Experimental Device for Measuring
Sandy Soil Sinkage Parameters

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Summary

The instrumentation of the sinkage device and the measurements of the response of Tottori dry sand to normal loading in laboratory condition are presented. The sinkage tests were conducted by means of electrically driven loading equipment at quasi-static speed of approximately 13.3 mm/s through a depth of 120 mm. The vertical plate sinkage and the load applied to the plate were measured. From our experimental data, the sinkage parameters k_c, k_ϕ and n in Bekker pressure-sinkage equation could be derived. The results showed that the used experimental device was suitable for identifying the soil sinkage parameters in relation to off-road mobility. It was found that the values k_c, k_ϕ and n were different between rectangular plates of low aspect ratio and the circular plates, but the difference is practically negligible between rectangular plates of high aspect ratio and the circular plates having radii equal to the width of the rectangular plates.

Keywords: Sandy soil, Sinkage test, Sinkage parameters, Off-road vehicle mobility

I. Introduction

The measurement and characterization of terrain properties are some of the basic issues in terrain-vehicle system engineering. Among the terrain measuring methods in relation to vehicle mobility, the bevameter developed by Bekker has evaluated a good simulation of vehicle loading conditions. The bevameter techique is comprised of two separate tests. One is a set of plate penetration tests and other is a set of shear test. In penetration test, a plate is used to simulate the ground contact area of a vehicle running gear, and the pressure-sinkage relationship for the terrain is measured for predicting the normal pressure distribution on the vehicle-terrain interface. In the shear tests, the relationship between shear stress and shear displacement at various normal pressures is measured for calculating the soil cohesion and the angle of internal friction in order to predict the shear stress on the interface. Accordingly, the terrain parameters obtained by bevameter are usually used for evaluating the terrain-vehicle interactions by many authors.

For measuring the pressure-sinkage relationship of terrain, the device for in situ or laboratory sinkage tests can be used. Goodman (1963) used an experimental equipment to obtain load sinkage soil values for evaluating the effects of remolding on soil constants to use in soil-vehicle relationships. Wong (1980) used a bevameter with a portable automatic data processing for field

measurements of the terrain properties in relation to off-road mobility. Youssef (1982) and McKyes (1985) used sinkage devices to determine soil parameters in laboratory condition. Earl (2001) used sinkage device for studying the behaviour of soil under normal load in a soil bin as well in field soil. For modelling the sinkage test in tilled soil for mobility study, Benoit (2004) used sinkage equipments to conduct penetration tests in small and large soil bins.

Some models for describing the pressure-sinkage relationship of homogeneous terrain have been developed by Bekker (1956), Reece (1964) and led to further investigations especially conducted by Wong (1980). However, an empirical pressure-sinkage model in relation to vehicle mobility was first introduced by Bernstein in 1913 as follows:

$$p \cong k z^{0.5} \tag{1}$$

where p is the normal pressure in kPa, z is the plate sinkage in m, k is the modulus of inelastic deformation.

Equation 1 was later modified by Goriatchkin *et al* in 1936 in the form:

$$p = k z^{n} \tag{2}$$

where n is the exponent of sinkage and takes any value between zero and one.

The disadvantage of Eq. 2 is that the value of k is assumed to remain constant for a given soil, but it varies depending on the form of the test plates. Much later, Bekker (1956) modified this model by introducing k_c and k_ϕ to account for cohesion and internal friction of soil, respectively, and these empirically determined constants are independent of the plate radius or plate width. The Bekker pressure-sinkage equation is written as follows:

$$p = \left(\frac{k_c}{b} + k_\phi \right) z^{n} \tag{3}$$

where b is the radius of a circular plate or smaller dimension of a rectangular plate in m, k_ϕ is the friction modulus of sinkage in kPa/m^n, and k_c is the cohesive modulus of sinkage in kPa/m^{n-1}.

