained, then the expressions for the hydrodynamic seawater pressure acting on the pile body are obtained. Considering the soil as the viscoelastic medium, the governing equations for the outer and inner soil are established. The coupled equations are directly solved, and the expressions for the displacement and resistance of the outer and inner soil are obtained. By using the displacement continuous condition at pile-soil interfaces, velocity continuous condition at pile-seawater interfaces and boundary conditions of piles, the analytical solution for the displacement of the offshore large-diameter pipe piles under horizontal dynamic loads is obtained, and the horizontal dynamic compliance factor of pile top is defined. The solution is compared with the FEM results to verify the correctness. The effects of hydrodynamic seawater pressure, length of pile embedded in seawater, outer and inner pile radii, pile modulus and soil modulus on the horizontal dynamic characteristics of offshore large-diameter pipe piles are analyzed.

Key words: ocean engineering; large-diameter pipe pile; horizontal vibration; hydrodynamic pressure; compliance coefficient

0 引言

中国正积极推进海洋强国战略, 海洋资源开发产业发展十分迅速, 高桩码头、跨海桥梁、海洋平台、风电机组、输电塔等海上构筑物不断涌现, 各种大直径管桩也因各自的优点和特点广泛应用于上述大型海

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洋工程中。海上构筑物存在复杂的荷载条件, 海上构筑物的桩基础不仅需要承受上部结构的自重荷载, 同时需要承受风荷载、波浪力、水流力、地震作用等水平动荷载, 在极端环境工况下, 巨大的水平向荷载会引起桩基础发生较大的水平变形, 使得风机停机、油气平台倾斜失效。此外, 当桩基础和上部结构一阶自振频率与这些动荷载的激振频率接近时, 容易发生共振, 在基础和结构中引起更大的内力从而导致其产生崩塌破坏。研究水平动荷载作用下海洋工程中大直径管桩的受荷机理, 对于中国科技兴海的战略发展具有重要的科学意义和工程实用价值。

近几十年, 广大学者对水平动荷载下桩的动力响应问题开展了深入的研究。早期应用最广泛的计算模型是Winkler模型^[1-2], 其将桩周土和桩底土对桩的作用简化为弹簧和阻尼器的形式, 但Winkler模型的缺点是不能真正的考虑桩-土耦合振动, 且在实际工程中难以精确的确定模型参数取值。后来Novak等^[3]提出平面应变假定建立了简化桩土耦合振动理论, 并基于这一理论展开了各种桩基振动特性的基础性研究, 得到了许多重要结论。Novak平面应变理论的缺陷是忽略了土体内部纵向应力梯度的变化, 应用到实际工程中时难免带来误差。与之相比, 将土体视为三维连续介质, 严格考虑桩土耦合作用及桩侧土竖向应力梯度变化的桩振动解析理论, 在理论上更为精确。Novak等^[4]将土体考虑为一个有限厚度的土层并考虑土体纵向应力梯度变化, 得到了水平动载作用下刚性支承桩振动响应解析解。余俊等^[5]将土体考虑为饱和两相介质, 通过引入势函数对Biot动力固结方程解耦, 研究了饱和土中端承桩的水平振动响应。章敏等^[6]则研究了非饱和土中端承桩的水平振动特性。

以上这些研究均假定桩完全埋入土体中, 然而海洋桩基多采用高桩的形式^[7-8], 其变形机理与完全埋入式桩基有明显的差异。许多学者曾对动荷载下高桩基础水平动力响应问题进行了研究。马宏旺等^[9]采用数值模拟的方法研究了循环荷载作用下海上风电单桩基础水平动力特性。任青等^[10]基于动力Winkler模型, 提出了考虑桩顶竖向荷载的海洋群桩基础水平振动模型。Hu等^[11]研究了考虑桩身轴力的饱和土地基中高桩基础的水平动力响应。

上述研究都是将高桩基础未埋入土中部分桩体考虑为自由段, 而海洋桩基础其上部桩身是埋入海水中, 桩身水平振动引起海水动水压力会对桩的水平振动特性产生影响。付鹏等^[12-13]在徐汉忠^[14]针对水中圆柱梁水平振动响应研究的基础上系统研究了海洋高桩基础水平振动响应问题, 得到了一些有益的结论。但其研

究是针对实心桩, 而海洋工程中得到广泛应用的大直径管桩由于其薄壁中空的特性及桩芯土的存在与实心桩振动特性存在显著差异^[15]。本文假设海水为无黏性不可压缩流体, 考虑海洋大直径管桩与土体及流体的相互作用, 求解得到了海洋大直径管桩基础水平振动响应解析解, 并分析了其水平振动响应特性, 本文研究成果可为海洋大直径管桩基础的工程设计提供参考。

1 定解问题的建立

本文计算模型如图1所示, 桩长为 H , 外半径为 r_1 , 内半径为 r_2 的大直径管桩埋入上覆海水下卧刚性基岩的黏弹性土层中。海水深度和土层厚度分别为 H_1 , H_2 。管桩桩顶受到谐和激振水平荷载 $P e^{i\omega t}$ 作用, 其中 P 为水平荷载幅值, ω 为荷载频率, t 为时间。

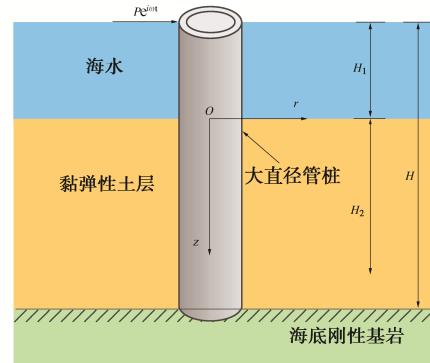


图1 桩-土-海水系统计算模型示意图

Fig. 1 Conceptual model for pile-soil-seawater system

(1) 流体运动控制方程

将海水假定为无黏性不可压缩流体, 其控制方程为拉普拉斯方程, 在柱坐标系下可表示为

$$\frac{\partial^2 \phi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \phi_j}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \phi_j}{\partial \theta^2} + \frac{\partial^2 \phi_j}{\partial z^2} = 0 \quad , \quad (1)$$

式中, ϕ_j 为海水速度势函数, $j = 1, 2$ 。当 $j = 1$ 时, 上述方程和参数对应桩周海水, 当 $j = 2$ 时, 其对应管桩内壁腔内海水。

(2) 土体运动控制方程

根据弹性动力学理论, 忽略土体竖向位移, 建立桩周土和桩芯土在柱坐标系上的运动控制方程为

$$G^* \nabla^2 u_{rj} + (\lambda^* + G^*) \frac{\partial e_j}{\partial r} - \frac{G^*}{r^2} \left(2 \frac{\partial u_{\theta j}}{\partial \theta} + u_{rj} \right) + G^* \frac{\partial^2 u_{rj}}{\partial z^2} = -\rho_s \omega^2 u_{rj} \quad , \quad (2)$$

$$G^* \nabla^2 u_{\theta j} + (\lambda^* + G^*) \frac{\partial e_j}{r \partial \theta} - \frac{G^*}{r^2} \left(u_{\theta j} - 2 \frac{\partial u_{rj}}{\partial \theta} \right) + G^* \frac{\partial^2 u_{\theta j}}{\partial z^2} = -\rho_s \omega^2 u_{\theta j} \quad , \quad (3)$$

