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Research Article

Measurement of Degree of Compaction of Fine-Grained Soil Subgrade Using Light Dynamic Penetrometer

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To determine the degree of compaction of subgrades filled with fine-grained soil, the compaction test and light dynamic penetrometer (LDP) test were carried out for low liquid-limit clay samples with different water contents in laboratory. Then, a prediction equation of the penetration ratio (PR) defined as the depth per drop of the hammer of LDP, degree of compaction (K), and water content (ω) was built. After that, the existing fine-grained soil subgrades on LDP-based field tests were excavated. The on-site PR values, water contents, and degrees of compaction of slopes were obtained. The estimated degrees of compaction using the prediction equation were compared with measured values of the degree of compaction in field. The results show that there is good consistency between them, and an error within 3.5% was obtained. In addition, the water content should be determined firstly while using the prediction equation which is proposed in this study. Therefore, a numerical method of the water content of a subgrade was developed, and the predicted and measured water contents were compared, which shows a relatively high relativity. Then, the degree of compaction of fine-grained soil subgrades can be calculated according to the predicting equation, which involves the penetration ratio (PR) and the numerically calculated water content as input instead of the measured value in the field.

1. Introduction

In civil engineering, the investigation of the strength and integrity of every highway subgrade becomes necessary to optimize pavement structural performance and safety [1]. The degree of compaction is a significant index of investigation to achieve the goal of in situ quality control/quality assurance of granular pavement layers (subgrade, subbase, and base) [2–4]. If the results of investigation do not meet the requirements of compaction in design, the carrying capacity of the subgrade would be lower and then some distresses would occur such as the settlement of the subgrade and the cracking of pavement [5]. Traditionally, one of the activities during the subgrade investigation is determination of degree of compaction with different field and laboratory tests such as the sand-cone method [6] and cutting ring method [7, 8]. Although these evaluation methods are the best and reliable, they have relatively complicated steps and take much time to have the end result [9]. In addition, the soil samples in these methods need to be cored or excavated on the subgrade which is destructive and can have significant impact on pavement performance [10]. To overcome these shortcomings, many nondestructive and time-saving determination methods and equipment have been developed [11–13].

As a nondestructive, effective, fast, and reliable testing method, the dynamic cone penetrometer (DCP) has been introduced as a criterion for testing the foundation capacity in specifications of American Association of State Highway and Transportation Officials (AASHTO) and South Africa [14]. This device provides continuous and uninterrupted stratigraphic data when its cone probe is driven into soil along the vertical depth. The data obtained from the DCP have got a strong theoretical acceptance and can be used to comprehensively assess the foundation soil. The application of the DCP

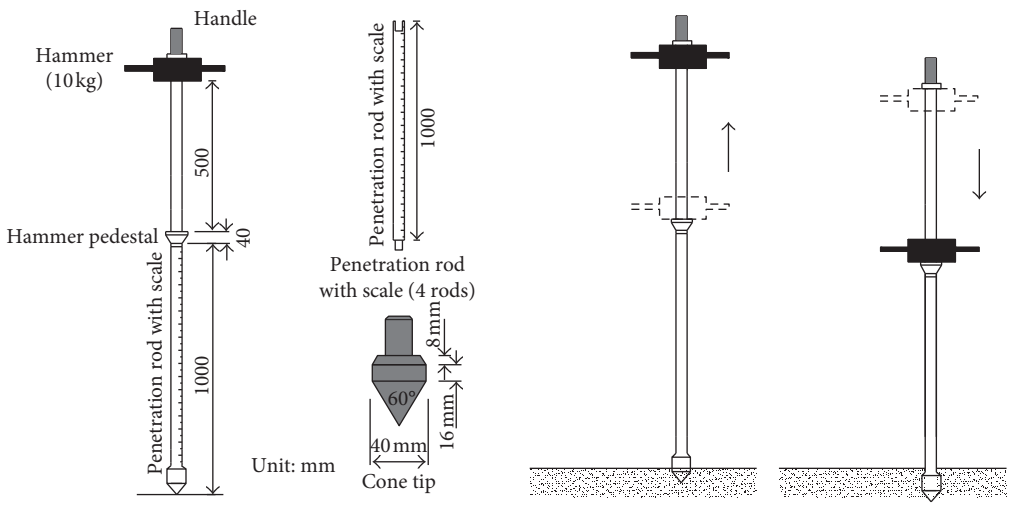


Figure 1: Diagram of the LDP device and principal.

