The Next Generation of Testing with LWD to Assess the In-Situ Permanent Deformation of Geomaterials under Repeated Loading

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ABSTRACT

This study focuses on evaluating in-situ permanent deformation in fine-grained soils through the application of a specially designed Repeated Light Weight Deflectometer (LWD) test. The primary objective is to investigate how water content and applied stress levels influence permanent deformations in the field. Additionally, the study aims to assess the utility of LWD-derived data in predicting permanent strains. Results indicate a significant correlation between permanent deformations and key parameters, such as the number of load cycles, applied stress levels, and water content. It is observed that permanent deformations increase proportionally with these variables, particularly in cases of elevated water content and higher stress levels. The soil demonstrates an increased susceptibility to accumulating permanent deformations, persisting even after numerous LWD load applications. In response to these findings, a predictive model is presented to estimate accumulated permanent strain, exhibiting a commendable fit to data for moisture contents up to 22%, corresponding to an average water content of 19%. Ultimately, this research underscores the pivotal role of water content and applied stress levels in determining permanent deformation characteristics in fine-grained subgrade soils. The study also provides a valuable predictive model derived from repeated in-situ LWD measurements, offering critical insights into the field permanent deformation behaviour of subgrade soil. This simple and time-saving test enhances engineering practices for pavement design and construction.

Keywords: Accumulated permanent deformations; applied stresses; in-situ tests; repeated light weight deflectometer; modelling; water content.

1. Introduction

Geotechnical failures often result from inadequate recognition or evaluation of conditions prior to the construction of the pavement system. The stiffness and strength of unbound subgrade materials are critical factors in pavement failure. Stiffness modulus (Mr) has gained attention as a material stiffness concept, but its testing is costly and time consuming. Existing pavement design standards rely on simpler and faster tests such as static plate loading and CBR, but these may not efficiently correlate with dynamic responses under actual traffic loads. Bridging this gap, especially for Mechanistic-Empirical Pavement Design (MEPD), requires the estimation of material properties through simple dynamic tests, preferably in the field (Kuttah 2020).

This study focuses on evaluating the efficiency of the Light Weight Deflectometer (LWD) in calculating dynamic moduli of fine-grained subgrade soils in situ. Numerous LWD tests were carried out to measure the dynamic deformation moduli of clayey subgrade soils, eliminating plastic deformation and capturing elastic deformation. The procedure proved useful in estimating the dynamic behaviour of the selected soil.

Permanent deformation (PD) in geomaterials contributes significantly to surface rutting, which affects ride quality Puppala et al (2009). The accumulation of PD depends on factors such as stress levels, load cycles, material strength, loading history, stress rotation, moisture content and fines content (Lekarp et. al. 2000, Xiao et. al., 2015). Stress levels and load cycles emerge as critical factors (Ramosa et al., 2020). Previous studies have focused on understanding the behaviour of PD under repeated traffic loading. Rahman and Erlingsson (2015) predicted PD behaviour based on mean (p) and deviatoric (q) stresses collected from dynamic triaxial tests. Their model was further modified by Kuttah (2021) to fit the LWD data. In this study, the Kuttah (2021) model was used to predict the cumulative PD measured from a single stage in-situ repeated LWD as a function of number of cycles (N), stress levels and water content for a silty sand subgrade. The use of LWD for field PD measurements helps to identify weak points in road pavements, allowing proactive measures to be taken to reduce future rutting and maintenance.

2. The Permanent Strain

The focus of current research is on mechanistic-empirical models for predicting the permanent strain of unbound road materials. These models can correctly simulate the response of materials, are easy to implement and depend on fewer parameters than conventional elastoplastic models (Ramosa et al., 2020).

One of the first simple models proposed, which relates plastic strains to the number of load applications and other factors, was the model of Monismith et al. (1975), as shown in Eq. (1) below:

$$\varepsilon_p = a\,N^b \quad (1)$$

where:

ε_p= Accumulated plastic strain (%)

N= Number of load applications

a, and b= Parameters that represent the influence of other factors.

