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Load bearing capacity of soil as a homogeneous finite half-space

PhD Thesis

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LIST OF SYMBOLS, ABBREVIATIONS

Symbols

B and c	Constants
D	Diameter of the loading area
h	Height of the compacted zone
H	Soil depth or soil thickness
H/R or H/D	Relative depth
k	Load carrying capacity factor
k_{app}	Apparent sinkage modulus
$p/\Delta\gamma \cdot D$	Pressure number
p	Applied pressure
z	Sinkage of a flat plate
z/D	Relative sinkage
n	An exponent of deformation

Greek symbols

ρ	Soil density
Π	Dimensionless number
γ	Unit weight of the soil
ε	Strain

1. INTRODUCTION, OBJECTIVES

1.1. Introduction

Bearing properties in the normal direction form the mechanical properties that soil is often split into. Pressure-sinkage relationship equations identified as being representative of bearing. To this day, the characterisation of the load bearing capacity of soil, otherwise known as the pressure-sinkage relationship is incomplete. The manner in which the load bearing capacity, which reflects the soil density and thickness of the finite half-space, is impacted by the loading surface diameter provokes a lack of certainty in this area. The generalisation of experimental findings regarding load bearing capacity of soils is a significant challenge due to the altering hardness of soil in the finite thickness and the behaviour of the finite half-space.

Analysing the load bearing capacity of soil functioning as a homogenous finite half-space is a research objective of this work. Additionally, an examination of the parameters of pressure sinkage relationships in distinct scenarios will take place alongside an investigation of the incessantly growing deformation zone throughout the sinkage of the loading plate, the cone-shaped compact zone beneath the loading surface, and the compaction of the soil. Lastly, the manner in which load bearing capacity is impacted by soil depth, loading surface diameter, and soil density will be explored.

1.2. Objectives

A meticulous examination of the effects of deformation from loading upon soil and the issues that finite half-space soil confronts with regard to load bearing capacity form the principal objectives of this work. Through the adoption and implementation of distinct soil thickness levels on sandy loam soil, multiple densities and plate diameters. The mentioned aims are further described below:

- Investigate the compact zone under loading surface and defining the transition zone.
- Developing an equation of the load bearing capacity factor k, for expressing the deformation of soil after the interaction zone .
- Generalizing the pressure sinkage equation by taking account the effect of soil density, loading surface diameter and soil thickness .
- Examine the pressure and load bearing capacity of shallow homogenous upper layer.

2. MATERIALS AND METHODS

In this chapter, I present the procedures and experimental methods used to achieve my research goals.

2.1. Bevameter

A bevameter instrument (Fig. 1) used to simulate the finite thickness of soil. The overall dimensions of the apparatus are 200 cm in length, 100 cm in width, and 120 cm in height. The experimental device includes: mechanical structure which contains fixed as well as movable parts. Furthermore, soil bin, instrument box (hydraulic parts and the electric switch), and sinkage plates. In addition, it includs hydraulic system, measuring unit data (S-beam load cell and analogue displacement encoder) and collecting unit (strain gauges (Spider 8)).

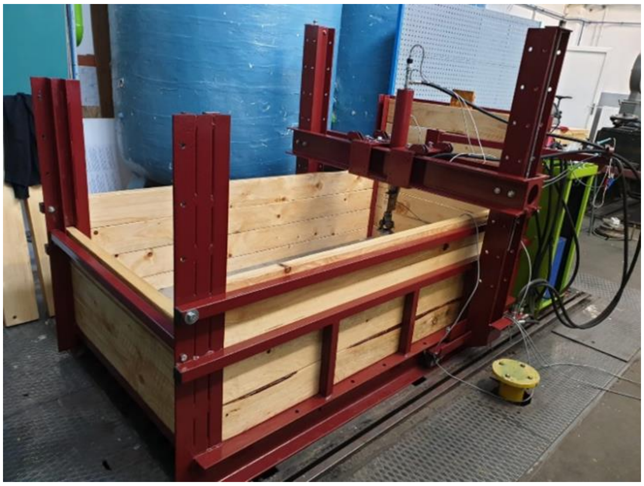

Fig. 1. Bevameter instrument

2.2. Soil preparation

Soil about 1000 kg was collected from a fields and transferred to the laboratory. Afterthat, the soil was sieved utilizing a 5 mm mesh to eliminate the coarse parts and plant roots. The soil stored in place where the soil does not dry. The soil was classified as a sandy loam soil with a composition analysis of clay (<0.002 mm), sand (2–0.05 mm) and silt (0.05–0.002 mm).