From Eq. 3, soils can be defined in a sinkage test by three parameters k_c, k_ϕ, and n which describe empirically the vertical stress-strain relationship. In homogeneous soil, these parameters can be determined if continuous or repetitive loading sinkage tests are made with at least two plates having different radius or width. Then, from two sets of test data, the best fitting values of the above sinkage parameters are derived as described by Bekker (1956), Wong (1980), and Mc Kyes and Fan (1985). To evaluate the goodness of fit as fitting the experimental data with the Bekker equation, the following parameter can be used (Wong, 1980):

$$\varepsilon = 1 - \frac{\sqrt{\sum (p_m - p_c)^2 / (N-2)}}{\sum p_m / N} \tag{4}$$

where ε is the goodness of fit in curve fitting, p_m is the measured pressure, p_c is the calculated pressure using Eq. 3, and N is the number of data points used for curve fitting.

This study describes the instrumentation of a sinkage device and measurements of the vertical response of loose dry Tottori sand to normal loading in laboratory condition. This research also validates the hypothesis that the difference between the values of k_c, k_ϕ and n obtained with

circular plates and rectangular plates having width equal the radius of circular plates is practically negligible. In addition, it examines whether the sinkage of rectangular plates of low aspect ratios having width equal to the diameter of circular plates could be accurately predicted by the Bekker pressure-sinkage equation from the results of sinkage tests using two small circular plates.

II. Materials and Methods

1. Soil samples

In predicting off-road vehicle performance at a given location, the soil parameters might be determined in the most critical condition expected from the field. Laboratory reproducibility of sandy soil with low soil mass and low moisture content seems to reproduce easily its original condition. In this laboratory trial, dry Tottori sand was used in order to obtain homogeneous soil samples of repeatable conditions. The physical properties and conditions of the sand are given in Table 1. Some tests such as grain size distribution and specific gravity were performed to classify the soils according to USDA classification systems. The values of cohesion and angle of internal friction of tested soils were obtained from shear test data using direct shear box.

The 350 mm thick sand sample were prepared in homogeneous one-layer configuration with desired bulk density in small bins having the same base of 390 mm x 700 mm and 400 mm height (Fig 1a). The bins were made by 10 mm thick acrylic sheet. The width and height of the soil bins were limited by the access space of the loading device, which is shown in Fig. 1b. Each sand sample was prepared by filling the bin with 143.5 kg of dry sand in seven layers of 50 mm thick, with no compaction resulting in approximately 1.5 g/cm^3 bulk density. The water content and the bulk density measured in the bin are given in Table 1. After each test, the sand sample was loosened by hand shovel then weighted and refilled the bin following the above procedure. This remolding method has a good repeatability that makes it possible to prepare the uniform sand samples of repeatable properties. Number of replication of each test was three times in order to minimize the scatter caused by the random non-homogeneity of the soil samples.

Table 1. The physical properties of Tottori sand

Soil	Dry Tottori sand
Classification	Fine-medium sand
Water content	0.35%
Bulk density	1.5 g/cm
Specific gravity	2.74
Cohesion	2 kPa
Angle of internal friction	38°

2. Sinkage device

The sinkage tests were conducted by applying the principle of constant penetration rate to the sinking of the plates into the soil samples. The plate sinkage and the force applied to the plate were measured. The pressure applying at the contact between soil and plate surface was deduced from the measured force and the plate area.

The sinkage device consists of a load cell (NEC 9 E 01-L 8) of 2 kN capacity (Fig. 1d) at-

Fig. 1. The sinkage device: a) sand sample; b) loading equipment; c) sinkage plate;
d) load cell; e) data acquisition system

tached to the horizontal beam of electrically driven loading equipment through a rigid frame. The sinkage plate is connected to the load cell by a rigid rod allowing a maximum sinkage of 150 mm. The sinkage tests were performed using two circular plates with radius of 25 and 35 mm. The plate diameter was chosen with respect to the width of the soil bins since previous experimental data indicated that a ratio of soil sample width to sinkage plate diameter of 5 to 1 is necessary to minimize the sidewall effect (Goodman, 1961).

