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Consolidation behavior of soft deposits considering the variation of prefabricated vertical drain discharge capacity

Yue-Bao Deng [a,*], Gan-Bin Liu [a], Meng-Meng Lu [b], Kang-he Xie [c]

[a] Institute of Geotechnical Engineering, Ningbo University, Ningbo 315211, China
[b] School of Mechanics and Civil Engineering, China University of Mining & Technology, Xuzhou 221008, China
[c] Research Center of Coast and Urban Geotechnical Engineering, Zhejiang University, Hangzhou 310058, China

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ABSTRACT

This paper is primarily focused on why and how to consider the varied discharge capacity during simulations of consolidation via prefabricated vertical drains (PVDs) for soft soil deposits. First, the existing studies regarding discharge capacity are summarized and discussed. These studies conclude that the discharge capacity of PVDs at sites vary with the confining pressure and consolidation time. Next, a series of analytical solutions that consider the variation of discharge capacity with ground depth, consolidation time or both simultaneously are presented and compared. Applications of these solutions and of the newly introduced parameters are described. Then, a well-documented case history on ground treatment with PVDs is analyzed, in which the parameters related to the time-dependent discharge capacity were obtained from laboratory tests. A comparison between a classical solution and the newly presented method indicates that consideration of the varied discharge capacity in the consolidation theory can better predict the consolidation process of PVD-improved ground.

1. Introduction

Prefabricated vertical drains (PVDs) have been applied worldwide in many soft soil engineering projects over the past few decades (e.g., [23,6,29,12,1,8,28,21,20,7]). In addition, in China, with the continuous increase of embankment construction projects and reclamation projects in coastal belts, there will still be a large number of PVD applications in the near future [35].

A PVD installed in a thick, soft soil layer serves as a drainage channel, which has the function of facilitating the radial flow of water from the soft deposits, thereby accelerating the consolidation of soft ground under imposed loading. The effectiveness of this ground treatment method is closely related to the discharge capacity, which is defined as the rate of flow through the drain at a hydraulic gradient of unity [16,4,6]. The discharge capacity of a PVD is affected by a series of factors in the field, and it changes during the consolidation process [17]. For example, the pores of the filter sleeve can become clogged when the fine particles in the surrounding soil are gradually entrapped within the fibers of the PVD. Consequently, the discharge capacity of the PVD decreases and the consolidation process is impeded.

A series of analytical solutions, such as Barron [2] solution with an ideal drain assumption and Hansbo [15] solution considering both the smear effect and well resistance, can be adopted to simulate the consolidation behavior of soft ground improved with PVDs. However, with the assumption that the discharge capacity is infinitely high or constant throughout the entire consolidation process, all of these classical solutions ignore the changes in discharge capacity during the consolidation process. The limitations of these solutions will likely result in errors in estimating the time to the final primary consolidation. For example, in the Wenzhou shoal project [33,32], which is situated on deep silty clay ground, the PVD was set with a square layout, with a spacing of 1.5 m and a length of approximately 20 m. According to the measured layered settlement data (the monitoring lasted 25 months and the loading process lasted 18 months), the degree of consolidation for the soil layer at a depth of 4 m reaches 90%, whereas it is only 30% for the PVD penetrating through the soil layer. In addition, a clear deviation exists between the measured value and the preliminary design value.

Because of the aforementioned reasons, the authors developed new closed-form solutions that consider the change in discharge capacity with depth, time or both simultaneously [13,14]. The rationality of these solutions was preliminarily verified by a comparison study that employed a large-scale laboratory test. Based

* Corresponding author.
E-mail address: dengyuebao@nbu.edu.cn (Y.-B. Deng).

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on this previous work, in this paper, the factors that affect the discharge capacity and the variation in discharge capacity with ground depth and consolidation time are summarized and discussed. Then, the application of these newly presented solutions, including parameter evaluation, is comprehensively illustrated. Finally, a case history example is analyzed, in which the results predicted using the newly presented solution are compared with those obtained using a classical solution.

2. The varied discharge capacity

The discharge capacity, q_w, governs the performance of PVDs and thus affects the rate of consolidation [16,4,6]. Therefore, intensive studies have been performed to determine the actual characteristics of PVD discharge capacity (e.g., [19,26,4,3,10,17,31,24]). According to these reports, the following factors strongly influence the discharge capacity:

(1) PVD type. Different types of PVDs have different core structures, stiffnesses, and durabilities. The core structure of a PVD generally determines the discharge area and its stiffness. If the core structure of a PVD provides more space for water flow, the PVD will have a higher discharge capacity. A stiffer PVD can tolerate higher compression and bending, which will better maintain continuous flow channels in its core. Biological and chemical attacks at the site will deteriorate the performance of the PVD, and thus, the durability of the PVD is also a factor that affects the discharge capacity.