More recent models depend on the mean (*p*) and deviatoric (*q*) stresses have been developed, as does the model developed by Rahman and Erlingsson (2015), see Eq.2.

$$\varepsilon_p = a\,S_f\,N^{b\,S_f} \quad (2)$$

where ε_p is the accumulated permanent strain, *N* is the total number of load cycles, *a* and *b* are model parameters associated with the material and the term S_f takes into account the effect of stress state in permanent deformation accumulation given as:

$$S_f = \frac{\{\frac{q}{p_a}\}}{\{\frac{p_m}{p_a}\}^{\alpha}} \quad (3)$$

where p_m is the hydrostatic stress (one third of the sum of the principal stresses, θ), *q* is the deviator stress, p_a is the reference stress here taken equal to the atmospheric pressure 100 kPa and α is a parameter obtained from regression analysis.

Kuttah (2021) modified Eq. 2 to fit the accumulative permanent strains measured from a single stage in-situ repeated LWD as a function of the number of cycles (N), stress levels and water content for silty sand subgrade soil, as shown in Eq (4) below.

$$\varepsilon_p = a\ W^c\ S\ N^{b\,S} \quad (4)$$

where ε_p is the accumulated permanent strain, *N* is the total number of load cycles, *a* and *b and c* are regression parameters associated with the material, *W* is the water content measured during LWD testing in (%), and *S* is as defined in Eq.5.

$$S = p/p_a \quad (5)$$

where:

p= Applied stress level during testing in (kPa) = applied load /area of LWD plate. Note that the diameter of the used plate in this study was 30 cm.

p_a= A reference stress =100 kPa

The model given in Eq. 4 has been adopted in this study to predict the accumulative permanent strain measured from a single stage in-situ repeated LWD for the clayey soil tested, as will be discussed later in this report.

3. Testing Methodology

3.1. Testing plan

The project methodology and implementation steps were as follows:

Material classification tests were carried out at VTI to define the main physical and mechanical properties of the materials to be tested (e.g. particle size distribution, liquid limit (LL) and plastic limit (PL), compaction characteristics and specific gravity).

The in-situ LWD tests were carried out on a compacted layer of the selected soil in a test pit located in the backyard of VTI in Linköping. During the in-situ LWD tests, the deformation moduli were measured in addition to the elastic and plastic deformations under repeated loading at different stress levels and water content conditions. In parallel with the LWD tests, laboratory moisture tests were carried out using the oven drying method.

The in-situ repeated LWD tests adopted were carried out at stress levels of approximately 24 kPa, 37 kPa and 50 kPa. These stress levels have been chosen to simulate the actual range of stresses applied to such weak clayey soils by moving vehicles for paved and unpaved road bases. Due to the expected low bearing capacity of the tested soil, a maximum stress level of 50 kPa was adopted. It should be noted that LWD testing at stress levels below 24 kPa cannot be achieved using 30 cm diameter in-situ LWD (as used in this study). This is because in order to generate lower loads, the drop height must be significantly reduced and, if this is done, the falling weight will bounce faster than it can be grasped, resulting in few additional successive rebound impacts of the LWD weight.

3.2. Equipment used

3.2.1. The Light weight deflectometer (LWD) used in this study

A multifunctional light weight deflectometer was used in the current research, see Figure 1.

Figure 1. The VTI's LWD used in the study.

During the test, the falling mass (of 10 kg) strikes the plate, generating a load pulse, the magnitude of which can be adjusted according to the drop height and weight of the LWD. The ground deflection of the tested material is measured by a seismic transducer (geophone) through a central hole in the loading plate. The base diameter of the loading plate used in this study was 300 mm. The drop height can be easily and quickly adjusted by a moveable release handle and the peak value of the impact force is based on actual measurements from the load cell, see Figure 1.

