Method for Estimating Subgrade Reaction Modulus by Measuring Wheel-terrain Interactions

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Abstract –

For several years, the compaction quality of embankments has been controlled by the dry bulk density and water content. However, the quality assessment is time consuming and merely a point measurement. We are developing a method that measures the mechanical properties of soil by observing the soil - wheel interaction behavior. In this study, we have proposed a method for estimating the subgrade reaction modulus of the soil by towing a wheel on the ground surface. This paper describes the theoretical basic concept of this method and discusses its validity with the results obtained from a laboratory model experiment.

Keywords –

Soil compaction; Quality control; Subgrade reaction modulus

1 Introduction

For several years, the quality control of soil compaction has been assessed by measuring soil density and water content. However, the measurement is time consuming and is only a point measurement. Recently, a new technique called "intelligent compaction [1]" has become widespread; this is because the quality is controlled by the number of roller passes required to achieve the desired compaction. Intelligent compaction using a GNSS-mounted roller enables real-time continuous measurements. In contrast, the number of roller passes is only considered to be an index without a physical meaning.

In this study, we have proposed a soil testing method that allows us to continuously evaluate the rigidity of soil (subgrade reaction modulus) by towing a wheel on the surface of the ground. Figure. 1 depicts an illustrative example of the possible future applications of this technique. One possible application is a mobile measurement in which a wheel-type testing tool is equipped in a construction vehicle. The other application is also a mobile measurement using a wheeled roller. The

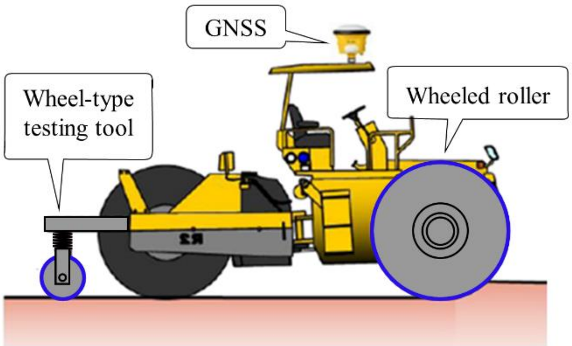


Figure 1. Possible future applications of the wheel testing tool

proposed method has the following two advantages:

- Direct measurements for assessing the mechanical properties of soil: As mentioned above, the existing methods for examining the quality control of soil compaction assess the physical properties of soil (e.g., soil density and water content) or calibrated index. This is based on the premise that as far as the compacted soil satisfies the desired control value, the quality also satisfies the requirements for mechanically stabilizing the soil structure. The proposed method directly provides the subgrade reaction modulus, which is an important mechanical parameter that is commonly used in pavement designs, foundation designs, and for predicting the behaviors of other soil-structures. We consider that the proposed method allows direct assessment to determine whether the compaction quality meets the requirements of the design.
- Continuous real-time measurements: As for in-situ soil investigation techniques for assessing the stiffness/rigidity of soil surface, the plate load test, California Bearing Ratio (CBR) test, and Falling Weight Deflectometer (FWD) are commonly used in practice [2]. The existing methods evaluate the point measurement of soil rigidity whereas the proposed method evaluates the continuous spatial distribution of soil rigidity.

At present, we have not implemented mobile measurement using a vehicle-mounted device under actual situations; therefore, we cannot evaluate the practicality of the proposed method. As a feasibility study, this paper describes the theoretical basic concept of the method for estimating the subgrade reaction modulus and discusses its validity with the results obtained from a laboratory model experiment.

2 Method for estimating subgrade reaction modulus

The mechanism of wheel-soil interaction is complicated, as depicted in Figure. 2. When a rigid wheel travels on soft soil, a rut occurs on the soil surface. In addition to the soil compression that generates the rut, plastic soil flows of a soil bed occur at the front, rear, and sides of the wheel. Considering that the rate of energy input to the wheel is consumed by the soil-wheel interaction, we obtain the following energy conservation equation:

$$\dot{E}_t + \dot{E}_d = \dot{D}_c + \dot{D}_p + \dot{D}_e + \dot{D}_l \tag{1}$$

where $\dot{E}_t$ and $\dot{E}_d$ are the external rate of work performed by the drawbar pull and driving force, respectively; $\dot{D}_c$ and $\dot{D}_p$ are the rate of internal energy dissipation due to soil compression and plastic soil flows, respectively; $\dot{D}_e$ is the rate of potential energy variation of the wheel; $\dot{D}_l$ is the rate of mechanical energy transformation loss due to friction inside the wheel.

