**Proceedings of the XVIII ECSMGE 2024**
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-92


# Repeated LWD test to assess the stiffness properties of clayey soil

## Essai répété de LWD pour évaluer les propriétés de rigidité d'un sol argileux

D. Kuttah*
*Swedish National Road and Transport Research Institute,VTI, Road and Track Engineering Division, Linköping, Sweden*
**dina.kuttah@vti.se*

**ABSTRACT**: Geotechnical failures are often the result of not recognizing or adequately evaluating conditions prior to construction of a pavement system. The dominant geotechnical factor(s) for many pavement distresses is/are the stiffness and/or strength of the subgrade materials (U.S. Department of Transportation, 2006). To investigate further the stiffness properties of geotechnical materials, the current study has been undertaken to evaluate the feasibility of using a new multifunctional light weight deflectometer (LWD) to determine the in-situ dynamic deformation moduli (Evd) of clayey soil under repeated loading. This method is considered simple and a time saving technique to measure the in- situ dynamic properties of geotechnical materials. A sandy silty clay soil has been chosen for testing. At the beginning, the soil was compacted in a test pit, and then, series of in-situ repeated LWD were conducted at different ranges of water contents (namely 16%, 19% and 24%) under various applied stress levels (namely, 24 kPa, 38 kPa and 50 kPa). The test results have showed that increasing the water content decreases the dynamic deformation moduli, similarly, increasing the applied stresses decreases the dynamic deformation moduli as well. The multiple regression analysis has been used to model the dynamic deformation moduli of the tested soil based on the measurements reported from repeated in-situ LWD tests. A strong correlation has been found between the Evd and the water content, degree of saturation and applied axial stresses for the tested soil with high correlation coefficient of 0.99.

**RÉSUMÉ**: Les défaillances géotechniques sont souvent le résultat d'un manque de reconnaissance ou d'évaluation adéquate des conditions avant la construction d'un système de chaussée. Le(s) facteur(s) géotechnique(s) dominant(s) pour de nombreuses dégradations des chaussées est/sont la rigidité et/ou la résistance des matériaux de fondation (U.S. Department of Transportation, 2006). Afin d'étudier plus avant les propriétés de rigidité des matériaux géotechniques, la présente étude a été entreprise pour évaluer la faisabilité de l'utilisation d'un nouveau déflectomètre léger multifonctionnel (LWD) pour déterminer les modules de déformation dynamique in situ (Evd) d'un sol argileux soumis à des charges répétées. Cette méthode est considérée comme une technique simple et peu coûteuse en temps pour mesurer les propriétés dynamiques in situ des matériaux géotechniques. Un sol argilo-sableux a été choisi pour les essais. Au début, le sol a été compacté dans une fosse d'essai, puis une série d'essais LWD répétés in situ ont été effectués à différentes gammes de teneurs en eau (à savoir 16%, 19% et 24%) sous différents niveaux de contraintes appliquées (à savoir 24 kPa, 38 kPa et 50 kPa). Les résultats des essais ont montré que l'augmentation de la teneur en eau diminue le module de déformation dynamique, de même que l'augmentation des contraintes appliquées diminue également le module de déformation dynamique. L'analyse de régression multiple a été utilisée pour modéliser les modules de déformation dynamique du sol testé sur la base des mesures rapportées par les tests LWD in situ répétés. Une forte corrélation a été trouvée entre l'Evd et la teneur en eau, le degré de saturation et les contraintes axiales appliquées pour le sol testé avec un coefficient de corrélation élevé de 0,99.

**Keywords:** Applied stress levels; multiple regression analysis; repeated LWD test; stiffness properties; water content.