The main innovation in the LWD used is that it has been fitted with a control beam linked to a central LVDT to register the plastic deformation during the test at the centre line of the load. This development allows continuous monitoring and display of load versus accumulated soil deformation loops in a manner similar to the stress-strain behaviour under different cyclic loading conditions and hysteresis loops typically collected during RLT testing.

This feature allows instant determination of the number of drops (cycles) required during the LWD to bring the soil response as close as possible to the elastic state. In other words, the multi-functional LWD developed allows the plastic (permanent) and elastic (recoverable) components of deformations to be measured separately.

3.2.2. Nuclear density gauge

The Nuclear Density Gauge (NDG) was used in this study to determine the in-situ density and moisture content of the tested soil in the test pit. Measurement can be performed on materials less than125 mm in diameter. For more information about this test see Vägverket Publ. No. 1993: 26 (1993).

4. Characteristics of the Tested Soil

A sandy silty clay soil was selected for this study. A series of laboratory tests were carried out on the selected soil to determine its physical properties, namely grain size distribution, clay and silt fractions, soil classification, specific gravity, liquid and plastic limits, compaction characteristics and soil classification.

The clay content of the soil was tested using the sediment method at SGI (Swedish Geotechnical Institute) and the test results showed that the soil consisted of 37.5% clay particles (≤ 0.002 mm), a fine content of 75.7% (clay and silt), a sand fraction of 21.9% and a gravel fraction of 2.4%.

According to VVTK Väg (2008), the tested soil is of material type 5 (with frost hazard class 4). According to SS-EN ISO 14688-2 (2004), the soil is classified as sandy silty clay.

The compaction properties of the soil under study were determined by modified Proctor test as per ASTM D1557 (2012). The soil samples were compacted at different molding water contents ranging between 7 to 27% to determine the water-density relationship. The existence of irregularly (double peak) shaped compaction curve is clearly shown in Figure 2.

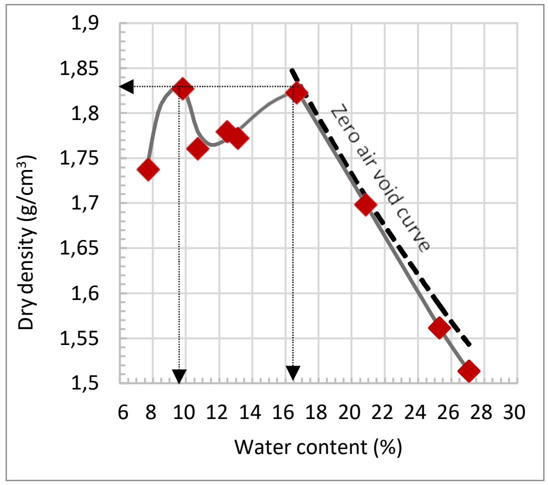

Figure 2. Compaction curve of the tested soil.

The results of the compaction tests revealed that the tested soil has a maximum dry density of 1.825 g/cm^3 at two optimum moisture contents of 9.5% and 16.5%, as shown in Figure 2.

The specific gravity of the selected soil was tested according to SS 027115 (1989), and it was found to be 2.65.

The liquid and plastic limits were determined at SGI according to SS 027120 (1990) and SS 027121 (1990) respectively. The tests results revealed a liquid limit (LL) of 37% and a plastic limit of (PL) 17.8% resulting in plasticity index of 19.2%.

5. In-situ Testing of the Selected Subgrade Soil

In-situ tests were carried out on the selected soil, namely, field density and moisture content tests, and repeated in-situ LWD tests. These tests were carried out in a test pit compacted with the selected soil under controlled conditions, see Figure 3.

Figure 3. Compaction of the subgrade soil in the test pit.

The test pit is located in the backyard of the Swedish Road and Transport Research Institute (VTI) and is approximately 10 m long x 5 m wide x 1.5 m deep. It has been equipped with a concrete well with a water discharge motor, which can be used to control the ground water level during the tests. The test pit is also instrumented with a roof panel that can be opened and closed by an electric motor to control the test conditions in the test pit as much as possible.

