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ORIGINAL PAPER

RESILIENT MODULUS OF SOIL USING FOR SUBGRADE OF PAVEMENT: A CASE STUDY IN VIETNAM

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ABSTRACT

Resilient modulus (Mr) is one of the crucial parameters, which is used for the design of a multi-layer pavement system. The Mr is defined as a ratio between deviatoric cyclic axial stress to the recoverable axial strain. In general, the Mr is measured through the cyclic triaxial compression test. Besides, other tests such as light weight deflectometer (LWD) and dynamic cone penetrometer (DCP) were also employed to calculate the Mr of subgrade soil. In this study, two types of soil in Vietnam were taken and used for determining the Mr in the laboratory. Two field tests (i.e LWD and DCP) were also implemented for comparison. The results of this study show that the Mr of soil was positively related to compaction degree and confining pressure regardless of soil type. However, the changes of the Mrs under different deviator stresses varied with the type of subgrade soil. The Mr increased with the greater deviator stress for the two types of soil. Furthermore, the field LWD testing method can be effectively utilized to determine the resilient moduli of soil samples tested under similar conditions with a high level of accuracy. Finally, it was found that the dynamic penetration index has a good relationship with the dynamic deformation modulus. This correlation may thus yield a satisfactory estimation with an appropriate coefficient of determination.

1. INTRODUCTION

The resilient properties of soil are one of the basic properties that affect the short-term deformation of pavement structure. The resilient property can be employed for analyzing the mechanical properties of multi-layer systems for estimating cracking, roughness, rutting, etc. Thus, the resilient modulus (Mr) of pavement is known as an important key parameter, which is needed for the design of a multi-layer pavement system. It was reported that Mr was recommended to replace the California Bearing Ratio (CBR) for pavement design (Li et al., 2011; AASHTO, 2008). The Mr is defined as the ratio between the cyclic axial stress to the recoverable axial strain (Gabr and Borden, 2016). In general, the Mr of the subgrade layer can be determined from the laboratory test based on Standard AASHTO T-307.

Indeed, the AASHTO Guide for Design of Pavement Structures suggested that there are various approaches to determining the Mr, including laboratory testing, back computing using the results of the non-destructive test, prediction of Mr from correlations with other parameters, and estimation of Mr from of original design and construction data (Mamatha and Dinesh, 2017). It is indicated that the Mr of the subgrade is strongly affected by soil conditions (i.e. physical properties (e.g. unit weight, moisture content), soil type, and stress level). There are some studies investigated the influence of these parameters on the values of Mr. It is known that the Mr of soil is not a constant stiffness parameter, but Mr is strongly dependent on stress condition, which consists of soil type and its structure (Li and Selig, 1994), confining and deviator stress, gradation of soil, size of the specimen, compaction, and testing procedure (Zaman et al., 1994). It was reported that some factors significantly affect the Mr of subgrade. Previous studies showed that when the saturation degree and moisture content of soil increase, the Mr values decrease (Butalia et al., 2003; Heydinger, 2003). In contrast, the value of Mr increases with an increase in the soil unit weight (Allen, 1996). However, it was reported that the effect of unit weight on the Mr is small in comparison with the effect of stress level and moisture (Rada and Witczak, 1981). The increase of the deviator stress generally causes a reduction of the Mr of cohesive soil because of the softening effect (Rada and Witczak, 1981). However, the laboratory test (triaxial compression test) to determine Mr is expensive and complicated as well as time-consuming. Thus, some previous studies have been conducted to establish the empirical correlation for estimating the value of Mr using the physical properties of soil (Farrar and Turner, 1991; Hudson et

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Table 1 Physical and mechanical properties of Ninh Binh soils and Bac Giang soils.

No.	Experimental criteria	Symbol	Unit	Ninh Binh soil (A2-7)	Bac Giang soil (A2-6)
1	#200 passing	-	%	14.3	25
2	Liquid limit	LL	%	42.53	32.7
3	Plastic index	PI	%	11.69	21.21
4	Maximum dry unit weight	ρ_d^{max}	g/cm^3	1.765	1.878
5	Optimum water content	W$_{opt}$	%	17.7	17
6	CBR at 95 percent of maximum dry density (R95)	CBR	%	12.4	10.4

al., 1994). These empirical relationships reduce the laboratory expense but they cannot express the stress dependency of the Mr, or they cannot simulate the different stress conditions in the field. Many previous studies have been implemented over the past two decades to model the stress dependency of the Mr by estimating the coefficients of the constitutive model. For example, some previous studies (Mohammad et al., 2008; White et al., 2007) suggested various models for predicting the coefficients (k1, k2, and k3) of the constitutive model using the physical parameters of soils.