was further investigated by previous researchers. Siekmeier et al. [15], George et al. [16], and Mukabi [17] built the empirical formula combining the penetration ratio (PR) of the DCP with the elasticity modulus and California bearing ratio (CBR). Mohammadi et al. [18], Alghamdi [19], Emre et al. [20], and Yang et al. [21] have gained some beneficial achievements to evaluate the subgrade compactness by the DCP, and the correlation between the degree of compaction, penetration ratio, and water content was established. The advantage of using the DCP is testing the soil properties in its natural density and moisture content state. These applications of the theory and method of the DCP have been accepted for different soils, and they provide a way to the empirical correlations based on the statistical analyses of field tests and soil properties.

The light dynamic penetrometer (LDP) is also a non-destructive method to evaluate the performance of the soil layer, which has a similar working principle to the DCP's. Compared to the DCP, its hammer is lighter and the drop distance is shorter, which is convenient and fast for the field testing of subgrade using the LDP instead of the DCP. Therefore, the objective of this paper is to test the degree of compaction of the fine-grained soil subgrade using the LDP. First, the principles and steps of the LDP-based test were introduced. The compaction and LDP tests of a typical low liquid-limit clay were conducted in the laboratory, and a quadratic predicting equation between the degree of compaction (K), the penetration ratio (PR), and the water content (ω) was established. Then, the validity of this equation was verified by the field tests of fine-grained soil subgrades. Finally, a numerical method for calculating the water content of subgrades was put forward and verified. Thus, the degree of compaction of fine-grained soil subgrades can be calculated according to the quadratic predicting equation, which uses the penetration ratio (PR) and the numerically calculated water content instead of the measured value in the field.

2. Device and Testing Method of LDP

The light dynamic penetrometer (LDP), a small-sized portable foundation soil in situ test penetrometer, consists of a hammer (10 kg in weight and 500 mm in drop distance), a penetration rod (1,000 mm long and a total of 4 rods), and a conical head (40 mm in diameter and 60° at the conical tip), as shown in Figure 1. When a field test is conducted using the LDP, the depth and drops of the hammer of the LDP are recorded when the cone tip is driven into soils by the hammer. The penetration ratio (PR), defined as the depth per drop of the hammer, can reflect the properties of soil layers.

When a test using the LDP is conducted, the following procedure should be carried out:

(1) The testing site should be flat, and a record book also should be prepared.

(2) Cone tip and penetration rod with scale should be assembled and connected. The penetration rod should always be perpendicular to the ground surface when the test is in progress.

(3) When the test is in progress, the penetration rod should be held on by one tester. The hammer should be lifted and released along the penetration rod. At the same time, the penetration frequency and depth are needed to be recorded.

3. LDP-Based Lab Test and Prediction of Degree of Compaction

3.1. LDP-Based Lab Test. The soil samples were taken from the Nanchang-Zhangshu expressway widening project in Jiangxi Province. The liquid limit, plastic limit, optimum moisture content, maximum dry density, and particle size analysis were conducted for soil classification and basic properties. Their liquid limit and plastic limit are 35.8% and 22.8%, respectively. According to the compaction test, the optimum moisture content and maximum dry density are 13.0% and 1.954 g/cm^3, respectively. The particle size analysis shows that 0.075 mm passing percentage of the soil samples is 82.2%. Therefore, the soil sample was categorized as a low liquid-limit clay according to the standard of *Test*

(a) (b)

Figure 2: LDP-based lab test.

Methods of Soils for Highway Engineering (JTG E40-2007) in China.