## 1 INTRODUCTION

With the introduction of the concept of resilient modulus (*Mr*) as the material stiffness, considerable attention has been dedicated to evaluating the behaviour of subgrade soils using repeated load triaxial test (Gomes Correia & Gillett, 1996, Lekarp et al., 2000). However, the resilient modulus tests are relatively expensive and time consuming. As a result, many of the pavement design standards are based on material properties evaluated using simpler and faster tests such as the static plate loading test, static *CBR*, and others (Razouki and Kuttah, 2004, Araya, et al. 2012). Although these static tests are very common all over the world, they cannot always be correlated efficiently to the dynamic response of the pavement structure under the actual traffic loading of moving vehicles. Therefore, it has become necessary to estimate the material properties using simple dynamic tests (preferably, field tests) to reduce the gap between the requirement on material stability and properties measured in the field and that used in Mechanistic-Empirical Pavement Design (*MEPD*) (Kuttah, 2020, 2021 and 2023). Therefore, this study was mainly dedicated to assessing the efficiency of using the light weight deflectometer devise (*LWD*) in computing the dynamic moduli of fine-grained subgrade soil directly in-situ. For this purpose, several in-situ *LWD* tests have been carried out to measure the dynamic deformation moduli of clayey subgrade soil. The *LWD* tests have been carried out for many successive falling weight's drops at each tested point to eliminate as much as possible the plastic deformations that usually take place at the beginning of the test and as a result, the measured deformation moduli have mainly been related to the elastic deformations as confirmed in previous similar projects. The new procedure has been found to be quite useful to estimate the dynamic behavior of the selected soil tested in this study.

## 2 THE MODULUS OF ELASTICITY

The modulus of elasticity given in the following equation is calculated for one-layer system based on Boussinesq theory (1885).

$$E=2k(1-v^2)/Ar_o \quad (1)$$

where,

$k$=Load (peak)/deformation (peak)

$r_o$= The plate radius.

$A$= Stress distribution factor

$v$= Poisson's ratio

Note that $A=\pi$ for uniform stress distribution shape (mixed soil)

$A=3\pi/4$ for parabolic stress distribution (Granular material)

$A$=4 for inverse-parabolic stress distribution (Cohesive soil)

This equation assumes the test media to be a linearly elastic, isotropic, homogeneous semi-infinite continuum. Two of the parameters required for determining the modulus, the shape factor for distribution of the contact stress between the plate and the soil ($A$) and Poisson's ratio ($v$), are assumed. Some *LWD* manufacturers give users the option of selecting values for $A$ and $v$ while others assume fixed values.

For the current study, the *Evd* is calculated using Eq. 1, assuming, $A$=4 and $v$= 0.35.

Although the setup and test times for *LWD* are relatively short (Siekmeier et al. 2009), there are some concerns about the effectiveness of the *LWD* in testing layered systems. This concern is mainly attributed to the fact that the *LWD's* zone of influence may extend beyond the thickness of the tested layer. Elhakim et.al. (2014) investigated the zone of influence of the *LWD* by performing the *LWD* test on calcareous and siliceous sands placed in layers with varying thicknesses (10, 20, 40, 60, and 80 cm) resting on a rigid boundary (concrete floor). They found that the *LWD* reading reflects the stiffness of both the tested soil and the rigid boundary. The influence of the rigid base boundary on the *LWD* modulus diminishes with increasing the thickness of the sand layer. For soil layer thickness to plate diameter ratios of 1.5 to 2, the effect of the rigid layer is considered negligible. Furthermore, tests performed using siliceous sands show similar findings. Tompai (2008) and Nazzal (2003) found also that the zone of influence of the *LWD* to vary between 1 and 2 times the plate diameter something which is in good agreement with the findings reported by Elhakim et. al. (2014). These findings have been considered during *LWD* tests performed in this study.