2.3. Experimental procedure

The tests were conducted under controlled condition inside laboratory. Different soil thicknesses and bulk densities used in the tests. With each thickness and bulk density, the soil bin was filled with soil up to specific thickness in layers, each layer of 5 cm. For getting different bulk densities, different way to compress the soil was employed. For example, with soil density 1.2 g/cm^3 the soil bin filled up with the soil without any compressing, while for soil density 1.3 g/cm^3 the soil compressed by using light metal plate. Moreover, with soil density 1.4 g/cm^3, the soil compressed with using wood plate. With higher bulk density like 1.5 g/cm^3

or more, the soil compressed by using wood plate with additional weight on the plate. The soil surface was levelled precisely to limit the stress concentration on conglomerated points at the soil surface below the loading plate. Three different circular sinkage plates of 10, 15 and 20 cm diameter was used for the purpose of applying load. The sinkage plate attached to the force sensor and brought close to the soil surface by running the bevameter. The S-beam load cell and analogue displacement encoder were employed to measure the vertical force and displacement, respectively. The experiments of the current work were performed at a 3 cm/s penetration rate of the sinkage plate. The force and displacement sensors were transferring the signals to Spider 8. After that, the Spider sent the measured data to a computer where the Catman software was utilized for evaluating and forming the force-time and displacement-time graphs. The displacement and force data received from the computer were used to represent the relation of pressure-sinkage curves.

2.4. Determining moisture content and bulk density of the soil

The moisture content and the bulk density determined by the sampling method (core sampler) where several soil samples were taken during and after the tests. These samples were dried in the oven at 110°C for 24 hours. The samples were weighed by using scale before and after drying to define the bulk density and moisture content.

2.5. Confined compression test

The confined compression test was performed in small soil bin Fig. 2 a. The load applied on the soil surface by performing the big sinkage plate of bevameter as shown in Fig. 2 b.

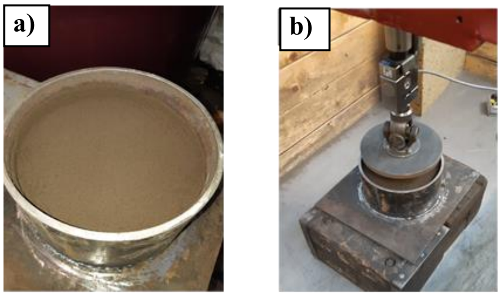

Fig. 2. Small soil bin: a) Filled with soil and b) During the test

3. RESULTS

This chapter presents the results that were achieved and discusses them in regard to the scientific findings established.

3.1. Deformation under pressure plate as a function of depth/ diameter ratio

This study presents the deformation zones of plate sinkage test by considering the active zone under loading surface in addition specified the interaction zone between them which mentioned as transition zone (breaking points) as shown in Fig. 4. The breaking point as critical relative sinkage (z_o/D) can be determined according to the following equation,

$$\frac{z_o}{D} = \frac{H}{D} - 1. \tag{1}$$

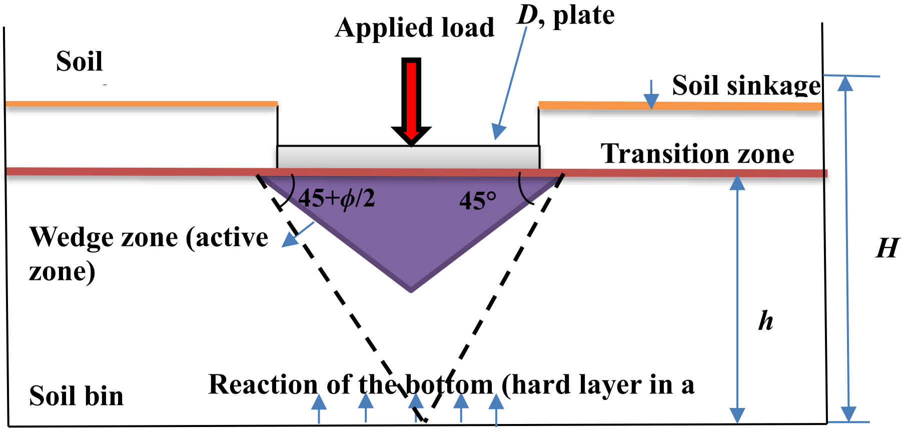

Fig. 4. Schematic of the plate sinkage test

3.2. Similarity numbers

The load bearing factor k, for given soil, depends on the soil density (ρ) or specific weight (γ) and plate diameter (D). By considering these quantities k, $\Delta\gamma$ and D, a dimensionless number (Π) can be drawn as shown in the below equation,