The prediction of the Mr was predicted using empirical models in the previous studies on the basis of physical properties and stress state (Dai and Zollars, 2002; Mohammad et al., 1999; Rahim, 2005). However, these models are only used for specific regions and these models are needed to verify in order to estimate the Mr of other local soil. Besides, it was reported various constitutive models can be used to compute the Mr as a function of stress parameters, including bulk, confining, deviatoric, and octahedral shear stress (Andrei et al., 2004; Pezo, 1993). Besides, another way is to use the expedient in-situ approaches such as dynamic cone penetrometer (DCP) and lightweight deflectometer (LWD) to predict Mr. For instance, previous studies proposed correlations to predict the Mr of subgrade using the result of LWD at specific deviatoric stress and confining pressure (Mohammad et al., 2008). Other studies predicted Mr of subgrade soil based on E_{LWD} with an assumption of Poisson's ratio and shape factor for both cohesive and cohesionless soils at a confining pressure and deviator stress (Mohammad et al., 2008; White et al., 2007). The results of these previous studies indicated that the prediction of Mr can be implemented via the result of the LWD test. Indeed, there are few studies conducted to compare the results of Mr from the cyclic triaxial test and the results of the LWD test in the world. However, up to date, there is a limited study on the Mr of subgrade soil in Vietnam condition. Thus, this is the first study that was conducted to investigate the Mr of subgrade soil in Vietnam using the cyclic triaxial compression test. For comparison, the field LWD test was also conducted for comparison. Futhermore, a Dynamic cone penetrometer (DCP) was also conducted and the relationship between the results of LWD and DCP was established.

2. MATERIALS AND METHODS

2.1. MATERIALS

In order to investigate the Mr of subgrade soil, two types of soil from two locations in two provinces (Bac Giang and Ninh Binh provinces) of Vietnam were collected. The particle distribution curves for Ninh Binh (NB) samples and Bac Giang (BG) samples are shown in Figure 1. The physical properties and mechanical properties of soil samples are shown in Table 1. Bac Giang soil is classified as A2-7, according to the AASHTO standard, whereas Ninh Binh soil is A2-6.

2.2. MEASUREMENT

2.2.1. CYCLIC TRIAXIAL COMPRESSION TEST

Before conducting the cyclic triaxial compression test, the cylindrical specimens with a diameter of 71 mm and a height of 142 mm were prepared in the laboratory via a proctor compaction test. All specimens were compacted at the optimum water content. Resilient modulus tests were conducted on the prepared soil specimens based on AASHTO T-307. The prepared soil specimens were subjected to a cyclic triaxial compression test with a specific magnitude with a load duration of 0.1 s and 0.9 s for the resting period. The cyclic triaxial compression test was conducted at different deviator stress and confining pressure levels based on the AASHTO T-307 (T307-99, 2017). In this study, 100 cycles after preconditioning of 1000 cycles were applied for each combination. The total recoverable axial strain of the specimens was recorded and used for computing the Mr. The last five cycles in each combination were used to compute the Mr and the average Mr was reported. This indicates that each specimen with different stress states have 15 values of Mr. The tests were stopped when the total vertical strain is larger than 5 % (T307-99, 2017). From the result of the cyclic triaxial compression test, a concept of cyclic resilient modulus is shown in Figure 2, the Mr can be calculated using the below equation (NCHRP, 2003).

