ARTICLE IN PRESS

HOSTED BY

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Soils and Foundations xxx (2018) xxx–xxx

SOILS AND FOUNDATIONS

www.elsevier.com/locate/sandf

Design chart for the modified hyperbolic method

Wei Guo [a,b,c], Jian Chu [d], Wen Nie [d,*]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, China
[b] School of Civil Engineering, Tianjin University, 135 Yaguan Road, Jinnan District, Tianjin 300350, China
[c] Formerly School of Civil & Environmental Engineering, Nanyang Technological University, Singapore
[d] School of Civil & Environmental Engineering, Nanyang Technological University, Blk N1, 50 Nanyang Ave, 639798 Singapore, Singapore

Received 1 June 2017; received in revised form 5 December 2017; accepted 18 December 2017

Abstract

The modified hyperbolic method is used in practice to predict the ultimate primary consolidation settlement of compressible ground. This paper presents a new relationship between the average degree of consolidation for combined vertical and horizontal consolidation U_{vh} and the non-dimensional vertical time factor T_v, with a new parameter, v_{hv}, introduced. v_{hv} is defined as the ratio of the time factor in the horizontal direction to that in the vertical direction. This relationship is then adopted to calculate the slope of the linear segment of the theoretical hyperbolic plot (T_v/U_{vh} vs T_v), λ, which is a key factor in the modified hyperbolic observational method presented by Tan (1995). A design chart for λ as a function of v_{hv} is proposed. Using this design chart, the determination for λ can be simplified from a procedure involving three parameters to only one, v_{hv}. A new procedure for the use of the modified hyperbolic method is proposed. The new procedure is verified using a well-documented case history.

Keywords: Consolidation; Hyperbolic method; Ground improvement

1. Introduction

The average degree of consolidation is one of the most commonly adopted design specifications used to evaluate the achieved degree of ground improvement using the vacuum and surcharge preloading methods. The average degrees of consolidation can be determined as the percentage of current settlement to the ultimate primary consolidation settlement. One popular method to predict the ultimate primary consolidation settlement is the observational method, including Asaoka's method (Asaoka, 1978), a modification of Asaoka's method (Guo and Chu, 2017), the hyperbolic method (Sridharan and Sreepada Rao, 1981; Sridharan et al., 1987; Tan et al., 1991; Chung et al., 2014) and a modification of the hyperbolic method (Tan, 1993, 1994, 1995; Tan and Chew, 1996).

The modified hyperbolic method is a method for predicting the ultimate primary consolidation settlement using the linear segment between U_{60} and U_{90} in the t/δ vs t plot to present the δ vs t relationship and shown as,

$$\frac{t}{\delta} = \alpha t + \beta \tag{1}$$

where α is the slope and β is the intercept of the linear segment between U_{60} and U_{90} in the t/δ vs t plot; t is the consolidation time, and δ is the monitored settlement; U_{60} and U_{90} are the average degrees of consolidation, at 60% and 90%, respectively.

The ultimate primary consolidation settlement δ_{ult} can be obtained as,

Peer review under responsibility of The Japanese Geotechnical Society.
* Corresponding author.
E-mail address: wnie001@e.ntu.edu.sg (W. Nie).

https://doi.org/10.1016/j.sandf.2018.02.014
0038-0806/© 2018 Production and hosting by Elsevier B.V. on behalf of The Japanese Geotechnical Society.