$$\Pi = \frac{k}{\Delta\gamma \cdot D}. \tag{2}$$

An approximate similarity can be characterized by two similarity numbers (Π) and (H/D), these numbers multiplied with each other as shown in Eq.3 this equation is restricted for plate diameter of 20 cm and relative depth $1 < H/D < 2$

$$\frac{k \cdot H}{\Delta\gamma \cdot D^2} = 1150\ . \tag{3}$$

By employing the load bearing number of Eq. 3 in conventional pressure-sinkage equation Eq. 4 which represents the generalized pressure-sinkage equation in dimensionless form considering the effect of soil density and the finite depth can be derived,

$$\frac{p}{\Delta\gamma \cdot D} = 1150\,\frac{D}{H}\left(\frac{z}{D}\right)^{n} \quad . \tag{4}$$

The constant 1150 is valid only for the used soil but the form of Eq. 4 is generally valid. The *H*/*D* ratio is varied between 1 and 2 which is mostly the case in the practice.

we do not examine here the effect of exponent *n* and, therefore, if a measured plate-sinkage curve shows some deviation from n=0.8 then it is purposeful to make a correction based on the equality of measured pressure and relative sinkage in the following form:

$$p = k_x\left(\frac{z}{D}\right)^{n_x} = k\left(\frac{z}{D}\right)^{0.8}, \tag{5}$$

from which we get

$$k = k_x\left(\frac{z}{D}\right)^{n_x - 0.8} . \tag{6}$$

Obviously, if n_x=0.8 then k_x=k. for correction we use a measured point near to the breaking point.

3.3. Interaction of the compact zone with the effect of a rigid layer

The experimental results (Fig. 5) of plate sinkage test showing the deformation zones in the soil which are build up (befor breaking), compact (after breaking) and ransition zones. The transition zone called the breaking point and mentioned as critical relative sinkage (z_o/D).

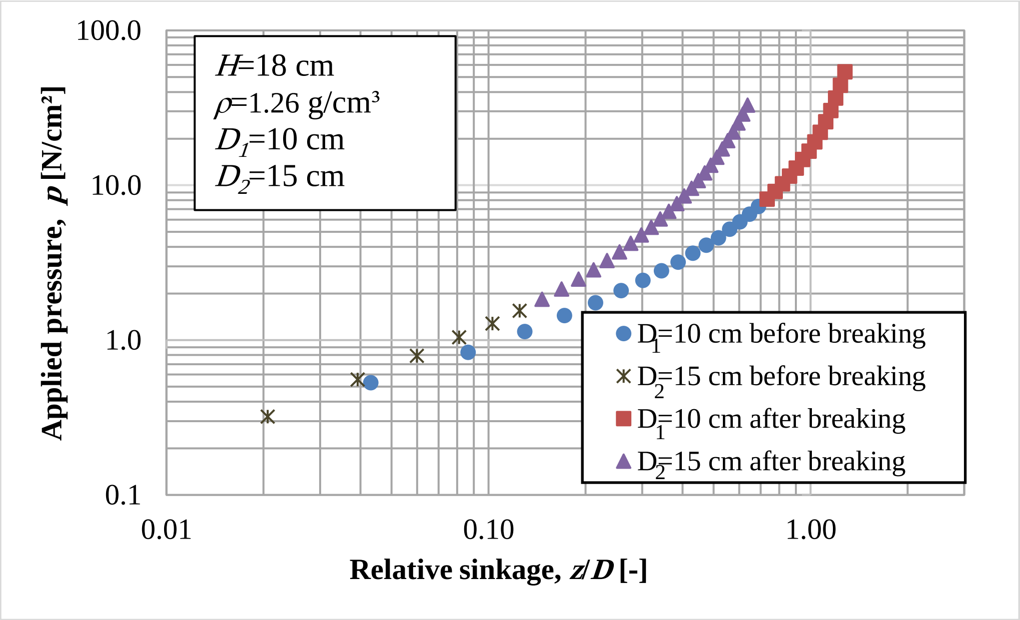

Fig. 5. Pressure-sinkage curves of soil thickness of 18 cm at density of 1.26 g/cm^3

3.4. New pressure–sinkage relationship equation

The experimental results show that a new pressure–sinkage model is possible by presenting a new sinkage modulus consisting of the affection of the soil's hard layer but retaining common plate-sinkage eqation:

$$p = k_{app}\left(\frac{z}{D}\right)^n, \tag{5}$$

$$k_{app} = k + B\left(e^{c\left(\frac{z}{D}-\frac{z_0}{D}\right)} - 1\right). \tag{6}$$

1. For the first part of pressure sinkage curves before breaking points where $z/D < z_o/D$, the apparent sinkage modulus equals the common modulus:

$$k_{app} = k\ . \tag{7}$$

2. For the second part of pressure sinkage curves after breaking points where $z/D > z_o/D$, the apparent sinkage is as seen in Eq. 6.

