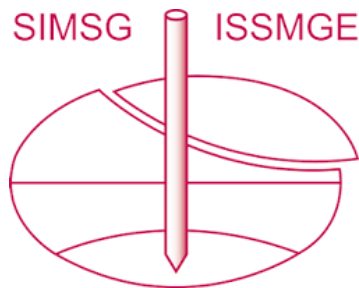


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*The paper was published in the Proceedings of the 8<sup>th</sup> International Symposium on Deformation Characteristics of Geomaterials (IS-PORTO 2023) and was edited by António Viana da Fonseca and Cristiana Ferreira. The symposium was held from the 3<sup>rd</sup> to the 6<sup>th</sup> of September 2023 in Porto, Portugal.*

# Measurement of subgrade soil permanent deformations under repeated loadings during simple in-situ test

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## ABSTRACT

It is well known that permanent deformation has a significant influence on the performance of pavements because it leads to an increase in maintenance operations and costs and reduces ride quality. Therefore, it is important to predict the permanent deformations during the design stage.

Due to the fact that up to date there is no simple test equipment and procedure that enables a direct in-situ measurement of permanent deformations of subgrade soil under repeated loading, the current research has been undertaken to evaluating a new testing approach to fulfil this requirement. The current study deals with developing a new multifunctional light weight deflectometer (LWD) that can be used to determine the in-situ permanent deformations of subgrade soil due to repeated loading by simple, cheap and time saving testing approach.

It was concluded that the suggested repeated light weight deflectometer test could give a powerful material assessment and pavement design tool for the analysis of compacted subgrade soil used in this study. The developed LWD that can measure the permanent deformations directly could be utilized to establish the risk level of permanent deformations in the subgrade soil in pavement constructions during the design and construction stages.

**Keywords:** Permanent deformations; Repeated light weight deflectometer; Silty sand subgrade; Water content.

## Acronyms:

LL= Liquid limit

LVDTs= Linear Variable Differential Transformers

LWD= Light weight deflectometer

NDG= Nuclear Density Gauge

p= applied stress level (kPa)

PL= Plastic limit

R<sup>2</sup>= Coefficient of determination

SGI= Swedish Geotechnical Institute

TRV= Trafikverket

UGMs= Unbound granular materials

VTI= The Swedish National Road and Transport Research Institute

W= Water content (%)

## 1. Introduction

According to Lekarp (1999), pavement unbound materials exhibit an elastoplastic behaviour under repeated loads. The axial deformation of the material under repeated loading conditions consists of two parts, namely, the recoverable (resilient) strain and the plastic (permanent) strain (Lekarp, 1999).

Permanent deformation usually occurs in the geomaterials (base, subbase or subgrade soils) which are responsible for the surface rutting and that can lead to significant passenger discomfort and reduces ride quality (Puppala, 2009).

Therefore, many studies have been conducted to understand the permanent deformation (PD) behaviour of UGMs and the factors that affect the PD behaviour of UGMs under repeated traffic loading (Erlingsson and Rahman, 2013, Kuttah 2021).

Permanent deformation is a complex process that directly depends on many influencing factors, namely, the applied stress levels, number of load applications, the strength of material, the loading history, the effect of principal stress rotation, moisture content (degree of

saturation), matric suction, fine content, density (degree of compaction), aggregate type, particle size distribution (gradation), and the amount and type of fines (plastic or non-plastic), (Lekarp et. al. 2000, Xiao et. al, 2015 and Alnedawi et. al. 2019). However, the stress level and number of load cycles emerge as the most important factors (Ramosa et al., 2020).

Among several factors that compromise the ability of flexible pavement structures to sustain mechanical loads without the accumulation of permanent deformation (PD), the moisture content of the unbound materials is one of the most relevant (Rahman and Erlingsson, 2015 and Silva et al, 2021). The moisture content of the pavement layers varies with the infiltration of rainwater through cracks in the pavement or from the uncoated shoulders, variation of the level of the water table, and the migration of moisture between the layers due to temperature variations, among other processes (Lima et al 2019).

There are a number of laboratory tests currently used to evaluate the permanent deformation of geomaterials; they attempt to reproduce in situ stress conditions in pavements. Laboratory investigations using cyclic

triaxial tests, simple and cyclic shear tests, resonant column and hollow cylinder tests, among others have been carried out (Ramosa et al., 2020).

