Characterisation of in situ soils based on the resilient soil modulus obtained using Light Weight Deflectometer (LWD)

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Keywords: LWD, static plate load test, resilient modulus Evd, static modulus Ev1 and Ev2

ABSTRACT

The Light Weight Deflectometer (LWD) is a portable device that measures the onsite dynamic or resilient modulus (Evd) of subgrade soils and pavements. The LWD, which has been used extensively in Europe and the United States, has become popular for assessing the stiffness of embankments, structural fills and other earth structures. It assesses the bearing capacity, the stiffness and the compaction degree of soils that have a maximum grain size of 63mm. The LWD assessment considers the stiffness (or compressibility) characteristics of the materials under testing to a depth of 600mm below plate level. The paper presents available correlations between Evd with the static soil modulus Ev obtained from static plate load tests. It also presents how Evd can be linked with CBR and thus be useful for pavement design, but also with the subgrade reaction modulus K of the assessed soils. It also discusses the fundamental principles behind the testing along with the benefits that may arise from its use on specific applications. Such applications include the design and construction monitoring of gravel rafts, the design of pavements, engineered and non-engineered fills, landfills, MSE walls, pipelines and services, evaluation of ground improvement effectiveness and soil stiffness mapping.

1 INTRODUCTION

The Light Weight Deflectometer (LWD) is a portable device that measures the onsite dynamic or resilient modulus (Evd) of subgrade soils and pavements. It is suitable for cohesionless, cohesive and mixed types of soils with a maximum grain size of 63mm. It can be used on natural subgrade and subsoils, unbound base layers, granular layers, soil stabilised with lime or other additives. The LWD test method has been gaining in popularity following its use in European countries and the USA for over 30 years. The test method was originally designed to measure the resilient modulus (Evd) of an in-situ material which indicates the material's stiffness. The LWD can be perceived as an on-site simulation of a laboratory cyclic triaxial test for unbound or bound materials. The tested soil volume by the LWD is 300mm in diameter and 600mm in depth. Numerous standards have been developed for the LWD and allow the characterisation of various materials based on Evd, which can facilitate the estimation of bearing capacity and the compaction degree of engineered fills. This is extremely beneficial for infrastructure design and testing as it allows a fundamental engineering property (Evd) to be measured and used in the design and construction process.

The resilient modulus (Evd) represents the elastic response of the soil specimen after many cycles of loading. Cyclic triaxial tests, used for measuring the resilient modulus (Evd) of untreated base/sub-base materials, are expensive and difficult to execute in New Zealand. This has caused the measurement of such an important geotechnical parameter to often be ignored during the design and construction process of infrastructure in New Zealand. The LWD test method therefore offers a great alternative for measuring the onsite resilient modulus, at a fraction of the laboratory cost. It should be noted that CBR characterises a soil based on its failure to penetration; this is an indirect measure of soil strength. In contrast to resilient modulus, CBR is not a fundamental material property. However, the use of CBR is well justified in the geotechnical community as it is widely accepted for pavement design.

2 LWD TEST METHOD, STANDARDS AND APPARATUS

2.1 LWD test method and standards

The principle of this test was developed in 1981. The test simulates a truck with a 10ton axle weight travelling on a road at 80km per hour. A steel plate of 300mm diameter is placed on the soil to be tested. A 10kg weight drops from a height of 72 cm onto the plate. The load pulse creates a soil pressure of 100kPa under the plate. The approximate duration of the load pulse is around 17ms and it is created by means of engineered springs located above the plate. An acceleration sensor is arranged on the load plate. The generated acceleration signal is recorded. From single and double integration of the acceleration signal, the velocity and the displacement (settlement) of the plate is calculated.

From this simple test method the recorded values can be used for determining:

- Resilient or dynamic soil modulus (Evd)
- Bearing capacity
- Dynamic spring stiffness (Kvd)
- Degree of compaction and compaction quality control

The resilient modulus Evd is given in MPa by the equation:

$$\text{Evd} = \frac{22.5}{s} \tag{1}$$

where s is the measured plate settlement in mm.

The specifications for the LWD apparatus are defined in both ASTM E2835-11 and ZTVE-StB 09 and conform to strict equipment production criteria. The apparatus is also required to be calibrated on an annual basis by an accredited calibration institute.

Numerous international standards have been produced following the inception of the LWD as a test procedure. The two main internationally accepted test methods are:

- ASTM E2835-11: American Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device
- ZTVE-StB 09: German Engineering Code for Soil and Rock in Road Construction

While these test methods are the most widely accepted in industry, many other standards have been produced to complement more specific design codes and procedures. Some other available international standards on LWD include:

- TP BF-StB B 8.3 version 2012: German Engineering Code for Soil and Rock in Road Construction
- ZTV E-StB 09: German additional terms of contract and rules for earthwork in road construction
- ZTV T-StB 95: German additional terms of contract and rules for subbases in earthworks
- ZTV A-StB 97: German additional terms of contract and rules for excavation in traffic access

- RVS 08.03.04 March 2008: Austrian regulation - Compaction test by means of dynamic plate load test
- RIL 836, Deutsche Bahn AG: Guideline for the use of the Light Drop-Weight Tester in railway construction
- UNE 103807-2:2008: Spanish regulation - Plate Load Test by means of the Light Drop Weight Tester-Part 2
- TB 10102-2004, J338-2004: Chinese regulation - Standard for soil testing in railway construction

The number of standards available shows that the test procedure is widely accepted and utilised for a diverse range of engineering applications throughout the globe. This also provides a simple platform for the integration of the LWD into New Zealand design and construction procedures through the utilisation of these existing standards.