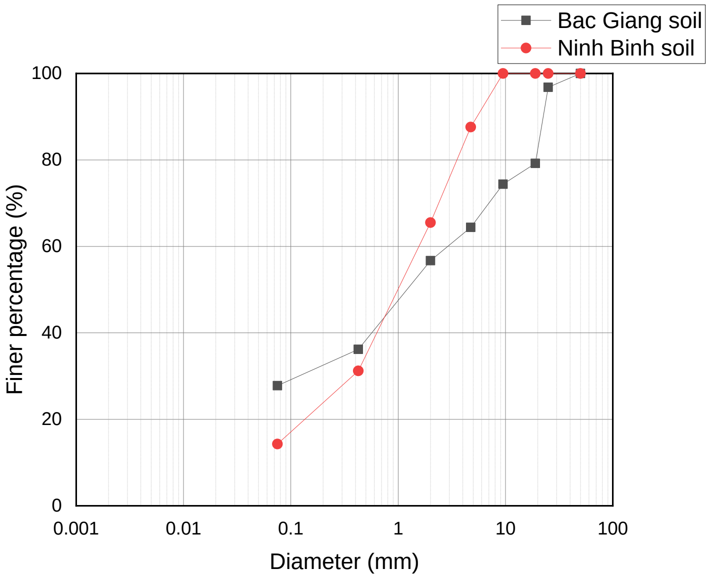


Fig. 1 Particle size distribution curve for Ninh Binh soil and Bac Giang soil.

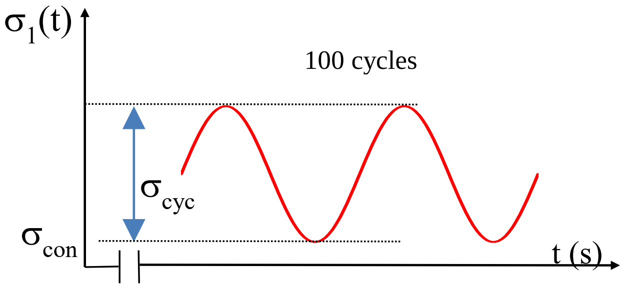


Fig. 2 Concept of cyclic resilient modulus (after NCHRP, 2003).

$$M_r = \frac{\Delta\sigma_d}{\Delta\varepsilon_{axial}} \quad (1)$$

where $\Delta\sigma_d$= deviatoric stress, $\Delta\varepsilon_{axial}$= recoverable axial strain.

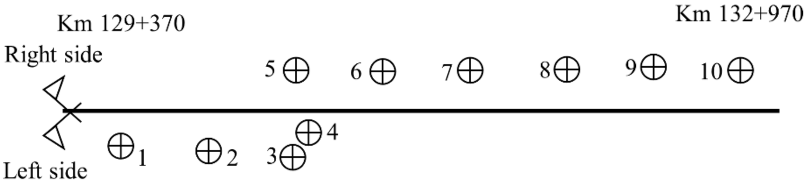
2.2.2. *LIGHT WEIGHT DEFLECTOMETER (LWD)*

To evaluate as well as analyze the application of two soil types for the subgrade filling at field construction, the in-situ lightweight deflectometer (LWD) apparatus was employed to determine the dynamic deformation modulus (E_{vd}) of compacted materials by measuring deflection using a known force. By analyzing the relationship between deflection and material modulus under specific force conditions, the LWD device provides the in-situ modulus of geomaterials. This modulus is an essential parameter used to evaluate the properties of pavement structural layers. The apparatus used in this study has a plate with a diameter of 300 mm, a drop weight of 15 kg with a distance of up to 525 mm, and a maximum falling force of 20 kN. The procedure for conducting the LWD test was according to the ASTM E2583-20 ("ASTM E2583-2020 - Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)," n.d.). The LWD test was performed on 10 points at the subgrade belonging to the Bac Giang highway asphalt pavement in Vietnam to compare with the Mr values obtained by the cyclic triaxial compression test in the laboratory, as shown in Figure 3. The applied load ring was 5 kN corresponding to 70 kPa applied vertical axial stress for all testing points. Before LWD testing, the content of moisture and compaction degree of all points were checked, and the results confirmed that their moisture content and compaction degree were closer to the optimum moisture content and above 95 % relative compaction, respectively.