式中, $\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2}$ 为拉普拉斯算子, $u_{rj}(r, \theta, z)$, $u_{\theta j}(r, \theta, z)$ 为土体径向和切向位移; $\lambda^* = \lambda(1 + 2i\beta_s)$, $G^* = G(1 + 2i\beta_s)$ 为土体复拉梅常数, 其中 $i = \sqrt{-1}$, β_s 为土体阻尼比, ρ_s 为土体密度, $e_j = \frac{\partial u_{rj}}{\partial r} + \frac{u_{rj}}{r} + \frac{\partial u_{\theta j}}{r \partial \theta}$ 为土体体应变, 同理, $j = 1, 2$ 。当 $j = 1$ 时, 上述方程和参数对应桩周土, 当 $j = 2$ 时, 其对应管桩内壁桩芯土。

(3) 管桩水平振动方程

埋入海水和土层段的管桩控制方程分别为

$$E_p^* I_p \frac{\partial^4 u_{pw}}{\partial z^4} - \rho_p A_p \omega^2 u_{pw} + f_{w1} + f_{w2} = 0 \quad (-H_1 \leq z \leq 0), \quad (4)$$

$$E_p^* I_p \frac{\partial^4 u_{ps}}{\partial z^4} - \rho_p A_p \omega^2 u_{ps} + f_{s1} + f_{s2} = 0 \quad (0 \leq z \leq H_2), \quad (5)$$

式中, u_{pw} , u_{ps} 为埋入海水段和埋入土层段的管桩水平位移, f_{w1} , f_{w2} 为作用于单位长度桩身的海水动水压力, f_{s1} , f_{s2} 为作用于单位长度桩身的土体抗力, $E_p^* = E_p(1 + 2i\beta_p)$ 为管桩复弹性模量, 其中 E_p 为桩弹性模量, β_p 为桩身材料阻尼比, I_p 为管桩截面惯性矩, A_p 为管桩截面面积, ρ_p 为桩身材料密度。

2 方程求解

2.1 海水运动方程求解

(1) 桩周海水运动方程求解

基于分离变量法, 海水速度势函数可表示为

$$\phi_1 = R_1(r)\Phi_1(\theta)Z_1(z)i\omega e^{i\omega t}. \quad (6)$$

为简便起见, 下文表达式中省略时间因子 $e^{i\omega t}$ 项。

式(1)的通解为

$$\phi_1 = [A_{w1}I_m(hr) + B_{w1}K_m(hr)] \cdot [C_{w1}\sin(m\theta) + D_{w1}\cos(m\theta)] \cdot [E_{w1}\cos(hz) + F_{w1}\sin(hz)]i\omega, \quad (7)$$

式中, $I_m(hr)$, $K_m(hr)$ 分别为第一类和第二类 m 阶修正贝塞尔函数, A_{w1} , B_{w1} , C_{w1} , D_{w1} , E_{w1} , F_{w1} 为待定系数。

海水边界条件假定为

$$\phi_1 \Big|_{z=-H_1} = 0, \quad (8)$$

$$\frac{\partial \phi_1}{\partial z} \Big|_{z=0} = 0, \quad (9)$$

$$\phi_1 \Big|_{r \rightarrow \infty} < \infty. \quad (10)$$

将式(7)代入上述边界条件可得

$$\phi_1 = \sum_{n=1}^{\infty} A_{wn} K_1(h_n r) \cos(h_n z) i\omega \cos \theta, \quad (11)$$

式中, $h_n = \frac{(2n-1)\pi}{2H_1}$, $n = 1, 2, 3, \dots$ 。

海水中的动水压力为

$$q_1 = -\rho_w \frac{\partial \phi_1}{\partial t} = \rho_w \omega^2 \sum_{n=1}^{\infty} A_{wn} K_1(h_n r) \cos(h_n z) \cos \theta, \quad (12)$$

式中, ρ_w 为海水密度。

作用于单位长度桩身的海水动水压力为

$$f_{w1} = \int_0^{2\pi} q_1 \Big|_{r=r_1} r_1 \cos \theta d\theta = \pi r_1 \rho_w \omega^2 \sum_{n=1}^{\infty} A_{wn} K_1(h_n r_1) \cos(h_n z). \quad (13)$$

(2) 桩芯海水运动方程求解

与桩周海水方程求解过程类似, 可求得桩芯海水速度势函数通解为

$$\phi_2 = [A_{w2}I_1(hr) + B_{w2}K_1(hr)] \cdot [C_{w2}\sin(m\theta) + D_{w2}\cos(m\theta)] \cdot [E_{w2}\cos(hz) + F_{w2}\sin(hz)]i\omega, \quad (14)$$

式中, A_{w2} , B_{w2} , C_{w2} , D_{w2} , E_{w2} , F_{w2} 为待定系数。

桩芯海水边界条件假定为

$$\phi_2 \Big|_{z=-H_1} = 0, \quad (15)$$

$$\frac{\partial \phi_2}{\partial z} \Big|_{z=0} = 0, \quad (16)$$

$$\phi_2 \Big|_{r=0} < \infty, \quad (17)$$

将式(14)代入以上边界条件, 可得

$$\phi_2 = \sum_{n=1}^{\infty} A_{w2n} I_1(h_n r) \cos(h_n z) i\omega \cos \theta. \quad (18)$$

桩芯海水动水压力为

$$q_2 = \rho_w \frac{\partial \phi_2}{\partial t} = -\rho_w \omega^2 \sum_{n=1}^{\infty} A_{w2n} I_1(h_n r) \cos(h_n z) \cos \theta. \quad (19)$$

作用于单位长度桩身的海水动水压力为

$$f_{w2} = \int_0^{2\pi} q_2 \Big|_{r=r_2} r_2 \cos \theta d\theta = -\pi r_2 \rho_w \omega^2 \sum_{n=1}^{\infty} A_{w2n} I_1(h_n r_2) \cos(h_n z). \quad (20)$$

2.2 土体运动方程求解

(1) 桩周土体运动方程求解

对方程(2)、(3)进行微分变换 $\frac{\partial(2)}{\partial r} + \frac{(2)}{r} + \frac{\partial(3)}{r \partial \theta}$,

可得

$$(\lambda^* + 2G^*) \nabla^2 e_1 + G^* \frac{\partial^2 e_1}{\partial z^2} + \rho \omega^2 e_1 = 0. \quad (21)$$

通过分离变量法容易得到方程(21)的通解为

$$e_1 = [A_{s11}K_m(q_1 r) + B_{s11}I_m(q_1 r)] \cdot [C_{s11}\sin(m\theta) + D_{s11}\cos(m\theta)] \cdot [E_{s11}\sin(gz) + F_{s11}\cos(gz)], \quad (22)$$

式中, $q_1^2 = \frac{G^* g^2 - \rho \omega^2}{\lambda^* + 2G^*}$, A_{s11} , B_{s11} , C_{s11} , D_{s11} , E_{s11} , F_{s11} 为待定系数。

