Design and performance evaluation of bevameter equipment

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Abstract
The depth of tilting in agricultural soil is 30–40 cm, which approximates the equivalent contact diameter of tires for the off-road vehicle. The soil thus tends to have an upper loose layer and a hard layer underneath, which leads to changes in the soil behavior. The effect of the hard layer can be defined by determining a specific point (breaking point) in the pressure (p)-sinkage (z) curve. The present study aims to design and construct a bevameter instrument can be used to simulate the hard layer in soil. Besides, specifying the breaking point and the effect of the hard layer on the soil behavior. In addition to the feature of a high applied load can be measured, the significance of this device comes from the easiness of changing the thickness of the soil which is in demand to be investigated. The device includes a mechanical structure, a hydraulic system, measuring sensors, and a data collection unit. Two sinkage plates with different diameter were employed for characterizing the relationship between the applied load (applied pressure) and the vertical deformation (sinkage). Indoor tests were also conducted to evaluate the device’s performance and study soil penetration resistance. The test was developed using sandy loam soil sieved through a 0.5 mm mesh. The soil bin was filled with soil up to 0.3 m thickness as a layer of 0.1 m. The soil density and moisture content for the soil was calculated as 1.245 g/cm³ and 12.3%, respectively. The device’s results showed that the hard layer changes the soil’s behavior as the soil becomes more compact. This layer also increased the values of sinkage exponent (n) and sinkage modulus (k) and implicitly modified the soil properties. Many experiments were carried out and discussed to validate the results.

Keywords : Plate penetration test, Pressure-sinkage relationship, Bekker model, Soil deformation, Hard layer

1. Introduction

Soil deformation is the main factor in the off-road environment that determines vehicle mobility and leads to sinking and slipping of the wheels (Jang et al., 2016; Li and Yuan, 2019). The soil’s mechanical properties (soil penetration resistance and shear stress) affect machine mobility by limiting traction (Taghavifar and Mardani, 2017). Researchers have designed and developed equipment that can measure these properties. The cone penetrometer is the primary instrument used to provide a standard uniform method of characterizing the soil’s penetration resistance (Cho et al., 2015). Moreover, Boon et al. (2005) designed, developed, and examined an automated soil penetrometer–shearometer unit to measure shear stress and soil penetration resistance in situ. This developed unit was used to create a comprehensive database concerning the energy and power demand mapping of the agricultural field operations. Lee et al. (2010) designed and constructed a digital soil cone index (CI) measuring device to measure soil strength that replaced conventional analog type devices. Garciano et al. (2012) developed a portable soil test device to measure shear, sinkage, and frictional parameter of soil in situ. A towed vehicle’s rolling losses were determined using the penetrometre by Méthé and Kiss (2015). Pillinger et al. (2018) used the cone penetrometer employing cone index (CI) to define the soil-density distribution in the soil’s deeper layers. Further, Cho et al. (2015) designed an in-situ measuring system to assess the horizontal soil strength at multiple depths in real-time while moving across a soil bin. Cho et al. (2016) evaluated real-time horizontal
Another technique to measure and characterize soil properties is the bevameter system. Of the numerous measuring techniques, this method provides the closest simulation of vehicle loading conditions (Wong, 2010). Upadhyaya et al. (1993) used the bevameter technique by establishing a portable machine that was connected to the tractor to measure the soil sinkage with three rectangular plates. Furthermore, the shear displacement with five diverse rectangular grouser plates on a loam soil type was checked. Alexandrous and Earl (1995) proposed an equipment of hydraulic bevameter that accommodates with the tractor and proved that it could distinguish the pre-compaction stress of field soils in situ with good accuracy. Further, Gotteland and Benoit (2002) created an experimental device named DECART that was powered by a hydraulic ram and could conduct penetration tests in the laboratory and in-situ with a variety of soils (silty sand, sand, and silt) and different diameters of plates. Yu (2006) constructed an equipment using the bevameter procedure to obtain the soil parameters required for the traction modeling based on analytical methods. Massah and Noorolahi (2010) designed a tractor-mounted bevameter with various sizes and shapes (circular, oval, and rectangular) of plates and examined in the field of loam soil type.

To describe the responses of the soil to different types of loading, it is important to determine the functional relationships such as the pressure–sinkage relationship and shear stress–shear displacement relationship (Wong, 2010). The simplest pressure-sinkage relationship was proposed by Bernstein-Goriatchkin, as shown in Eq. (1) (Meirion-Griffith and Spenko, 2011).

\[ p = k z^n \]  

where \( p \) is the pressure applied to the soil, \( z \) is the sinkage of soil, \( k \) is the sinkage modulus, and \( n \) is the sinkage exponent.

