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混凝土芯砂石桩复合地基固结计算

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摘要: 混凝土芯砂石桩复合地基具备了刚性桩复合地基承载力高及砂井地基排水固结快这两方面优点。复合地基固结计算中需要考虑其独特的刚性桩-砂桩-土荷载传递及环形排水边界。采用桩土荷载分担考虑芯桩的应力集中, 建立能考虑混凝土芯砂石桩复合地基环形排水通道的加固区固结计算模型, 并采用改进谢康和法计算下卧层的固结。基于现场实测的桩土荷载, 借助本文方法计算分析了试验段工程的超静孔压消散规律、固结度增长规律以及沉降发展规律, 计算结果与现场实测结果较为吻合, 验证了该方法的合理性。

关键词: 混凝土芯砂石桩; 固结; 环形排水通道; 解析解

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混凝土芯砂石桩复合地基是采用新型软土地基处理技术加固的地基^[1-3], 其加固原理是: 混凝土芯桩主要体现承受竖向荷载的功能; 环形砂石桩除可以加大芯桩侧摩阻力增强刚性芯桩承载力外, 还能加快施工期产生的超静孔隙水压力的消散^[4-5]。复合地基由混凝土芯桩及外包环形砂石桩、桩间土和碎石加筋垫层共同形成, 从结构组成上讲, 它属于柔性基础下刚性桩网结构复合地基, 但与桩网结构复合地基相比, 桩间土的固结性状更加突出。

针对目前路堤下复合地基固结问题, 已有不少研究成果^[6-11], 但主要是针对碎石桩、搅拌桩等柔性桩, 并且大多沿用了等应变假定。刘吉福^[12]指出碎石桩等散体材料桩、搅拌桩等柔性桩在路堤下基本上是等应变, 然而对于混凝土桩等刚性桩而言, 等应变假定显然难以成立。

对于路堤下桩网结构复合地基, 由于桩土模量差异较大, 随着桩间土固结沉降和桩土差异沉降增大, 路堤填土中产生土拱效应, 桩间土承担的荷载向桩体转移。桩间土中的超静孔隙水压力是由桩间土所承担的路堤填土荷载所引起的。因此, 如果能够合理确定桩间土所分担的荷载, 其固结计算就转化成了典型的太沙基固结问题。同样, 对于混凝土芯砂石桩, 如果能够得到环形砂石桩和桩间土组成的单元体所分担的路堤填土荷载, 其固结计算也就转化成了散体材料桩复合地基的固结问题。所以, 混凝土芯砂石桩复合地基固结计算的难点就成了如何确定桩、土的荷载分担。此外, 其特有的环形排水通道增加了固结计算的难度。

本文根据混凝土芯砂石桩复合地基荷载传递规律, 将混凝土芯砂石桩复合地基的固结计算转化为等应变条件下的环形砂石桩地基的固结计算。

1 加固区固结模型的建立

1.1 计算简图

取环形砂石桩和桩间土组成的单元体作为计算模型(如图1)。图1中 H 为加固区土层厚度; E_s, E_w 分别

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为桩间土和砂石桩的压缩模量; r_w 为砂石桩半径; r_c 为混凝土芯桩半径; r_e 为排水影响区半径; r_s 为扰动区半径; $\bar{\sigma}$ 为砂石桩和桩间土分担的平均荷载。 k_s, k_h 分别为桩间土扰动区和非扰动区的水平渗透系数; k_w, k_v 分别为砂石桩和桩间土的竖向渗透系数。

1.2 基本假定

固结模型建立的基本假定有:①芯桩和桩间土等应变假定不成立,设芯桩的桩体荷载分担比为 G ;②环形砂石桩和桩间土等应变假定成立,环形砂石桩和土体均受侧向约束,并且竖向变形相等;③扰动区和非扰动区土体除水平向渗透系数不同外,其他性质相同;④土体中水的渗流服从 Darcy 定律;⑤荷载瞬时施加,荷载引起的复合地基中附加应力沿深度不变;⑥采用桩周流量连续假定,忽略环形砂石桩径向渗流。即在任一深度 z 处,从桩间土体流入砂石桩的水量等于砂石桩向上的出水量。