In order to study the influence of water content on the PR measured by the LDP, different soil specimens with 5 initial water contents and 5 dry densities were prepared. The water contents of soil samples were set to 9%, 13%, 16%, 19%, and 23%, covering the possible moisture content range of subgrade soils in China. The degrees of compaction of the subgrade are 96% and 93%, respectively, according to the requirements of the current specification in China. In order to improve the accuracy of the LDP-based test, the degrees of compaction of 82%, 86%, 90%, 94%, and 98% of soil samples were selected. The samples of 152 mm × 220 mm (diameter × height) were prepared by the static pressure method by 5 layers, as shown in Figure 2. The relationships between the water content and PR with different degrees of compaction were curved in Figure 3. It can be seen in Figure 3 that the minimum PR value is found nearby the optimum water content for the same degree of compaction, and the PR values decrease with the increasing degree of compaction values for the same water content. As mentioned above, the penetration ratio (PR) of the LDP can reflect the density properties of soil layers. Thus, the relationship between the PR, degree of compaction (K), and water content (ω) of soils can be built according to the results of the LDP [18–21], as shown in the following equation:

$$K = 0.1538\omega^2 - 3.9713\omega - 1.1284\text{PR} + 121.3193 \left(R^2 = 0.897\right), \quad (1)$$

where K is the degree of compaction of soil (%), PR is the penetration ratio (mm/drop), and ω is the water content of soil (%).

3.2. LDP-Based Field Test. A typical section of K24 + 600, where the soil samples were taken from, was selected. The light dynamic penetrometer (LDP) tests were carried out

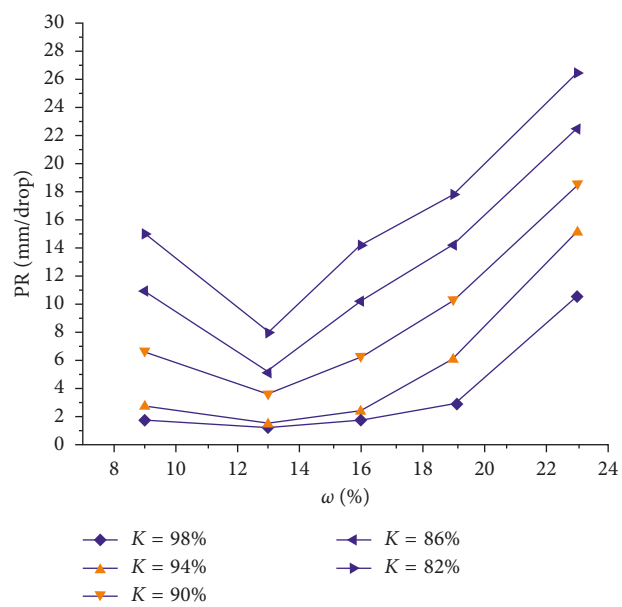
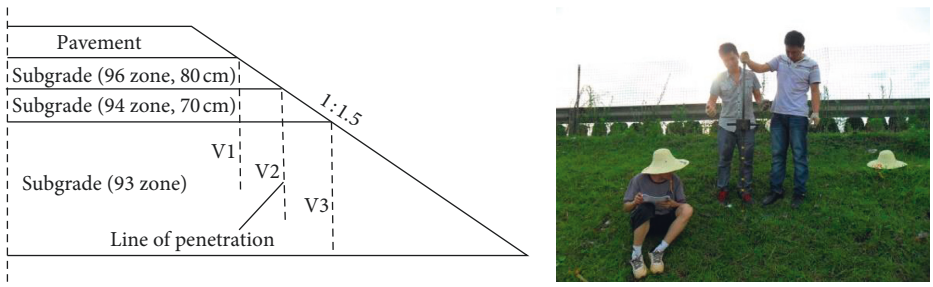


Figure 3: PR-ω under different compaction conditions.

from the top of 96 zone (i.e., the degree of compaction of 96%), 94 zone, and 93 zone of the existing subgrade, with a penetrating depth of 360 cm, as shown in Figure 4. The test data were recorded for every 20 cm penetration depth.

Figure 5 shows the PR values of different testing programs. It can be seen from Figure 5 that the PR values gradually increase with the increasing depth, which indicates that the degree of compaction of subgrades' slope soil gradually decreases with the increasing depth. The PR value is about 13 mm per stroke of the hammer within the depth of 100 cm of the subgrade slope and distributes relatively uniformly. The reason is that the LDP-based field test was conducted in summer, and the water contents of slope surface were relatively low. The PR values increase gradually and are 14 mm to 20 mm per hammering within the depth of



(a) (b)

Figure 4: (a) Diagram of LDP-based test. (b) LDP-based field test.