桩周土边界条件假定为

$$\frac{\partial u_{r1}}{\partial z} \Big|_{z=0} = \frac{\partial u_{\theta1}}{\partial z} \Big|_{z=0} = 0, \quad (23)$$

$$u_{r1} \Big|_{z=H_2} = u_{\theta1} \Big|_{z=H_2} = 0, \quad (24)$$

$$u_{r1}|_{r \rightarrow \infty} = u_{\theta1}|_{r \rightarrow \infty} = 0 \quad . \quad (25)$$

将式(22)代入边界条件可得

$$e_1 = \sum_{n=1}^{\infty} A_{s11n} K_1(q_{1n}r) \cos(g_n z) \cos \theta \quad , \quad (26)$$

$$\text{式中, } g_n = \frac{(2n-1)\pi}{2H_2}, \quad n = 1, 2, 3, \dots$$

u_{r1} , $u_{\theta1}$ 可表示为

$$\left. \begin{aligned} u_{r1}(r, \theta, z) &= \bar{u}_{r1}(r, z) \cos \theta \quad , \\ u_{\theta1}(r, \theta, z) &= \bar{u}_{\theta1}(r, z) \sin \theta \quad . \end{aligned} \right\} \quad (27)$$

将式(26), (27)代入式(2), (3)并分别相加和相减得到

$$\begin{aligned} G^* \left(\frac{\partial^2}{\partial r^2} + \frac{\partial}{r \partial r} - \frac{4}{r^2} + \frac{\partial^2}{\partial z^2} \right) U_1 + \rho \omega^2 U_1 \\ = \sum_{n=1}^{\infty} (\lambda^* + G^*) A_{s11n} q_{1n} K_2(q_{1n}r) \cos(g_n z) \quad , \end{aligned} \quad (28)$$

$$\begin{aligned} G^* \left(\frac{\partial^2}{\partial r^2} + \frac{\partial}{r \partial r} + \frac{\partial^2}{\partial z^2} \right) V_1 + \rho \omega^2 V_1 \\ = \sum_{n=1}^{\infty} (\lambda^* + G^*) A_{s11n} q_{1n} K_0(q_{1n}r) \cos(g_n z) \quad , \end{aligned} \quad (29)$$

$$\text{式中, } U_1 = \bar{u}_{r1} + \bar{u}_{\theta1}, \quad V_1 = \bar{u}_{r1} - \bar{u}_{\theta1}.$$

基于分离变量法并考虑上文土体边界条件, 可得

$$U_1 = \sum_{n=1}^{\infty} [\gamma_n A_{s11n} K_2(q_{1n}r) + A_{s12n} K_2(q_{2n}r)] \cos(g_n z), \quad (30)$$

$$V_1 = \sum_{n=1}^{\infty} [\gamma_n A_{s11n} K_0(q_{1n}r) + A_{s13n} K_0(q_{2n}r)] \cos(g_n z), \quad (31)$$

$$\text{式中, } q_{2n}^2 = \frac{G^* g_n^2 - \rho \omega^2}{G^*}, \quad \gamma_n = \frac{(\lambda^* + G^*) q_{1n}}{G^* (q_{1n}^2 - g_n^2) + \rho \omega^2},$$

A_{s12n} , A_{s13n} 为待定系数。

考虑土体体应变定义, 可得

$$A_{s13n} = -A_{s12n} \quad . \quad (32)$$

因此桩周土位移 u_{r1} , $u_{\theta1}$ 可表示为

$$u_{r1} = \sum_{n=1}^{\infty} \left[\gamma_n A_{s11n} \frac{K_2(q_{1n}r) + K_0(q_{1n}r)}{2} + A_{s12n} \frac{K_2(q_{2n}r) - K_0(q_{2n}r)}{2} \right] \cos(g_n z) \cos \theta \quad , \quad (33)$$

$$u_{\theta1} = \sum_{n=1}^{\infty} \left[\gamma_n A_{s11n} \frac{K_2(q_{1n}r) - K_0(q_{1n}r)}{2} + A_{s12n} \frac{K_2(q_{2n}r) + K_0(q_{2n}r)}{2} \right] \cos(g_n z) \sin \theta \quad . \quad (34)$$

桩周土与管桩交界面处的连续条件可表示为

$$\left. \begin{aligned} u_{r1} &= u_p \cos \theta \quad , \\ u_{\theta1} &= -u_p \sin \theta \quad . \end{aligned} \right\} \quad (35)$$

将式(33), (34)代入式(35), 可得

$$A_{s12n} = \delta_{1n} A_{s11n}, \quad (36)$$

$$\text{式中, } \delta_{1n} = -\frac{\gamma_n K_2(q_{1n}r)}{K_2(q_{2n}r)}.$$

根据式(33), (34)可求得桩周土应力为

$$\begin{aligned} \sigma_{r1} &= \sum_{n=1}^{\infty} A_{s11n} \left\{ \left[(\lambda^* + 2G^*) K_1(q_{1n}r) - 2G^* \gamma_n \frac{K_2(q_{1n}r)}{r} \right] - \right. \\ &\quad \left. 2G^* \delta_{1n} \frac{K_2(q_{2n}r)}{r} \right\} \cos(g_n z) \cos \theta, \end{aligned} \quad (37)$$

$$\begin{aligned} \tau_{r\theta1} &= -G^* \sum_{n=1}^{\infty} A_{s11n} \left\{ 2\gamma_n \frac{K_2(q_{1n}r)}{r} + \right. \\ &\quad \left. \delta_{1n} \left[q_{2n} K_1(q_{2n}r) + 2 \frac{K_2(q_{2n}r)}{r} \right] \right\} \cos(g_n z) \sin \theta. \end{aligned} \quad (38)$$

进而可求得单位长度桩身受到的桩周土体抗力为

$$\begin{aligned} f_{s1} &= -\int_0^{2\pi} (\sigma_{r1} \cos \theta - \tau_{r\theta1} \sin \theta) \Big|_{r=r_1} r_1 d\theta \\ &= -\pi r_1 \sum_{n=1}^{\infty} A_{s11n} [(\lambda^* + 2G^*) K_1(q_{1n}r_1) + \\ &\quad G^* \delta_{1n} q_{2n} K_1(q_{2n}r_1)] \cos(g_n z) \quad . \end{aligned} \quad (39)$$

(2) 桩芯土体运动方程求解

与求解桩周土方程过程类似, 容易求得桩芯土体应变通解为

$$e_2 = [A_{s21} K_m(q_1 r) + B_{s21} I_m(q_1 r)] \cdot [C_{s21} \sin(m\theta) + D_{s21} \cos(m\theta)] \cdot [E_{s21} \sin(gz) + F_{s21} \cos(gz)], \quad (40)$$

桩芯土边界条件假定为

$$\frac{\partial u_{r2}}{\partial z} \Big|_{z=0} = \frac{\partial u_{\theta2}}{\partial z} \Big|_{z=0} = 0, \quad (41)$$

$$u_{r2} \Big|_{z=H_2} = u_{\theta2} \Big|_{z=H_2} = 0, \quad (42)$$

$$u_{r2} \Big|_{r \rightarrow \infty} = u_{\theta2} \Big|_{r \rightarrow \infty} = 0. \quad (43)$$