In this study, we have postulated a condition in which a rigid wheel is towed on a soil surface without a driving torque. In this situation, the wheel slip does not occur. In addition, plastic soil flows do not occur when the wheel sinkage is small. This suggests that the rate of internal energy dissipation due to plastic soil flows can be ignored. Furthermore, assuming a condition in which the mechanical energy transformation loss and variations in the wheel elevation are also negligible, Eq. (1) can be rewritten as

$$\dot{E}_t = \dot{D}_c \tag{2}$$

Eq. (2) suggests that the input energy rate is consumed by the soil compaction for generating the rut. Denoting the towing speed and drawbar pull as V and F, respectively, the input energy rate can be written as

$$\dot{E}_t = FV \tag{3}$$

In contrast, assuming that the load–settlement relationship of the surface soil can be approximated as $p = k_w z$, where k_w is the subgrade reaction modulus and z is the wheel sinkage, then the rate of internal energy dissipation due to soil compression can be expressed as

$$\dot{D}_c = \frac{1}{2} k_w z^2 BV \tag{4}$$

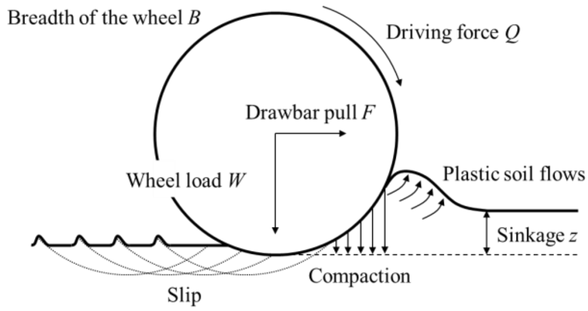


Figure 2. Soil-wheel interaction

where B is the breadth of the wheel.

By substituting Eq. (3) and Eq. (4) into Eq. (2), the subgrade reaction modulus can be obtained as follows:

$$k_w = \frac{2F}{z^2 B} \tag{5}$$

Eq. (5) suggests that it is possible to continuously estimate the variation in k_w as the wheel rotates by measuring F and z. Note that although the wheel load (W) is not explicitly included in Eq. (5), it will certainly influence both F and z.

Although we ignored $\dot{D}_e$ in Eq. (2), it could be taken into account by considering the following equation:

$$\dot{D}_e = W\Delta h \tag{6}$$

where Δh is the increment in the wheel elevation.

$\dot{D}_l$ can also be experimentally obtained by measuring the drawbar pull (F_0) of the wheel traveling on a horizontal rigid surface (this situation does not cause any energy dissipation except $\dot{D}_l$).

$$\dot{D}_l = F_0 V \tag{7}$$

3 Verification by laboratory model experiment

3.1 Experimental setup

In this study, a laboratory model experiment was performed to validate the theoretical concept of our proposed method. Figure. 3 depicts the experimental setup used in this study. An aluminum wheel with a diameter of 200 mm and breadth of 100 mm was used. As mentioned above, we used a wheel that spins freely in this experiment. A sheet that was made of rough sandpaper was attached onto the wheel surface to avoid slipping. The wheel could move freely in the vertical direction, and the wheel load (W) was adjusted using counterweights. The wheel was towed using a feed screw that was further controlled by an electric motor. A load cell was installed between the wheel and support jig to