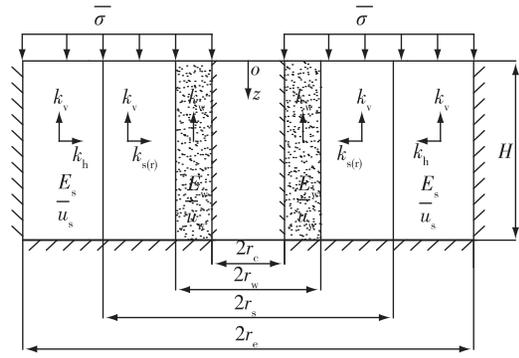


图1 加固区计算示意

Fig. 1 Simplified analysis model for consolidation area

$$\left[2\pi r dz \frac{k_s}{\gamma_w} \frac{\partial u_s}{\partial r} \right] \Big|_{r=r_w} = - \pi (r_w^2 - r_c^2) dz \frac{k_w}{\gamma_w} \frac{\partial^2 \bar{u}_w}{\partial z^2} \tag{1}$$

由式(1)可以考虑砂石桩环形排水通道对复合地基固结的影响。

1.3 土体分担的荷载计算

设瞬时施加在地基上的总荷载为 $\pi r_e^2 \bar{p}$, 芯桩的桩体荷载分担比为 G 。所以有桩间土和环形砂石桩共同分担的总荷载为:

$$\sigma_T = \pi r_e^2 \bar{p} (1 - G) \tag{2}$$

所以,桩间土和砂石桩分担平均荷载为: $\bar{\sigma} = \frac{r_e^2 \bar{p} (1 - G)}{(r_e^2 - r_c^2)}$ (3)

1.4 土体固结方程和求解条件

对环形砂石桩和桩间土组成的单元体,由荷载平衡条件及基本假定,有:

$$\pi (r_e^2 - r_w^2) \bar{\sigma}_s + \pi (r_w^2 - r_c^2) \bar{\sigma}_w = \pi (r_e^2 - r_c^2) \bar{\sigma} \tag{4}$$

$$\frac{\bar{\sigma}_s - \bar{u}_s}{E_s} = \frac{\bar{\sigma}_w - \bar{u}_w}{E_w} = \varepsilon_v = \varepsilon_z \tag{5}$$

$$\bar{u}_s = \frac{1}{\pi (r_e^2 - r_w^2)} \int_{r_w}^{r_e} 2\pi r u_s(r) dr \tag{6}$$

令 $n = \frac{r_e}{r_w}, m = \frac{r_c}{r_w}, s = \frac{r_s}{r_w}, Y = \frac{E_w}{E_s}$ 可得:

$$\bar{u} = \frac{1}{\pi (r_e^2 - r_c^2)} \left[\int_{r_w}^{r_e} 2\pi r u_s(r) dr + \int_{r_c}^{r_w} 2\pi r u_w(r) dr \right] = \frac{(n^2 - 1) \bar{u}_s + (1 - m^2) \bar{u}_w}{n^2 - m^2} \tag{7}$$

由式(4),(5)和(7)可得:

$$\varepsilon_v = \frac{(n^2 - m^2) \bar{\sigma} - [(n^2 - 1) \bar{u}_s + (1 - m^2) \bar{u}_w]}{E_s [n^2 - 1 + (1 - m^2) Y]} = \frac{(n^2 - m^2) \bar{\sigma} - (n^2 - m^2) \bar{u}}{E_s [n^2 - 1 + (1 - m^2) Y]} \tag{8}$$

由式(8)可得: $\frac{\partial \varepsilon_v}{\partial t} = - \frac{n^2 - m^2}{E_s [n^2 - 1 + (1 - m^2) Y]} \frac{\partial \bar{u}}{\partial t}$ (9)

土体的固结方程^[4-8]:

$$\frac{k_s}{\gamma_w} \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_s}{\partial r} \right] + \frac{k_v}{\gamma_w} \frac{\partial^2 \bar{u}_s}{\partial z^2} = - \frac{\partial \varepsilon_v}{\partial t}, r_w \leq r \leq r_s \quad (10)$$

$$\frac{k_h}{\gamma_w} \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{\partial u_s}{\partial r} \right] + \frac{k_v}{\gamma_w} \frac{\partial^2 \bar{u}_s}{\partial z^2} = - \frac{\partial \varepsilon_v}{\partial t}, r_s < r \leq r_e \quad (11)$$