The cyclic triaxial test (repeated load triaxial RLT test) is the most widely used to study of geomaterials subjected to cyclic loads (Rahman and Erlingsson, 2015, and Ramosa, 2020). However, the RLT test is relatively expensive and time consuming. Therefore, many road and transport administrations including the Swedish transport administration (Trafikverket, TRV) have paid a particular attention to find a simple and a time saving technique to evaluate the unbound layers and subgrade soil quality and properties directly in the field during roads construction.

Nowadays, the light weight deflectometer (LWD) has widely been used overseas and become more and more popular in quality assurance of roads due to its light weight and time saving procedures. In this study, VTI's LWD has been developed further to predict accumulated plastic deformations of a selected subgrade soil compacted at a test pit of 1.5 m depth. Predicting permanent deformation accumulation of a compacted road layer by simple field tests will give a good and early indication on the material behaviour under repeated loading, something which enable instance decision making during road construction. The decision may result in adopting early actions like, further compaction, stabilization requirement or some stress levels and moisture restrictions before continuing compacting the next road layer. Hence, an improvement in construction quality will be achieved resulting in an increase in pavement service life.

## 2. Testing methodology

### 2.1. Testing plan and flowchart

At the beginning, a local available silty sand subgrade soil has been chosen for testing. Materials classifications tests have been carried out at VTI to define the main physical and mechanical properties of the soil to be used for testing.

The in-situ LWD tests have been carried out on a newly compacted subgrade layer in a test pit located at the backyard of VTI in Linköping. During the in-situ LWD tests, the elastic and plastic deformations have been measures under repeated loading at different stress levels and water content conditions. These measurements will help in identifying the weak points in the tested road layers and the influencing factors that will likely resulted in more permanent deformations than others.

Fig.1 shows a detailed flow chart for the testing procedure. It can be seen from Fig. 1 that the adopted in-situ repeated LWD tests have been carried out at stress levels of about 50 kPa, 100 kPa, and 200 kPa. These stress levels have been chosen to simulate the real ranges of applied stresses on the subgrade soil by moving vehicles for subgrade soil used for paved and unpaved roads of thin superstructure.

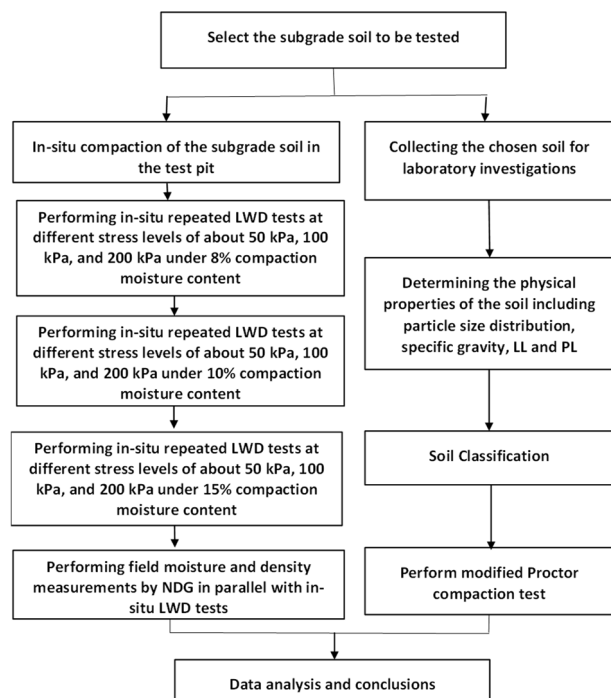


Figure 1. Flowchart of the testing program.

### 2.2. Equipment used and working principles

The light weight deflectometer (LWD) test has been used to determine the surface soil deflections by means of geophones placed in direct contact with the ground surface. In many LWD test, a falling mass (of 10 kg) impacts a steel plate and the central deflection of the tested material surface due to impact loading is measured through a hole in the loading plate by a highly accurate, seismic transducer (geophone). The basic diameter of the loading plate used in this study was 200 mm. The drop height could be easily and quickly adjusted by a movable release handle and the peak value of the impact force has been reported based on actual measurements from a mounted load cell, see Fig. 2.