## 3 TESTING METHODOLOGY

A commonly available sandy silty clay subgrade soil was selected to be used in the current project. Material classification tests have been carried out to define the main physical and mechanical properties of the materials to be used for testing (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 chosen soil in a test pit located at the backyard of *VTI* in Linköping using a multi-functional *LWD*. During the in-situ *LWD* tests, the deformation moduli have been measured under repeated loading at different stress levels and water content conditions. Laboratory moisture tests have been carried out using oven drying method in parallel with the *LWD* tests. The Nuclear Density Gauge (*NDG*) was also used in this study to determine the in-situ density and moisture content of the tested soil in the test pit. The in-situ repeated *LWD* tests have been carried out at stress levels of about 24 kPa, 38 kPa, and 50 kPa. These stress levels have been chosen to simulate the real ranges of applied stresses on such weak clayey subgrade soil by moving vehicles for subgrade used for paved and unpaved roads. Due to the expected low bearing capacity of the tested soil, a maximum stress level of 50 kPa has been adopted. Note that *LWD* testing at stress levels lower than 24 kPa cannot be achieved using in-situ *LWD* with 30 cm plate diameter (as the one used in this study). This is because generating lower loads requires to reduce the drop height significantly and, if so, the dropping weight will bounce faster than one manages to grab it resulting in uncounted additional successive rebound blows of the *LWD* weight.

## 4 CHARACTERISTICS OF THE TESTED SOIL

The particle size distribution test has been performed for the selected soil according to SS-EN 933-1 (2004) and the result of the test is illustrated in Figure 1 below.

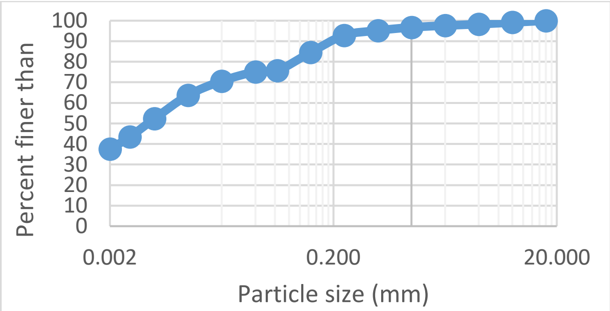


*Figure 1. Particle size distribution of the tested soil.*

The clay content in the soil was tested by sediment method at *SGI* (Swedish Geotechnical Institute) and the test results showed that the soil consisting of 37.5% clay particles (≤ 0.002 mm), fine content of 75.7% (clay and silt), the sand fraction was 21.9% and gravel fraction was 2.4%. 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 a plasticity index of 19.2%.

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, see Figure 2.

The results reveled that the compaction curve is irregularly (double peak) shaped as shown in Figure 2. 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%.