将式(40)代入边界条件可得

$$e_2 = \sum_{n=1}^{\infty} A_{s21n} I_1(q_{1n}r) \cos(g_n z) \cos \theta. \quad (44)$$

u_{r2} , $u_{\theta2}$ 可表示为

$$\left. \begin{aligned} u_{r2}(r, \theta, z) &= \bar{u}_{r2}(r, z) \cos \theta \quad , \\ u_{\theta2}(r, \theta, z) &= \bar{u}_{\theta2}(r, z) \sin \theta \quad . \end{aligned} \right\} \quad (45)$$

类似桩周土求解过程, 可得

$$\begin{aligned} G^* \left(\frac{\partial^2}{\partial r^2} + \frac{\partial}{r \partial r} - \frac{4}{r^2} + \frac{\partial^2}{\partial z^2} \right) U_2 + \rho \omega^2 U_2 \\ = -\sum_{n=1}^{\infty} (\lambda^* + G^*) A_{s21n} q_{1n} I_2(q_{1n}r) \cos(g_n z) \quad , \end{aligned} \quad (46)$$

$$\begin{aligned} G^* \left(\frac{\partial^2}{\partial r^2} + \frac{\partial}{r \partial r} + \frac{\partial^2}{\partial z^2} \right) V_2 + \rho \omega^2 V_2 \\ = -\sum_{n=1}^{\infty} (\lambda^* + G^*) A_{s21n} q_{1n} I_0(q_{1n}r) \cos(g_n z) \quad , \end{aligned} \quad (47)$$

$$\text{式中, } U_2 = \bar{u}_{r2} + \bar{u}_{\theta2}, \quad V_2 = \bar{u}_{r2} - \bar{u}_{\theta2}.$$

方程(46), (47)的解为

$$U_2 = \sum_{n=1}^{\infty} [-\gamma_n A_{s21n} I_2(q_{1n}r) + A_{s22n} I_2(q_{2n}r)] \cos(g_n z), \quad (48)$$

$$V_2 = \sum_{n=1}^{\infty} [-\gamma_n A_{s21n} I_0(q_{1n}r) - A_{s22n} I_0(q_{2n}r)] \cos(g_n z), \quad (49)$$

因此桩芯土位移 u_{r2} , $u_{\theta2}$ 可表示为

$$u_{r2} = \sum_{n=1}^{\infty} \left[-\gamma_n A_{s21n} \frac{I_2(q_{1n}r) + I_0(q_{1n}r)}{2} + A_{s22n} \frac{I_2(q_{2n}r) - I_0(q_{2n}r)}{2} \right] \cos(g_n z) \cos \theta, \quad (50)$$

$$u_{\theta2} = \sum_{n=1}^{\infty} \left[-\gamma_n A_{s21n} \frac{I_2(q_{1n}r) - I_0(q_{1n}r)}{2} + A_{s22n} \frac{I_2(q_{2n}r) + I_0(q_{2n}r)}{2} \right] \cos(g_n z) \sin \theta. \quad (51)$$

类似地, 基于桩芯土与管桩交界面处的连续条件可求得

$$A_{s22n} = \delta_{2n} A_{s21n}, \quad (52)$$

$$\text{式中, } \delta_{2n} = \frac{\gamma_n I_2(q_{1n}r_0)}{I_2(q_{2n}r_0)}.$$

单位长度桩身受到的桩芯土体抗力为

$$f_{s2} = \int_0^{2\pi} (\sigma_{r2} \cos \theta - \tau_{r\theta2} \sin \theta) \Big|_{r=r_2} r_2 d\theta \\ = \pi r_2 \sum_{n=1}^{\infty} A_{s2n} [(\lambda^* + 2G^*) I_1(q_{1n}r_2) - G^* \delta_{2n} q_{2n} I_1(q_{2n}r_2)] \cos(g_n z). \quad (53)$$

2.3 管桩水平振动方程求解

将上文求得的桩周和桩芯海水动水压力和土体抗力代入管桩控制方程 (4), (5) 中, 可得

$$E_p^* I_p \frac{\partial^4 u_{pw}}{\partial z^4} - \rho_p A_p \omega^2 u_{pw} + \pi r_1 \rho_w \omega^2 \sum_{n=1}^{\infty} A_{w1n} K_1(h_n r_1) \cos(h_n z) + \pi r_2 \rho_w \omega^2 \sum_{n=1}^{\infty} A_{w2n} I_1(h_n r_2) \cos(h_n z) = 0, \quad (54)$$

$$E_p^* I_p \frac{\partial^4 u_{ps}}{\partial z^4} - \rho_p A_p \omega^2 u_{ps} - \pi r_1 \sum_{n=1}^{\infty} A_{s1n} [(\lambda^* + 2G^*) K_1(q_{1n}r_1) + G^* \delta_{1n} q_{2n} K_1(q_{2n}r_1)] \cos(g_n z) \pi r_2 \sum_{n=1}^{\infty} A_{s2n} [(\lambda^* + 2G^*) I_1(q_{1n}r_2) - G^* \delta_{2n} q_{2n} I_1(q_{2n}r_2)] \cos(g_n z) = 0. \quad (55)$$

式 (54), (55) 解的形式为

$$u_{pw} = N_{w1} \sin(kz) + N_{w2} \cos(kz) + N_{w3} \sinh(kz) + N_{w4} \cosh(kz) - \sum_{n=1}^{\infty} \zeta_{w1n} A_{w1n} \cos(h_n z) - \sum_{n=1}^{\infty} \zeta_{w2n} A_{w2n} \cos(h_n z), \quad (56)$$

$$u_{ps} = N_{s1} \sin(kz) + N_{s2} \cos(kz) + N_{s3} \sinh(kz) + N_{s4} \cosh(kz) - \sum_{n=1}^{\infty} \zeta_{s1n} A_{s1n} \cos(g_n z) - \sum_{n=1}^{\infty} \zeta_{s2n} A_{s2n} \cos(g_n z), \quad (57)$$

$$\text{式中, } k^4 = \frac{\rho_p A_p \omega^2}{E_p^* I_p}, \quad \zeta_{w1n} = \frac{\pi r_1 \rho_w \omega^2 K_1(h_n r_1)}{E_p^* I_p (h_n^4 - k^4)}, \quad \zeta_{w2n} = \frac{\pi r_2 \rho_w \omega^2 I_1(h_n r_2)}{E_p^* I_p (h_n^4 - k^4)},$$

$$\zeta_{s1n} = -\frac{\pi r_1 [(\lambda^* + 2G^*) K_1(q_{1n}r_1) + G^* \delta_{1n} q_{2n} K_1(q_{2n}r_1)]}{E_p^* I_p (g_n^4 - k^4)}, \quad \zeta_{s2n} =$$

$$\frac{\pi r_2 [(\lambda^* + 2G^*) I_1(q_{1n}r_2) - G^* \delta_{2n} q_{2n} I_1(q_{2n}r_2)]}{E_p^* I_p (g_n^4 - k^4)}.$$