Since the plate form has strong effect upon the values of sinkage parameters, and consequently upon plate sinkage prediction, four sets of rectangular plates having different aspect ratios were also used in order to verify how accurately the sinkage of these plate could be predicted from the results of the two circular plates. Two sets of rectangular plates of 3 and 6 aspect ratios having width equal to the radius of circular plates were used for modeling the ground contact of a tracked vehicle: 25 mm by 75 mm, 35 mm by 105 mm and 25 mm by 150 mm, 35 mm by 210 mm. Other two sets of rectangular plates of approximate 1.4 and 2.0 aspect ratios having width equal to the diameter of circular plates were used for modeling the ground contact of pneumatic tire at shallow sinkage: 50 mm by 70 mm, 70 mm by 100 mm and 50 mm by 100 mm, 70 mm by 140 mm. Although the sizes of used plates were small in loose homogeneous sand samples, all plates deformed the sand with the same patterns so-called local shear failure (Bekker, 1960). Therefore, such small plate sizes have practically no effect on the values of sand sinkage parameters.

3. Experimental procedure and data acquisition

To characterize the quasi-static pressure-sinkage relationship of loose dry Tottori sand, each plate was moved vertically downwards into the soils through a depth of 120 mm at a constant speed of 13.3 mm/s by means of the loading equipment. Since bottom effects in the sand samples with a height of 350 mm seems to become apparent at 120 mm sinkage, the data of lower sinkage were used to derive the soil sinkage parameters in Eq. 3. The experimental data were collected at a rate of 10 Hz by using a data acquisition system (Fig. 1e) (NR-500 series, Keyence) connected to the load cell. Measurements were recorded on a portable computer. The pressure at contact surface between sand and sinkage plate was deduced from the measured normal loads and the

plate area to obtain pressure-sinkage curves. The plate sinkage was calculated by multiplying the elapsed time of each experiment recorded by the data acquisition system with the given sinkage rate.

4. Data processing

The tests were carried through a shallow sinkage of 120 mm, where the soil had passed the elastic behavior to the plastic behavior. Three-time replication of each test was made then the mean values of pressure were obtained from the results of three sinkage tests for each plate. The methods for calculating sinkage parameters introduced by Mc Kyes (1985) were used to obtain the values of k_c, k_ϕ, and n in the Bekker equation.