Bekker separated the sinkage modulus into two parts (as shown in Eq. (2)), with one representing the effect of the angle of internal shearing resistance and the other representing the effect of soil cohesion. Moreover, the geometry of the contact patch was taken into account (He et al., 2019).

\[ p = \left( \frac{k_c}{b} + k_\phi \right) z^n = k_{eq} z^n \]

where \( b \) is the smaller dimension of the contact patch (the smaller side dimension for a rectangular plate or diameter of a circular one), \( k_c \) is a sinkage modulus influenced by soil cohesion, \( k_\phi \) is a sinkage modulus affected by soil friction angle, and \( k_{eq} \) is the modulus equivalent. The values of the parameters in Eq. (2) can be obtained from the results of two tests with two different widths (diameter) plates. For determining the best fit, the measured sets of pressure and sinkage values should be analyzed graphically or analytically. From the two sets of test data, two curves represented by two equations, \( n \) was usually considered an average value (\( n_{av} \)), as shown in the equation below:

\[ n_{av} = \frac{n_{b1} + n_{b2}}{2} \]  

where \( n_{b1} \),is the value of \( n \) for the first plate width and \( n_{b2} \) is the value of \( n \) for the second plate width.

In addition, two values of \( k_{eq} \) can be derived, deriving \( (k_{eq})_{b1} \) from the data acquired using a plate with width \( b_1 \) and \( (k_{eq})_{b2} \) from the data gained using a plate with width \( b_2 \). The values of \( k_c \) and \( k_\phi \) can then be calculated through the following equations (Wong, 2010):

\[ k_c = b_1 b_2 (k_{eqb1} - k_{eqb2})/(b_2 - b_1) \]

\[ k_\phi = k_{eqb1} - \frac{(k_{eqb1} - k_{eqb2}) b_2}{b_2 - b_1} \]

Agricultural soil is cultivated to a depth of 30–40 cm. Hence, there is an upper loose layer and hard layers underneath. Thus, the pressure distribution estimation in this case differs from one with no hard layer (Sitkei et al., 2019). It is difficult to study the behavior of the soil with a hard layer (finite thickness) in terms of estimating the soil’s load-bearing capacity and extrapolating the experimental results.

It is evident from the literature that there is no real standardization of devices, and thus, most researchers design and built their own bevameter according to their specific requirements. The present study describes the design and construction of a laboratory bevameter device used to evaluate the load-bearing capacity of soil in case of finite thickness.
As mentioned above, the finite thickness indicates that there is a hard layer in the soil body. Hence, the effect of the hard layer can be defined by determining a specific point (breaking point) in the pressure ($p$)-sinkage ($z$) plot. Two different diameters of circle plates sinkage were used to achieve these requirements and determine the soil pressure-sinkage parameters exhibited in Eq. (2). Statistical analysis and graphs produced from the collected data showed that the curves had two parts, with the first one being the behavior of the soil from the surface to the breaking point and the second being after the breaking point which shows the effect of the hard layer. In addition, the hard layer significantly impacted the soil parameters which are $k_{eq}$ and $n$.

2. Bevameter parts design

2.1 Mechanical structure

The overall dimensions of the apparatus are 200 cm in length, 100 cm in width, and 120 cm in height. The experimental device includes fixed as well as movable parts. The fixed part (shown in Fig. 1a) is the frame that contains the soil bin and is formed of two longitudinal rails, steel bars supporting the base of the bin, four corners of angle steel with a groove that can carry the wood pieces forming at the sides of the soil bin, four fixed horizontal steel bars that can support the sides, and three fixed vertical steel bars for the length sides that can support the sides while pushing the soil. Mild steel hollow rectangle sections are used to construct sides and the supporting base while angle steel with some adjustments to make it more suited to carry the sides are used to construct the corners. The moveable parts (illustrated in Fig. 1b) form a frame established of three parts, two vertical and one horizontal (it has rail from two sides). Pairs of threaded rod M10 of 97 cm length were assembled with the vertical part of the mobile frame to provide stability for the vertical movement. The mobile frame moves longitudinally inside the fixed longitudinal rail, and this movement is guided with rollers that prevent any rotation or lateral movement. The other movable parts are steel bars linked to the corner of the fixed frame using a hexagon head bolt to add more height to the soil bin and support the wood pieces. The hydraulic cylinder, force, and displacement sensors are carried using a holder on the mobile frame’s longitudinal part. This holder can move transversely on the rails and is directed by a roller. As the mobile frame moves in two directions, any point on the entire soil surface can be tested. Supplementary parts are also used to support the tubes that carry the hydraulic fluid to the hydraulic cylinder.