Figure 2. The VTI's light weight deflectometer which can measure the permanent deformations of the tested soil separately. Photo: Dina Kuttah, VTI.

The main invention in the new developed LWD is that it has been supplied with a control beam linked to a central LVDT to register the plastic deformations during testing at the centerline of loading. This development

enables a continuous monitoring and displaying of the permanent deformations and load versus accumulated soil deformation loops similar to the stress-strain loops usually collected during RLT tests, see Fig.3.

This function enables instant determination of the number of drops (cycles) required during the LWD to bring, as much as possible, the soil to near elastic state. In other words, using the developed multifunctional LWD, the plastic (permanent) and elastic (recoverable) components of the deformations can be measured directly and separately. The data collection software is installed in a PC coupled to the LWD control panel. The time history graph from both the deflection sensors and the load sensor can be displayed in the PC screen in real time. Relevant information such as name, place, weather and comments can be added to the data file for each measuring point. The collected tests data can be printed as a report or can be exported to other software like Excel for further processing.

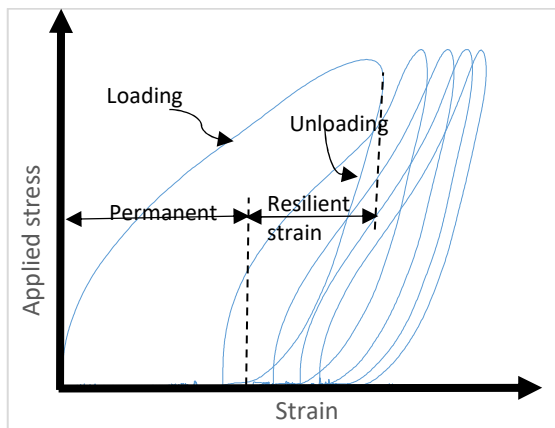


Figure 3. Granular material behaviour under repeated loading.

### 3. Laboratory testing

A silty sand subgrade soil has been chosen to be tested in this study. Series of laboratory tests were performed on the selected soil to determine its physical properties, namely, the particle size distribution, clay fraction, soil classification, specific gravity, liquid and plastic limits, and compaction characteristics.

The particle size distribution test on the selected soil has been carried out as per SS-EN 933-1 (2004) and the result is illustrated in Table 1.

The clay content in the soil was tested according to VTI method for grain size distribution analysis with laser diffraction [10 nm - 2 mm] and was found to be 5%.

According to VVTK Väg (2008), the tested soil is of material type 4A (mixed-grained soils with frost danger class 3). With respect to SS-EN ISO 14688-2 (2004), the soil is classified as a silty sand with 5% clay, see Fig.4.

The liquid and plastic limits were determined at SGI according to SS-EN ISO 17892-12 (2018). The tests results revealed a liquid limit (LL) of 18% and a plastic limit of (PL) 14.3% resulting in 3.7% plasticity index.

The specific gravity of the selected soil was determined according to SS-EN 1097-6 (2013), annex G, and it was found to be 2.64.

The compaction properties were determined by modified Proctor test in accordance with ASTM D1557

(2012). The test was performed by compacting several soil samples using a cylindrical mold of 152.4 mm diameter.

The results of the compaction tests revealed that the tested soil has a maximum dry density of 2.03 g/cm<sup>3</sup> at about 8.2% optimum moisture content, see Fig. 5.

Table 1. Particle size distribution of the tested soil

Sieve, $\mu\text{m}$	% Finer than
22.4	100%
16	97%
11.2	96%
8	95%
5.6	94%
4	93%
2	90%
1	88%
0.5	84%
0.25	76%
0.125	62%
0.063	39.20%