III. Results and Discussion

The experimental results of sinkage tests are shown in Fig. 2a for set of circular plates and in Fig. 2b, c, d, e for each set of rectangular plates with similar aspect ratio. It was pointes out that
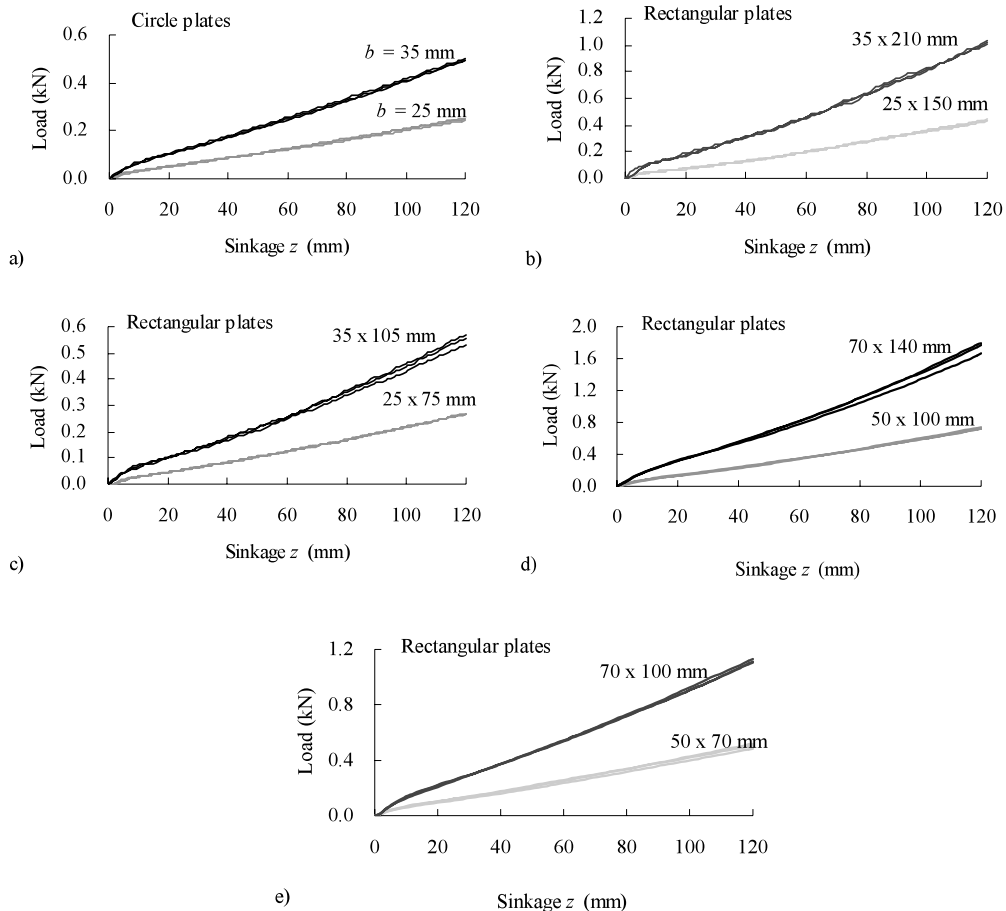

Fig. 2. Experimental results of sinkage tests: a) circular plates; b, c, d, e) rectangular plates of 6, 3, 2 and 1.4 aspect ratios respectively
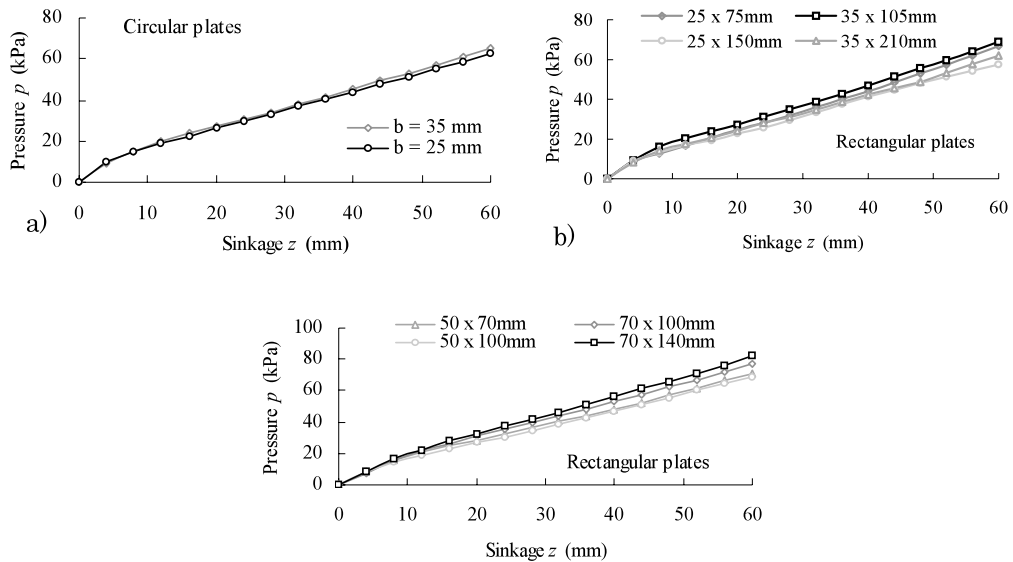
Fig. 3. Average pressure-sinkage curves: a) circle plates; b) rectangular plates of 3 and 6 aspect ratios; c) rectangular plates of 1.4 and 2 aspect ratios