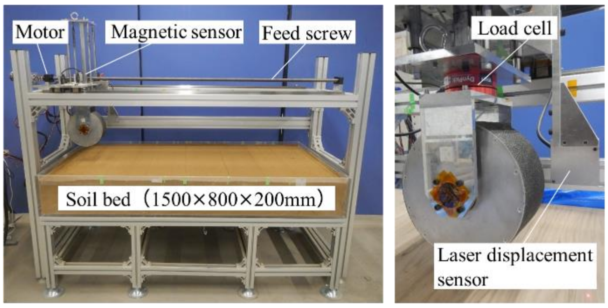


Figure 3. Experiment setup

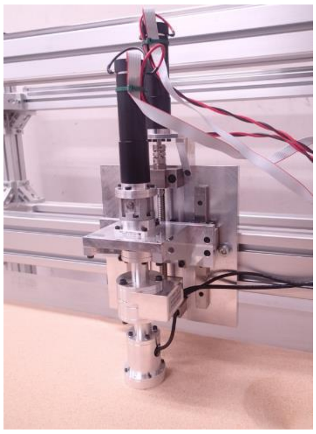


Figure 4. Small-diameter plate load test equipment

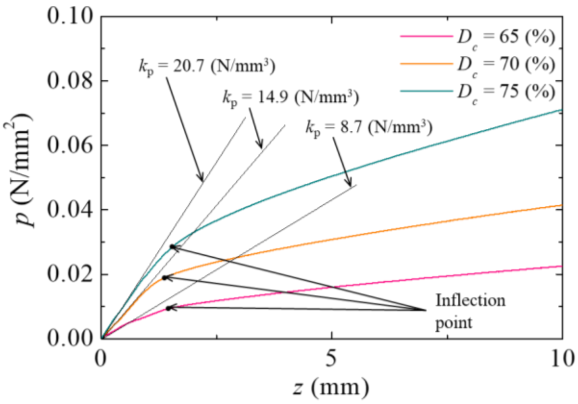


Figure 5. Typical examples of p-z relationship

measure the drawbar pull, F. The wheel elevation (h) was detected using a magnetic scale sensor attached to a support shaft that vertically moves in response to the soil surface topography and/or wheel sinkage. The wheel sinkage (z) was determined as the difference in the soil surface elevations at an arbitrary point between the wheel passes, and these were measured using a non-contact laser displacement sensor that was attached in front of the wheel and magnetic scale sensor as mentioned above.

In this experiment, the towing speed (V) was permanently set as 10 mm/s, and the wheel load (W) was changed to 68.6, 98.0, 127.4, and 156.8 N. Two types of decomposed granite soil were used for the model ground, namely, soil A: fine-grained sand with an average water content of 12.1%, and soil B: gravel-grained sand with an average water content of 14.9%. The soil bed was 1500 mm in length, 800 mm in width, and 200 mm in depth. The model ground was prepared to have three zones with different degrees of compaction: D_c = 65%, 70%, and 75% in the direction of travel, further indicating the varying rigidity of the soil surface with respect to the travel distance in one pass.

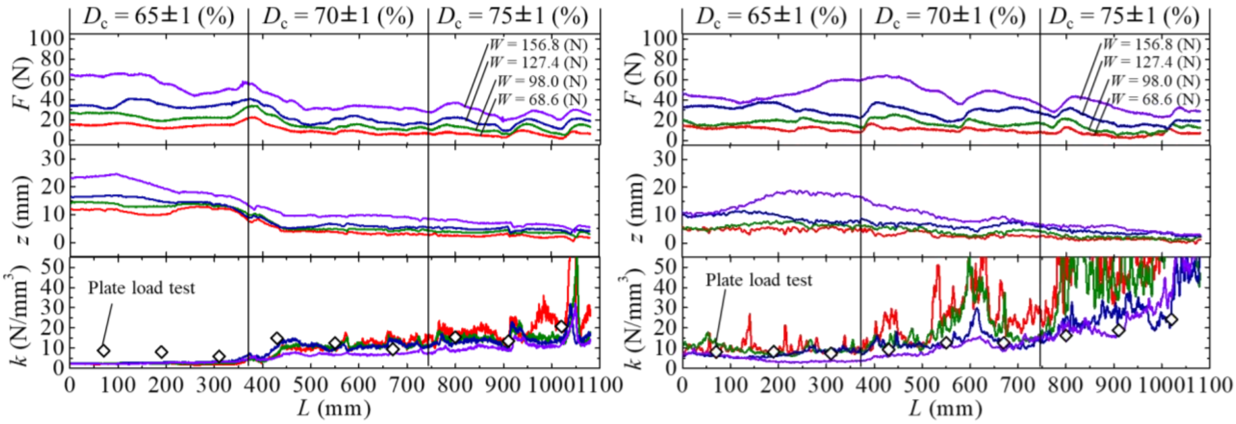
3.2 Small-diameter plate load test

In this study, the subgrade reaction modulus was independently measured using a small-diameter plate load test equipment (Figure. 4) to verify the estimate of k_w obtained by measuring the wheel-terrain interaction. A rigid circular plate with a diameter of 50 mm (same size as that of the CBR test), was set on the soil surface, and the plate was vertically pushed into the soil at a constant rate of 0.1 mm/s. The load-settlement behaviors (p-z relationship) were observed at various points on the model ground.