由管桩与海水流体交界面处速度连续条件及与土体交界面处位移连续条件:

$$\frac{\partial \phi_1}{\partial r} \Big|_{r=r_1} = \frac{\partial \phi_2}{\partial r} \Big|_{r=r_2} = \frac{\partial u_{pw}}{\partial t} \cos \theta, \quad (58)$$

$$u_{r1} \Big|_{r=r_1} = u_{r2} \Big|_{r=r_2} = u_{ps} \cos \theta. \quad (59)$$

将桩周、桩芯海水速度势和土体位移表达式以及管桩位移表达式代入, 可得

$$\sum_{n=1}^{\infty} A_{w1n} \eta_{w1n} \cos(h_n z) = \sum_{n=1}^{\infty} A_{w2n} \eta_{w1n} \cos(h_n z) \\ = N_{w1} \sin(kz) + N_{w2} \cos(kz) + N_{w3} \sinh(kz) + N_{w4} \cosh(kz) - \sum_{n=1}^{\infty} \zeta_{w1n} A_{w1n} \cos(h_n z) - \sum_{n=1}^{\infty} \zeta_{w2n} A_{w2n} \cos(h_n z), \quad (60)$$

$$\sum_{n=1}^{\infty} A_{s1n} \eta_{s1n} \cos(g_n z) = \sum_{n=1}^{\infty} A_{s2n} \eta_{s2n} \cos(g_n z) \\ = N_{s1} \sin(kz) + N_{s2} \cos(kz) + N_{s3} \sinh(kz) + N_{s4} \cosh(kz) - \sum_{n=1}^{\infty} \zeta_{s1n} A_{s1n} \cos(g_n z) - \sum_{n=1}^{\infty} \zeta_{s2n} A_{s2n} \cos(g_n z), \quad (61)$$

$$\text{式中, } \eta_{w1n} = -\frac{h_n}{2} [K_0(h_n r_1) + K_2(h_n r_1)], \quad \eta_{w2n} = \frac{h_n}{2} [I_0(h_n r_2) + I_2(h_n r_2)], \\ \eta_{s1n} = \gamma_n \frac{K_2(q_{1n}r_1) + K_0(q_{1n}r_1)}{2} + \delta_{1n} \frac{K_2(q_{2n}r_1) - K_0(q_{2n}r_1)}{2}, \\ \eta_{s2n} = -\gamma_n \frac{I_2(q_{1n}r_2) + I_0(q_{1n}r_2)}{2} + \delta_{2n} \frac{I_2(q_{2n}r_2) - I_0(q_{2n}r_2)}{2}.$$

由式 (60), (61) 容易得到

$$A_{w2n} = \frac{\eta_{w1n}}{\eta_{w2n}} A_{w1n}, \quad (62)$$

$$A_{s2n} = \frac{\eta_{s1n}}{\eta_{s2n}} A_{s1n}. \quad (63)$$

将式 (62) 代入式 (60), 式 (63) 代入式 (61), 可得

$$N_{w1} \sin(kz) + N_{w2} \cos(kz) + N_{w3} \sinh(kz) + N_{w4} \cosh(kz) - \sum_{n=1}^{\infty} \frac{\zeta_{w1n} \eta_{w2n} + \zeta_{w2n} \eta_{w1n}}{\eta_{w2n}} A_{w1n} \cos(h_n z) = \sum_{n=1}^{\infty} \eta_{w1n} A_{w1n} \cos(h_n z), \quad (64)$$

$$N_{s1} \sin(kz) + N_{s2} \cos(kz) + N_{s3} \sinh(kz) + N_{s4} \cosh(kz) - \sum_{n=1}^{\infty} \frac{\zeta_{s1n} \eta_{s2n} + \zeta_{s2n} \eta_{s1n}}{\eta_{s2n}} A_{s1n} \cos(g_n z) = \sum_{n=1}^{\infty} \eta_{s1n} A_{s1n} \cos(g_n z). \quad (65)$$

将式 (64) 两边同时乘以 $\cos(h_n z)$ 并在区间 $[-H_1, 0]$ 上积分, 式 (65) 同时乘以 $\cos(g_n z)$ 并在区间 $[0, H_2]$ 上积分, 可得

$$A_{w1n} = \eta_{w2n} (\chi_{w1n} N_{w1} + \chi_{w2n} N_{w2} + \chi_{w3n} N_{w3} + \chi_{w4n} N_{w4}), \quad (66)$$

$$A_{s1n} = \eta_{s2n} (\chi_{s1n} N_{s1} + \chi_{s2n} N_{s2} + \chi_{s3n} N_{s3} + \chi_{s4n} N_{s4}), \quad (67)$$

式中

$$\begin{aligned}\chi_{w1n} &= \frac{2 \int_{-H_1}^0 \sin(kz) \cos(h_n z) dz}{H_1(\eta_{w1n}\eta_{w2n} + \zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})}, \\ \chi_{w2n} &= \frac{2 \int_{-H_1}^0 \cos(kz) \cos(h_n z) dz}{H_1(\eta_{w1n}\eta_{w2n} + \zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})}, \\ \chi_{w3n} &= \frac{2 \int_{-H_1}^0 \sinh(kz) \cos(h_n z) dz}{H_1(\eta_{w1n}\eta_{w2n} + \zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})}, \\ \chi_{w4n} &= \frac{2 \int_{-H_1}^0 \cosh(kz) \cos(h_n z) dz}{H_1(\eta_{w1n}\eta_{w2n} + \zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})}, \\ \chi_{s1n} &= \frac{2 \int_0^{H_2} \sin(kz) \cos(g_n z) dz}{H_2(\eta_{s1n}\eta_{s2n} + \zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})}, \\ \chi_{s2n} &= \frac{2 \int_0^{H_2} \cos(kz) \cos(g_n z) dz}{H_2(\eta_{s1n}\eta_{s2n} + \zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})}, \\ \chi_{s3n} &= \frac{2 \int_0^{H_2} \sinh(kz) \cos(g_n z) dz}{H_2(\eta_{s1n}\eta_{s2n} + \zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})}, \\ \chi_{s4n} &= \frac{2 \int_0^{H_2} \cosh(kz) \cos(g_n z) dz}{H_2(\eta_{s1n}\eta_{s2n} + \zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})}.\end{aligned}$$

继而可得到:

$$A_{w2n} = \eta_{w1n}(\chi_{w1n}N_{w1} + \chi_{w2n}N_{w2} + \chi_{w3n}N_{w3} + \chi_{w4n}N_{w4}), \quad (68)$$

$$A_{s2n} = \eta_{s1n}(\chi_{s1n}N_{s1} + \chi_{s2n}N_{s2} + \chi_{s3n}N_{s3} + \chi_{s4n}N_{s4})。 \quad (69)$$

