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EXPERIMENTAL AND NUMERICAL STUDY FOR THE EFFECT OF VACUUM PRELOADING ON SOFT SOIL IMPROVEMENT

M. A. M. SAKR

Department of Structural Engineering, Faculty of Engineering, Tanta University, Egypt

A. AL NIMR

Department of Structural Engineering, Faculty of Engineering, Mansoura University, Egypt

A. M. BASHA

Department of Civil Engineering, Faculty of Engineering - Kafrelshiekh University, Egypt

ABSTRACT: The current research is concerned with a study on the effect of vacuum preloading conjunction with conventional surcharge loading for soft soil improvement experimental and numerical. Several experimental tests were performed by using a large-scale consolidometer were performed to examine the effect of vacuum and to determine parameters such as the extent of smear zone and the soil permeability characteristics. The experimental tests studied numerically using the method of finite elements. The settlement and excess pore pressure associated with a combined vacuum and surcharge load indicate that applying a vacuum has significant effect. The results indicated that the water content decreased with radial distance and the hydraulic conductivity in the smear zone of the PVD increased due to using vacuum pressure. Also, the time required to reach at certain degree of consolidation decreased with using vacuum preloading. Large-scale consolidometer and numerical simulation can be used in the preliminary design works which may reflect the influence on the cost estimate of the used of vacuum preloading technique.

INTRODUCTION

There are several methods for soft soil improvement. Recently, vacuum consolidation with prefabricated vertical drains is a soft ground improvement method that has been successfully used by geotechnical Engineers to accelerate the rate of consolidation and improve the soft soil properties. In 1952, Kjellman was the first one to introduce the vacuum preloading method. Many researchers stated that the effective stress in the soil mass is increased by the application of vacuum pressure, where the vacuum preloading reduces the pore pressure without need to increase the total stress and the effective stress is increased due to the reduced atmospheric pressure in the soil mass. Thousands of hectares of land have been reclaimed in Tianjin, China using the vacuum preloading method when clay slurry dredged from seabed which is used as a fill material for land reclamation. Where the clay slurry fill is very soft to be loaded by fill surcharge, the vacuum preloading method can be ideally used for consolidation of the clay slurry as stated by Chu et al, 2008. Rujikiatkamjorn and Indraratna, (2007) noted that the rate of radial consolidation in PVD-improved soil is controlled by four factors; intact radial hydraulic transport properties of the soil, PVD size and spacing, drain hydraulic resistance (well resistance), and disturbed zone size and its transport properties. As discharge capacities of most PVDs available in the market are relatively high, the well resistance effect can be ignored in most practical cases.

In 2011, Saowapakpiboon et al stated that the vacuum preloading method can reduce the large quantity of surcharge fill material and its associated instability problem. Many researchers stated that the simulation of vacuum consolidation of soft soil using triaxial test is the most effective method to determine the increasing rate of strength of the ground corresponding to loading rate during consolidation process, due to restriction using field test during construction process, the cause of damage of airtight sheet membrane and losing of vacuum pressure. Deng et al., (2013) mentioned that both of laboratory tests and field investigations show that the discharge capacity decreases with time due to PVDs deformation and blocking. In this paper, a series of large scale consolidometer tests were performed to study the effect of vacuum and surcharge loading and the results were presented in details.

EXPERIMWNTAL WORK

Test Setup

The large-scale consolidometer was used in the laboratory tests as shown Figure 1. The main body consists of a stainless steel cylindrical cell (315 mm inside diameter with 4mm wall thickness and 850 mm high) with flanges in both sides that allow them to be bolted together. The cylinder stands on a aluminum base. The inside surface is very smooth. In order to reduce the friction effect along the boundary of the stainless steel cylindrical cell, grease was used. The upper and lower plates were made of aluminum with a 40 thick were connected by four steel rods of 16 mm diameter. Four guides were installed on the upper plate to guide the piston. They were arranged on a circle with diameter 250 mm. “O” rings were used to seal the upper and lower plates and the piston to the cylindrical cell. The surcharge loading system with a maximum capacity of 8 bar was applied by an air jack compressor system through the upper plate to the top of the piston. The vacuum loading system with a maximum capacity of 100 kPa was applied through a hole in the centre of rigid piston. The instrumentation, including a linear variable settlement measurement and miniature pore pressure transducers, were installed to monitor the consolidation behavior. The cell could also be equipped with a specially designed mandrel which enabled the prefabricated vertical drains to be inserted vertically along the central axis of the cell.