100 cm to 360 cm. In addition, it can be seen from Figure 5 that though V1, V2, and V3 started from the top of different zones, their PR values are almost the same within the depth of 100 cm. It shows that there is no obvious difference in properties of the subgrade within this scope in spite of the fact that their initial degrees of compaction are different. Also, Figure 5 shows that the PR values of V3 section are larger than those of the other two sections, which indicates that the water contents of the bottom subgrade are larger than those of the top subgrade.

3.3. Measurement of Degree of Compaction and Water Content of Subgrade Slope. To investigate the changes of the degree of compaction and water content of the subgrade slope of K24 + 600, it was excavated manually to a ditch with a 50 cm width and a 510 cm depth along the V1 section. The degree of compaction and water content were measured by the cutting ring test method on the horizontal planes with a vertical distance of 20 cm. The lowest horizontal plane is on the bottom of the ditch. For every horizontal plane, two soil samples with a distance of 20 cm in the longitudinal direction (parallel to the traffic direction) were selected, as shown in Figure 6. Their average values were taken as the final values for this location.

Figure 7 shows the measured water contents and degrees of compaction. It can be seen in Figure 7(a) that the water content increases gradually with the increasing depth and becomes relatively stable below the depth of 200 cm. The water contents are between 18% and 27% within the depth of 200 cm and 21% to 27% below the depth of 200 cm. This is because the water content for the top depth is controlled by the climate and that for the bottom depth is controlled by the ground water. The former changes sharply for different seasons, while the latter is stable with seasonal changes. It can be seen in Figure 7(b) that the degree of compaction changes sharply from 80% to 93% within the depth of 200 cm. For the depth below 200 cm, the degrees of compaction are relatively stable, changing from 82% to 88%.

3.4. Comparison of Predicted and Measured Degrees of Compaction. The estimated degrees of compaction using (1) and the measured values are shown in Figure 8. It can be seen in Figure 8 that they are relatively consistent. The root mean square errors between the estimated and measured degrees of compaction at V1, V2, and V3 vertical sections are 3.44%, 3.24%, and 3.31%, respectively, and the average of root mean square errors is 3.33%. Therefore, the differences between the estimated and measured degrees of compaction are acceptable, which means that the predicting equation of degrees of compaction based on the PR and water content has a satisfactory accuracy.

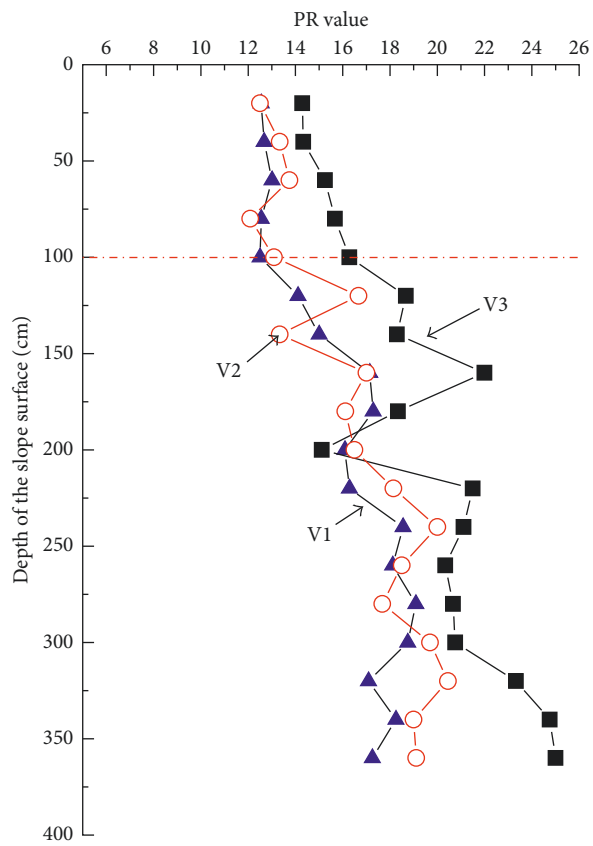


Figure 5: PR values for different sections.