至此可得到埋入海水段和埋入土层段的管桩桩身位移、转角、弯矩和剪力的表达式为

$$\begin{aligned}u_{pw} &= N_{w1}[\sin(kz) - \sum_{n=1}^{\infty} \kappa_{w1n} \cos(h_n z)] + N_{w2}[\cos(kz) - \\ &\quad \sum_{n=1}^{\infty} \kappa_{w2n} \cos(h_n z)] + N_{w3}[\sinh(kz) - \sum_{n=1}^{\infty} \kappa_{w3n} \cos(h_n z)] + \\ &\quad N_{w4}[\cosh(kz) - \sum_{n=1}^{\infty} \kappa_{w4n} \cos(h_n z)],\end{aligned} \quad (70)$$

$$\begin{aligned}\phi_{pw} &= N_{w1}[k \cos(kz) + \sum_{n=1}^{\infty} \kappa_{w1n} h_n \sin(h_n z)] + N_{w2}[-k \sin(kz) + \\ &\quad \sum_{n=1}^{\infty} \kappa_{w2n} h_n \sin(h_n z)] + N_{w3}[k \cosh(kz) + \sum_{n=1}^{\infty} \kappa_{w3n} h_n \sin(h_n z)] + \\ &\quad N_{w4}[k \sinh(kz) + \sum_{n=1}^{\infty} \kappa_{w4n} h_n \sin(h_n z)],\end{aligned} \quad (71)$$

$$\begin{aligned}\frac{M_{pw}}{E_p^* I_p} &= N_{w1}[-k^2 \sin(kz) + \sum_{n=1}^{\infty} \kappa_{w1n} h_n^2 \cos(h_n z)] + N_{w2}[-k^2 \cos(kz) + \\ &\quad \sum_{n=1}^{\infty} \kappa_{w2n} h_n^2 \cos(h_n z)] + N_{w3}[k^2 \sinh(kz) + \sum_{n=1}^{\infty} \kappa_{w3n} h_n^2 \cos(h_n z)] + \\ &\quad N_{w4}[k^2 \cosh(kz) + \sum_{n=1}^{\infty} \kappa_{w4n} h_n^2 \cos(h_n z)],\end{aligned} \quad (72)$$

$$\begin{aligned}\frac{Q_{pw}}{E_p^* I_p} &= N_{w1}[-k^3 \cos(kz) - \sum_{n=1}^{\infty} \kappa_{w1n} h_n^3 \sin(h_n z)] + N_{w2}[k^3 \sin(kz) - \\ &\quad \sum_{n=1}^{\infty} \kappa_{w2n} h_n^3 \sin(h_n z)] + N_{w3}[k^3 \cosh(kz) - \sum_{n=1}^{\infty} \kappa_{w3n} h_n^3 \sin(h_n z)] + \\ &\quad N_4[k^3 \sinh(kz) - \sum_{n=1}^{\infty} \kappa_{w4n} h_n^3 \sin(h_n z)],\end{aligned} \quad (73)$$

$$\begin{aligned}u_{ps} &= N_{s1}[\sin(kz) - \sum_{n=1}^{\infty} \kappa_{s1n} \cos(g_n z)] + N_{s2}[\cos(kz) - \\ &\quad \sum_{n=1}^{\infty} \kappa_{s2n} \cos(g_n z)] + N_{s3}[\sinh(kz) - \sum_{n=1}^{\infty} \kappa_{s3n} \cos(g_n z)] + \\ &\quad N_{s4}[\cosh(kz) - \sum_{n=1}^{\infty} \kappa_{s4n} \cos(g_n z)],\end{aligned} \quad (74)$$

$$\begin{aligned}\phi_{ps} &= N_{s1}[k \cos(kz) + \sum_{n=1}^{\infty} \kappa_{s1n} g_n \sin(g_n z)] + N_{s2}[-k \sin(kz) + \\ &\quad \sum_{n=1}^{\infty} \kappa_{s2n} g_n \sin(g_n z)] + N_{s3}[k \cosh(kz) + \sum_{n=1}^{\infty} \kappa_{s3n} g_n \sin(g_n z)] + \\ &\quad N_{s4}[k \sinh(kz) + \sum_{n=1}^{\infty} \kappa_{s4n} g_n \sin(g_n z)],\end{aligned} \quad (75)$$

$$\begin{aligned}\frac{M_{ps}}{E_p^* I_p} &= N_{s1}[-k^2 \sin(kz) + \sum_{n=1}^{\infty} \kappa_{s1n} g_n^2 \cos(g_n z)] + N_{s2}[-k^2 \cos(kz) + \\ &\quad \sum_{n=1}^{\infty} \kappa_{s2n} g_n^2 \cos(g_n z)] + N_{s3}[k^2 \sinh(kz) + \sum_{n=1}^{\infty} \kappa_{s3n} g_n^2 \cos(g_n z)] + \\ &\quad N_{s4}[k^2 \cosh(kz) + \sum_{n=1}^{\infty} \kappa_{s4n} g_n^2 \cos(g_n z)],\end{aligned} \quad (76)$$

$$\begin{aligned}\frac{Q_{ps}}{E_p^* I_p} &= N_{s1}[-k^3 \cos(kz) - \sum_{n=1}^{\infty} \kappa_{s1n} g_n^3 \sin(g_n z)] + N_{s2}[k^3 \sin(kz) - \\ &\quad \sum_{n=1}^{\infty} \kappa_{s2n} g_n^3 \sin(g_n z)] + N_{s3}[k^3 \cosh(kz) - \sum_{n=1}^{\infty} \kappa_{s3n} g_n^3 \sin(g_n z)] + \\ &\quad N_4[k^3 \sinh(kz) - \sum_{n=1}^{\infty} \kappa_{s4n} g_n^3 \sin(g_n z)],\end{aligned} \quad (77)$$

式中, $\kappa_{w1n} = (\zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})\chi_{w1n}$, $\kappa_{w2n} = (\zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})\chi_{w2n}$, $\kappa_{w3n} = (\zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})\chi_{w3n}$, $\kappa_{w4n} = (\zeta_{w1n}\eta_{w2n} + \zeta_{w2n}\eta_{w1n})\chi_{w4n}$, $\kappa_{s1n} = (\zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})\chi_{s1n}$, $\kappa_{s2n} = (\zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})\chi_{s2n}$, $\kappa_{s3n} = (\zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})\chi_{s3n}$, $\kappa_{s4n} = (\zeta_{s1n}\eta_{s2n} + \zeta_{s2n}\eta_{s1n})\chi_{s4n}$ 。

桩顶边界条件为

$$M_{pw} \Big|_{z=-H_1} = 0 \quad Q_{pw} \Big|_{z=-H_1} = P e^{i\omega t}, \quad (78)$$

桩底边界条件为

$$u_{ps} \Big|_{z=H_2} = 0 \quad \phi_{ps} \Big|_{z=H_2} = 0. \quad (79)$$

同时管桩满足如下连续条件:

$$\left. \begin{aligned}u_{pw} \Big|_{z=0} &= u_{ps} \Big|_{z=0}, \\ \phi_{pw} \Big|_{z=0} &= \phi_{ps} \Big|_{z=0}, \\ M_{pw} \Big|_{z=0} &= M_{ps} \Big|_{z=0}, \\ Q_{pw} \Big|_{z=0} &= Q_{ps} \Big|_{z=0}\end{aligned} \right\} \quad (80)$$

将式(70)~(77)确定的桩身位移、转角、弯矩和剪力表达式代入边界条件和连续条件式(78)~(80)得到一个八元一次线性方程组,求解这一线性方程组可得到待定系数 N_{w1} , N_{w2} , N_{w3} , N_{w4} , N_{s1} , N_{s2} , N_{s3} , N_{s4} ,将得到的系数带回原方程即可得到桩身位移和应力解析解。