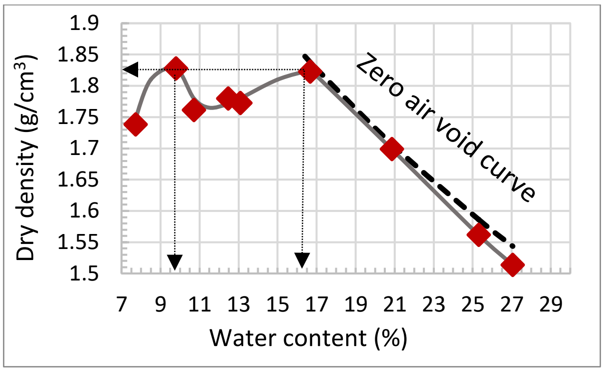


*Figure 2. Compaction curve of the tested soil.*

## 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 using *VTI's* multifunctional *LWD*, see Figure 3.

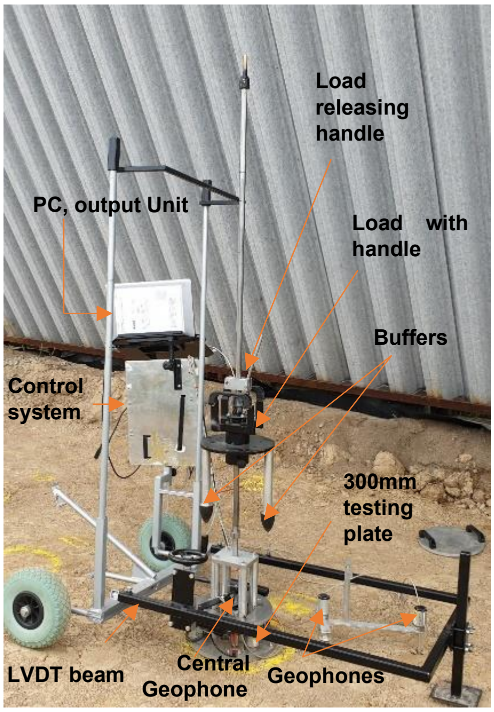


*Figure 3. The VTI's light weight deflectometer used in this study.*

These tests were carried out in a test pit compacted with the selected soil under controlled conditions. The test pit is located at the backyard of the Swedish Road and Transport Research Institute (*VTI*) and it is approximately 10 m long x 5 m width x 1.5 m depth. It has been equipped with a concrete well with a water discharging motor that can be used to control the ground water level during testing. The test pit is also instrumented 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.

## 6 RESULTS AND DISCUSSIONS

### 6.1 In-situ measurements of deformation moduli *Evd*

Figure 4 shows the effect of consecutive dropping of the falling weight on the average *Evd* of various points tested at three different moisture contents under 24 kPa, 38 kPa and 50 kPa applied stresses.

In Figure 4 with (16%) water content (i.e., the lowest tested water content), one can notice obvious fluctuation in readings of *Evd* with the number of falling weight drops while for higher water contents the fluctuation in readings almost diminished. This could be attributed to the high particle interlocking and shearing between the particles at the lowest water content of 16% which is near the optimum. This high particle interlocking, and high friction between the particles enables the energy transfer between the particles and hence rearrangement of particles within the soil matrix under the plate after each *LWD* drop something which causes fluctuation in readings with the successive falling weight drops. In the case of higher moisture content and hence high degree of saturation, as for the case of 19% and 24% water content, the friction between the particle has been decreased and less rearrangement of particles has been taken place with successive *LWD* drops something which resulted in more even *Evd* readings. Also, it can be noticed that for the case of tests carried out at 16% water content, the trendlines indicate that *Evd's*, in general, have been increasing slightly with increasing the number of *LWD* drops for the three applied stress levels conditions. This increase in *Evd* with increasing the number of repeated load cycles owing to the densification. With increasing the water contents, such increasing trend of *Evd* with the number of *LWD* drops has been diminished. This means that *Evd* attained a steady state due to the steadiness of the elastic deformation with the number of load cycles.

Furthermore, it can be seen from Figure 5 that increasing the water content decreases the dynamic moduli. The *Evd's* dropped from about 35kPa to about 20 kPa when the water contents increased from 16% to 24% for the case of 24 kPa applied pressure. Similarly, the *Evd's* dropped from about 23kPa to about 6 kPa for the same increase in water content for the case of 50 kPa applied pressure.