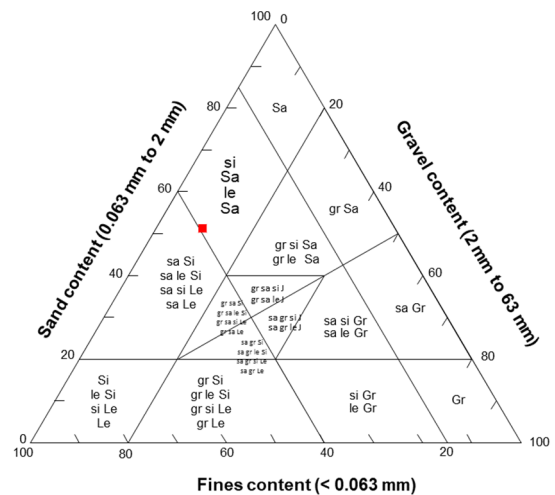


Figure 4. Tested soil classification

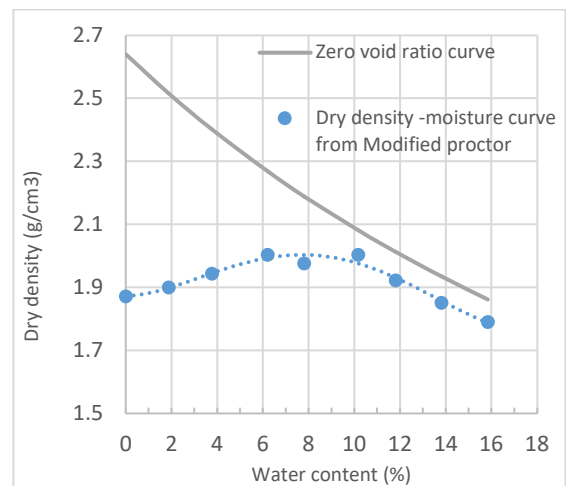


Figure 5. Compaction curve of the tested sandy soil.

## 4. In-situ testing

The tests data and findings collected from in-situ tests carried out on the selected silty sand subgrade soil are illustrated and discussed in this paragraph.

These tests were carried out on a test pit compacted with the selected soil under controlled conditions, as discussed in detail the following paragraph.

### 4.1. In-situ compaction

A test pit at the backyard of the Swedish Road and Transport Research Institute (VTI) was constructed for in-situ testing as shown in Fig.6.

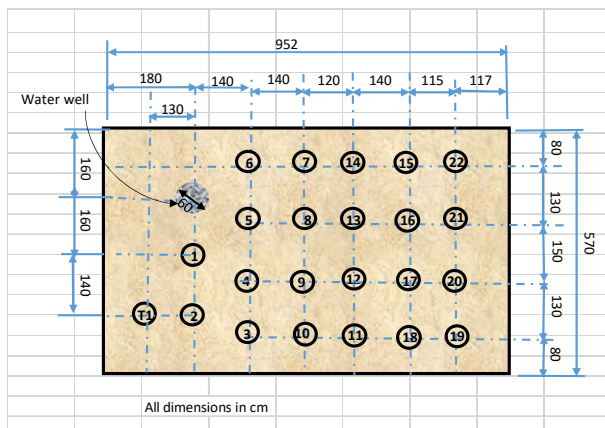


**Figure 6.** Compaction and preparing of the subgrade soil in the test pit.

The test pit was approximately 9.5 m long x 5.7 m width x 1.5 m depth and equipped with an electric drive motor roof panel that can be opened and closed with the help of an electric motor to control as much as possible the testing conditions in the test pit. A concrete well with a water discharging motor was constructed in the test pit to control the ground water level during testing. The work started by placing and compacting the selected subgrade soil thoroughly using a small vibrator, see Fig. 6.

### 4.2. Testing layouts

When the compaction completed, the final subgrade surface was marked with circles representing the selected places of the points to be tested, as shown in Figure 7.



**Figure 7.** Position of the points tested on the final compacted soil.

So, it can be seen from Fig. 7 that a total of twenty-two points have been prepared and tested by LWD at different water contents and applied stress levels.

### 4.3. In-situ moisture content and density measurements

Table 2 shows a summary of the chosen LWD applied stresses on the tested points together with the water content and relative compaction measurements during testing as conducted by NDG tests. The tested points were grouped to three groups based on the convergence in testing time point and water content (W). Each group of near testing water content (namely, 8%, 10% and 15%) shown in Table 2 includes three subgroups of points tested at target stresses of 50 kPa, 100 kPa and 200 kPa.