Initially, the newly selected subgrade material was placed in the test pit and thoroughly compacted using a small vibrator. The soil was compacted in layers, each layer being approximately 60 cm thick. When compaction was complete, the final subgrade surface was marked with circles representing the selected locations of the points to be tested, as shown in Figure 3.

After compaction of the soil, LWD tests were carried out at water contents between 18 and 22%. Within this range of water contents, the LWD tests were carried out at three different applied stress levels, namely 24 kPa, 37 kPa and 50 kPa.

After completion of these tests, the compacted soil was dried in the sun for a few days. The second series of LWD tests was then carried out at a water content of between 15% and 18%, after which the compacted soil was watered, and the water content increased to approximately 22-27%. After watering, the material was left for a few hours before testing to ensure, as far as possible, that the water content had been thoroughly distributed throughout the depth of the test pit. The third series of field LWD tests were then carried out at the same assumed stress levels.

The Nuclear Density Gauge (NDG) was used to determine the in-situ density and moisture content of the tested soil in the test pit. The results of the NDG tests are given in Table 1 together with the adjusted field moisture content of the samples collected using the oven drying method.

Samples for laboratory moisture determination were collected from each point simultaneously with the field NDG measurements.

The tested points were divided into three groups based on the convergence in testing time and corresponding water content (W) ranges of the tested points. Each group of near test water contents contains three sub-groups of points tested at target stresses of 25 kPa, 37 kPa and 50 kPa. Note that the aim was to test two points at each water content and applied stress combination, but a few points tested at 1.7 kN applied load at different water contents encountered problems. As previously mentioned, in order to achieve 1.7 kN, the corresponding drop height of the LWD load should be relatively short. As a result, when the load was released, it sometimes bounced off faster than you could grab it. When such problems occurred, the corresponding test points were excluded from the analysis.

It can also be seen from Table 1 that one point was tested with an applied load of 2.6 kN at 15-18% water content, while three points were tested with the same load at 18-22% water content. This was because when the overall tests were finished and the results were collected, it was found that even before the watering stage, one of the points tested in the low water content group had a high-water content which was more within the other selected water content group, so this point tested at 2.6 kN was moved to the group tested at 18-22% water content.

Table 1: Summary of the results of tested points properties and the test conditions.

W range of group (%)	Average W for a group %	Load (kN)	Vertical stress kPa	Field wet density (kg/m^3)	Degree of saturation
15-18	16	3.5	49.5	1863	0.68
		3.5	49.5	1934	0.74
		3.5	49.5	1863	0.66
		3.5	49.5	1827	0.62
		2.6	36.8	1790	0.59
		1.77	25.0	1905	0.73
18-22	19	3.5	49.5	1907	0.81
		3.5	49.5	1863	0.72
		2.6	36.8	1844	0.78
		2.6	36.8	1905	0.77
		2.6	36.8	1823	0.70
		1.77	24.0	1863	0.73
		1.77	24.0	1907	0.79
22-27	24	3.5	49.5	1858	0.89
		3.5	49.5	1858	0.86
		2.6	36.8	1858	0.84
		2.6	36.8	1858	0.83
		1.77	24.0	1886	0.84

6. Results and Discussions

6.1. Deformation measurements during LWD testing

As previously described, the VTI's LWD can measure the permanent and recoverable deformation components under the centreline of the drop weight using a central geophone and central LVDT. This additional capability allows the accumulated load-deformation loops to be collected and plotted for each point tested. Figure 4 shows typical examples of the effect of repeated loading on the accumulated permanent deformation in the case of points tested at an average water content of 19%.

It can be seen from these figures that the tested soil is not truly elastic but undergoes some irreversible deformation after each load application. It can be seen that at the end of the seventieth LWD load application, the increment of non-recoverable (plastic) deformation is much smaller compared to the resilient/recoverable deformation.

Figure 5 shows typical curves for the effect of successive LWD drops on the total, elastic and plastic deformations of a 2.6 kN falling weight (at approximately 19% water content).