相应的径向边界条件: $r = r_e$ 时, $\frac{\partial u_s}{\partial r} = 0$; $r = r_s$ 时, $k_s \frac{\partial u_s}{\partial r} = k_h \frac{\partial u_s}{\partial r}$; $r = r_w$ 时, $u_s = u_w = \bar{u}_w$ 。

1.5 控制方程推导

参照文献[7-10]可以得到:

$$\bar{u} = \bar{u}_w + \frac{\gamma_w r_e^2 F_a}{2k_h} \left[- \frac{n^2 - 1}{E_s [n^2 - 1 + (1 - m^2) Y]} \frac{\partial \bar{u}}{\partial t} + \frac{k_v}{\gamma_w} \left(\frac{\partial^2 \bar{u}}{\partial z^2} - \frac{1 - m^2}{n^2 - m^2} \frac{\partial^2 \bar{u}_w}{\partial z^2} \right) \right] \quad (12)$$

其中:

$$F_a = \left(\ln \frac{n}{s} + \frac{k_h}{k_s} \ln s - \frac{3}{4} \right) \frac{n^2}{n^2 - 1} + \frac{s^2}{n^2 - 1} \left(1 - \frac{k_h}{k_s} \right) \left(1 - \frac{s^2}{4n^2} \right) + \frac{k_h}{k_s} \frac{1}{n^2 - 1} \left(1 - \frac{1}{4n^2} \right) \quad (13)$$

$$\bar{u} = \bar{u}_w - A \frac{\partial^2 u_w}{\partial z^2} \quad (14)$$

式中: A 是一个正常数, 其表达式为: $A = \frac{1 - m^2}{n^2 - m^2} \frac{r_e^2 k_w F_a}{2k_h}$ (15)

从式(12)和(14)中消去 \bar{u} 可得关于 \bar{u}_w 的偏微分方程:

$$B \frac{\partial^4 \bar{u}_w}{\partial z^4} + C \frac{\partial^2 \bar{u}_w}{\partial z^2} + A \frac{\partial^3 \bar{u}_w}{\partial t \partial z^3} - \frac{\partial \bar{u}_w}{\partial t} = 0 \quad (16)$$

式中: B, C 均为常数, 表达式如下:

$$B = - \frac{c_v [n^2 - 1 + (1 - m^2) Y] (1 - m^2) r_e^2 k_w F_a}{2(n^2 - 1)(n^2 - m^2)k_h} \quad (17)$$

$$C = \frac{c_h k_w [n^2 - 1 + (1 - m^2) Y] \left[(1 - m^2) + (n^2 - 1) \frac{k_v}{k_w} \right]}{(n^2 - 1)(n^2 - m^2)k_h}$$

如图1所示, 单元体底面不透水, 顶面透水, 方程边界条件为:

$$\begin{cases} \bar{u}(z, t) = 0, \bar{u}_w(z, t) = 0 & (z = 0) \\ \frac{\partial \bar{u}(z, t)}{\partial z} = 0, \frac{\partial u_w(z, t)}{\partial z} = 0 & (z = H) \end{cases} \quad (18)$$

参考文献[9], $t=0$ 时, 环形砂石桩和桩间土组成的单元体总附加应力全部由桩间土和砂石桩中的孔隙水承担, 即有效应力为零, 此时桩间土和砂石桩均未发生变形, $\varepsilon_v = \varepsilon_z = 0$, 则由式(5)得:

$$\bar{\sigma}_s = \bar{u}_s, \bar{\sigma}_w = \bar{u}_w \quad (19)$$

由式(7)得:

$$\bar{u}(z, 0) = \bar{\sigma}(z, 0) \quad (20)$$

1.6 控制方程求解

参考文献[7-10]的解法, 设控制方程解的形式为:

$$\bar{u}_w = \sum_{a=1}^{\infty} T_a(t) \sin\left(\frac{M}{H}z\right) \quad (21)$$