**Table 2.** Summary of the moisture contents and the applied stress levels of the tested points

Point No.	Applied stress (kPa)	W %	Field dry density (kg/m <sup>3</sup> )	Average W for a group (%)	Average relative compaction (%)
10	50	8.12	1887	8	91.9
12		8.27	1858		
11	100	8.12	1887		
8		8.42	1830		
9	200	8.27	1858		
1		10.4	1739		
3	50	10.4	1833	10	89.3
5		10.4	1739		
13	100	9.48	1789		
2		10.4	1833		
4	200	10.4	1833		
14		9.48	1789		
6	150	9.0	1875	15	87.7
7		9.0	1875		
16	50	15.3	1810		
17		15.4	1746		
21	100	15.3	1810		
15		15.1	1812		
22	200	15.1	1812		
18		15.4	1746		
19	150	15.4	1746		
20		15.4	1746		

### 4.4. In-situ repeated LWD tests

The in-situ LWD started directly after completing the compaction of the subgrade soil (during which the water contents were around 10%) and marking the points on the compacted soil surface at the test pit. Series of LWD tests were carried out at the three target applied stresses, namely, 50 kPa, 100 kPa and 200 kPa. During all the in-situ repeated LWD tests, the LWD plate diameter was 200 cm, but by changing the drop height of 10 kg drop weight, the applied stresses have been varied to achieve the target stresses.

In order to carry out LWD at water content drier than the initial water content of 10%, the steel cover of the test pit was left open for several hours in order to dry the soil under sunshine and then the LWD tests were carried out at a water content of about 8% under the similar target applied stresses.

Later, to carry out LWD tests on a water content wetter than the latest water content of 8%, the soil in the test pit was watered. After few hours of waiting, to ensure consistence water content penetration and distribution through the soil layer, the LWD tests were performed at about 15% water content. For details of the exact stresses and water content of each individual point, see Table 2 above.

## 5. Results and discussions

### 5.1. Effect of repeated loading on soil deformations during LWD testing

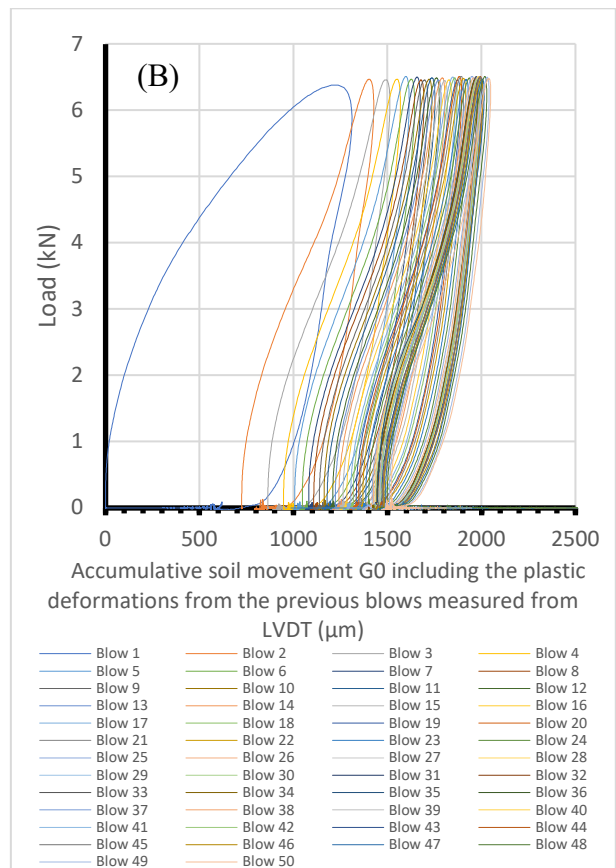
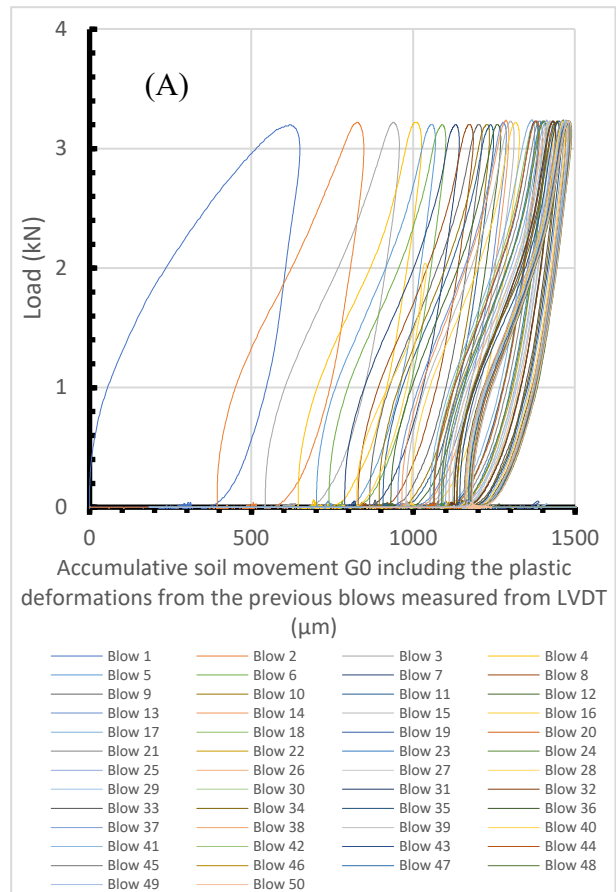
As mentioned previously, the multifunctional LWD can measure the tested layer permanent and recoverable deformations under the centreline of the drop weight separately. The central geophone (used to measure the total deformation) and a LVDT (used to measure the plastic deformation), both placed along the center of the dropping weight to measure the total and plastic deformation on the soil surface directly through a hole on the center of the steel plate. The LVDT was coupled also to a control beam to measure the absolute plastic deformation. The measurement of plastic deformations by a mounted LVDT is important because the plastic deformations cannot be conducted from the central geophone due to the general integration errors usually encountered.