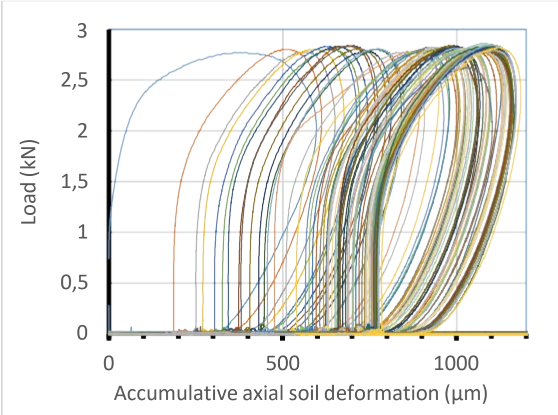

Figure 4. Load- deformation loops for a point tested at 19% water content under about 2.6 kN applied load.

From Figure 5 it can be seen that the plastic deformations decrease as the number of drops increases, approaching zero at around 55 to 60 drops. Similarly, the oscillation of the total and plastic deformations dies out as the number of drops increases. The slight jump in the total deformation (and hence elastic deformation) curve between drops 43 and 45 can be attributed to a slight local movement of the LWD geophone during the drop of the falling weight. This jump was not detected in the plastic deformation curve as the central plastic deformations were measured by the central LVDT. A decreasing trend in the total deformation curve with increasing number of drops was also reported, rapidly during the first few LWD drops.

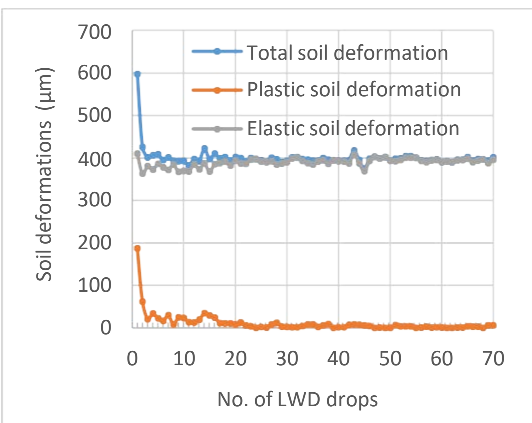

Figure 5. A typical example on the effect of successive LWD drops on the total, plastic and elastic deformations for a point tested at 19% water content under 2.6 kN applied load.

6.1.1. Effect of repeated loading, stress levels and water contents on soil plastic deformations during LWD testing

In this project, the effect of repeated loading on the plastic (permanent) soil deformations during LWD testing is of particular interest and has therefore been studied in detail. Figure 6 shows the effect of repeated loading on the permanent soil deformations during repeated LWD testing at different water contents and stress levels.

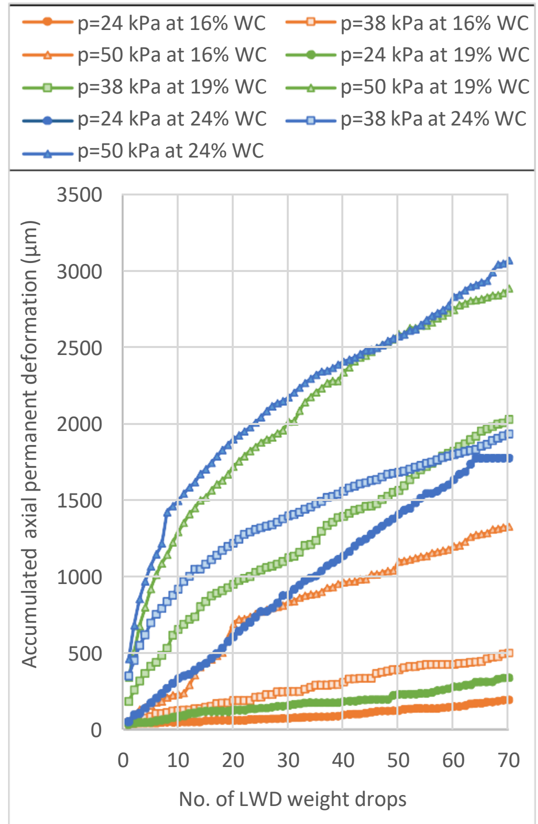

Figure 6. Effect of repeated loading on the permanent deformations during LWD testing at different water contents and applied stress levels.

