Water content and modulus relationship of a compacted unsaturated soil

Zhang Dingwen Liu Songyu Zhang Tao

(School of Transportation, Southeast University, Nanjing 210096, China)

Abstract: In order to assess the performance of the embankment soil under various climate conditions during the period of service, the modulus behaviour of an unsaturated compacted soil is evaluated using the constant water content triaxial test. Since the water content measurement method is simple and economical and it is used widely in engineering, the soil suction is replaced by the water content and the relationship between the water content and the modulus is developed. The compacted samples are prepared with different compacted water contents, and samples with a similar water content subjected to drying or wetting procedures prior to the triaxial test are also investigated. The effect of the water content and the confining pressure on the modulus is analyzed. The results show that the modulus decreases with the increase in the water content and a power function can be proposed to quantitatively describe the relationship between the modulus and the water content in the range of the measured water content. The modulus increases with the increase in the confining pressure of the compacted soil. However, the effect of the water content on the modulus is more pronounced than that of the confining pressure. This research can be referenced for the compacted embankment soil assessment in-service period.

Key words: modulus; water content; unsaturated compacted soil

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The compacted embankment is often in an unsaturated state upon the ground surface. Due to the rising water table, infiltration, evaporation and traffic loading, the water content of the compacted embankment soil is changed over the service life of the embankment irrespective of the initial water content imposed during construction[1−3]. In order to assess the embankment performance, the influence of water content variations should be considered in such a way that the anticipated in-service conditions are taken into account[4].

In fact, numerous researchers have performed field investigations on the water content changes in embankment subgrade soil during the post-compaction state[5−7]. It appears that under a given environmental and climatic regime, the water content of subgrade soil eventually reaches equilibrium after construction and this is referred to as the equilibrium water content[6]. Since the soil water characteristic curve[8] has been extensively used in the study of the unsaturated soil and it relates to the water content and soil matric suction, the equilibrium water content can be represented by the soil suction and it is correlated to the average value of the Thornthwaite climatic index I_m. The Thornthwaite climatic index is a characteristic of a site's climatic influence over a distinct period[4]. For instance, Perana et al.[9] advised that the equilibrium soil suction value of subgrade soil can be determined based on the average I_m value and the soil index properties.

Modulus E presents the stress-strain behaviour of soil and it has been widely used in various constitutive models of soils. The modulus is sensitive to the water content and the stress state of soils. Therefore, it is important to understand the influence of water content variations on the modulus. A number of experimental investigations have focused on the relationship of the suction or water content with the modulus of soil[7−8, 10−12]. From the previous investigations, the modulus is related to the soil suction, and higher soil suction results in a higher modulus. Some recent studies[4, 13] have also investigated the influence of matric suction on the small-strain shear modulus.

Recently, interest in directly introducing water content into the assessment of the mechanical behaviour of the unsaturated soil has increased markedly[14−15]. This is because the measurement of suction is often tedious and time-consuming while the measurement of the water content is simple and economical. It is a suitable choice to use the water content replacing the suction, at least for engineering practice.

The objective of this study, therefore, focuses on relating the modulus of the unsaturated compacted soil to the water content. Knowing the relationship between the modulus and the water content for a given soil type and the compaction effort, the change in the modulus of the compacted soil can be estimated from the given ranges of the equilibrium water content value over the service life of the embankment. Therefore, a series of constant water

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Biography: Zhang Dingwen (1978—), male, doctor, associate professor, zhangdw@seu.edu.cn.

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content triaxial tests are conducted on samples compacted with various initial water contents and compacted samples after drying and wetting in an unsaturated state.

1 Materials and Method

1.1 Material

The soils used in this investigation are obtained from the Nafferton Farm near Newcastle upon Tyne, UK. The soil is sampled at 2.0 m depth under the ground surface. In order to reduce the variations in densities of the compacted samples, the material is sieved through a 2.0 mm sieve to remove large particles. The properties of the soil are shown in Tab. 1. The clay has a low plasticity with a liquid limit of 43.3% and a plastic limit of 23.7%. Based on the wet sieving and hydrometer analysis, the soil used in this research consists of 27.8% sand and 72.2% fines (37.7% silt and 34.5% clay). The clay activity of the soil material is 0.57, classifying the soil as an inactive clay. The optimum water content and the maximum dry density are $w_{\mathrm{opt}} = 15\%$ and $\gamma_{\mathrm{d,max}} = 1.719\ \mathrm{mg/m^3}$ with a modified proctor procedure, in accordance with BS 1377[16].