Soil bin was developed with a steel sheet base of 20 mm thickness and rectangular wood plates with a 10 cm thickness placed inside the corners of the fixed part to set up the sides. Of these, three sides are changeable and one is fixed. Numerous wood plates were used to alter the bin’s height and examine different soil thicknesses. The instrument box contains the hydraulic parts and the electric switch and was with 86 cm height, 41 cm width, and 65 cm length. The box was placed behind the fixed side of the soil bin. Further, the sinkage plates were formed of a circular shape steel and three different diameters (100 mm, 150 mm, and 200 mm) and 10 mm thickness. The sinkage plates were joined using a thread into the load cell that was connected with the displacement sensors to the end of the hydraulic cylinder. These parts are all displayed in Fig. 2 from the front, side, and top views as well as the isometric view. Figure 3 depicts the device including all parts after manufacturing and assembling.
2.2 Control system

Figure 4 shows a schematic diagram of the bevameter’s control system and includes a hydraulic system, measurement sensors, and data collection unit.

2.2.1 Hydraulic system

The hydraulic unit was used to apply force on the sinkage plates and was formed of the following parts with appropriate fittings:

1. A hydraulic cylinder that was made of stainless steel to apply vertical force on the sinkage plates. It was designed and manufactured in Fatér hidraulika kft, Hungary. It is a front-flange mounted hydraulic cylinder with specifications such as double-acting hydraulic cylinder, maximum pressure of 80 bar, a max stroke of 300 mm, piston diameter of 75 mm, and piston velocity speed between 20 and 30 cm/min.

2. A pressure flow control valve (2FRM5-32/3 Q, Ponar wadowice, Poland) that is a two-way flow control valve that establishes the fluid flow constant in one direction and allows free flow in the opposite direction. That is, it controls the piston’s speed by regulating the flow rate of the hydraulic fluid that enters the hydraulic cylinder.
This valve can also adjust the sinkage plates’ penetration rate up to 3 cm/s.

3. A directional control valve (P40, Hydro-pack, Europe) that directs the fluid flow to the required line. It is manually controlled with four-ports. Three-positions type of the directional control valve was used.

4. A filter (HF502-20.122-AS-FG02, Ikron, Italy) that was used to protect the system components from the fluid’s contaminant particles.

5. A pump (C1.25x1T1B, Industrialtechnic SC, Bulgaria) was used to deliver the hydraulic liquid to the hydraulic system. Hydraulic pipes were also employed for transmitting the hydraulic fluid to the hydraulic cylinder so that the sinkage plate could apply force on the soil surface. A pressure gauge with a 25 MPa capacity was used to monitor the pressure level. All the hydraulic parts mentioned above (except the hydraulic cylinder) as well as the electric motor and the main switch were assembled in the instrument box.

2.2.2 Measuring unit

The measuring unit, as shown in Fig. 4, consists of an S-beam load cell (HBM, Germany) made of stainless steel with 30 kN capacity to measure the applied vertical load.

Analogue displacement encoder (MLO-POT-0360 -TLF, FESTO, Germany) with a 300 mm stroke was also included to measure the vertical displacement (sinkage). The slider of the displacement sensor was connected to the end of the hydraulic cylinder rod and was simultaneously moving.

2.2.3 Data collecting unit

The data collecting system, as shown in Fig. 4, includes strain gauges (Spider 8) that work with the software Catman version 5.1. The inputs to the spider 8 include the electric power and the signals from force and displacement sensors, whereas the output was connected to a laptop where the input signal of the applied force and displacement is analyzed using the Catman software. Consequently, the pressure and sinkage can be calculated from these data.

3. The transition area

The existence of a hard layer within a certain depth below the footing (circular or rectangular) can significantly impact the soil’s load-bearing capacity. A hard layer primarily modifies the pressure distribution in the soil. It is remarkable that the pressure of a firm layer (finite thickness) is 60% higher than that in infinite half-space (Sitkei et al., 2019). When the load is applied on the soil, the upper layer behaves similar to infinite thickness until the deformation of the soil reaches the breaking point or transition area. After this point, the pressure increases and the compaction raises in the soil body. Defining the breaking point is thus crucial for determining the starting point of the effect of the hard layer. Figure 5 shows the failure zone under the load that is applied from the plate. The thickness (h) of this zone defined by Eq. (6).
where $D$ is the plate diameter, and $\varphi$ is the internal friction of the soil. The sinkage at breaking point can be defined by Eq. (7).

$$z_{at\ breaking\ point} = H - h$$  

where $H$ is the thickness of the soil in the soil bin.