3 对比验证与参数分析

3.1 对比验证

为了验证本文解的正确性,将本文理论解与有限元模拟结果对比,图2为利用ABAQUS软件建立的桩-土-海水系统数值分析模型,桩-土-海水参数按照3.2节所列数据进行赋值,为避免边界反射效应的影响,桩周土和海水径向距离设置为桩半径的20倍,并在土体外侧采用无限元边界,海水外侧采用非反射边界。有限元模型中桩采用B31梁单元,土体采用C3D8R单元,海水采用AC3D8声单元,桩-土和桩-海水界面设置Embedded接触,土-海水界面设置Tie接触,而后建立稳态动力分析步对其频域响应特性进行分析。图3所示为本文理论解与有限元计算结果得到的桩顶柔度因子实部对比情况,从图中可以看出,本文理论解与有限元模拟计算结果较为吻合,从而进一步验证了本文解的正确性。

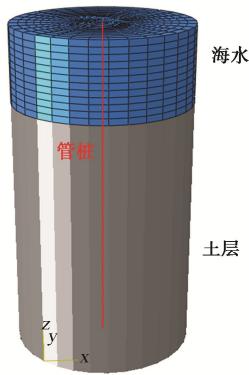


图2 桩-土-海水系统数值分析模型

Fig. 2 Numerical model for pile-soil-water system

3.2 桩顶水平动力柔度因子特性分析

根据式(70)可得在桩顶作用谐振荷载 $P e^{i\omega t}$ 下的桩顶水平位移,定义桩顶水平动力柔度因子 C_{hh} :

$$C_{hh} = \frac{u_{pw}|_{z=-H_1}}{P}, \quad (81)$$

式中, C_{hh} 为单位水平荷载作用下桩顶产生的水平位移幅值,即是表征桩顶柔度的参数。下文对海洋大直径管桩基础桩顶柔度因子特性进行分析,主要分析动水压力、海水深度、桩内外半径、桩土模量、桩土阻尼比等参数对桩顶柔度因子的影响。参数分析中,如

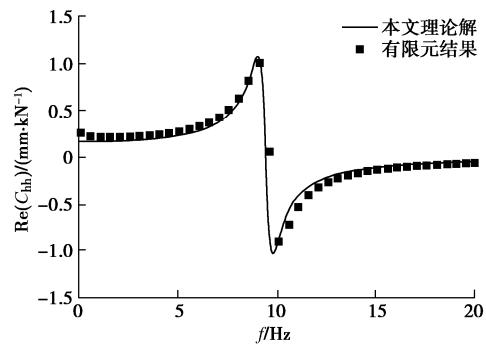


图3 本文理论解与有限元模拟得到的桩顶柔度因子实部对比

Fig. 3 Comparison of dynamic compliance coefficient between present solution and FEM simulation

何其他特殊说明,计算参数取值为 $H_2 = 20$ m, $H_1/H_2 = 0.3$, $r_1 = 0.5$ m, $r_2 = 0.8 r_1$, $E_p = 30$ GPa, $G = 50$ MPa, $\rho_p = 2400$ kg/m³, $\rho_s = 1600$ kg/m³, $\rho_w = 1000$ kg/m³, $\beta_p = 0.025$, $\beta_s = 0.05$, $\nu_s = 0.3$ 。

图4给出了考虑海水动水压力及不考虑动水压力时海洋管桩桩顶水平动力柔度因子随频率的变化情况。

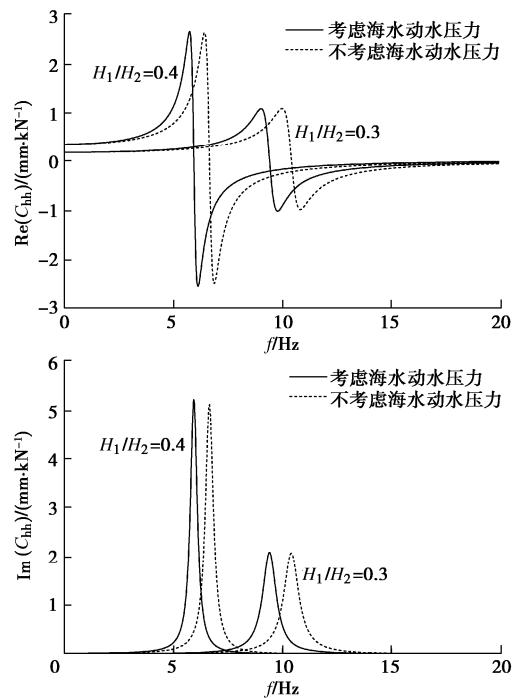


图4 动水压力对桩顶水平动力柔度因子的影响

Fig. 4 Effects of hydrodynamic pressure on horizontal dynamic compliance coefficient

与完全埋入式桩基础不同,海洋高桩基础的桩顶水平动力柔度因子存在共振现象,在低于共振频率时,桩顶柔度因子一直随频率增大而逐渐增大,实部表示真实的柔度,虚部表示吸收振动能量的阻尼,在达到

共振频率时其实部和虚部数值极大, 这对海洋桩基础上部结构的水平承载性能是极其不利的, 需要在其动力设计中考虑这一现象。从图4可以看出, 考虑海水动水压力计算的得到的桩顶水平动力柔度因子的共振频率比不考虑动水压力时小, 即海水动水压力作用使得桩更容易在较低频率时发生共振。同时可以发现, 海水动水压力对桩顶水平动力柔度因子共振幅值影响不大。

图5给出了埋入海水段桩身长度对桩顶水平动力柔度因子的影响, 可以看出, 当埋入海水段桩身很短 ($H_1/H_2 = 0.1$) 时, 桩顶柔度因子基本没有发生共振, 此时更接近于完全埋入式桩的柔度因子特性, 随着埋入海水段桩身长度逐渐增大, 低频段桩顶柔度幅值显著增大, 同时桩顶柔度因子共振现象变得显著, 同时其共振频率显著减小且共振幅值显著增大。图6, 7给出了管桩外半径和内半径对桩顶水平动柔度因子的影响, 可以发现, 随着外半径增大, 低频段桩顶柔度幅值显著减小, 桩顶柔度因子的共振频率增大, 共振幅值减小, 而随着内半径与外半径比值的减小, 低频段桩顶柔度幅值减小, 同时桩顶柔度因子共振频率和共振幅值也减小, 这种减小趋势随着内外半径比值继续减小逐渐减弱, 管桩的桩顶柔度因子共振频率和共振幅值显著大于实心桩。

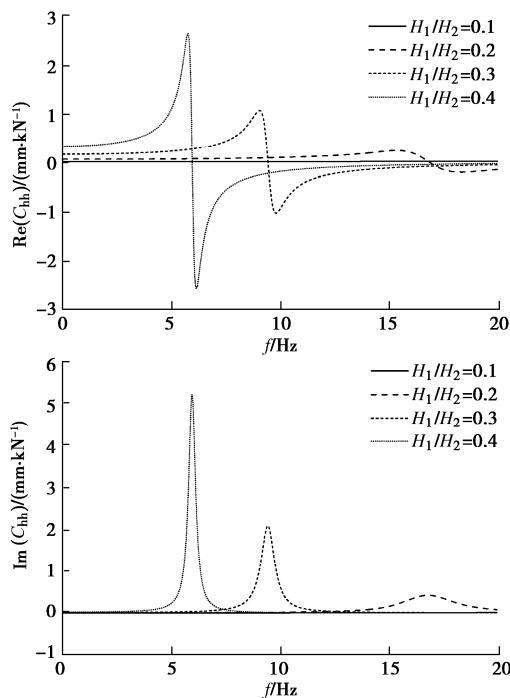


图5 埋入海水段长度对桩顶水平动力柔度因子的影响

Fig. 5 Effects of length of pile embedded in seawater on horizontal dynamic compliance coefficient