The processing of pressure-sinkage curves and k_{app} curves shown in Fig. 6.

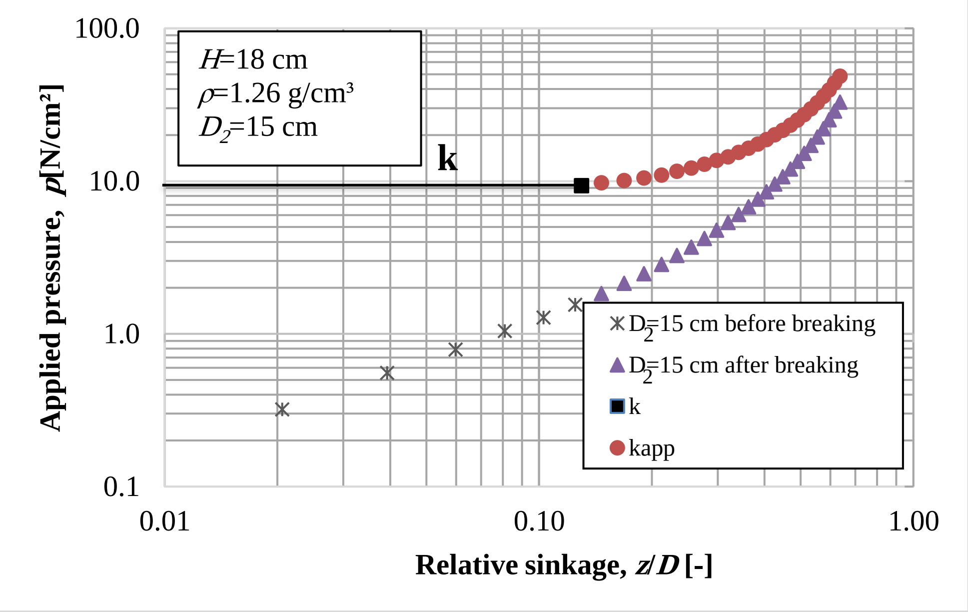

Fig. 6. Pressure-sinkage curves with k_{app} curves

3.5. Effect of finite depth on the load bearing capacity factor

Processing of experimental results for proving the validity of the suggested *k*=*f*(*ρ*, *H*/*D*) relationship is given in Fig. 7.