4. System performance and evaluation

The equipment was evaluated inside the laboratory to determine the parameters of Eq. 2 and the points that show the hard layer’s effect on the soil’s behavior. The soil was brought from the field to the laboratory and classified as a sandy loam with a texture analysis of sand (2–0.05 mm), mud (0.05–0.002 mm), and clay (<0.002 mm) (Pillinger, 2016). In the first step of soil preparation, the soil was sieved using a 5mm mesh to remove the plant roots and coarse parts. Thereafter, the soil bin was filled with soil up to 0.3 m thickness, with each layer of 100 mm. At every layer, the soil’s surface was leveled to ensure a homogenous surface. At the beginning of the test, a 0.15 m plate was mounted to the force sensor. Then, the sinkage plate was brought close to the soil surface by running the bevameter. The experiments were accomplished at a 3 cm/s penetration rate of the sinkage plate. The penetration points were implemented where the walls of the soil bin could not impact the data. The force and displacement sensors were sending the signals to the Spider 8, following which the Spider sent the measured signals to the Catman software on the laptop for assessing and generating the force-time and displacement-time graphs. The penetration continues until the bottom of the soil bin was influenced by the applied pressure that was observed by the force-time curve of Catman software. The force and displacement data collected from the computer were used to draw the pressure-sinkage curve. The same steps were implemented for the plate sinkage of 0.2 m diameter. Several soil samples were weighed to calculate the apparent bulk density. These samples were then dried in the oven at 110 C° for 24 hours to measure the moisture content. The moisture content was observed to be 12.3% and the apparent bulk density was 1.245 g/cm³.

The direct shear test applied to define the internal friction of the soil. The thickness of the failure zone (h) under the applied load defined by using the internal friction and plate diameter values in Eq. (6). The value of h used in Eq. (7) to define the sinkage (z) of the soil at breaking point. All the values of internal friction, thickness of failure zone and sinkage at breaking point are shown in Table 1. The experiments were conducted using two different sinkage plates with diameters of 0.15 m and 0.2 m to quantify the soil parameters and display the transition area (breaking point). To understand how the behavior of the soil under the applied load were affected, the pressure-sinkage curves of soil measurement were plotted on a logarithmic scale as illustrated in Fig. 6. It can be seen from the curves that pressure first increased progressively versus sinkage, as the soil under the plate was deformed. This shows that the soil behaves homogenously for the upper layer. Thus, the impact of the soil bin bottom does not exist. When the lower boundary of the soil’s deformation zone under the plate reached the breaking point ($z = 0.1476$ m for plate diameter of 0.15 m and $z = 0.0968$ for plate diameter of 0.2 m), the pressure increased rapidly with the increase of sinkage. This indicates that the bottom affects the soil’s behavior, as seen in the breaking area, and the soil becomes more compacted as the pressure instead of decreasing still increasing. The bigger plate applied more pressure than the smaller plate. Therefore, it senses the bottom of the bin sooner and the slope of the pressure sinkage curve reduces faster.

\[
h = \frac{D \tan(\varphi/2 + 45)}{2}
\]  

(6)
Table 1 Values of internal friction $\phi$ and the sinkage at breaking point.

| Soil thickness, H (m) | Plate diameter, D (m) | Internal friction, $\phi$° | h (m) | Sinkage at braking point, $z_{braking}$ (m) |
|----------------------|----------------------|---------------------------|------|------------------------------------------|
| 0.30                 | 0.15                 | 37.59°                    | 0.1524 | 0.1476                                    |
| 0.30                 | 0.20                 | 37.59°                    | 0.2032 | 0.0968                                    |

The power regression was applied to determine the values of the exponent of soil deformation ($n$) and equivalent modulus ($k_{eq}$). These values with the coefficient of determination ($R^2$) and the equations of the regression are listed in Table 2.

Table 2 shows that the hard layer represented by the bottom of the soil bin affects the values of soil properties, with the deformation exponent ($n$) increasing with the increase in the load carrying capacity factor ($k_{eq}$).

The values of $k_c$ and $k_\phi$ were calculated according to Eqs. 4 and 5, where the exponent ($n$) value is the average. These values are presented in Table 3.

To validate the results, two more soil density and thickness were examined (tabulated in Table 4 and 5 respectively). When the soil density was the variable parameter, a thickness of 0.3 m was used. The same procedure mentioned above for the experiment and analysis of the results was followed. The results show that the deformation ($n$) of the soil increased with increasing the load bearing capacity modulus ($k_{eq}$), which proves the hard layer effect on the soil properties.