It can be seen from Figure 6 that the lowest value of accumulated permanent axial deformation at the end of the 70th LWD drop was obtained for the points subjected to the lowest stress level of 24 kPa and tested at the lowest average water content of 16%, as expected. At the same stress level of 24 kPa, increasing the water content from 16% to 24% resulted in a relative increase in accumulated PD of 836%. Similarly, at the maximum applied stress level of 50 kPa, increasing the water content from 16% to 24% resulted in a 132% relative increase in accumulated permanent deformation. The reason for the smaller increase in permanent deformation under 50 kPa with increasing moisture content compared to the case of 24 kPa applied load is the very high accumulated permanent deformation reported for the points tested at 16% water content under 50 kPa applied load. This means that the highest applied stress level of 50 kPa resulted in high accumulated permanent deformations even at the lowest moisture content tested.

A similar trend was observed for points tested at 16% moisture content but subjected to increasing stress levels. Increasing the stress level from 24 kPa to 50 kPa at 16% water content resulted in a 600% relative increase in accumulated permanent deformations, whereas increasing the stress level from 24 kPa to 50 kPa at 24% water content resulted in only a 73% relative increase in accumulated permanent deformations.

The reason for the lower relative increase in permanent deformation at the higher moisture content of 24% with increasing applied stress is the very high accumulated permanent deformation reported for the point tested at 24% moisture content under 24 kPa applied stress. This means that the high moisture content of 24% resulted in very high accumulated permanent deformations even at the lowest applied stress of 24 kPa. Note that in the case of the points tested at 19% moisture content under a stress level of 37 kPa, as seen in Figure 6, the recorded accumulated permanent deformations were initially lower than the accumulated permanent deformations reported for the points tested at 24% moisture content under the same stress level of 37 kPa, as expected. The slopes of the two curves then continue to increase as the LWD load is increased, but at different rates. Thus, at the end of the 70th LWD load application, the accumulated permanent deformations for points tested at 24% moisture content under a stress level of 37 kPa were lower than the permanent deformations for points tested at 19% moisture content under the same applied stress. This can be attributed to two reasons, the first being the uneven effect of successive LWD load applications on particle movement under the LWD plate, which is related to material heterogeneity and other influencing factors such as compaction uniformity (the passes through the small vibratory compactor achieved in the field) and the moisture distribution ranges of each group as given in Table 1. Note that the soil compacted in the field at 19% and 24% is not saturated (see the degree of saturation given in Table 1 for the groups loaded at 38 kPa).

According to Figure 6, the PD values did not vary significantly as the water content varied (when increased from 19 to 24%). Water is more readily retained in the pores of the clay fines and the fines do not allow water to drain freely. This implies a low sensitivity of the compacted clay PD behaviour to increases in moisture content beyond the near optimum moisture content. Even for the points tested at 50 kPa applied stress, it can be seen that the PD behaviour implies low sensitivity when the moisture content increases from 19% to 24%, see Figure 6. In general, this phenomenon was observed more for the points tested at the higher stress levels of 37 kPa and 50 kPa than for the points tested at the low applied stress of 24 kPa.

6.1.2. Modelling the permanent strains reported during repeated LWD testing

As previously described in Section 2 "The Permanent Strains", the models given in Equations 1, 2 and 4 predicted the accumulated permanent strain, whereas in the adopted LWD test the permanent deformations could be measured instead of the permanent strains. In order to convert the permanent deformations measured by the LWD into permanent strains, the zone of influence of the LWD should be estimated. This is important in order to use these equations based on LWD test data.