Figure. 5 depicts examples of the p-z relationship obtained from the test for the model ground of soil A. From the figure, it could be observed that the p-z relationship has an inflection point after a certain settlement. The inflection is usually regarded as a point at which the material fails. In this study, the subgrade reaction modulus, hereinafter referred to as k_p, is determined as the initial slope that appears prior to the inflection point.

3.3 Results and discussion

Figure. 6 depicts typical examples of the drawbar pull (F), sinkage (z), and the estimated subgrade reaction modulus (k_w) obtained from the laboratory model experiment. k_p obtained from the plate-load tests were also plotted as ◇ in this figure. It can be observed from the figures that both F and z increase with an increase in W for each soil. With some exceptions, it also appears that both F and z tend to decrease with an increase in D_c. In Figure. 6 (a), k_w obtained for each W is consistent regardless of W in the zone when D_c = 65%, where the degree of compaction is relatively small. This provides evidence to support the hypothesis that k_w does not explicitly depend on W in Eq. (5). However, when the degree of compaction increases (in the zone when D_c = 65% and 75%), the differences in k_w due to W becomes remarkable. In particular, when W is small, as in W = 68.6 and 98.0 N, the estimates of k_w show random fluctuations further resulting in huge gaps between k_w and k_p. From Eq. (5), it can be noted that k_w is inversely proportional



(a) Soil A: fine-grained sand (b) Soil B: gravel-grained sand

Figure 6. Experiment results and estimated subgrade reaction modulus

to z^2, and thus, k_w drastically increases when z decreases by one order of magnitude. The gaps can be attributed to the fact that the wheel with a smaller wheel load travels on a zone with a higher degree of compaction, thus resulting in a considerably small sinkage.

Figure. 7 depicts the comparison between k_w and k_p. The plots of k_w are the extracted data corresponding to the points at which k_p was measured using the plate load test equipment. It can be noted that k_w has an approximately positive correlation with k_p, and many of them are consistent with each other. However, it could be seen that k_w tends to underestimate k_p when subgrade reaction modulus is relatively small. In addition, k_w tends to overestimate k_p when W is relatively small. Possible reasons for this inconsistency are as follows. The underestimation occurred when the soil rigidity was small, further implying that the plastic soil flows occurred owing to the excessive sinkage under the soft soil. In this study, we ignored the internal energy dissipation due to the plastic soil flows, and the energy conservation equation was simplified as in Eq. (2). This assumption may yield an underestimation. Conversely, the reason for the overestimation may be due to the small sinkage that was used to calculate k_w, as mentioned earlier. Although Eq. (5) may be simple to estimate, a positive correlation between k_w and k_p could be observed. Even though there is still room for improvement and experimental verification, we conclude that the feasibility of the proposed method was confirmed from the laboratory model experiment.

4 Conclusion

In this study, we have proposed a method for estimating the subgrade reaction modulus of soils from wheel-terrain interaction measurements. The experimental results demonstrated the potential of the proposed method for estimation of subgrade reaction

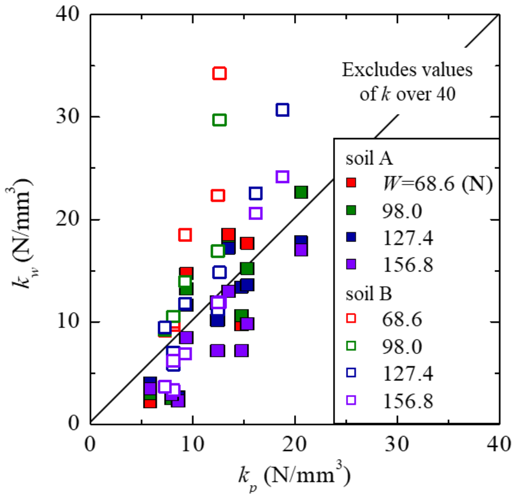


Figure 7. Comparison between k_w and k_p

modulus. However, it was revealed that the estimation equation had some limitations. We plan to proceed with the study for its practical use by improving the estimation equation.

References

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