Material Properties

The used soil in the laboratory tests is commercially known as bentonite as shown in Figure 2a. The amount of soil required for each test was about 0.51m^3. the bentonite are summarized in Table 1. Filter jacket and drain core of used PVDs are shown in Figure 2b. The length of PVDs which used in the laboratory tests was equal to 650 mm. The prefabricated vertical drains (PVDs) used in this study were supplied by CeTeau, Drain number CT-D811.Table 2 summarizes the PVDs parameters used in laboratory test and the shape of the mandrel was used to enable the PVDs to penetrate the soil to required depth.

Excess Pore Pressure Transducer

Three excess pore pressure transducers with display were connected to monitor the pore pressure with range from -1 to +6 bar in the test soil during consolidation process. Pore pressure transducers probes inserted into the soil through the wall of the consolidometer cell at depths 100 mm, 300 mm, 500 mm from the top surface of the soil as shown Figure 3. The excess pore pressures were monitored and recorded throughout the test.

Test Procedure

This study was conducted on remolded soil, which was made by adding a sufficient amount of water until its water content reached about 1.20 times of its liquid limit. The soil was mixed in a mechanical mixer and transferred into a container, till reach the amount of soil required to fill the cylindrical cell. Then, the soil was transferred in layers to cell. For each layer, the air bubbles were eliminated by using a mechanical vibrator. The initial void ratio is controlled by defining the water content of mixed clay in each test. The drainage was allowed to flow in one way. Throughout the whole test, the settlement was monitored by the settlement gauge. Table 3 summarizes experimental testing program.

NUMERICAL MODELLING

The Finite Elements Method FEM is an effective numerical technique because of its numerous applied fields such as groundwater flow, multiphase flow, and mass flow through pours medium. It is flexible in simulation and introduce accurate. In the present study, Geo-Studio 2004 software is used. The analysis performed in two sequent steps; first one is the seepage analysis which use SEEP/W module, which computes the water levels, and piezometeric heads. Second one is the consolidation analysis which use SIGMA/W module. The bottom and outer boundaries were set as impermeable as shown in Figure 6.4. The vertical loading pressure (surcharge) was applied at the top of the cell. The horizontal displacement boundary was fixed (i.e. no movement in the horizontal direction), while vertical displacement was permitted. The coefficient of vertical permeability determine from odometer test which varies with vertical effective stress.

SEEP/W program use the finite element method to solve the problem. Which is employed to simulate the unit cell of a prefabricated vertical drain, where an elastic analysis was conducted with y= 0 to simulate the condition of zero lateral displacement. Where water flow is radial to the PVD, which it can be represent in form axisymmetric. The domain was divided to two main region. First region is smeared zone and second region is undisturbed zone. The element used in analysis is mesh pattern structured Quadrilaeral. The problem domain is 650 mm in height and 162.5 mm in width.

SIGMA/W uses result from SEEP/W to solve for consolidation analysis over the domain. The consolidation analysis, based on Biot’s solution is used in SIGMA/W. The top, bottom and outer boundaries were set as impermeable. The horizontal displacement boundary was fixed which mean there is no movement in the horizontal direction, while vertical displacement was permitted.

The coefficient of vertical hydraulic conductivity assumed to be equals to the coefficient of horizontal hydraulic conductivity for undisturbed zone with average values $k_v= k_c= 1.08\times10^{-8}$ m/sec. p is defined as the ratio between horizontal hydraulic conductivity for undisturbed zone (k_c) to horizontal hydraulic conductivity for disturbed zone (k_s). c_h is known as coefficient of redial consolidation. Mean while c_h and p are the more effective parameters in consolidation settlement simulation.