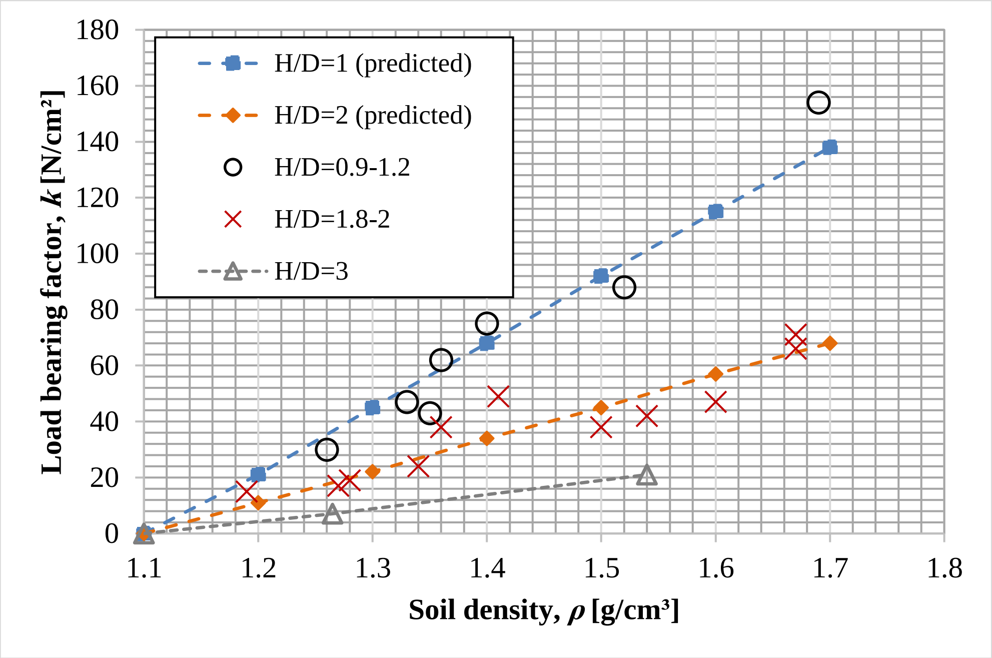

Fig. 7. Experimental and predicted load bearing capacity factor as a function of soil density for different *H*/*D* ratio

The proof of the dimensionless load bearing number is demonstrated in Fig. 8

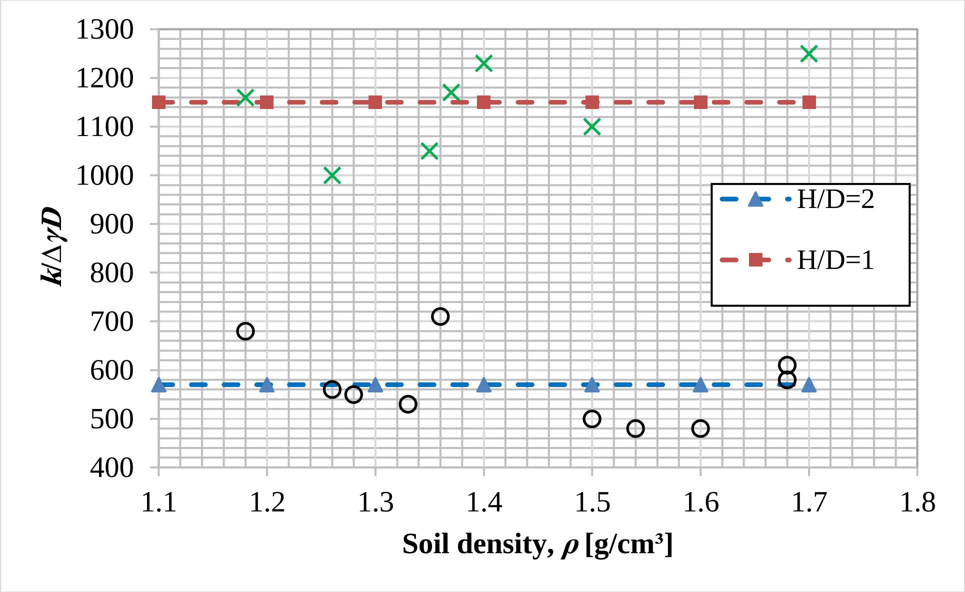

Fig. 8. Load bearing capacity number as a function of soil density for two *H*/*D* ratios

The *H*/*D*=1 line contains measurement data for *H*/*D*=0.9 and 1.2, while the second line for *H*/*D*=1.8 and 2.0. Again, despite of a given scattering, the dimensionless number seems to be constant for a wide range of soil densities.

3.6. Generalized pressure-sinkage equation

Based on the dimensionless load bearing number, a new pressure number, also in dimensionless form, has been derived. The proof of this pressure number is given in Fig. 9 using experimental data for two *H*/*D* ranges as a function of relative sinkage. The experimentally determined point are well grouped along the previously suggested lines for different *H*/*D* ratios. This finding indicates the validity of expected general regularity for the homogenous finite half-space. Important, that the relative soil thickness is a new and distinct variable influencing soil deformation which should be taken into account.

3.7. Behaviour of soil in shallow layer

In shallow homogenous upper layer, $H/D \leq 0.5$ the soil under loading surface behaves like closed space compaction. For compression, the compaction of closed space (confined test) and plate sinkage test in soil bin is shown in Fig. 10. Despite the stress-strain curves of the bevameter and confined tests are slightly diverged, but the soil behaviour seems similar. Moreover, there is no cone shape compact zone under the plate with the bevameter test, as the pressure and the load-bearing capacity modulus are increasing steeply. The calculated compaction equations are:

under the plate unconfined compaction

$$p = 36.5 \left(\frac{\varepsilon}{1-\varepsilon}\right)^{2.1}, \tag{8}$$

for closed space compaction

$$p = 34.5 \left(\frac{\varepsilon}{1-\varepsilon}\right)^{2.2}. \tag{9}$$

For higher compaction the exponents slightly increase.