式中: $M = \frac{2a-1}{2}\pi$ ($a = 1, 2, 3, \dots$)。该解满足定解问题边界条件(18)。

将式(21)代入控制方程(16),两边同乘 $\sin\left(\frac{M}{H}z\right)$ 并在 $[0, H]$ 上关于 z 积分可得:

$$T'_a(t) + \frac{B(M/H)^4 - C(M/H)^2}{1 + A(M/H)^2} T_a(t) = 0 \quad (22)$$

方程(22)的解为:

$$T_a(t) = A' \exp(-\beta_a t) \quad (23)$$

$$\beta_a = - \frac{B\left(\frac{M}{H}\right)^4 - C\left(\frac{M}{H}\right)^2}{1 + A\left(\frac{M}{H}\right)^2} = \frac{[n^2 - 1 + (1 - m^2)Y] \left(\frac{M}{H}\right)^2 (1 - m^2) c_v + \frac{2}{r_e^2 F_a} \left[(1 - m^2) + \frac{k_v}{k_w} (n^2 - 1) \right] c_h}{(n^2 - 1) \left[(n^2 - m^2) \frac{2k_h}{k_w F_a M^2} \frac{H^2}{r_e^2} + (1 - m^2) \right]} \quad (24)$$

$$\text{将式(21)代入式(14)可得: } \bar{u}(z, t) = \sum_{a=1}^{\infty} \left[1 + A \left(\frac{M}{H} \right)^2 \right] T_a(t) \sin\left(\frac{M}{H}z\right) \quad (25)$$

$$\text{式(25)代入初始条件(20)可得: } \sum_{a=1}^{\infty} \left[1 + A \left(\frac{M}{H} \right)^2 \right] T_a(0) \sin\left(\frac{M}{H}z\right) = \bar{\sigma}(z) \quad (26)$$

两边同乘以 $\sin\left(\frac{M}{H}z\right)$ 并在 $[0, H]$ 上关于 z 积分可得:

$$T_a(0) = 2 \int_0^H \bar{\sigma} \sin\left(\frac{M}{H}z\right) dz / \left\{ H \left[1 + A \left(\frac{M}{H} \right)^2 \right] \right\} \quad (27)$$

$$\text{由式(23)和(27)可得: } T_a(0) = A' = 2\bar{\sigma} / \left\{ M \left[1 + A \left(\frac{M}{H} \right)^2 \right] \right\} \quad (28)$$

$$\text{则有: } T_a(t) = 2\bar{\sigma} / \left\{ M \left[1 + A \left(\frac{M}{H} \right)^2 \right] \right\} \exp(-\beta_a t) \quad (29)$$

将式(29)代入式(21)和(25)可得砂石桩和单元体中的超静孔压分别为:

$$\bar{u}_w(z, t) = \sum_{a=1}^{\infty} 2\bar{\sigma} / \left\{ M \left[1 + A \left(\frac{M}{H} \right)^2 \right] \right\} \sin\left(\frac{M}{H}z\right) \exp(-\beta_a t) \quad (30)$$

$$\bar{u}(z, t) = \sum_{a=1}^{\infty} \frac{2\bar{\sigma}}{M} \sin \frac{Mz}{H} \exp(-\beta_a t) \quad (31)$$

1.7 固结度计算

$$\text{固结度表达式: } U_p(t) = \int_0^H (\bar{\sigma} - \bar{u}) dz / \int_0^H \bar{\sigma} dz \quad (32)$$

$$\text{将式(31)代入式(32)可得: } U_p(t) = 1 - \sum_{a=1}^{\infty} \frac{2}{M^2} \exp(-\beta_a t) \quad (33)$$

1.8 解的验证

当 $r_c \rightarrow 0$ 时,即 $m \rightarrow 0$,此时 β_a 表达式退化为:

$$\beta_a = \frac{[n^2 - 1 + Y] \left(\frac{M}{H}\right)^2 c_v + \frac{2}{r_e^2 F_a} \left[1 + \frac{k_v}{k_w} (n^2 - 1) \right] c_h}{(n^2 - 1) \left[n^2 \frac{2k_h}{k_w F_a M^2} \frac{H^2}{r_e^2} + 1 \right]} \quad (34)$$

式(34)为文献[9]散体材料桩复合地基的解。当 $r_c \rightarrow 0$ 时,混凝土芯砂石桩复合地基也退化为砂石桩复合地基。

$$\text{当 } r_c \rightarrow r_w \text{ 时,即 } m \rightarrow 1 \text{ 时, } \beta_a \text{ 表达式也退化为: } \beta_a = M^2 c_v / H^2 \quad (35)$$

固结度表达式则退化为：
$$U_p(t) = 1 - \sum_{a=1}^{\infty} \frac{2}{M^2} \exp(-M^2 c_v / H^2) \quad (36)$$