(2) Lateral stress. Induced from preload, surcharge or vertical load, the lateral stress from the surrounding soil considerably affects the PVD discharge capacity because it decreases the cross-sectional area of the PVD by squeezing the filter sleeve into the core of the PVD. Many research efforts have examined the effects of lateral stress on the discharge capacity and have reached a consensus that the discharge capacity decreases with increasing lateral stress (e.g., [4,31]).

(3) Siltation or clogging. As the consolidation process continues, fine soil particles gradually infiltrate into the core of the PVD and consequently clog the drainage channels, thereby reducing the discharge capacity. Holtz et al. [19] suggested that if the characteristics of the filter sleeves of PVDs were satisfied for all criteria, the effect of siltation could be neglected. However, long-term laboratory tests [25,9] have demonstrated that clogging substantially reduces the discharge capacity and is a dominant factor in decreasing the discharge capacity.

(4) Deformation. The deformation of PVDs by folding, crimping, bending, buckling, or kinking that occurs due to large consolidation settlements may partially or completely reduce the discharge capacity, as shown in Fig. 1. The results of laboratory tests and field investigations agree that a large deformation of a PVD significantly influences its discharge capacity and will be more crucial than other factors [12,31,30].

(5) Hydraulic gradient. The discharge capacity is often measured under various hydraulic gradients. The effect of the hydraulic gradient on the discharge capacity differs according to different investigators [19,4,31]. However, recent reports have indicated that the hydraulic gradient has an impact on the test results and that the test discharge capacity decreases with increasing hydraulic gradient [31].

A summary of these factors reveals that there are controversies concerning (1) whether the discharge capacity will decrease significantly, thereby making the well resistance apparent or not; (2) the major factor responsible for the decrease in discharge capacity during the consolidation process; and other such factors. These disagreements may result from the use of different test equipment or different test methods or because of the selection of different types or sizes of PVDs. For example, in a long-term laboratory test evaluating a PVD in a soil sample, a short-length PVD will have a relatively large stiffness and the decrease in the discharge capacity will be slight. Conversely, the decrease in discharge capacity for a long PVD will be more obvious. In addition, the clogging effect will be more apparent for a long PVD.

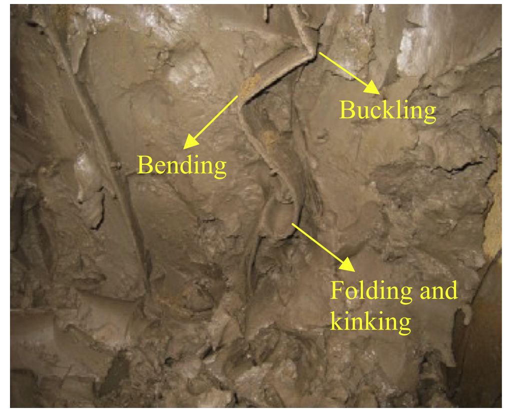

Fig. 1. Deformed drain in a laboratory model test (after [30]).

On the other hand, the actual characteristics of the discharge capacity of a PVD are not yet fully understood, but conclusions regarding the influence of the lateral confining pressure and the decrease in discharge capacity during the consolidation process have reached a good consensus. Combined with Fig. 2, which shows a schematic diagram of installed PVDs in a site, the aforementioned conclusions allow the following to be inferred: (1) as PVDs push into soft ground, the confining pressure from the surrounding soil varies with the ground depth, which results in the PVD discharge capacity possessing a spatial characteristic; and (2) due to bending, siltation, clogging, aging and related factors, the discharge capacity of PVDs decreases with the development of consolidation, which results in the discharge capacity possessing a time-dependent characteristic. Here, the spatial characteristic and the time-dependent characteristic of the discharge capacity of PVDs are collectively referred to as the varied discharge capacity.

Notably, the effect of varied discharge capacity on consolidation will be more apparent for a deep, soft soil deposit. On the one hand, as the confining pressures from the top and bottom of the surrounding soil exert a large difference, the discharge capacities of PVDs at different ground depths are significantly different. On the other hand, because of the long consolidation time and large deformation for deep soft ground, the influences of deformation, siltation, clogging and aging on PVD discharge capacity are obvious, and thus, the long-term value of q_w will significantly decrease. The existing consolidation theory for PVD systems assumes that

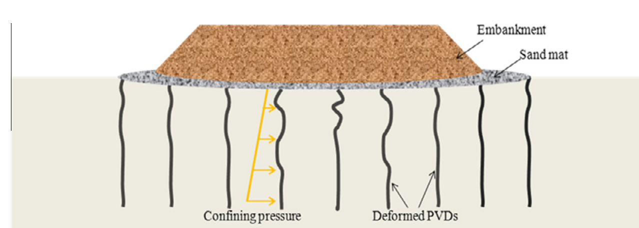

Fig. 2. Sketch of PVDs in an actual situation.