Tab. 1 Property parameters of the soil

Water content/%	Special gravity	Liquid limit/%	Plastic limit/%	Plasticity index	Particle size distribution/%		
					Sand (>0.075 mm)	Silt (0.075 to 0.002 mm)	Clay (< 0.002 mm)
22.6	2.70	43.3	23.7	19.6	27.8	37.7	34.5

1.2 Sample preparation

The soil is dried in the atmosphere and then is sieved through a 2.0 mm mesh to remove large particles. After the soil is oven dried for a minimum period of 24 h, a desired distilled water is added to achieve the desired water content. A kitchen stand mixer is used to mix the water into the clay for a total mixing time of 10 min. Upon the completion of mixing, the soil is put into a plastic bag and is left to equalise for 24 h for homogenisation of the water content within the soil. Finally, the soil is compacted using a dynamic compaction machine.

Samples are compacted as 100 mm in diameter and 200 mm in height with the modified proctor procedure, in accordance with BS 1377[16]. Since the field embankment fill is usually compacted with an optimum water content, in order to study the effect of the initial compaction water content, the samples are compacted at three different levels of compaction water content: 7% wet of optimum, 5% wet of optimum and near optimum with the modified proctor effort. After compaction, the sample is extracted from the mold and its initial weight, height and diameter are measured.

In addition, to simulate the in-service water content of the soil under various climate conditions, it is decided to perform constant water triaxial tests on samples with different water contents under the same initial conditions. In other words, samples with similar water content will be subjected to drying or wetting procedures, prior to the triaxial testing, in order to replicate different stages of the subgrade in service with various climate conditions[17].

The drying procedure employed is air drying. Samples are left to dry in the atmosphere, while the sample mass is continuously measured. This is carried out inside a temperature controlled laboratory to ensure constant conditions (temperature) while drying. As soon as the sample reaches the target mass (and hence target water content), it is wrapped in a cling film and left to equalise. By sealing the sample and allowing a period of equalisation, the water inside the sample should distribute in a more homogeneous form.

The procedure to increase the water content within the sample is a more laborious system when compared to the drying procedure. The samples are subjected to the wetting process developed by Mendes[17] by using mini-foggers. After wetting, the samples are wrapped in a cling film and left to equalise. Mendes[17] verified that this method can wet the samples homogeneously and uniformly.

Tab. 2 summarizes the compacted water content, the water content after drying and wetting processes, the dry density, the void ratio and the degree of saturation of the specimen. Each test is identified in the forms Cxx(yy) by the compacted water content (xx) and the confining pressure (yy) for compacted samples, Dxx-zz(yy) for samples dried from the compacted water content (xx) to the water content before the triaxial test (zz) and Wxx-zz (yy) for samples wetted from the compacted water content (xx) to the water content before the triaxial test (zz).

1.3 Test methods

Constant water content tests are carried out on all the samples listed in Tab. 2 using the Wykeham Farrance double cell triaxial cell. The constant water content triaxial test consists of two stages. First, the specimen is subjected to constant water content compression under isotropic conditions at a fixed confining pressure until the volume stabilizes and the pore water pressure equilibrates. Then the specimen is sheared under constant water content conditions by increasing the deviator stress. In each test, the shearing stage is continued to reach 20% strain to attempt to observe ultimate conditions.

Tab. 2 Summary of samples for triaxial test

Test number	Compacted water content/%	Water content before triaxial test/%	Dry density/ (g · cm^{-3})	Void ratio	Degree of saturation/%
C15(50)	14.77	14.77	1.839	0.47	87.91
C15(50)	14.75	14.75	1.931	0.48	83.77
C15(150)	15.17	15.17	1.815	0.49	83.80
C15(300)	14.62	14.62	1.837	0.47	83.87
W15-19(150)	15.21	18.45	1.715	0.58	93.83
W15-19(300)	15.44	19.37	1.693	0.60	90.56
W15-20(50)	14.61	19.70	1.732	0.56	96.51
W15-20(150)	15.09	19.75	1.667	0.62	95.84
W15-22(50)	14.67	22.00	1.659	0.63	94.43
C20(50)	19.41	19.41	1.748	0.55	96.08
C20(150)	19.77	19.77	1.728	0.56	94.77
C20(300)	19.64	19.64	1.728	0.57	93.55
C20(300)	20.17	20.17	1.709	0.58	93.69
D20-15(50)	19.72	15.08	1.828	0.48	85.11
D20-15(150)	19.15	15.56	1.792	0.51	82.76
D20-15(300)	18.75	15.19	1.816	0.49	84.05
W20-21(150)	19.24	20.68	1.677	0.61	95.12
W20-22(50)	19.40	21.53	1.709	0.58	96.08
W20-22(300)	19.89	21.29	1.670	0.62	92.99
C22(50)	21.82	21.82	1.621	0.67	88.34
C22(150)	21.16	21.16	1.609	0.68	88.03
C22(300)	22.01	22.01	1.624	0.66	89.50
D22-20(50)	21.96	19.98	1.678	0.61	88.41
D22-20(150)	21.92	19.78	1.680	0.61	87.80
D22-20(150)	22.09	20.08	1.649	0.64	84.94
D22-19(150)	21.37	19.04	1.651	0.64	80.84
D22-16(50)	21.45	16.84	1.782	0.52	88.13
D22-16(300)	21.00	15.80	1.811	0.49	86.65
D22-14(150)	21.74	13.97	1.930	0.48	79.18