此时,混凝土芯砂石桩复合地基则退化为桩网结构刚性桩复合地基;而环形砂石桩和桩间土组成的单元也退化为桩间土,其固结问题即为太沙基一维固结。式(36)即为太沙基一维固结解。通过以上对解答的退化,可以说明本文解答的合理性。

2 下卧层简化的固结模型

对于未打穿的砂井地基和复合地基而言,下卧层的沉降不可忽略,固结计算时必须考虑下卧层的固结。关于下卧层固结计算的方法有 Hart 法、China 法、谢康和改进法等。Hart 法偏于保守,China 法则明显夸大了砂井作用,谢康和改进法计算结果介于前二者之间,同时,谢康和改进法能考虑井阻、涂抹作用对下卧层固结的影响^[7,10]。因此,对下卧层进行固结计算时,采用谢康和改进法确定竖向排水距离。

3 工程实例

3.1 计算参数

为验证本文计算方法的正确性,对江苏镇溧高速公路某桥头软基处理工程混凝土芯砂石桩复合地基试验段 K63+056 断面进行计算,并与现场实测数据^[13]进行对比分析。路堤设计高度 6 m,超载预压土方厚度为 2 m,路基宽度 35 m,路堤边坡坡率 1:2,软土层厚度 26.5 m,地基处理深度 22 m,采用振动沉管法施工,桩径 50 cm(其中芯桩为边长 20 cm 的方桩,混凝土强度 C20,成孔放入方桩后灌入中粗砂作为环形砂石桩),梅花型布置,桩间距 2.1 m。试验段加固示意图 2。表 1 为场地地层分布及物理力学性质。混凝土芯砂石桩施工参数为:桩径 0.5 m,桩间距 2.1 m,芯桩边长 0.2 m,加固区深度 22 m,下卧层深度 4.5 m,砂石桩渗透系数 0.1 m/d,压缩模量 10 MPa。根据实测的桩间土荷载利用本文方法计算固结度和孔压,桩间土荷载如图 3 所示。30,60,90,110,120 和 280 d 的现场累计沉降量分别为 9,19,28,34,42 和 64 cm。

表 1 地基土层分布及物理力学性质
Tab. 1 Physical and mechanical properties of soils

土层名称	深度/m	W/%	$\gamma/$ ($\text{kN} \cdot \text{m}^{-3}$)	e	$a_{1-2}/$ MPa^{-1}	$Es_{1-2}/$ MPa	快剪		$k/$ ($\text{m} \cdot \text{d}^{-1}$)
							c/kPa	$\varphi/(^{\circ})$	
杂填土	2.0~3.7								1×10^{-4}
粉质黏土	1.6~2.6	32.3	18.4	0.91	0.30	7.28	2.0	17.1	1×10^{-4}
淤泥质粉质黏土	6.6~10.9	38.8	17.9	1.07	0.49	4.47	7.0	24.5	8×10^{-5}
粉质黏土夹粉土	0.6~2.5	35.2	18.3	0.96	0.45	5.37	18	16.5	7×10^{-4}
粉土夹粉质黏土	0.7~2.9	33.9	18.5	0.93	0.41	5.68	10	25.5	4×10^{-4}
粉质黏土夹粉土	0.0~4.4	26.6	19.3	0.75	0.45	3.94	25	13.7	7×10^{-4}
粉质黏土	9.6~10.1	35.0	18.7	0.93	0.43	5.29	13.0	12.2	4×10^{-4}