2.2.3. *DYNAMIC CONE PENETROMETER (DCP)*

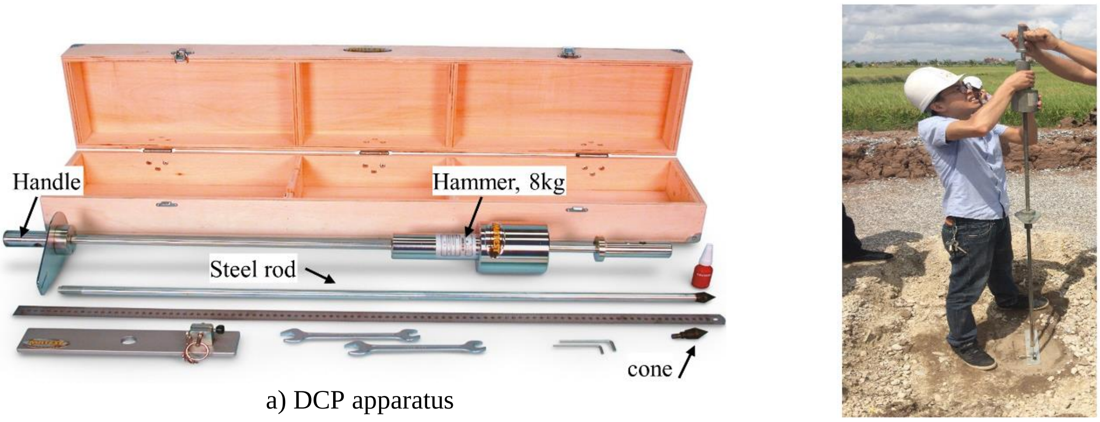
The dynamic cone penetrometer (DCP) has been shown to be an economical and efficient method for determining soil strength profiles (Du et al., 2016). This testing method is not only quick and simple but also highly portable, allowing for the characterization of granular materials in the field. This test was performed according to ASTM standard D6951-18 (ASTM D6951/D6951M). The DCP device in this study consists of a 15.8 mm diameter steel rod connected to a cone with a 20 mm base diameter and a 60-degree cone angle. The device is driven into the

a) LWD test at the field



b) Testing points at the subgrade soil

Fig. 3 Field LWD test on the subgrade soil belonging to the Bac Giang Highway asphalt pavement in Vietnam.



a) DCP apparatus

b) DCP test

Fig. 4 The DCP apparatus and test at the field.

soil by an 8 kg hammer, falling from a height of 575 mm, as shown in Figure 4. In this study, the positions for the DCP test were 1.0 m horizontally away from the corresponding LWD testing points. From the DCP test, the dynamic penetration index (DPI) is a parameter that is derived from the relationship between the penetration depth (measured in millimeters) and the number of blows (referred to as "blow") and calculated through the following Eq. (2) (ASTM D6951):

$$P_I = \frac{\Delta D_P}{N} \tag{2}$$

where P_I is the dynamic penetration index, mm/blow; ΔD_P and N are the penetration depth (mm) and the total number of blows (blow), respectively.

3. RESULTS AND DISCUSSION

3.1. *RESULTS OF CYCLIC TRIAXIAL COMPRESSION TEST*

The degree of compaction plays a crucial role in the subgrade design of highway asphalt pavement in Vietnam. Hence, the effect of the degree of compaction K, including 95 % and 98 % relative compactions, and soil type on the resilient modulus of specimens was investigated in this section. The optimum water contents obtained from standard Proctor test results of original aggregates were used to estimate the water contents for preparing the resilient modulus test specimens. One hundred cycles of loading-unloading were applied at each cyclic stress for all specimens to eliminate the effect of the number of loads on the results. Besides, 1000 cycles were

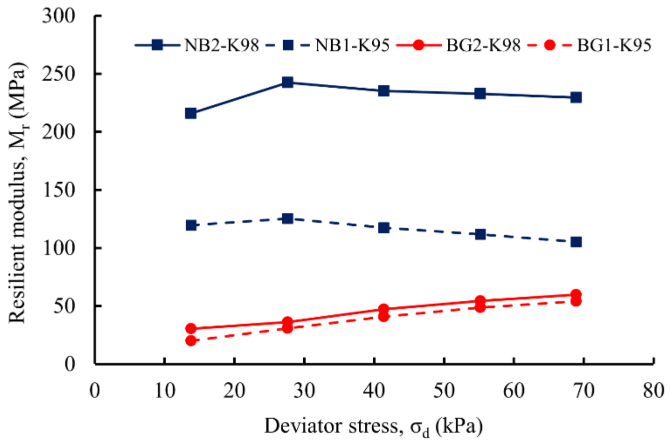
Table 2 The results of the triaxial loading sequence of all soils.