Fig. 6 Pressure–sinkage curves for the plate of 0.15 and 0.2 m.

Table 2 Soil parameters for each of sinkage plates before and after the breaking area.

| Plate diameter, D (m) | Equation of regression | $R^2$ | $n$ | $k_{eq}$ [kPa/m$^n$] |
|----------------------|------------------------|-------|----|---------------------|
|                      |                         |       |    |                     |
| Before breaking point |                        |       |    |                     |
| 0.15                 | *$y = 318.07x^{0.9926}$ | 0.98  | 0.992 | 318.07             |
| 0.2                  | $y = 702.02x^{0.9815}$  | 0.99  | 0.981 | 702.02              |
| After breaking point |                        |       |    |                     |
| 0.15                 | $y = 5505.9x^{2.3442}$  | 0.99  | 2.344 | 5505.9              |
| 0.2                  | $y = 9549.6x^{2.1037}$  | 0.98  | 2.103 | 9549.6              |

*The $y$ value represents the applied pressure (p), and $x$ value describes the sinkage ($z$).
Table 3 The soil characteristic properties of the Bekker model.

| Name                              | Value before breaking | Value after breaking |
|-----------------------------------|-----------------------|----------------------|
| Exponent of soil deformation, \(n_a\) | 0.986                 | 2.2235               |
| Cohesive modulus, \(k_c\) [kN/m\(^{1+n}\)] | -230.37              | -2426.22             |
| Frictional modulus, \(k_f\) [kN/m\(^{2+n}\)] | 1853.87             | 21680.7              |

Table 4 Values of soil parameters for two different density with thickness of 0.3 m.

| Destiny of the soil (g/cm\(^3\)) | Plate diameter, D (m) | Before breaking | After breaking |
|-----------------------------------|-----------------------|----------------|---------------|
|                                   |                       | n  | \(k_{eq}\) [kPa/m\(^n\)] | n  | \(k_{eq}\) [kPa/m\(^n\)] |
| \(\rho = 1.464\)                 | 0.15                  | 0.791 | 350.6       | 2.477 | 12104          |
|                                   | 0.2                   | 0.722 | 667        | 2.006 | 14652          |
| \(\rho = 1.539\)                 | 0.15                  | 0.835 | 708.8       | 1.938 | 7211.2         |
|                                   | 0.2                   | 0.782 | 1276.7     | 1.726 | 11458          |

Table 5 Values of soil parameters for two different thicknesses with soil density of 1.245 g/cm\(^3\).

| Soil thickness (m) | Plate diameter, D (m) | Before breaking | After breaking |
|-------------------|-----------------------|----------------|---------------|
|                   |                       | n  | \(k_{eq}\) [kPa/m\(^n\)] | n  | \(k_{eq}\) [kPa/m\(^n\)] |
| 0.26              | 0.15                  | 1.335 | 1265.6       | 2.978 | 51717          |
|                   | 0.2                   | 1.412 | 3547.7       | 1.909 | 12833          |
| 0.4               | 0.15                  | 0.736 | 533.33       | 1.923 | 3640.6         |
|                   | 0.2                   | 0.788 | 1092.1       | 1.96  | 8712           |

5. Conclusion

In this study, a bevameter instrument test device that could measure the vertical soil deformation and easily change the soil thickness was constructed. This device included a mechanical structure, a control system, and a measuring unit. This bevameter was designed to study the effect of the hard layer and the soil thickness’ changes on the pressure-sinkage relationship. The maximum applied load was 30 kN. Further, sinkage plates with two different diameters were employed to describe the soil pressure-sinkage relationship. A laptop with Catman software tool was used to facilitate real-time measuring and to record the applied loads as well as the resulting sinkage of the plate. Indoor tests were also conducted to evaluate the device’s performance by analyzing the soil’s behavior. The test was developed using sandy loam soil sieved through a 0.5 mm mesh. The soil bin filled with soil up to 0.3 m thickness at a 0.1 m layer. The soil density and moisture content for the soil was calculated to be 1.245 g/cm\(^3\) and 12.3%, respectively. To validate the results, two more soil density and thickness were examined. This study characterized the design and construction of bevameter as well as defined the breaking point and studied the effect of hard layer on the soil’s properties. The relationship between the applied pressure and sinkage showed that the hard layer affected the soil behavior and the soil properties, as the soil became more compact.

For future work, this bevameter device can be used to determine a new correlation for the load-bearing capacity of soil considering finite thickness and to generalize the experimental results.

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