RESULTS AND ANALYSIS

Consolidation Settlement

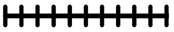
Figures 5 to 8 show a comparison of average consolidation settlement between numerical predictions for the axisymmetric condition and experimental testes. It can be seen that at the early stage of the curve there is approximate identical values of in consolidation settlement with different vacuum pressure. While the final consolidation settlements of the soil improved with PVDs and subjected to vacuum pressure associated with surcharge are increased with vacuum increase. The first part of the consolidation settlement curves is linear then the last part from the curves changes gradually. The settlement rate of the test soil was increased with vacuum pressure increase as shown in Figures 5 to 8. The magnitudes of final consolidation settlement for tested soil which subjected to same vacuum pressure and different surcharge loading were approximately the same values. The final consolidation settlement magnitudes increase with vacuum increase.

It can be clearly drawn from Figures 5 through 8 that there is a very small deviation between numerical and experimental results. Where the first part of consolidation curves, the numerical results are over estimated. In the last part of the consolidation curves, the numerical results are underestimated. The rate of consolidation settlement increase with vacuum increase and rate of consolidation settlement increase with increase of ratio between vacuum pressure to surcharge.

Table 1. Soil properties.

Clay Content (%)	*50-60*
Silt Content (%)	*40-50*
Sand Content (%)	*0.2*
Water Content, w (%)	*10*
Liquid Limit, LL (%)	*450*
Plastic Limit, PL (%)	*30*
Unit weight (kN/m3)	*18.80*
Specific Gravity, Gs	*2.60*

Table 2. Summary of PVDs and mandrel parameters.

	PVDs parameters	
Drain Core	*Configuration*	
	Material	*PP/PE*
	No. of Channels	*28*
	Colour	*Transparant-white*
Filter Jacket	*Material*	*PET*
	Colour	*Gray*
	Permeability (m/s)	*>5e10-4*
	Discharge capacity (m3/y)	*100*
Composite	*Weight (g/m)*	*70*
	Width (mm)	*100*
	Thickness (mm)	*3.50*
Mandrel parameters		
	Width(mm)	*120*
	Thickness(mm)	*8.0*
	Equivalent Diameter(mm)	*34.96*

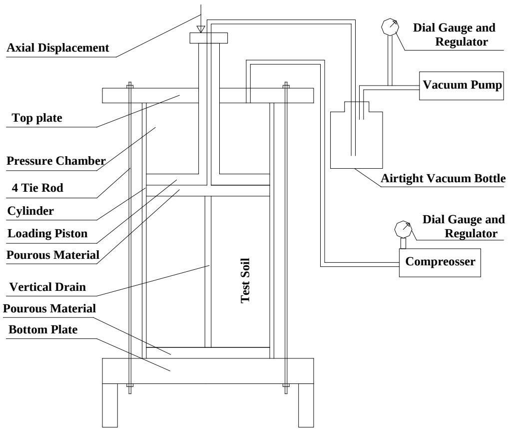


Figure 1. Sketch of the large scale consolidometer with vacuum preloading system.

a b

Figure 2. Materials used in laboratory tests (a) the bentonite and (b) the prefabricated vertical drains.

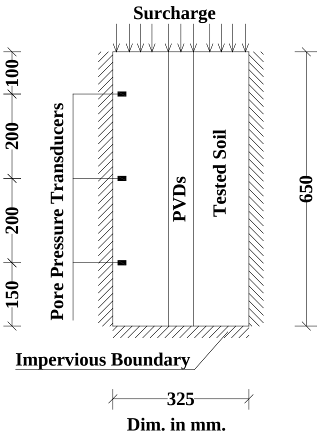


Figure 3. Schematic section of the large-scale consolidometer, showing the central drain, and typical locations of pore pressure transducers.