Table 2. The derived sinkage parameters

		k_c	k_ϕ	n
	Ciicular plates	2.54	428.97	0.76
Rectangular plates	Aspect ratio = 6	2.99	427.02	0.80
	Aspect ratio = 3	6.30	433.56	0.82
	Aspect ratio = 2	10.41	880.86	0.81
	Aspect ratio = 1.4	9.04	799.58	0.79

the remolding method for preparing the soil samples made them possible to achieve very closely repeatable results and it is clear that the groups of curves can be accurately represented by mean curves. These curves show two parts of straight line linked by a continuous change of slope. This was due to the rigid bottom effect of the soil bin.

Within soil sinkage of approximately 60 mm, these curves have small slope. Their slope then increases slightly as the plate's isobars of normal pressure extend deeper and reach the bottom of the soil bins. The slopes of the curves of larger plate increase faster because the larger plate often is affected by bottom effect sooner than smaller plate. Therefore, only the data obtained within sinkage of 60 mm were used for further processing in order to minimize the bottom effect. The mean pressure-sinkage curves are shown in Fig. 3.

From the experimental data, the conventional least squares method was utilized to derive the sinkage parameters k_c, k_ϕ and n in Eq. 3 for each set of plates. Table 2 summarizes the derived values of these parameters. It can be seen from Table 2 that in loose dry sand, the parameters derived from experimental data using various sizes of plates are different. For rectangular plates with low aspect ratios of 2.0 and 1.4, the difference between the values of the sinkage parameters and those obtained with the circular plates having the diameter equal to the width of rectangular plates was found to be large. However for rectangular plates having width equal to the radius of

circular plates, the difference is much reduced for plates with aspect ratio of 3 and practically negligible for plates with high aspect ratio of 6. This result agrees with the investigation of Hanamoto and Jebe (1961), which studied the effect of aspect ratio on the pressure-sinkage relationship for rectangular plates in sand. It is also noted that the k_c values determined in sinkage tests with rectangular plates of low aspect ratios were negative. However it is unnecessary to interpret such values since k_c is just a curve fitting constant without a unique physical meaning, which appears in an empirical equation.

The comparisons of the measured pressure-sinkage curves obtained with a rectangular plates having different widths of 25, 35, 50, and 70 mm with different aspect ratios of 6, 3, 2 and 1.4 and those predicted by the Bekker equation using the values of sinkage parameters obtained with circular plates are shown in Fig. 4 and Fig. 5. The goodness of fit for each prediction was calculated by Eq. 4. The results of this evaluation indicate that the sinkage parameters obtained with circular plates gave best prediction for the sinkage of 35 x 210 mm plate with goodness of fit of 95% (Fig. 4b). For other rectangular plates, the goodness of fit varied from 93% to 65%. In the case of the rectangular plates having width equal to the diameter of circular plates, the error for sinkage predictions are very large and it seems to increase when plate width increases (Fig. 5a, b).

Based on the results of laboratory trials, it appears that the k_c k_ϕ n-values determined in tests with small circular plates in loose dry sand could be used to predict the sinkage of a tracked vehicle with ground contact areas with aspect ratios enclosing between 6 and 3. However, these parameters could not be used for evaluations of vehicle ground contact areas having low aspect ratios of 1.4 and 2 such as pneumatic tires at shallow sinkage. This means more work is needed to define the aspect ratio effect in detail.
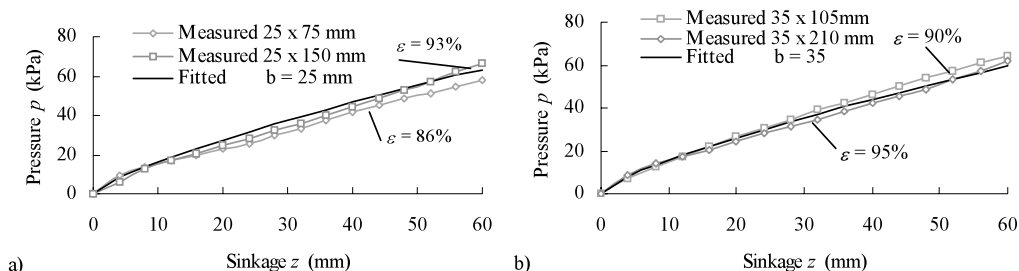