Correspondingly the accumulated load-deformation loops could be collected and plotted for each tested point using the developed LWD. Fig. 8 A and B show typical examples of the effect of repeated loading on the accumulated permanent deformations for the case of point 4 and point 9, respectively. It can be seen from these figures that the tested subgrade soil is not truly elastic but experience some nonrecoverable deformation after each load application.

Also, it can be shown in Fig. 8 A and B that at the end of the fiftieth LWD load application, the increment of nonrecoverable (plastic) deformation is much smaller compared to the resilient/recoverable deformation. Note that each tested point was loaded with many LWD load applications (drops) of one chosen applied stress level as given in Table 2.

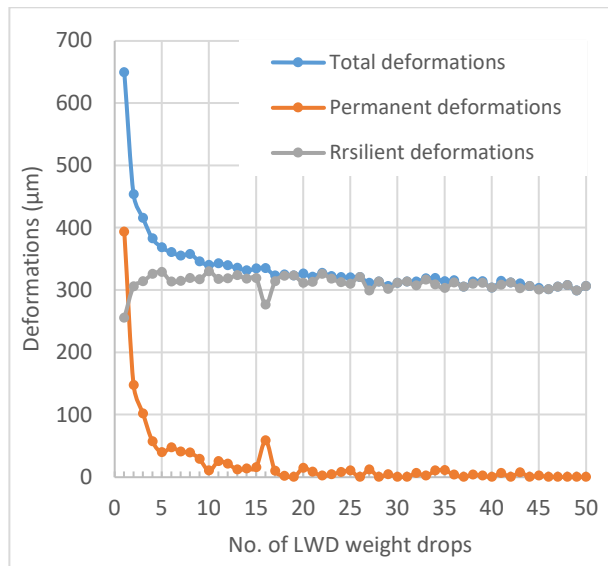
For each point, the effect of the number of drops on the progress of total deformation has been assessed. In addition, the effect of the number of drops on the progress of elastic (resilient) and plastic (permanent) deformation components has also been determined separately.

Fig.9 shows typical deformations curves for the effect of the number of LWD weight drops (cycles) on the total, resilient and permanent deformations during LWD testing on point 4.



**Figure 8.** (A)- Accumulated load-deformation loop for accumulated drops under about 100 kPa applied stress at 10% W (Point 4), (B)-Accumulated load-deformation loop for accumulated drops under about 200 kPa applied stress at 8% W (Point 9).

According to Fig.9, the permanent deformations reduce with increasing the number of drops and reach zero at around twenty-two LWD drops. The sudden increase of permanent deformation above zero at drop no. 16 may be attributed to a slight movement of the LWD during testing. The resilient (elastic) deformations increased gradually with the number of loadings and then the increase dies out with increasing the number of drops. Furthermore, a significant decrease trend of the total deformations curve with increasing the number of drops has been reported as well.