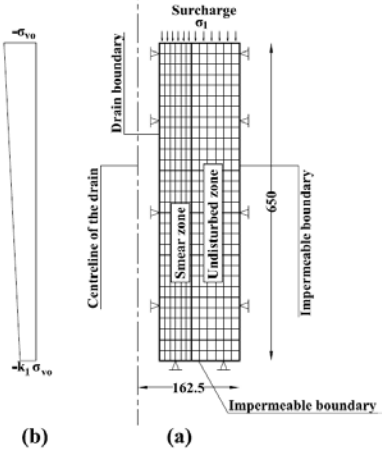


Figure 4. Model dimension and boundary conditions (a) mesh discretization. (b) vacuum pressure distribution a long vertical drain..

Table 3 Experimental test program

Case No.	*Tested soil depth (mm)*	*Air pressure (kPa)*	*Vacuum pressure (kPa)*
1	*650*	*20*	*20*
2		*20*	*30*
3		*30*	*20*
4		*30*	*30*

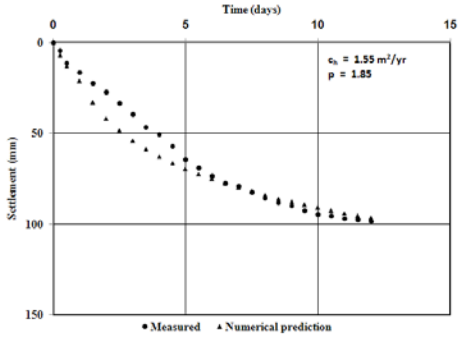


Figure 5. Comparison between the measured and predicted consolidation settlement for Test 1.

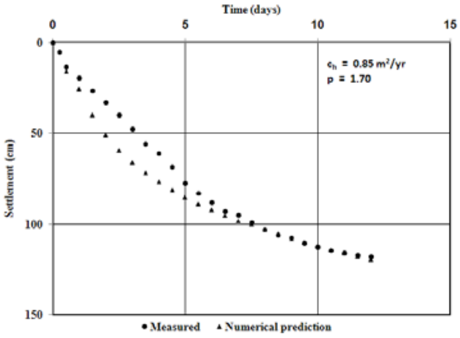


Figure 6. Comparison between the measured and predicted consolidation settlement for Test 2

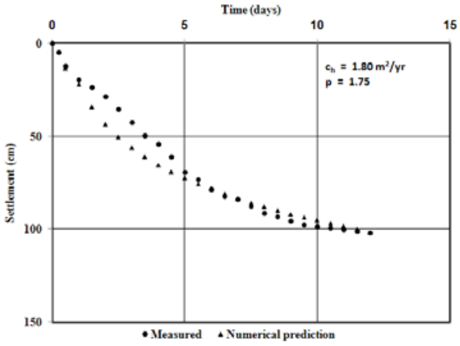


Figure 7. Comparison between the measured and predicted consolidation settlement for Test 3.

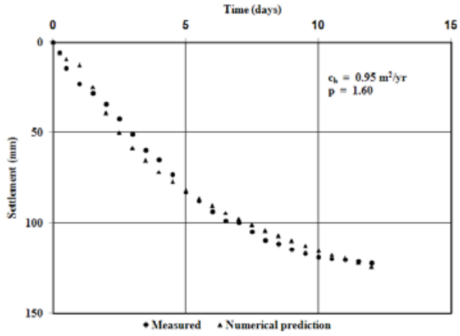


Figure 8. Comparison between the measured and predicted consolidation settlement for Test 4

CONCLUSIONS

The results clearly indicate that the system of prefabricated vertical drains (PVDs) combined with surcharge and vacuum preloading is an effective method for accelerating soft clay consolidation. The obtained results clarified that;

(1) The final consolidation settlement values increase with vacuum increase.

(2) The vacuum pressure is more significant than surcharge in decreasing water content and increasing the magnitude of final consolidation settlement.

(3) These comparisons confirmed the accuracy of the numerical simulation using GeoStudio 2004.

(4) The back-calculated c_h values for case studies improved with Vacuum-PVD were about 0.80 to 1.80 m^2/yr.

(5) The back-calculated p values for case studies improved with Vacuum-PVD were about 1.50 to 2.0.

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