4. Degree of Compaction according to Numerical Moisture Content

According to the above research, the degree of compaction of subgrade slope soil at different depths can be calculated based on the PR value and the measured water content. The former can be gained quickly using the LDP, and the latter is

Figure 6: Locations of soil samples.

time consuming. Therefore, a rapid method to determine the water content is the key to calculate the degree of compaction using (1). The water content of subgrade slope soil can be calculated using the numerical simulation, which is proved to be rational by some researchers using the GeoStudio software [22–25].

4.1. Test Parameters. This simulation needs some parameters including the hydraulic properties, thermodynamic properties, physiological parameters, and meteorological parameters of soils. All the needed parameters are shown in Table 1. Their values can be referred to the literature [22].

4.2. Calculated and Measured Water Content Values. Then, a numerical modelling of the subgrade slope of K24 + 600 was completed according to the method of the literature [22, 26, 27]. Water content was calculated using the parameters mentioned above, and the results of calculated water content values of soil are shown in Figure 9. The measured values for the section of K24 + 600 are also drawn in Figure 9. It can be seen in Figure 9 that the calculated and measured water contents of V1, V2, and V3 sections show a good coincidence in general. Due to the inhomogeneity of the subgrade and the measured errors, some data are scattered. Besides the discrete points, the root mean square errors between the measured and calculated water contents of V1, V2, and V3 sections are 1.19%, 1.53%, and 1.34%, respectively, and their average value is 1.35%. It shows a relatively high accuracy for engineering practices. Therefore, the water content of the subgrade in different depths can be calculated using the numerical method.

4.3. Degree of Compaction Based on Calculated and Measured Water Contents. Furthermore, to investigate the accuracy of the degrees of compaction from (1) using the calculated and

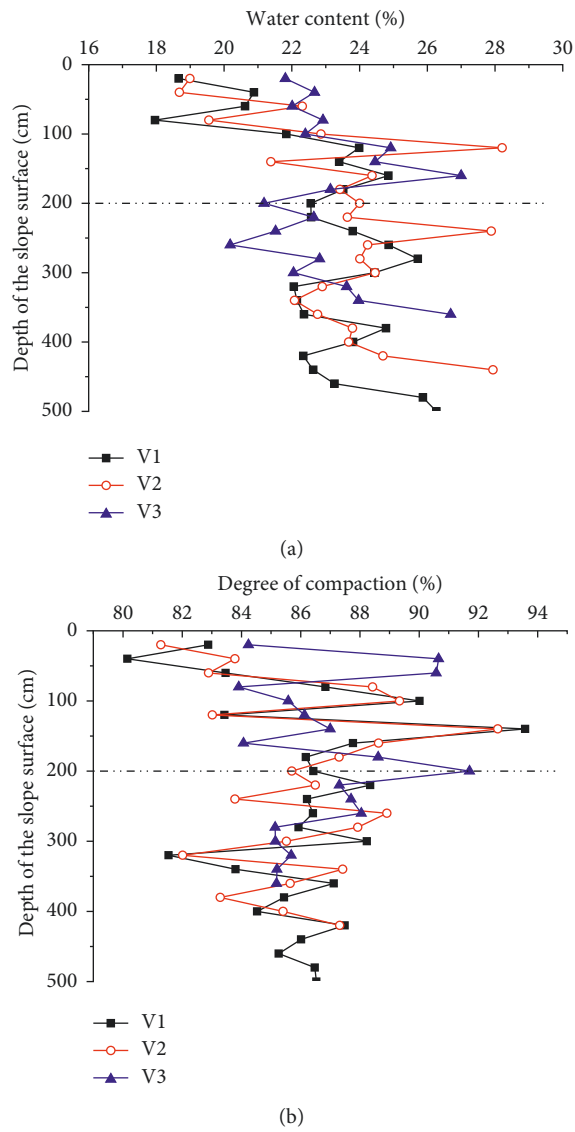


Figure 7: Water contents (a) and degrees of compaction (b) for the existing subgrade.

measured water contents, they are shown in Figure 10. It can be seen from Figure 10 that the estimated degrees of compaction of the subgrade based on the numerical water content, in general, do not deviate from the measured values significantly. Due to the inhomogeneity of the subgrade and the measured errors, some test points are scattered. Besides three discrete points, the root mean square errors between the estimated and measured degrees of compaction are 2.80%, 3.53%, and 2.46% for V1, V2, and V3 sections, respectively, and their average value is 2.93%. It shows that, for an existing subgrade, these degrees of compaction estimated by (1) according to the numerical and measured water contents are almost equivalent. Since the water content of any depth in subgrades can be determined using the numerical method in this study without excavating the subgrade slopes, which is much more time-saving than the measurement in the field, the PR and numerical water content can be used to predict the degree of compaction using (1) quickly.