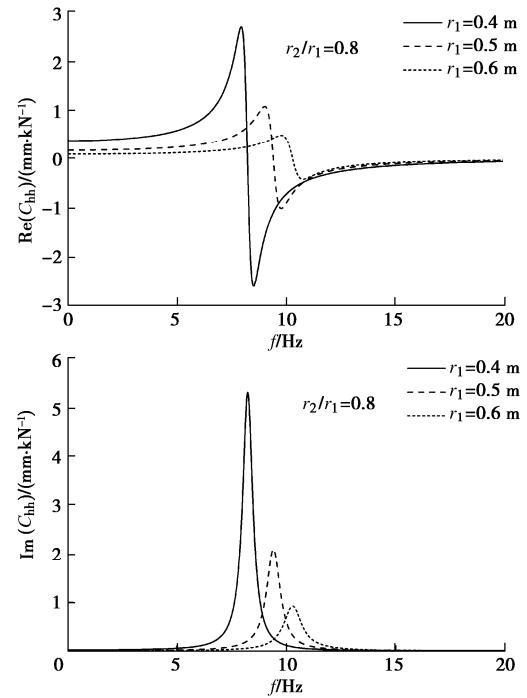


图6 管桩外半径对桩顶水平动力柔度因子的影响

Fig. 6 Effects of outer pile radius on horizontal dynamic compliance coefficient

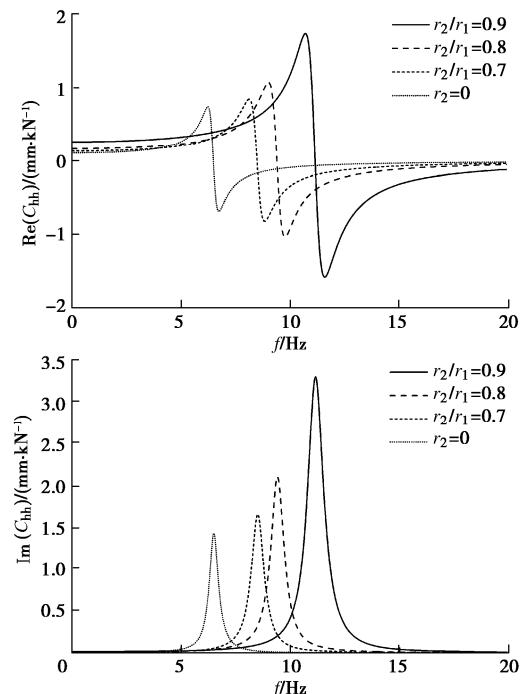


图7 管桩内外半径比值对桩顶水平动力柔度因子的影响

Fig. 7 Effects of ratio of inner to outer pile radii on horizontal dynamic compliance coefficient

图8, 9给出了桩身弹性模量和土体剪切模量对桩顶水平动力柔度因子的影响, 随着桩身弹性模量的增大, 低频段桩顶柔度幅值显著减小, 桩顶柔度因子的共振频率增大, 共振幅值显著减小, 而随着土体剪切模量的增大, 低频段桩顶柔度幅值减小, 桩顶柔度因

子的共振频率增大, 其共振幅值略有增大, 但当土体剪切模量增大到较大值时, 其对低频段桩顶柔度幅值和桩顶柔度因子共振幅值的影响不再明显。

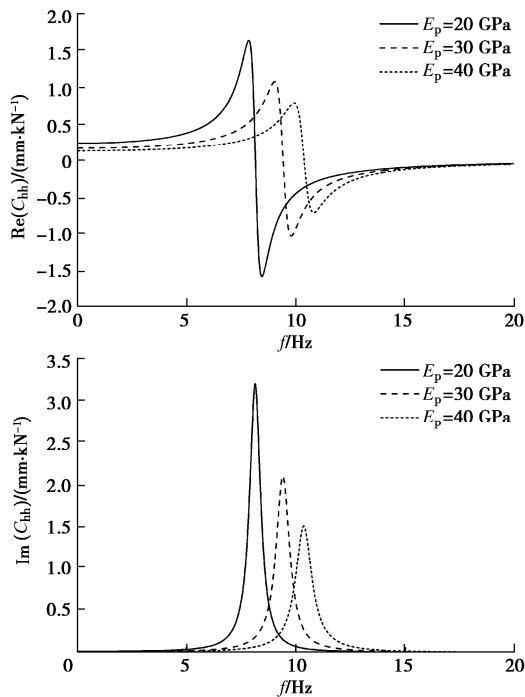


图 8 桩身弹性模量对桩顶水平动力柔度因子的影响

Fig. 8 Effects of elastic modulus of pile on horizontal dynamic compliance coefficient

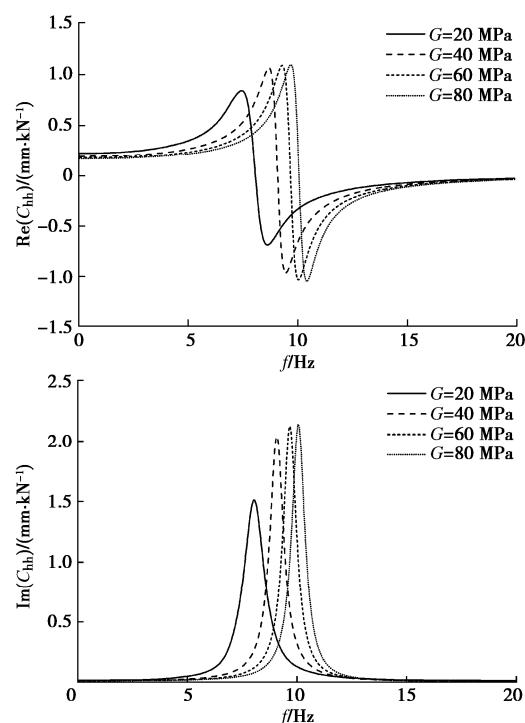


图 9 土体剪切模量对桩顶水平动力柔度因子的影响

Fig. 9 Effects of elastic modulus of pile on horizontal dynamic compliance coefficient

4 结 论

本文考虑海水动水压力作用和桩-土-流体耦合振动, 求解得到了黏弹性地基中海洋大直径管桩水平动力响应解析解, 基于所得解对大直径管桩桩顶动力柔度因子进行了参数分析, 得出 3 点结论。

(1) 海水动水压力作用使得桩更容易在较低频率时发生共振, 但对桩顶水平动力柔度因子共振幅值影响不大。

(2) 埋入海水段桩身长度增大, 低频段桩顶柔度幅值显著增大, 同时桩顶柔度因子共振频率显著减小且共振幅值显著增大。管桩外半径增大, 桩顶柔度因子的共振频率减小, 共振幅值增大, 内半径与外半径比值减小, 桩顶柔度因子共振频率和共振幅值也减小。

(3) 桩身弹性模量增大, 桩顶柔度因子的共振频率增大, 共振幅值显著减小, 土体剪切模量增大, 低频段桩顶柔度幅值减小, 桩顶柔度因子的共振频率增大。

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