**Figure 9.** Effect of repeated loading on total, resilient and permanent soil deformations during LWD testing on point 4 (under about 100 kPa applies stresses at 10% W).

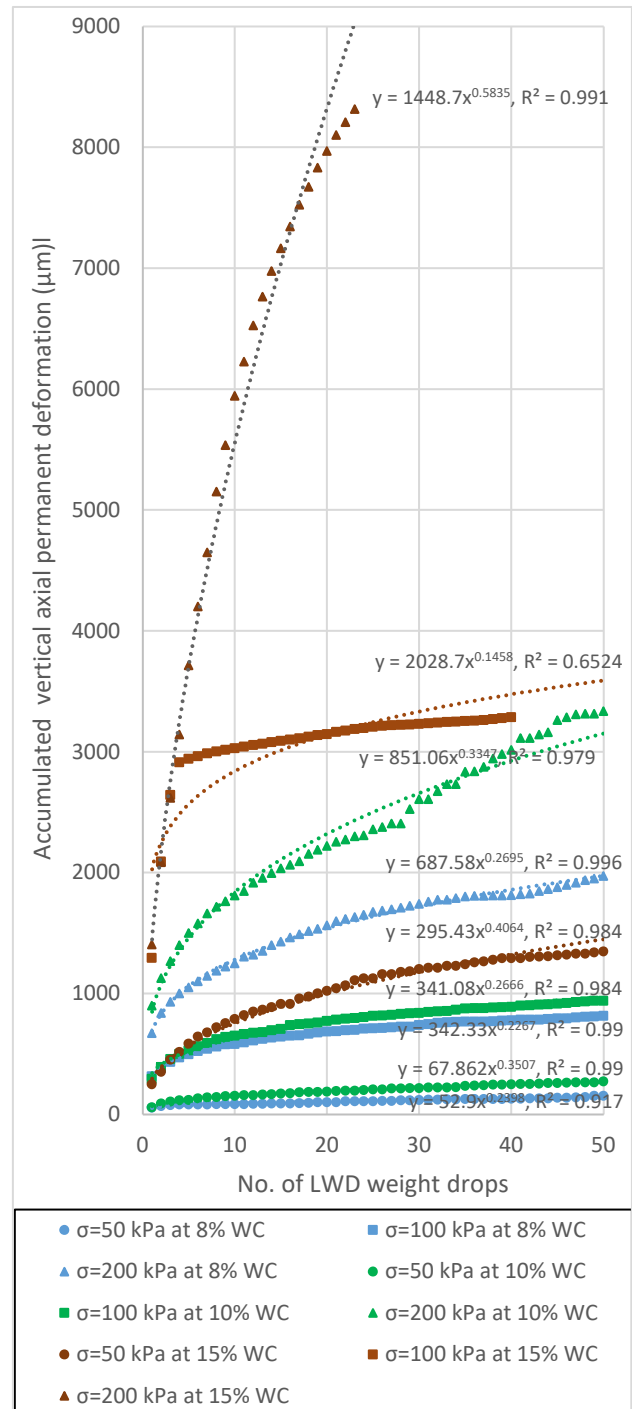
## 5.2. Effect of repeated loading, stress levels and water contents on soil permanent deformations during LWD testing

In this study, the effect of repeated loading on the permanent soil deformations during LWD testing is of particular interest, and therefore, it has been studied in detail. Fig.10 shows the effect of repeated loading on the permanent soil deformations during repeated LWD testing at different water contents and stresses levels. In addition, Fig. 10 shows the modelling functions (the power-law functions) that correlates the accumulated vertical axial permanent deformations to the number of LWD weight drops. The power-law functions have been chosen because they have resulted in the highest coefficient of determination among all other available modelling functions.

It can be noticed from Fig.10 that the lowest permanent vertical deformations recorded at the end of the 50th LWD drop, were for the points subjected to the lowest stress level of 50 kPa and tested at the lowest water content of 8%. At the same stress level of 50 kPa, increasing the moisture content to 10% and 15% resulted in 78% and 778% increase in permanent deformation values, respectively.

The highest permanent deformations were reported for the points subjected to the highest stress level of 200 kPa and tested at the highest water content of 15% at the

end of the 23rd LWD drop. Increasing the number of LWD drops further caused extreme deformations that were beyond the measuring limits of the used deformation measuring sensors, see Fig.10.