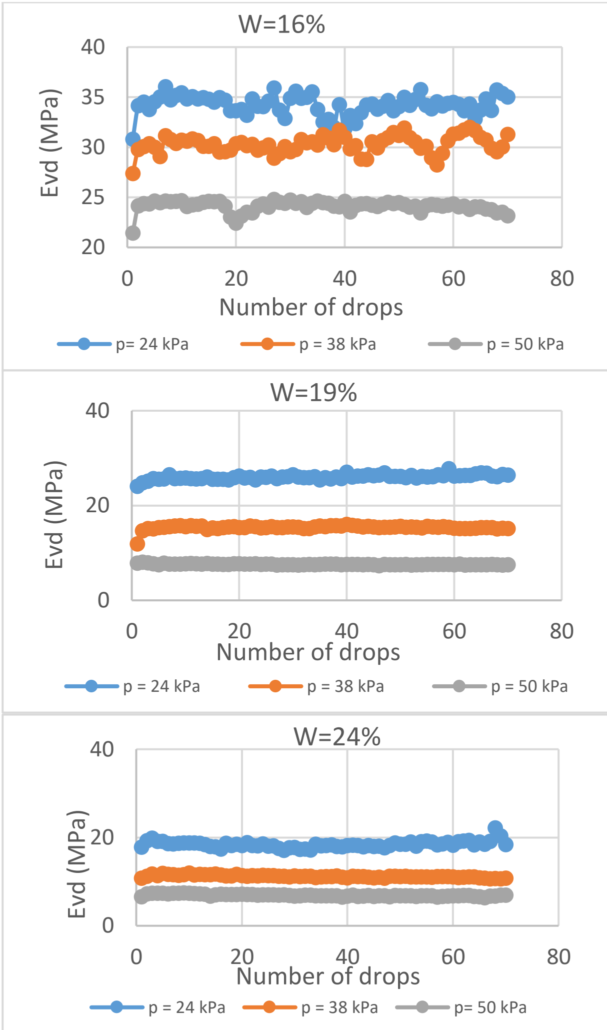


*Figure 4. The average Evd measured by in-situ LWD tests on many points tested at various water contents under different applied pressures of 24, 38 and 50 kPa.*

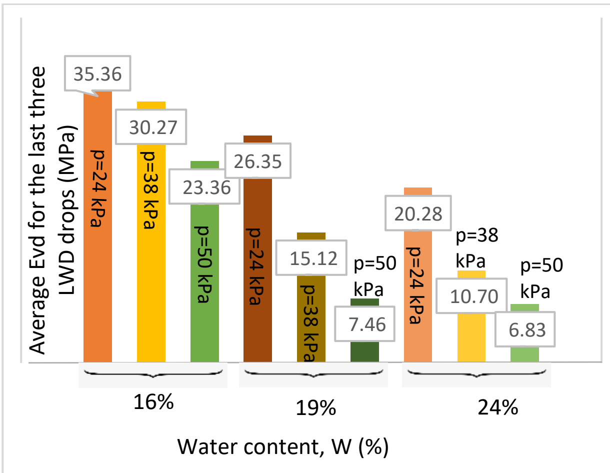


*Figure 5. Effect of water contents and applied stresses on the LWD measurement for the tested clayey soil.*

Thom and Brown (1987) attributed this behaviour to the effect of water since stiffness of the compacted material decreases due to the reduction of inter-particle bonds. Also, these tests are carried out at different densities, so the changes in stiffness observed are due to different densities.

## 6.2 Modelling of the measured deformation moduli *Evd's*

Over the last decades, a lot of effort has been made to develop models that can describe and predict the non-linear resilient behavior of road materials.

In this study, multiple regression analysis has been used to correlate the measured deformation moduli *Evd's* to the water content, applied pressure and degree of saturation or density parameters, as given in the following equations, see Figure 6:

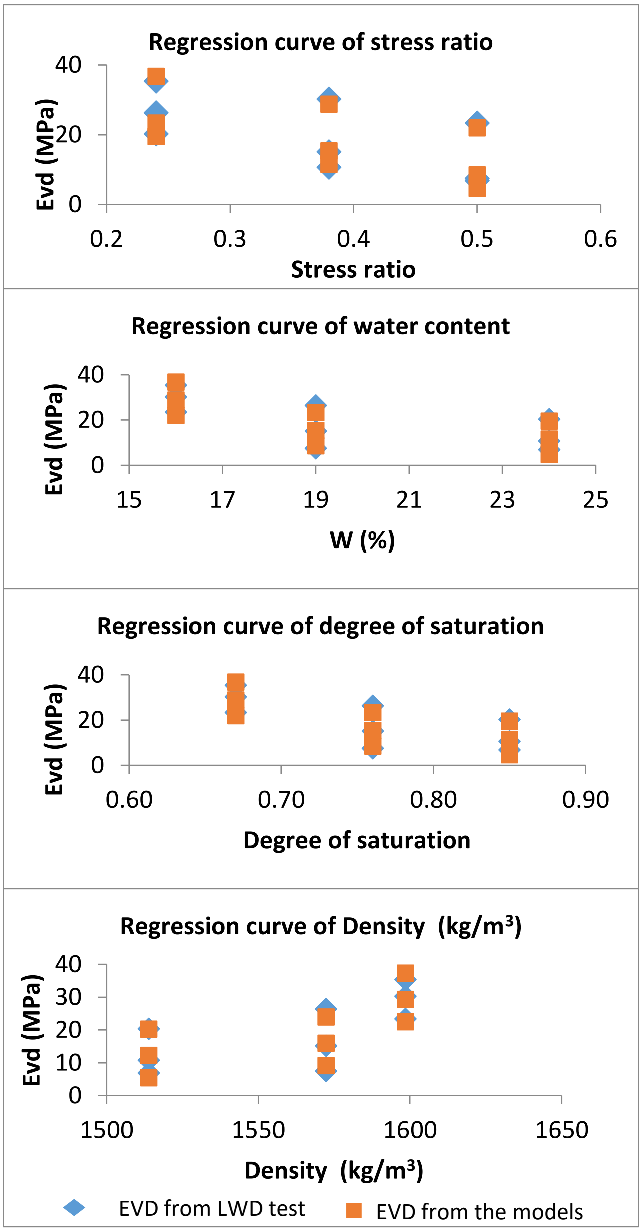


*Figure 6. Regression curves describing the correlation between measured Evd and calculated Evd using Eq. 2.*

$$Evd=180.9-57(S)+4.8(W)-309.3(SR) \quad (2)$$

$$Evd=2292.8-57(S)-15{,}3(W)-1{,}248(D) \quad (3)$$

where, *Evd* is the deformation moduli in MPa, *S* is the normalized applied stress level = *p/pa*, *p* is the axial applied stress during repeated *LWD* tests, *pa* is a reference stress of 100 kPa, *W* is the water content in %, *SR* is the degree of saturation and D is the field dry density in kg/m3.

A strong correlation has been found with multiple correlation coefficient of 0.988 representing very strong correlation after Ott and Longnecker (2010), see Figure 6.

## 7 CONCLUSIONS AND RECOMMENDATIONS

The overall tests results have been analyzed and the relations between the materials parameters collected from in-situ repeated *LWD* tests and those predicted by defined equations has been identified for the sandy silty clay tested in this project, as follows:

1. It has been observed that for the case of *LWD* tests carried out at 16% water content, the *Evds* curves reported slight increasing trend with increasing the number of LWD drops for the three applied stress levels conditions. With increasing the water contents, such increasing trend of Evd with the number of LWD drops has been diminished.
2. It has been noticed that for tests carried out at 16% water content, the lowest tested water content adopted in this study, the readings fluctuated with the number of falling weight drops while for higher water contents of 19% and 24%, the fluctuation in readings almost diminished. It has also been noticed that increasing the water content decreases the dynamic moduli, similarly, increasing the applied stresses decreases the dynamic deformation moduli as well.
3. Regarding the prediction of the dynamic deformation moduli *Evd*, a strong correlation has been found between the *Evd* and the water content, applied axial stresses, and degree of saturation or density for the tested soil with high correlation coefficient of 0.988.

The models adopted in this study to estimate the dynamic deformation moduli, namely Eq. 2 and Eq.3, are sophisticated enough and easy to use. These models are valid for the material used in this study and can be used to solve practical problems concerning the stiffness estimation under repeated traffic loading for engineering purposes.

## ACKNOWLEDGEMENTS

The author is grateful for the financial support provided by the Swedish Transport Administration.

Thanks also to KUAB AB for developing further the VTI's lightweight deflectometer in cooperation with the author.


## REFERENCES


Araya, A. A., Huurman, M., Molenaar A. A. and Houben L.J.M. (2012). Investigation of the resilient behavior of granular base materials with simple test apparatus, *Materials and Structures* 45:695-705. https://doi.org/10.1617/s11527-011-9790-1.

ASTM D1557 (2012). Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft$^3$-2,700 kN-m/m$^3$, ASTM International, West Conshohocken, PA, United States.

Boussinesq, M. J. (1885). *Application des potentiels a l'étude de l'équilibre et du mouvement des solides élastiques, avec des notes étendues sur divers points de physique mathématique et d'analyse*, Paris: Gauthier-Villard imprimeur libraire.