1.4 Definition of modulus

The modulus presents the stress-strain behaviour of soils and it has been widely used in various constitutive models of soils. The modulus is mathematically defined by the ratio of the deviator stress to the axial strain[18], as shown in Fig. 1. To investigate the influence of the non-linear stress-strain characteristic of soils on the modulus, three moduli are defined: the initial modulus with respect to 0.5% axial strain E_{initial}, the tangent modulus with respect to the maximum deviator stress E_t, and the tangent modulus with respect to 50% maximum deviator stress E_{50}. If the specimen exhibits a ductile behaviour in the deviator stress and axial strain curve, the stress at 15% of axial strain is regarded as the maximum deviator stress.

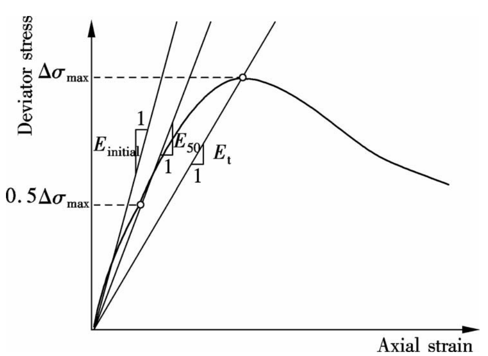

Fig. 1 Definition of modulus

2 Test Results and Discussion

2.1 Typical stress-strain curves of compacted soil

Fig. 2 presents the typical deviator stress and axial strain curves of compacted samples with similar initial water content and samples subjected to drying or wetting processes. It is clear that the sample with a low water content, i. e., 15%, manifests brittle behaviour, showing abrupt drops in post-peak stress with the strain. While the samples with a high water content, i. e., 20% and 22%, become much more ductile, showing the stress increasing gradually with the strain.

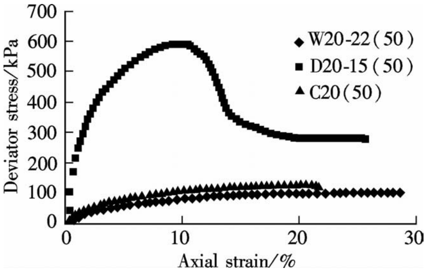

Fig. 2 Typical deviator stress and axial strain curves of compacted samples

The specimen subjected to the wetting procedure prior to the triaxial testing leads to an increase in water content, indicating that the soil specimen absorbs water to reach equilibrium. This process leads to the volume of the sample increasing and the density of the sample decreasing when the specimen is wetted from a compacted condition. Consequently, the modulus of the wetted specimen decreases compared with that of the compacted condition. Contrarily, the drying process indicates the volume of the sample decreasing and the density of the sample increasing, which results in the increase in the modulus. On the other hand, the wet of the optimum compacted specimen tends to exhibit a weaker soil fabric with respect to the optimum compacted specimen, which results in a lower modulus.

2.2 Effect of water content on modulus

The relationships between the moduli and the water content for specimens compacted with different water contents and specimens drying and wetting to various water contents are illustrated in Fig. 3. As expected, moduli increase as the water content decreases (i. e., following the drying process) for the range of water contents measured. A consistent tendency has also been observed by numerous researchers[4, 9–10, 12, 14]. A good correlation can be observed between the moduli (E_{initial}, E_{50}, E_t) and water content investigated, which can be expressed as a power function as follows:

$$E = aw^{-b} \tag{1}$$

where a and b are fitting parameters.

Fig. 3 also shows that higher moduli tend to occur for the specimens with a lower water content, which is attributed to the high suction of the specimens with a lower water content. The relationships between E_{50} or E_t and the water content show a higher coefficient of determination than that between E_{initial} and the water content. The axial displacement measure error due to the contact of the measurement system may be responsible for this. It is also clear that E_{initial} exhibits a higher value than E_{50} and E_t due to the nonlinear stress and strain behaviour of the soil.