Sequence No.	Confining pressure (kPa), σ_3	Deviator Stress (kPa), σ_{max}	Resilient Modulus (MPa), M_r			
			NB1-K95	NB2-K98	BG1-K95	BG2-K98
1	41.4	13.8	119.6	215.8	20.0	30.4
2	41.4	27.6	125.5	242.2	30.8	36.2
3	41.4	41.4	117.3	235.4	41.0	47.4
4	41.4	55.2	111.7	232.7	48.7	54.3
5	41.4	68.9	105.4	229.6	54.2	59.8
6	27.6	13.8	114.0	213.6	19.4	30.5
7	27.6	27.6	115.1	239.4	29.0	34.1
8	27.6	41.4	107.4	246.3	38.6	43.4
9	27.6	55.2	101.9	236.9	46.2	50.7
10	27.6	68.9	98.4	234.0	52.0	56.6
11	13.8	13.8	104.9	213.1	18.7	27.0
12	13.8	27.6	105.4	237.9	27.2	31.0
13	13.8	41.4	100.6	230.5	36.2	39.8
14	13.8	55.2	95.7	226.9	43.3	46.7
15	13.8	68.9	91.7	232.2	48.6	50.7

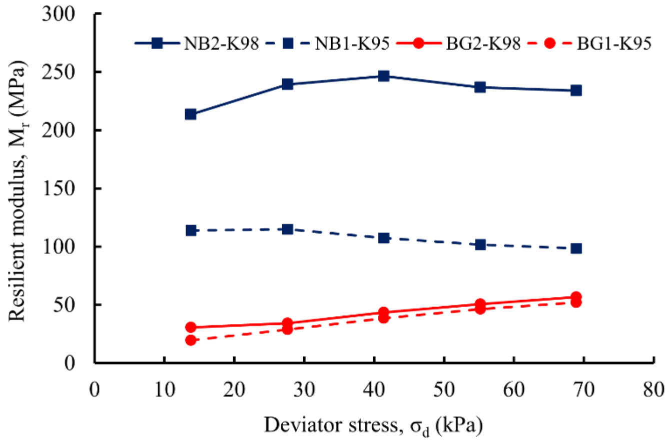
applied with a constant confining pressure (σ_3) of 41.4 kPa and deviator stress (σ_d) of 27.6 kPa to eliminate the imperfect contact between the specimens and the caps as well as minimize the plastic strain. The results of the resilient modulus of all soils are presented in Table 2.

Figure 5 shows the resilient modulus of specimens with different degrees of compaction K. As expected, the resilient modulus of specimens is positively correlated with K depending on confining pressure or soil types. It means that the increase in the degree of compaction led to the improvement of the resilient modulus of specimens. For example, the resilient moduli of NB2-K98 at a confining pressure of 41.4, 27.6, and 13.8 kPa were increased by 80.3-117.9 %, 87.3-137.8 %, and 103-153 % in comparison with those of NB1-K95 since σ_{max} ranged from 13.8 to 68.9 kPa. Meanwhile, the resilient moduli of BG2-K98 at a confining pressure of 41.4, 27.6, and 13.8 kPa were increased by 10.3-51.8 %, 8.9-57.2 %, and 4.3-44.2 % in comparison with those of BG1-K95 when σ_{max} ranged from 13.8 to 68.9 kPa. The results are in agreement with the observation by previous studies (Liu et al., 2019, 2023). Since the compaction degree was increased, the air voids in the specimens were decreased, leading to an improvement in density, deformation resistance, and resilient modulus. In pavement construction, density is often used as a quality control parameter, as it provides an indication of the degree of compaction achieved during construction. However, for pavement design and analysis, the concept of modulus is more relevant, as it represents the ability of the material to resist deformation under load. Consequently, the correlation between density and resilient modulus is further essentially investigated for determining the suitable compaction degree for subgrade soil based on the required modulus for pavement design.