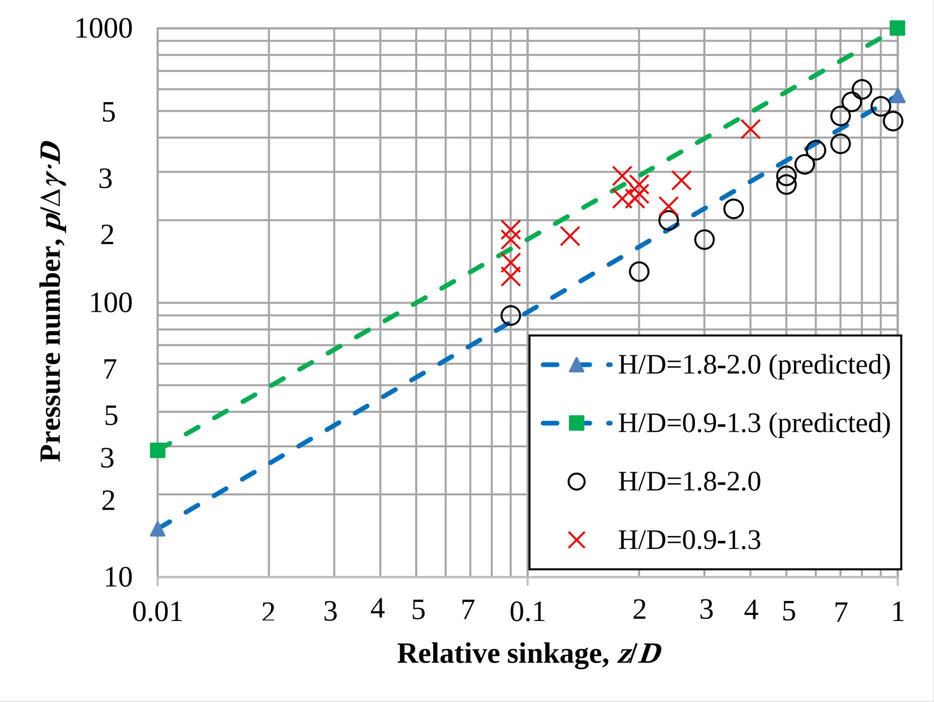

Fig. 9. Plot of pressure number as a function of relative sinkage for different soil thickness ratios *H*/*D*

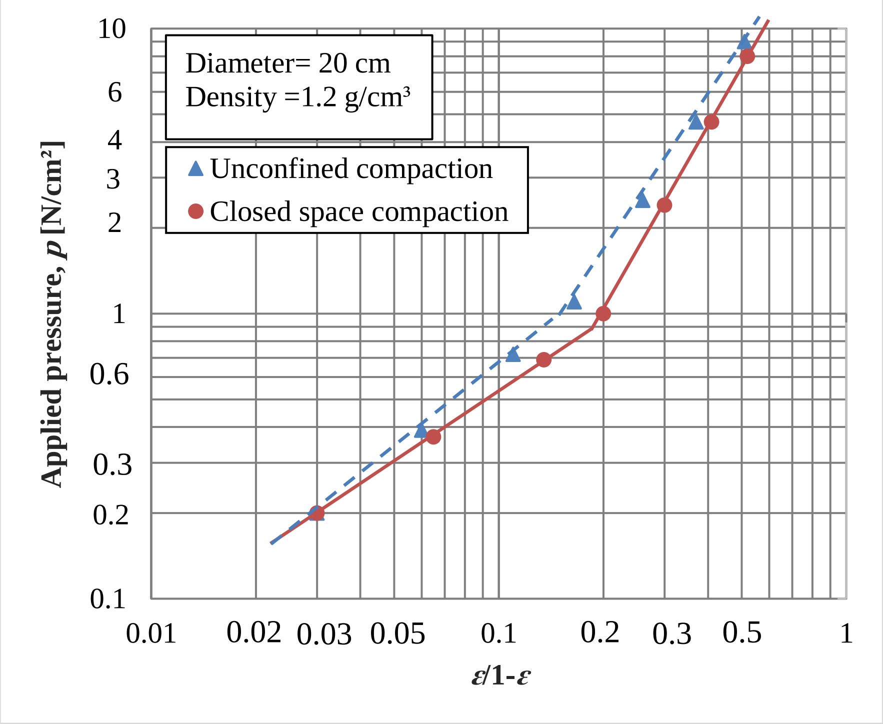

Fig. 10. Comparison of unconfined compaction in shallow layer and in closed space