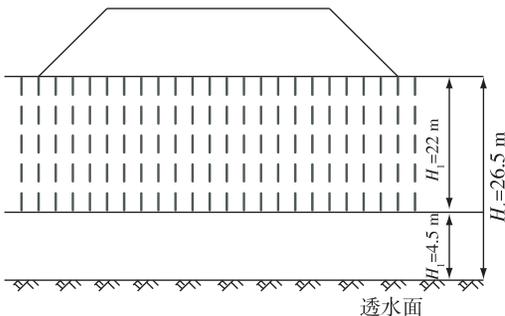


图 2 试验段加固示意
Fig. 2 Schematic diagram of test section

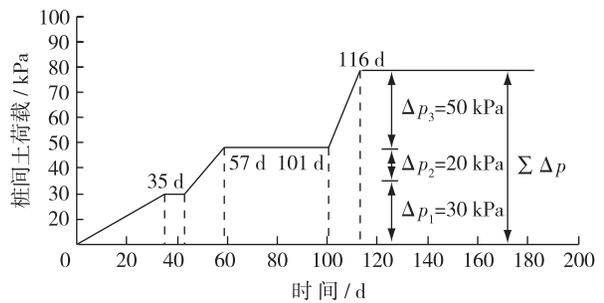


图 3 依据实测桩间土荷载修正后桩间土荷载
Fig. 3 Modified loads according to measured values

3.2 计算结果

采用改进的太沙基法对不同时期的固结度加以计算。2.0 m 深度处式(31)计算以及现场实测得到的超静孔压消散曲线见图4。结果表明,理论方法计算得到的孔压与实测孔压消散规律相似。

将理论计算得到的固结度与现场实测值进行对比分析,见图5。其中实测值是先利用三点法推算加固区和整个地基的最终沉降量,进一步推算得出了加固区及地基整体固结度发展规律。从图5可见,计算得到的加固区及复合地基固结度规律和固结度与实测值接近。

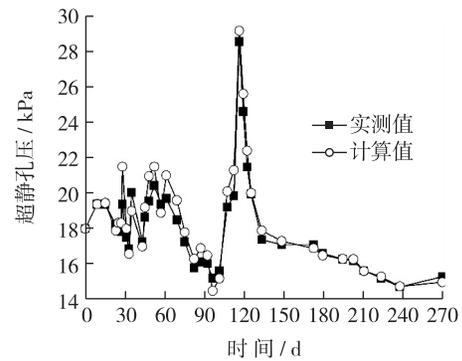


图4 超静孔压消散曲线

Fig. 4 Variation of excess pore pressure with time

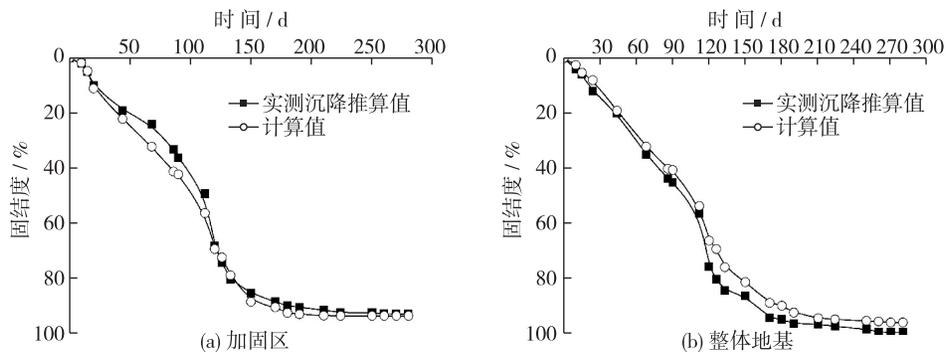


图5 加固区和复合地基固结度与随时间变化曲线

Fig. 5 Variation of consolidation degrees of improved zone and composite foundation with time

4 结 语

本文建立的混凝土芯砂石桩复合地基固结计算方法,综合考虑了砂石桩环形排水通道和桩体应力集中特点,比以往的计算方法更接近于实际工况。通过对工程实例的计算验证了本文方法的合理性,计算结果与实测数据较为吻合。本文采用实测的桩间土上荷载进行计算,没有给出确定桩体荷载分担比的计算方法,需进一步研究如何合理确定桩土荷载分担,进而完善本文提出的固结计算方法。

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A calculation method for consolidation of concrete core sand-gravel piles composite foundation under embankment

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Abstract: The composite foundation with concrete core sand-gravel piles has the advantages of high bearing capacity of the rigid pile composite foundation and fast drainage consolidation of sand well foundation. It is necessary to consider, in the calculation of the composite foundation consolidation, the unique load transfer among the rigid pile, sand pile and soil body, and the circular drainage channel. Considering the annular drainage section of sand-gravel columns composite foundation, using the initial condition of loads beared by soil and pile, the control equation and the analytical solutions for the composite foundation are obtained, and the average degree of consolidation is given by calculation. Finally the comparisons between the calculated results and the field measured data show that the calculated excess pore water pressure, the degree of consolidation and the settlement-time relationships are well consistent with those of the field data, by which the calculation method has been verified.

Key words: concrete core sand-gravel piles; consolidation; circular drainage channel; analytical solution