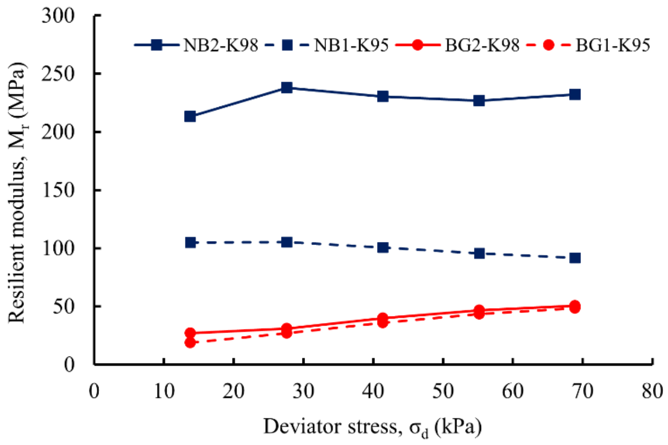
On the other hand, it is clear that the soil type also affected the Mr as shown in Figure 6. Accordingly, the resilient moduli of NB specimens were significantly higher than those of BG specimens irrespective of confining pressures or compaction degrees. It is due to the effect of different physical properties, as can be seen in Table 1. This observation is agreed with the reports from previous research works (Nguyen and Mohajerani, 2016). In addition, a previous study (Han and Vanapalli, 2016) suggested that the increase in confining stress could lead to a higher resilient modulus of the specimen. This can be attributed to the reason that the lateral expansion during axial cyclic loadings is more restricted by the increase in confining stress, which in turn enhances the stiffness. However, this suggestion could be obviously observed in the case of a compaction degree of 95 %, as shown in Figure 6a. Meanwhile, it can be seen from Figure 6b that the difference in resilient modulus due to the variable confining pressure was negligible regardless of soil type. It means that the effect of confining pressure on the resilient modulus of soil was noteworthy as the compaction degree was low. Interestingly, the resilient modulus of BG specimens was significantly increased since the deviator stress increased, whereas that of NB specimens was slightly decreased at the compaction degree of 95 %. At compaction degree of 98 %, the resilient modulus of NB specimens was not noticeably changed while that of BG specimens was slightly increased as the deviator stress increased. Kim and Kim (2007) mentioned that the resilient modulus either decreased slightly or reached constant values while the level of deviator stress was greater for cohesive subgrades. In contrast, the resilient modulus of granular materials could be increased. This trend could be observed by Liu et al. (2023).



a) Confining pressure, σ_3 = 41.4 kPa



b) Confining pressure, σ_3 = 27.6 kPa



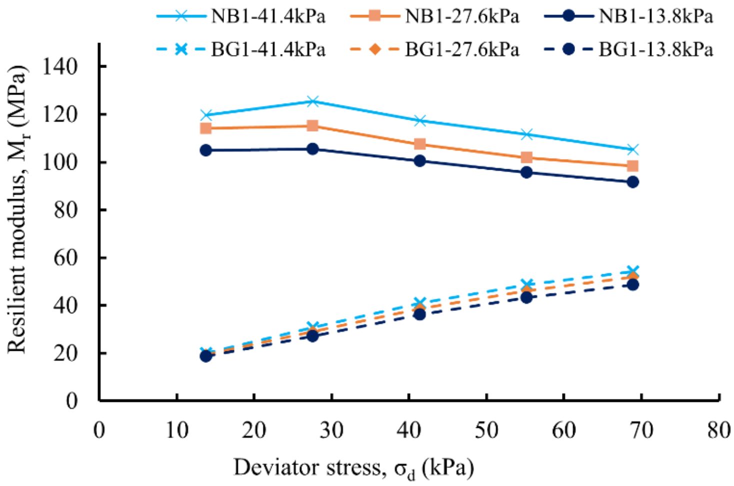
c) Confining pressure, σ_3 = 13.8 kPa

Fig. 5 Resilient modulus of samples under different confining pressure.