Fig. 4. Sinkage predictions for rectangular plates having width equal to the radius of circular plates: a) 25 mm plate width; b) 35 mm plate width
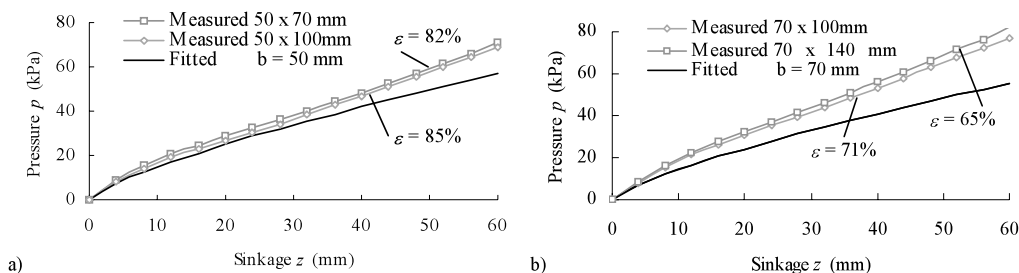

Fig. 5. Sinkage predictions for rectangular plates having width equal to the diameter of circular plates: a) 50 mm plate width; b) 70 mm plate width

IV. Conclusion

The results of laboratory trials show that the used experimental device together with the experimental methodology is suitable for measuring the sinkage parameters of loose dry Tottori sand in relation to vehicle mobility in the Bekker pressure-sinkage equation.

The difference between the values of k_c, k_ϕ, and n obtained from sinkage test with small circular plates and those obtained with rectangular plates of high aspect ratio is practically negligible. It means that the values of k_c, k_ϕ, and n determined in tests with small circular plates in loose dry sand can be used to evaluate the performance of off-road vehicles with ground contact areas of aspect ratio enclosed from 6 to 3.

For evaluations of off-road vehicle ground contact areas having low aspect ratios, the rectangular plates of low aspect ratios should be used to get maximum reliability of soil sinkage prediction.

References

Bekker, M. G.. (1956). Theory of Land Locomotion. The University of Michigan Press, 522 pp.

Benoit, O., Gotteland, Ph. (2004). Modelling of sinkage tests in tilled soils for mobility study. *Soil and Tillage Research*, 80, 215-231.

Earl, R. and Alexandrou, A. (2001). Deformation processes below a plate sinkage test on sandy loam soil: experimental approach. *Journal of Terramechanics*, 38, 153-162.

Emori R. and Churing D. (1966). Static and dynamic penetration tests of soil. *Journal of Terramechanics*, 3, 23-30.

Goodman, J., Lee, N. (1963). Effect of remolding on soil values related to vehicle mobility. *Proceedings of 1st International Conference on the Mechanics of Soil-Vehicle Systems*, 63-75.

Grahn, M. (1991). Prediction of sinkage and rolling resistance for off-road vehicles considering penetration velocity. *Journal of Terramechanics,* 28, 339-347.

Mc Kyes, E. and Fan, T. (1985). Multiplate penetration tests to determine soil stiffness moduli. *Journal of Terramechanics*, 22, 157-162.

Reece, A.R. (1964). Curve fitting technique in soil vehicle mechanics. *Journal of Terramechanics*, 1, 44-55.

Wong, J. Y. (1980). Data processing methodology in the characterization of the mechanical properties of terrain. *Journal of Terramechanics,* 17, 13-41.

Youssel, A. A., Ali, G. A. (1982). Determination of soil parameters using plate test. *Journal of Terramechanics,* 19, 129-147.

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