Nazzal (2003) and Tompai (2008) found that the LWD's zone of influence varies between 1 and 2 times the plate diameter, which is in good agreement with the results of Elhakim et al. (2014). Accordingly, the zone of influence of the LWD in this study was assumed to be 1.5 times the plate diameter of 30 cm (i.e. the zone of influence of the LWD in this study was assumed to be 45 cm).

In order to account for the effect of the number of load cycles, water content and applied stresses on the prediction of the accumulated permanent strain measured by repeated in-situ LWD tests, the model given in Equation 4 was found to be suitable for the current study.

This model requires a set of non-linear parameters, namely a, b and c, which would provide a reasonable fit of the model to the measured data. The optimization of the model parameters given in Eq. 4 was carried out in such a way that the sum of squares of the errors from the test data and the model predictions is minimized.

Table 2 below shows the parameters given in Eq. 4 that would give the best fit to the LWD test data for the points tested up to 22% water content.

Table 2. The parameters of Eq.4 that would provide the best fit to the LWD test data.

Model	a	b	c
Eq. 4	7.059E-08	1.047	4.896

Figure 7 shows the accumulated permanent strain (εp) as a function of load cycles for the data collected from repeated in-situ LWD and the developed model given in Eq. 4.

It can be seen from this figure that the increase in permanent strain does not behave in the same way under all stress and water content conditions.

As discussed earlier, εp increased with increasing water content and applied stress. It was noted that most of the εp accumulation occurred in the early part of the tests. The trend line of increasing accumulated εp with the number of LWD load applications continues to slope upwards even at the end of the 70th LWD load application, especially for the points tested at the highest applied stress of 50 kPa for the two average water contents of 16% and 19%, and even for the points tested at 37 kPa with an average water content of 19%.

Furthermore, it can be noted that the model given in Eq. 4 has shown a good fit of the accumulated permanent strain (εp) to the in-situ measured data from repeated LWD tests as a function of load cycles, stress levels and water content during testing.

Note that the model given in Eq. 4 could not model the accumulated permanent deformations for points tested at the highest average moisture content of 24% (water content ranged between 22 and 27%), but it gave a very good fit for points tested at water contents up to 22% under all selected applied stresses of 24 kPa, 37 kPa and 50 kPa, as shown in Figure 7.