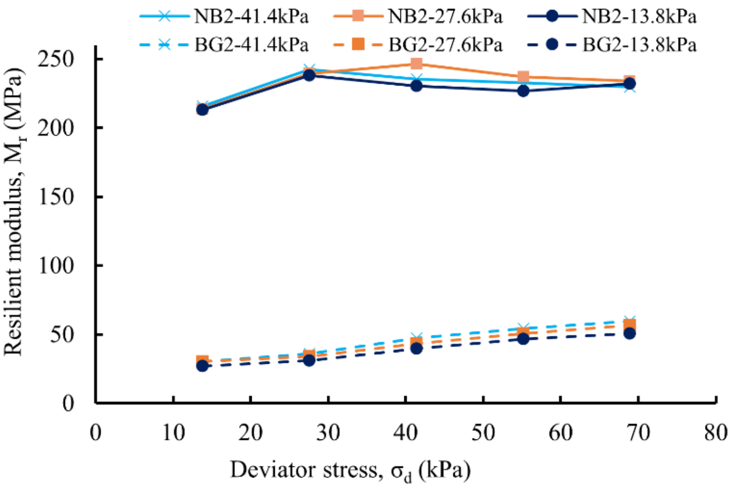
3.2. RESULTS OF LWD TEST

Kuttah (2021) concluded that the field LWD test could yield satisfactory outcomes for sandy soil following approximately 10-12 drops, as the plastic deformations were negligible, and the soil remained in an elastic state. Hence, the field LWD test in this study was carried out with at least 10 drops for each testing point. The results of the LWD test with the applied vertical axial stress of 70 kPa are shown in Table 3.

The comparison between resilient modulus from the cyclic triaxial compression test and dynamic deformation modulus from the LWD test is depicted in Figure 7. The values of resilient modulus measured from cyclic triaxial compression test were plotted as diamond symbols, whereas those of dynamic deformation modulus determined from LWD test were noted as circles symbols in Figure 7. It is worth noting that the LWD test and the cyclic triaxial compression



a) Compaction degree of 95



b) Compaction degree of 98

Fig. 6 Resilient modulus of samples under different degrees of compaction.

Table 3 The results of the field LWD test.

Testing point	1	2	3	4	5	6	7	8	9	10
Dynamic deformation modulus, E_{vd} (Mpa)	57.0	61.2	54.3	42.7	69.2	56.1	49.8	87.2	66.6	63.1

test differ mainly in their testing conditions and characteristics, such as the lateral confinement and drainage conditions. Hence, it is impossible to execute these two types of tests using the exact same testing procedure. However, it can be seen from Figure 7 that the dynamic deformation modulus results obtained under a vertical axial stress of 70 kPa nearly matched those of the Mr at an axial stress of 68.9 kPa when the LWD test was performed on the same soil with a compaction degree similar to that of the corresponding the cyclic triaxial compression test. This suggests that the field LWD test can be a reliable method for accurately estimating the resilient moduli of the same soil when tested under comparable conditions.

3.3. RESULTS OF DCP TEST

In this study, the DCP test at each point was stopped when the penetration depth was lower than 2 mm after 5 blows. The results of the DCP test are shown in Table 4. It is worth noting that predicting geotechnical parameters is a crucial aspect of civil engineering as it enables a better understanding of soil behavior during the design process. Establishing suitable correlations between different parameters is essential for achieving this objective. Moreover,

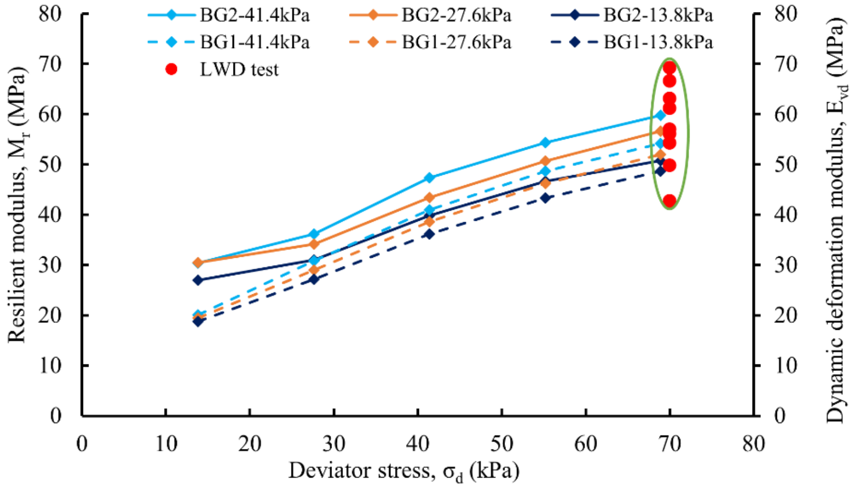


Fig. 7 Comparison between M_r and E_{vd}.