Nomenclature

c_h	coefficient of consolidation in horizontal (or radial) direction
c_v	coefficient of consolidation in vertical direction
D_e	diameter of an equivalent soil cylinder influenced by vertical drains
d_w	equivalent diameter of the vertical drain
H	vertical drainage length
m	drain pacing ratio $m = D_e/d_w$
n	integer, $n = 0, 1\ldots$
s	spacing of the vertical drain
t	consolidation time
t_{60}	time to achieve U_{60}
t_{90}	time to achieve U_{90}
T_h	non-dimensional horizontal (radial) time factor
T_v	non-dimensional vertical time factor
U_{60}	$U_{vh} = 60\%$
U_{90}	$U_{vh} = 90\%$
U_h	average degree of horizontal consolidation, %
U_v	average degree of vertical consolidation, %
U_{vh}	average degree of consolidation for combined vertical and horizontal consolidation, %
α	slope of the line segment between U_{60} and U_{90} in t/δ vs t plot
α_{60}	slope of the line between origin and δ_{60} in the t/δ vs t plot
α_{90}	slope of the lines between origin and δ_{90} in the t/δ vs t plot
α_t	tried slope of the line segment in t/δ vs t plot
β	intercept of the line segment between U_{60} and U_{90} in t/δ vs t plot
δ	consolidation settlement
δ_{60}	settlement at U_{60}
δ_{90}	settlement at U_{90}
δ_{ult}	ultimate consolidation settlement
λ	slope of the line segment between U_{60} and U_{90} in T_v/U_{vh} vs T_v plot
μ	factor to account for drains spacing
v_{hv}	ratio of time factor in horizontal and vertical direction

$$\delta_{ult} = \frac{\lambda}{\alpha} \quad (2)$$

where λ is the slope of the linear segment between U_{60} and U_{90} in the theoretical hyperbolic plots (T_v/U_{vh} vs T_v), T_v is the non-dimensional vertical time factor in vertical direction and $T_v = c_v t/H^2$, c_v is the coefficient of consolidation in the vertical direction, U_{vh} is the average degree of consolidation for combined vertical and horizontal consolidations.

The slopes to define the position of the U_{60} and U_{90} in the t/δ vs t plot can be calculated as (Tan, 1995),

$$\alpha_{60} = \frac{1}{0.6}\frac{\alpha}{\lambda} \quad (3)$$

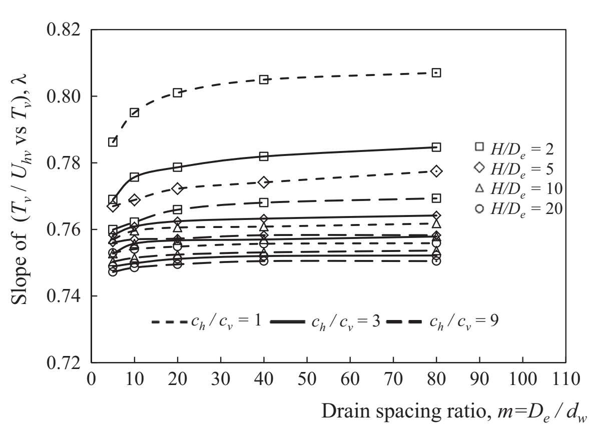

Fig. 1. Slope of the linear segment between U_{60} and U_{90} in the theoretical hyperbolic plot T_v/U_v vs T_v (after Tan, 1995).

$$\alpha_{90} = \frac{1}{0.9}\frac{\alpha}{\lambda} \quad (4)$$

where α_{60} and α_{90} are the slopes of the lines for the segments between origin and t_{60} and t_{90} in the t/δ vs t plot, respectively; t_{60} and t_{90} are the consolidation time to achieve U_{60} and U_{90}, respectively.

For clay consolidated by vacuum and surcharge preloading combined with vertical drains, Tan (1995) showed that λ is dependent only on the drain pacing ratio m, ratio between vertical drainage length and diameter of an equivalent soil cylinder influenced by the vertical drain, H/D_e, and the ratio of the coefficient of consolidation in the horizontal and vertical directions, c_h/c_v, as plotted in Fig. 1. However, the authors found that because too many parameters (etc. m, H/D_e, c_h/c_v) are involved in the Fig. 1, it is hard to accurately identify the λ value especially for the cases of m, H/D_e, c_h/c_v located between the boundaries, as shown in the legends.

In this paper, a new parameter, v_{hv}, defined as the ratio of the time factor in the horizontal and vertical directions, was introduced to redefine the relationship between U_{vh} and T_v. Then the T_v/U_{vh} vs T_v plots were used to calculate the λ value used in the modified hyperbolic observational method. The design chart for the λ value was also proposed in this paper, which simplified the identify process of λ used in the modified hyperbolic method from three parameters (etc. m, H/D_e, and c_h/c_v,) to only one v_{hv}. Guidelines for using the modified hyperbolic method and the proposed design chart of λ value were also presented in this paper.