4. NEW SCIENTIFIC RESULTS

This section presents the new scientific findings from the research as follows:

1. Transition zone of infinite to finite thickness

There are typically two deformation zones under loading, the build-up zone (infinite thickness) that has an increasing resistance and the compact zone (finite thickness). In addition, there is transition zone between them which reflect the effect of the rigid layer on the compaction. I introduced a relation to specify the transition zone by considering the relative sinkage (*z*/*D*) and relative depth (*H*/*D*). This interaction mentioned as breaking points (z_o/D),

$$\frac{z_o}{D} - \frac{H}{D} = 1,$$

where the constant slightly depends on the internal friction angle of soil.

2. Interaction zone with rigid layer

A resting compact zone of cone shape develops under the loading surface (plate or tyre) which, nearing the rigid layer, counter acts with the rigid layer increasing the vertical pressure and load bearing factor (*k*) in an exponential mode. Due to this interaction, I introduced an apparent load bearing factor (k_{app}) consisting of two parts: one (*k*) is the common and constant load bearing capacity factor valid under the critical depth z_o/D, and the second one is $B\left(e^{c\left(\frac{z}{D}-\frac{z_o}{D}\right)}-1\right)$ which increases with the deformation due to the interaction of compact zone with the rigid layer.

$$p = k_{app}\left(\frac{z}{D}\right)^n,$$

$$k_{app} = k + B\left(e^{c\left(\frac{z}{D}-\frac{z_o}{D}\right)}-1\right).$$

3. Generalizing the pressure-sinkage equation

A change in soil depth (*H*) modifies the strain ($\varepsilon = z/H$) as well as the compaction for the same deformation (*z*). I derived two dimensionless numbers by employing an approximate similarity. These dimensionless numbers are ($\frac{k}{\Delta\gamma \cdot D}$) which represents the infinite thickness and (*H*/*D*) which represents the finite thickness. Also, I derived and determined a dimensionless load bearing number by multiplying the dimensionless numbers aforementioned to combine the effect of the infinite and finite half-space which is invariant for a given soil.

$$\frac{k \cdot H}{\Delta\gamma \cdot D^2} = 1150.$$

Using this dimensionless number, I introduced the generalized pressure-sinkage equation taking into account the effect of soil density, loading surface diameter, and the soil depth *H*.

$$\frac{p}{\Delta\gamma \cdot D} = 1150 \frac{D}{H} \left(\frac{z}{D}\right)^{n}.$$

4. Shallow homogenous layer

Through the experimental results, I have proven in the case of shallow homogenous upper layer where $H/D \leq 0.5$, after a short pre-compaction, the pressure and load bearing are steeply increasing almost similarly to a closed space compaction process. In the whole space the pressure is almost the same without definite cone shaped zone.

5. CONCLUSIONS AND SUGGESTIONS

In conclusion, theoretical and experimental analysis has been conducted to study the load bearing capacity of sandy loam soil as a homogenous finite half space. The load bearing capacity represented by the pressure-sinkage relationship. The bevameter apparatus has been designed and constructed to examine the load bearing capacity and soil properties via applied normal load on soil surface. The experiments were conducted using three different diameters of circular sinkage plates with different soil thicknesses and different soil densities. The pressure–sinkage curves showed there are two deformation zones, the first one is the build-up zone where the load bearing capacity factor (k) is constant, the conventional pressure sinkage relationship can be applied for determining the soil properties k and n, the soil under the plate behaves similarly to when it is in the infinite thickness. The other zone is the interaction zone with the rigid layer where the soil behaves more exponentially and the load bearing capacity is varied. A relationship proposed to define the transition zone between the deformation zones which represented by breaking point as critical relative sinkage (z_o/D). Here, the compaction, as well as the deformation, increases rapidly. The conventional pressure sinkage relationship modified by suggesting new load bearing capacity factor (k_{app}) to convey this part. The values of k_{app} and the applied pressure are converging. Therefore, as the pressure increased, the sinkage modulus kapp also increased, which means the load-bearing capacity of soil increasing as well. The effect of finite depth (H) on the load bearing capacity factor (k) have been studied, the results showed that the load bearing capacity factor dependent on soil density where it increased with increasing the soil density. By using similarity number, a dimensionless number (Π) proposed to cover the relation of soils and finite half space. The new generalized pressure sinkage relationship suggested by employing the dimensionless number in the conventional pressure sinkage relationship. The new relation represents the generalized pressure-sinkage equation in dimensionless form considering the effect of soil density and the finite depth. The behaviour of shallow homogenous upper layer, $H/D \leq 0.5$, discussed and the result showed the soil under loading surface behaves like closed space compaction. The side motion of soil is prevented and in the most space under the plate the vertical motion take over. Therefore, the cone shaped compact zone cannot be developed in its classical form and there is no constant load bearing capacity factor k only the varying part exits.