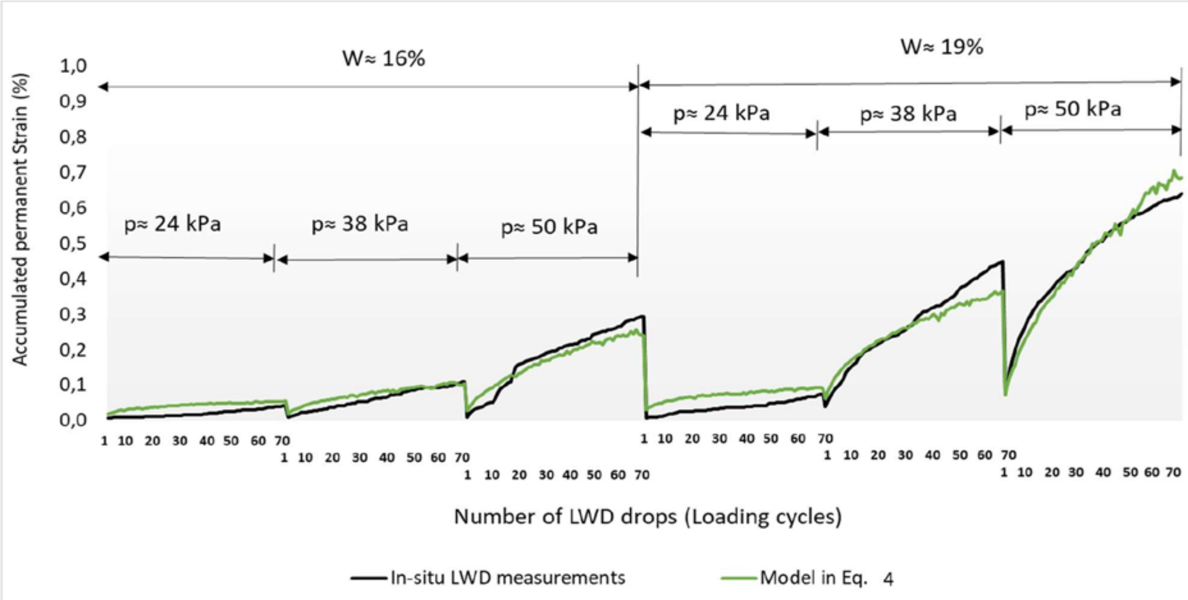

Figure7. The accumulated permanent strain as a function of loading cycles for the data measured by in-situ repeated LWD and the developed model given in Eq. 4 for water contents ranged between 15%.

7. Conclusions

This study has been carried out to evaluate the effect of water content and stress levels on the permanent deformation potential of the sandy silty clay tested in this study by using in-situ repeated LWD test. In addition, the study was focused also on comparing the measured in-situ LWD data with an adapted mechanistic-empirical model usually used to predict the permanent strains of unbound materials. The main conclusions are pointed out below:

- Despite the expected increase in accumulated permanent strains with increasing load cycles, applied stress levels and water content during the test, it's apparent that the behaviour of the permanent strains was not uniform under different stress levels and water content conditions. It can be seen that most of the permanent deformations were developed in the first few cycles and then the accumulation of permanent deformations (strains) continued its slow but steady decline during the last cycles of LWD loading for the points tested at the lowest stress levels and under average water contents of 16% and 19%. The material in the wettest condition, tested in this study, was more prone to the accumulation of permanent deformation (strain) even at the end of the 70th LWD drop when subjected mainly to medium and larger stress levels of 37 kPa and 50 kPa.
- At the same stress level of 24 kPa, increasing the moisture content from 16% to 24% resulted in 836% relative increase in accumulated permanent deformations. Similarly, at the maximum applied stress level of 50 kPa, increasing the moisture content from 16% to 24% resulted in 132% relative increase in accumulated permanent deformations.
- Increasing the stress level from 24 kPa to 50 kPa for points tested at 16% water content resulted in 600 % increase in the accumulated permanent deformations, while increasing the stress level from 24 kPa to 50 kPa at 24% water content resulted in only 73 % increase in the accumulated permanent deformations.
- For the tested subgrade soil, prediction model for accumulated permanent strains based on the repeated LWD measurements is suggested in this study. The model given in Eq. 4 has showed good matching to the accumulated permanent strain (εp) to the in-situ measured data from repeated LWD tests as a function of loading cycles, stress levels and water content lower than 22% (corresponding to an average water content of 19%).

8. Recommendations

The model used in this study to estimate the dynamic deformation moduli, namely Eq. 4, is sophisticated enough and easy to use. This model is valid for the material used in this study and can be used to solve practical problems of stiffness estimation under repeated traffic loading for engineering purposes.

Based on the plastic deformations provided by the repeated LWD tests, it was found that the subgrade material tested in this study is unsuitable for use at high water contents, regardless of whether it is subjected to low or high levels of loading. This is because at both the low and high stress levels that this subgrade may experience under varying traffic loads, the frequent extreme rainfall events will continue to cause high accumulated permanent deformations, indicating that the plastic ruts may be produced soon after the road is opened to traffic. Permanent deformation in the subgrade tested can be limited if a near optimum moisture content (≈16%) could be maintained.

Nevertheless, it is important to mention that the permanent deformation model (given in Eq. 4) used in this study to fit repeated LWD test data is recommended to be used in practice and tried in MEPD, keeping in mind that it is not suitable to predict permanent deformations for similar soils at high water content level. In addition, this model has been developed for specific materials and test conditions. When using it for test materials and conditions other than those for which it was developed, a combination of previous experience and engineering judgement should be considered.

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