According to the desiccation cracking tests of the soil, Kodikara et al.[19] presented a relationship between the modulus with respect to matric suction H and water content w as $H = 3E10w^{-4.0697}$, where H is given in kilopascals. The Young modulus E can be estimated by

$$E = H(1 - 2\mu) \tag{2}$$

where μ is the Possion ratio of the soil. A Poisson ratio of 0.45 can be used since the soil remains close to saturation[20]. Therefore, the change of the Young modulus E can be represented as

$$E = 3E9w^{-4.0697} \tag{3}$$

It is interesting that both sets of test results show similar trends and similar characteristics, although Kodikara et al.[19] carried out the tests from the saturated soil (i. e. a wide range of water content) while this study carries out the tests on unsaturated compacted soil (i. e. a narrow range of water content). The different fitting parameters respond for different properties of the soil (i. e., percent fines, mineral plasticity index).

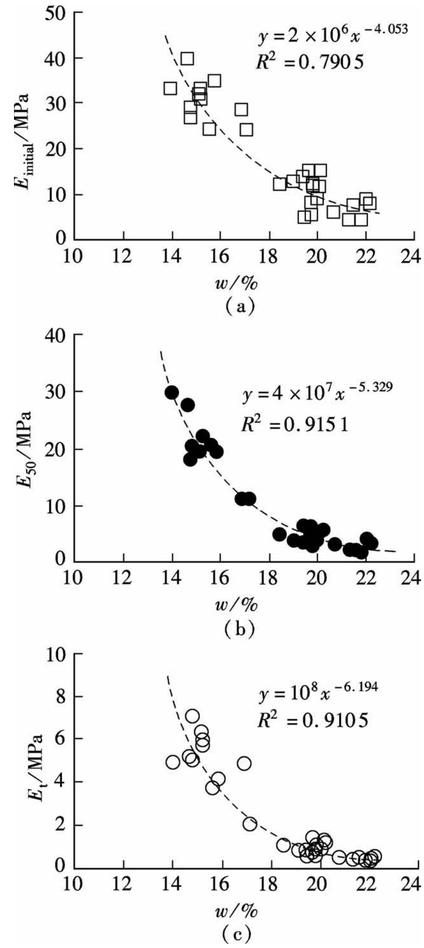

Fig. 3 Relationships between moduli and water content. (a) E_{initial}; (b) E_{50}; (c) E_t

2.3 Effect of confining pressure on modulus

For the sake of simplicity, only the variation tendency of E_{50} is reported and discussed in the following sections. Fig. 4 shows the variation tendency of E_{50} and the water content with various confining pressures. It can be seen that the increase in the confining pressure results in a higher modulus due to a tighter soil particles structure. In order to clearly comprehend the effects of the confining pressure, the E_{50} variation tendency is plotted with various water contents in Fig. 5. As shown in Figs. 4 and 5, the effects of the confining pressure on E_{50} becomes smaller as the water content increases, although there is a certain variability in the test results.

However, compared with the influence of the water content on E_{50}, the confining pressure has a less remarkable influence on E_{50}. According to Ref. [8], the suction in a given soil may be approximated by the exponential formula. A relatively small decrease in the water content of soil due to the drying results in a sharp suction increasing in an unsaturated state, which yields a close soil particles structure. Therefore, the water content has a more distinct influence on E_{50} than the confining pressure.