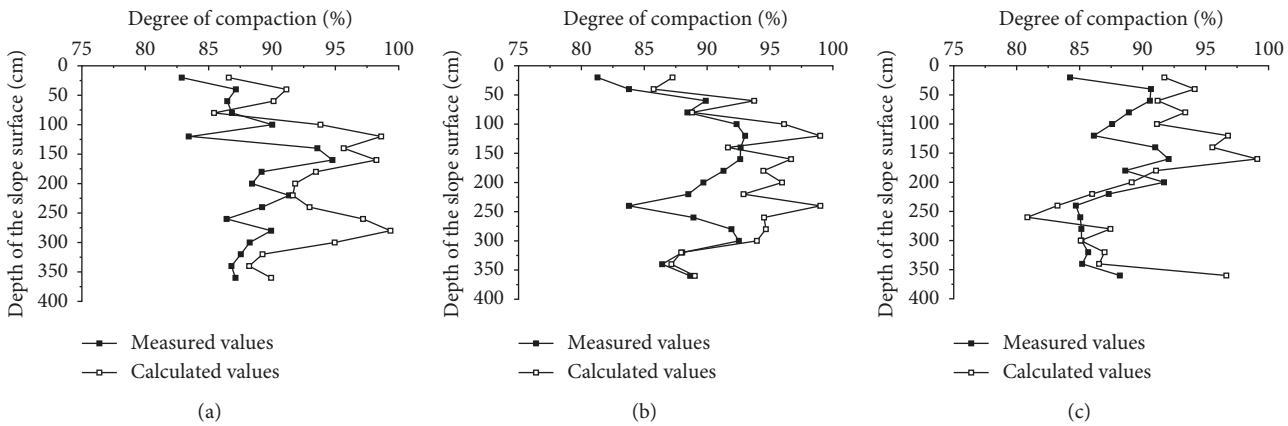


Figure 8: Estimated and measured degrees of compaction. Comparison of section: (a) V1; (b) V2; (c) V3.

Table 1: Parameters required for the numerical simulation [22].

Parameter category	Relevant parameter	Symbol	Unit
Hydraulic properties	Soil-water characteristic curve	SWCC	—
	Saturated infiltration coefficient	k_{ws}	m/s
Thermodynamic properties	Heat conductivity coefficient	λ_t	—
	Specific heat per unit volume	λ_v	J/(m^3·°C)
Physiological parameters of vegetations	Leaf area index	LAI	—
	Root depth index	D_R	M
Meteorological parameters	Daily average temperature	T	°C
	Daily relative moisture	RH	%
	Daily relative wind speed	U	m/s
	Daily average rainfall	P_r	mm