Elhakim, A. F., Elbaz, K., and Amer, M. I. (2014). The use of light weight deflectometer for in situ evaluation of sand degree of compaction, Housing and Building National Research Center HBRC Journal, 10, 298-307. http://ees.elsevier.com/hbrcj.

Gomes Correia, A. and Gillett, S. (1996). *Resilient behaviour of Soils*, In Flexible pavements edited by Gomes Correis, A. , Balkema, Rotterdam, ISBN 90 5410 523 2, resilient.pdf (uminho.pt).

Kuttah, D. (2020). Simple and quick evaluation of unbound materials bearing capacities that could be used as input data in Mechanistic-Empirical Pavement Design, VTI report 1054, ISSN 0347-6030, in Swedish. VTI rapport 1054 (diva-portal.org).

Kuttah, D. (2021). Determining the resilient modulus of sandy subgrade using cyclic light weight deflectometer test, *Transportation Geotechnics* 27, 100482, ISSN 2214-3912, https://doi.org/10.1016/j.trgeo.2020.100482.

Kuttah, D. (2023). Assessing the interactions among factors affecting the light weight deflectometer measurements, *Bulletin of Engineering Geology and the Environment*, 82, 238. https://doi.org/10.1007/s10064-023-03231-2.

Lekarp F, Isacsson U, Dawson A (2000). State of the art. II: Permanent strain response of unbound aggregates.", *J. Transp. Eng.* 126(1):76–83. https://doi.org/10.1061/(ASCE)0733-947X(2000)126:1.

Nazzal, D. M. (2003). *Field evaluation of in-situ test technology for QC/QA during construction of pavement layers and embankments*, (Master's thesis), Louisiana State University, Baton Rouge.

Ott, L. and Longnecker M. (2010). *An Introduction to Statistical Methods and Data Analysis*, Sixth Edition, Brooks/Cole, Cengage Learning, USA. ISBN-13: 978-0-495-01758-5.

Razouki, S. S. and Kuttah, D. K., (2004). Effect of Soaking Period and Surcharge Load on Resilient Modulus and California Bearing Ratio of Gypsiferous soils, *Quarterly Journal of Engineering Geology and Hydrogeology,* London, Vol. 37, pp. 155-164. http://qjegh.geoscienceworld.org/content/37/2/155.

Siekmeier, J., Pinta, C., Merth, S., Jensen, J., Davich, P., Camargo, F. & Beyer, M. (2009). Using the dynamic cone penetrometer and light weight deflectometer for construction quality assurance, Minnesota Department of Transportation, Report No. MN/RC 2009-12. https://www.lrrb.org/pdf/200912.pdf.

SS-EN 933-1 (2004). Tests for geometrical properties of aggregates, Part 1 "Determination of particle size distribution – sieving method, SIS, Swedish Standards Institute, Stockholm, Sweden.

Swedish Standard SS 027115 (1989). Geotechnical tests – Grain density and specific gravity. Edition 3, Swedish Standards Institute, Stockholm.

Swedish Standard SS 027120 (1990). Geotechnical tests - Cone liquid limit. Edition 2, Swedish Standards Institute, Stockholm.

Swedish Standard SS 027121 (1990). Geotechnical tests – Plastic limit. Edition 2, Swedish Standards Institute, Stockholm.

Thom, N. H. and Brown,S. F. (1987). Effect of Moisture on the Structural Performance of a Crushed-limestone Road Base, *Transportation Research Board, Transportation Research Record* 1121. http://worldcat.org/isbn/0309045010.

Tompai, Z. (2008). Conversion between static and dynamic load bearing capacity moduli and introduction of dynamic target values, *Periodica Polytechnica, Civil Engineering*, Hungary, 52–2: pp. 97-102. https://doi.org/10.3311/pp.ci.2008-2.06.

U.S. Department of Transportation (2006). Geotechnical Aspects of Pavements Reference Manual, Federal Highway Administration, Publication No. FHWA NHI-05-037, NHI Course No.132040, https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/.