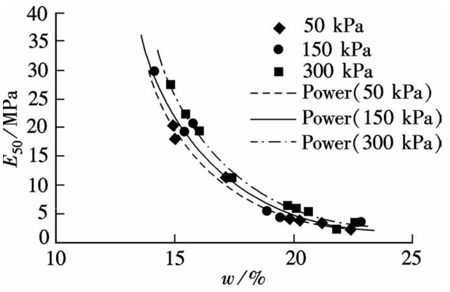

Fig. 4 Effect of confining pressure on E_{50}

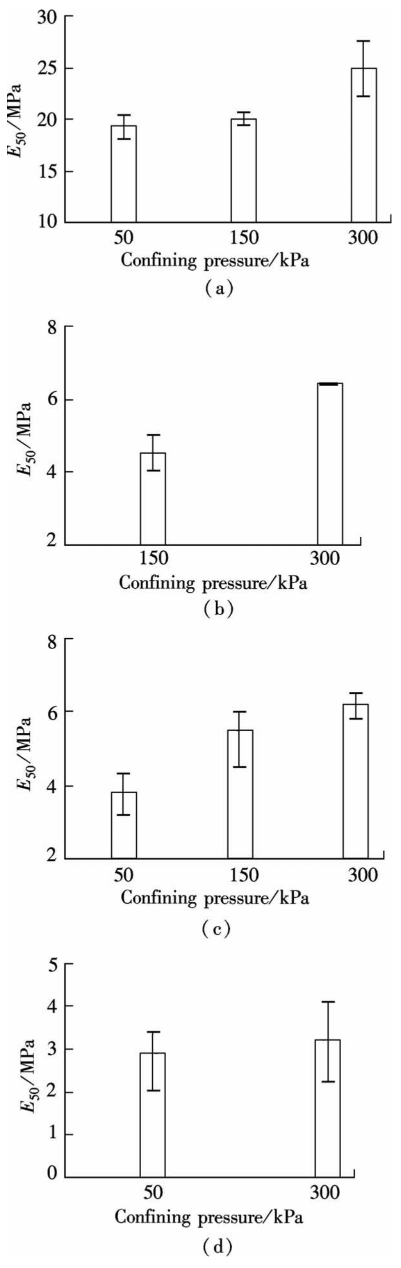

Fig. 5 E_{50} with various water contents and confining pressures. (a) $w=15\%$; (b) $w=19\%$; (c) $w=20\%$; (d) $w=22\%$

2.4 Effect of drying and wetting on modulus

In order to investigate the influence of water content history (i. e., the dry and wetting processes) on the modulus, test data in Fig. 3(b) is replotted in Fig. 6 for each sample treatment type respectively (i. e., samples tested at the compacted water content, wetting and drying water contents, respectively). It should be pointed out that the samples in this study just experienced drying or wetting processes once.

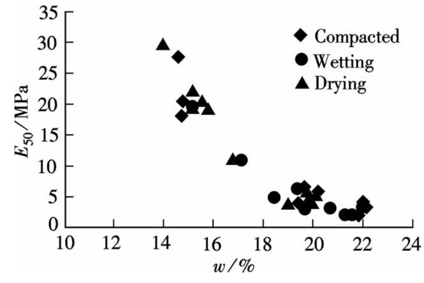

Fig. 6 Effect of drying and wetting on E_{50} of samples

As shown in Fig. 6, it is difficult to distinguish the influence of the water content history on the relationship between modulus E_{50} and the water content from this test results. Modulus E_{50} mainly depends on the water content. It should be noted that the specimens in this study are just subjected to a monotonous drying or wetting process. Zhang et al.[20] reported that repeated drying and wetting cycles irreversibly decrease the strength behaviours of unsaturated soil; therefore, the influence of repeated drying and wetting cycles on modulus E_{50} requires additional research.

3 Conclusions

The behaviour of the modulus of compacted unsaturated soil is evaluated using the constant water content triaxial tests. The compacted samples are prepared with different compacted water contents. Moreover, to simulate the in-service water content when soil is subjected to various climate conditions, samples with a similar water content are subjected to drying or wetting procedures prior to the triaxial testing. The following conclusions can be drawn:

1) In general, moduli increase with the decrease in water content. A power function is proposed to quantitatively describe the relationship between moduli and water contents. Test results reported in literature are used to verify the proposed function. Different fitting parameters represent different soil index properties.

2) The increase in the confining pressure results in a higher modulus and the effect of the confining pressure on the modulus becomes smaller as the water content increases.

3) The water content has a more remarkable influence than the confining pressure on the tangent modulus due to the sharp suction variation with water content variation.

4) Modulus E_{50} mainly depends on the water content. The influence of repeated drying and wetting cycles on

the modulus requires additional research.

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压实非饱和土的模量与含水率关系分析

章定文　　刘松玉　　张　涛

(东南大学交通学院,南京 210096)

摘要:为了客观可靠地评价实际工程中路基压实土的工程性能,在路基填筑设计时考虑了道路实际服务期内气候变化对路基压实土性能的影响. 鉴于含水率测试方法简单且应用广泛,直接采用含水率代替吸力寻求压实非饱和土模量和含水率之间的联系. 采用非饱和土三轴仪对不同初始压实含水率和经历干湿过程后不同含水率土样进行常含水率三轴试验,分析了含水率和围压等对土体模量的影响规律. 研究结果表明:土体含水率的增加会引起非饱和压实土体模量的降低,且在试验含水率范围内非饱和压实土体模量随含水率呈指数规律变化;土体模量随围压的增大而增加,但含水率对模量的影响较围压对模量的影响更为显著. 该研究可为服务期内非饱和压实路基土的性能变化评价提供参考.

关键词:模量;含水率;非饱和压实土

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