**Figure 10.** Effect of repeated loading on the permanent deformations during LWD testing at different water contents and applied stress levels stress at 8% W (Point 9).

Note that for the case of points tested at 15% moisture content under 100 kPa stress level, as seen from Fig.10, the trend of the permanent deformations curve shows high values at the first few LWD loading cycles and then the trend of increase in permanent deformations dies out after few LWD drops.

This observation is attributed to the loss of the plastic deformation data reported from point number 22 after few drops and therefore the curve was continued based

on the reported plastic deformation data from the other point only (point 15). This incident resulted in a nonuniform permanent deformations curve for this case with relatively poor power modelling (of  $R^2 = 0.65$ ) as compared to the other groups shown in Fig.10.

Regarding the effect of stress levels on the permanent deformations of points tested at the same water content, increasing the stress level from 50 kPa to 100 kPa and then to 200 kPa for points tested at 8% water content resulted in 431% and 1183 % increase in the permanent deformations, respectively.

Increasing the stress level from 50 kPa to 100 kPa and then to 200 kPa for points tested at 15% water content resulted in 154% and 648 % increase in the accumulated permanent deformations, respectively.

## 6. Conclusions and recommendations

Geomaterials exhibit elastoplastic behaviour during dynamic and repeated loading conditions. These loads are induced by the passage of a vehicle which then generates recoverable (resilient) deformation and permanent (plastic) deformation. Predicting this behaviour is still a challenge for geotechnical engineers as it implies the understanding of the complex deformation mechanism.

Correspondingly, this study was undertaken to evaluate the effect of water content and stress levels on permanent deformation potential of silty sand subgrade soil by using in-situ repeated light weight deflectometer test.

From the results of this research the following conclusions may be withdrawn:

- It was observed that the accumulated deformations components depend largely on the number of loading cycles. At the end of the fiftieth LWD load application, the increment of nonrecoverable (plastic) deformation was much smaller compared to the resilient/recoverable deformation for the tested silty sand subgrade soil.
- It was found that the accumulated permanent deformations increase with increasing the loading cycles, applied stress levels and water content during testing. From the results of the accumulated permanent deformations, it can be deduced that the increase in permanent deformations does not behave in the same way under all load and water contents conditions. One can notice that most of the permanent deformations have been developed at the first few cycles and then the accumulation of permanent deformations has continued its slow but steady decline during the last cycles of LWD loading for the points tested at the lowest stress levels and under 8% and 10% water contents. The material in the wettest water content tested in this study was more prone to the accumulation of permanent deformation when subjected to larger stress levels.
- It is suggested that the subgrade material tested in this study was demonstrated to be unsuitable for use under high water contents in case it will expose to traffic loading causes vertical applied stresses higher than 50 kPa. This is due to the fact

that, under high stress levels that this subgrade may experience under high traffic loading, and frequent rainy climate conditions, it will suffer from high accumulated permanent deformations after only few dozens of loading cycles which indicates that plastic ruts would be produced soon after opening the road to traffic. The permanent deformation in the tested subgrade soil can be limited if a controlled combination between applied stress levels and moisture contents are maintained. It is recommended to keep the applied stress level on a compacted subgrade layer of this soil around 50 kPa and the water content lower than 10% to avoid early failure of the layer after accumulated traffic loading.

- The in-situ repeated LWD test procedure adopted in this study has the potentials to be used for characterizing the permanent deformation behaviour of subgrade soils. It can provide a powerful and quick material assessment tool. This can considerably reduce the effort and time required for permanent deformation characterization as compared to more complicated tests.
- The regression equations given in this study, are accurate enough and easy to use. These equations can be used to estimate the soil settlement (plastic vertical deformations) subjected to repeated traffic loading for engineering purposes. Nevertheless, it is important to mention that they have been developed for specific materials and testing conditions (i.e. tested water contents, and stress levels). When using these equations for different testing materials and conditions as that they developed for, a combination of previous experience and engineering judgement should be considered.

## Acknowledgements

The author would like to thank the Swedish Transport Administration for the financial support of this research via the industry program BVFF (Bana Väg För Framtiden). Thanks also to KUAB AB for developing further the VTI's lightweight deflectometer in cooperation with the author.

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