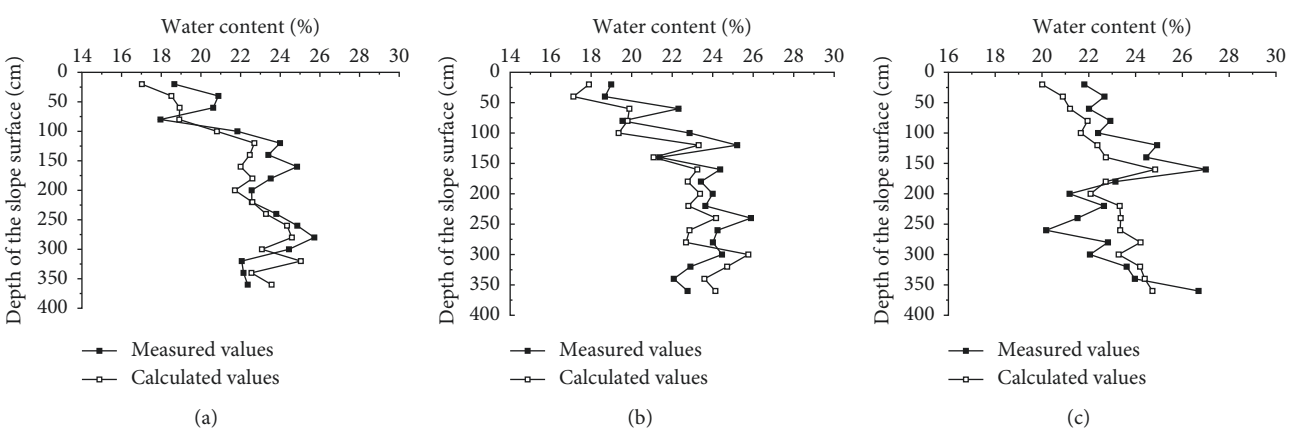


Figure 9: Calculated and measured water content values of soil at each vertical section. Comparison of vertical section: (a) V1; (b) V2; (c) V3.

5. Conclusions

The compaction test and light dynamic penetrometer (LDP) tests were carried out for low liquid-limit clay samples with different water contents in laboratory. The water content and degree of compaction were measured for a typical subgrade slope of K24 + 600 by the LDP test in field. Then, a prediction equation of the penetration ratio (PR), degree of compaction (K), and water content (ω) was built and verified. In order to avoid excavating the subgrade slope to measure its water content, a numerical method to determine the water content of a subgrade slope was put forward. It can be utilized to substitute the measured water content. Some major conclusions may be drawn as follows:

(1) A quadratic function between the degree of compaction, PR, and water content measured of low liquid-limit clay was established and verified. The root mean square error between the estimated and

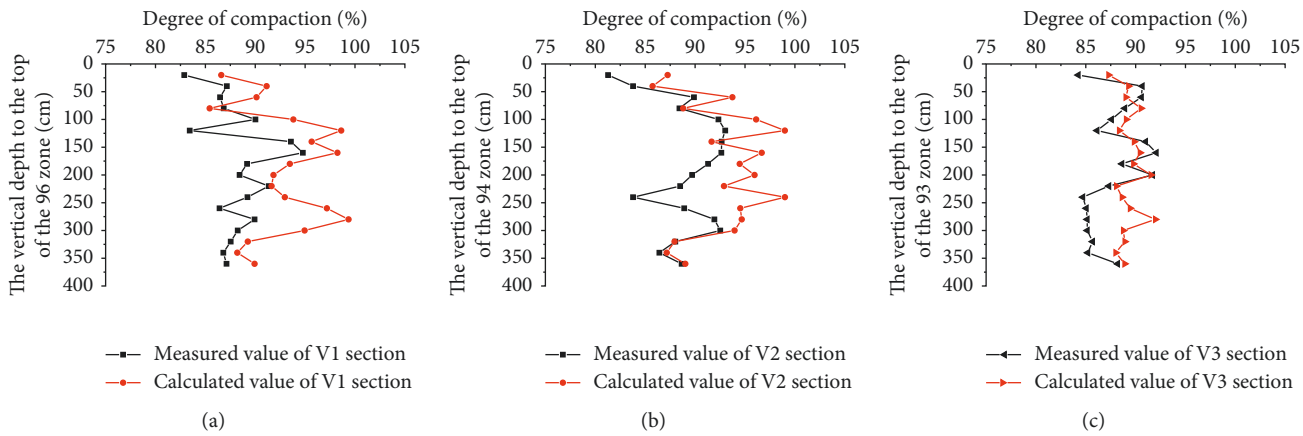


Figure 10: Degrees of compaction calculated according to different water contents. Comparison of section: (a) V1; (b) V2; (c) V3.

measured degrees of compaction was within 3.5%, which proves the validity of the relationship proposed in this study.

(2) It is difficult to measure the water content without excavating the subgrade slopes. A numerical method of water content for subgrade slope soils was proposed and verified. The results show that they have a relatively satisfactory accuracy. Therefore, this numerical method can be utilized to calculate the water content in subgrades, which is much more time saving than the on-site measurement.

(3) According to the numerical water content, the PR value obtained by the LDP-based field test, and the relationship between the degree of compaction, PR, and water content built in this study, the degree of compaction can be determined quickly. This method was proved to be rational by comparing the calculated and measured water contents.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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