As a recommendation, further experimental work should be conducted with inhomogeneous soil in the laboratory then in the field to validate the proposed new relations of load bearing capacity factor and the generalized pressure-sinkage relationship. Moreover, further work on other soil type should be carried out.

6. SUMMARY

LOAD BEARING CAPACITY OF SOIL AS A HOMOGENEOUS FINITE HALF-SPACE

The first section of this study dealt with the comprehensive analysis of load bearing capacity determination and lighted the gap in knowledge in the effect of the loading surface diameter on the load bearing capacity as a function of thickness of the finite half space. the next chapter describe the materials and processes used in the research for the experimental measurements, like designing and constructing a bevameter (plate sinkage test) for testing the soil behaviour under loading using wide ranging of soil properties and soil thickness. Thereafter, a theoretical part which includes prediction of soil sinkage and soil behaviours in the finite half space by employing some results from literature and some theories like Yegorov theory. Consequently, theoretical equations have been suggested for homogeneous finite half space to cover the soil behaviour of finite half space. The mechanical properties of the soil which are shown in the results section have been determined by employing the direct shear test. The results of the plate sinkage test can be classified into:

1. The deformation zones and the interaction of the compact zone with the action of a rigid layer have been explained by employing different sinkage plate diameter, various soil thickness and divers soil densities.
2. A new sinkage modulus(k_{app}) concerning the affection of the soil's hard layer have been proposed according to the experimental results,
3. The experimental results of load bearing capacity factor (k) with the soil density (ρ) showed that there is acceptable accuracy between the theoretical and experimental estimate.
4. Generalizing the pressure-sinkage equation have been discussed by comparing the experimental results of pressure number ($p/\Delta\gamma \cdot D$) and the relative sinkage (z/D) with the proposed model. The results show that there is reasonable converging between the theoretical and experimental estimate.
5. Regarding the shallow homogenous upper layer where $H/D \leq 0.5$, the results showed that the soil under loading surface behaves like closed space compaction. The side motion of soil is prevented and in the most space under the plate the vertical motion take over.

As a recommendation, more experimental work should be conducted with inhomogeneous soil in the laboratory then in the field to validate the proposed new relations of load bearing capacity factor and the generalized pressure-sinkage relationship. Moreover, further work on other soil type should be carried out.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Salman N. D.**, Pillinger G., Hanon M., Kiss P. (2020): Design and performance evaluation of bevameter equipment, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol. 14, No. 6, pp. JAMDSM0084-JAMDSM0084, doi: 10.1299/jamdsm.2020jamdsm0084, ISSN 1881-3054 (IF: 0.609*).
2. **Salman N. D.**, Pillinger G., Kiss P. (2021): Soil behaviour under load in case of finite thickness, International Review of Applied Sciences and Engineering,Vol. 12, No. 1, pp. 29-33, doi: 10.1556/1848.2020.00091, ISSN 2062-0810.
3. **Salman N. D.**, Kiss P. (2021): Application of two techniques used for measuring the soil strength: A review, Hungarian Agricultural Engineering, No. 39, pp. 29-41, doi: 10.17676/HAE.2021.39.29, ISSN 2415-9751.
4. **Salman N. D.**, Pillinger G., Kiss P. (2021): Soil behavior of shallow homogenous upper layer soil, Journal of Applied Science and Engineering (JASE), Vol. 25, No. 1, pp. 159 -164,

   doi: 10.6180/jase.202202_25(1).0016, ISSN 2708-9975.
5. **Salman N. D.**, Pillinger G., Hanon M., Kiss P. (2021): A modified pressure-sinkage model for studying the effect of a hard layer in sandy loam soil, Applied Sciences, MDPI, Vol. 11, No. 12, pp. 5499, doi:10.3390/app11125499, ISSN 2076-3417 (IF: 2.679*).
6. Keppler I., Bablena A., **Salman N. D.**, Kiss P. (2021): Discrete element model calibration based on in situ measurements, Engineering Computations, Emerald, Vol. ahead-of-print No. ahead-of-print. doi.org/10.1108/EC-05-2021-0288 (IF: 1.593*).