Table 4 The dynamic penetration index on subgrade soil.

Testing point	1	2	3	4	5	6	7	8	9	10
Dynamic penetration index, P_I (mm/blow)	35.3	33.1	37.4	39.6	35.0	37.5	36.0	25.9	32.0	32.4

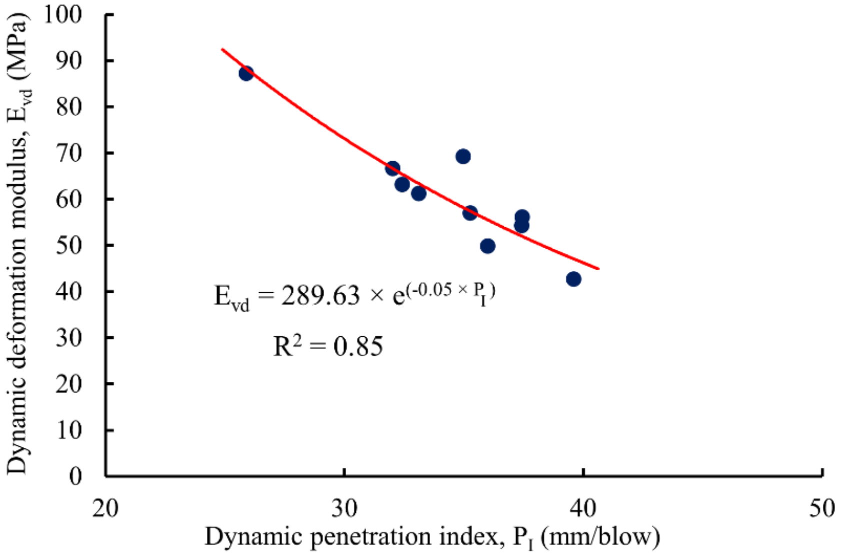


Fig. 8 Relationship between dynamic penetration index and dynamic deformation modulus.

conducting multiple tests on soil samples for geotechnical studies can be expensive, and predicting the primary soil parameters can significantly reduce the overall project costs. Meanwhile, the DCP test is a simple, lightweight, and cost-effective device that can be used with minimal training and in a short amount of time. Vakili et al. (2021) concluded that the dynamic penetration index has a strong correlation with other many soil engineering parameters. Hence, the approximate correlation between the dynamic penetration index and other factors, i.e., dynamic deformation modulus was established and shown in Figure 8. Obviously, there is a negative relationship between the dynamic penetration index and the dynamic deformation modulus. In other words, the dynamic penetration index increased as the dynamic deformation modulus of soil decreased. According to Rahmani et al. (2012), an R^2 value of 0.70 or higher is adequate for accurate and dependable prediction equations. Hence, the equation obtained from Figure 8 (R^2 = 0.85) can be effectively utilized to predict the correlation between the dynamic penetration index and the dynamic deformation modulus of the subgrade of this highway project in Vietnam. However, further investigation on this relationship of other soils or the correlation between dynamic penetration index and other characteristics should be done to obtain a good view of soil behaviors.

4. CONCLUSION

This paper presented a study of the resilient behavior of two tropical subgrade soils from Vietnam considering the effect of compaction degree and deviator stress level. The study was based on not only laboratory tests using cyclic triaxial compression tests but also site construction tests using LWD and DCP. Based on the results, some conclusions can be drawn as follows:

- The resilient modulus of soil was positively related to compaction degree and confining pressure regardless of soil type. However, the changes of the resilient modulus under different deviator stresses varied with the type of subgrade soil. The resilient modulus increased with the greater deviator stress. This observed behavior is typical for granular soils.
- The field LWD testing method can be effectively utilized to determine the resilient moduli of soil samples tested under similar vertical axial stress with a high level of accuracy.
- It was found that the dynamic penetration index has a good relationship with the dynamic deformation modulus. This correlation may thus yield a satisfactory estimation with an appropriate coefficient of determination.

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