2.2 Description of LWD apparatus

There are numerous, well designed and robust LWD equipment apparatus available internationally (Zorn ZFG 2000, Keros LWD, Dynatest 3031 LWD, HMP LFG Pro). Figure 1 shows a schematic view of the LWD apparatus. This equipment is small and portable, allowing it to be easily transported and utilised on a construction site by one technician.

The apparatus is controlled during testing by means of an electronic recorder that provides a step by step guidance to the operator during the testing process. This removes the potential for any measurement errors.

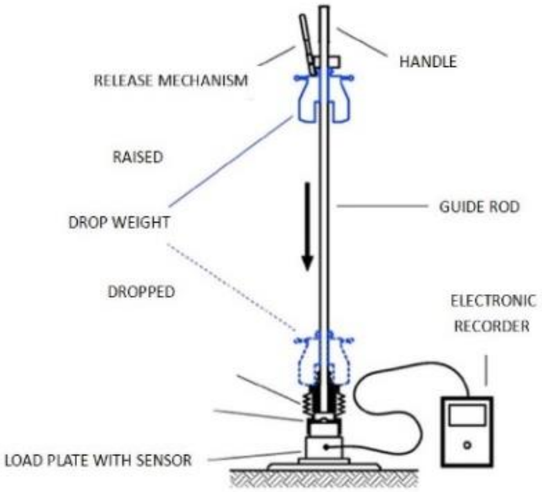

Figure 1: Components of the Light Weight Deflectometer (LWD) as per ASTM E2835-11

Following the test procedure, the electronic recorder on the apparatus provides an instant graphical and tabular display of the results which are then stored on the device for download. The apparatus also includes a GPS and a built-in printer that can instantly print the results onsite for quality assurance records.

3 GENERAL APPLICATIONS FOR LWD

The use of the LWD test method in New Zealand is a natural progression by utilisation of 'best practice' test methods as they become more widely recognised and accepted in the civil and geotechnical engineering industries. This, combined with the many benefits of the test method, is likely to benefit the following sectors:

- Site investigations for projects where the bearing capacity and settlement of shallow foundations is a key consideration
- Highways and Bridges: Design and construction monitoring of highway pavements and their subgrades, highway embankments, reinforced earth structures and MSE walls, backfills, granular fills behind abutments and retaining walls
- Earthworks and Land Development: earthworks of any type, trenches and services, landfills and backfilled areas, quality assurance testing for quarries and aggregates, compressibility of ground on derelict or contaminated land, quality assurance for temporary works, site feasibility and suitability assessment, subdivisions
- Geotechnical Engineering: gravel rafts, structural fills, compaction control of treated and untreated soils, foundation soils, evaluation of ground improvement effectiveness, soil stiffness mapping
- Civil Works and Infrastructure: canals, airports and airfields, pipe and services trenches, marine works

4 CHARACTERISATION OF IN SITU SOILS BASED ON LWD

4.1 Estimation of CBR and static modulus Ev

The LWD can assist in the characterisation of in situ soils using correlations to other well accepted test methods. The dynamic soil modulus (Evd) obtained using LWD, is well correlated with the static soil modulus (Ev1), obtained by static plate load tests (PLT), for both cohesive and cohesionless soils (refer to Figure 2). As the PLT is well correlated with CBR, the LWD can also assist in the characterisation of soils for use in pavement design.

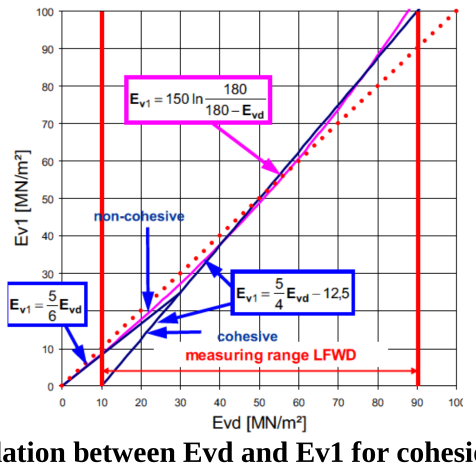

Figure 2: General correlation between Evd and Ev1 for cohesionless and cohesive soils

There is a plethora of comparative tests between dynamic (LWD) and static plate load tests (PLT) for both cohesive and granular soils (Adam and Kopf, 2004). These correlations relate Ev1 measured by static PLT, with Evd measured by LWD. A useful note that can be made for the relationship between Evd and Ev1 shown in Figure 2 for cohesionless or cohesive soils is the following:

When Evd ≤ 50MPa, Evd > Ev1 and when Evd ≥ 50MPa, Ev1 > Evd (2)

Another correlation suggested in the Austrian standard RVS 08.03.04 (2008), suggests the following correlations:

When Ev1 ≥ 25MPa, Evd = 10 + 0.8 Ev1 (3)

and when Ev1 < 25MPa, Evd = 1.2 Ev1 (4)

When conducting static plate load tests with a 762mm diameter plate, the CBR value can be estimated from the following equation (IAN 73/06, 2009):

$$CBR\ (\%) = 6.1 \times 10^{-8} \times (K_{762})^{1.733} \quad (5)$$

where K_{762} is the modulus of subgrade reaction (kN/m^3) for the 762mm plate. K_{762} is defined as the stress σ (in kPa) that causes 1.25mm settlement, divided by 0.00125m.

$$K_{762} = \frac{\sigma}{1.25x10^{-3}} \quad \text{in kN/m}^3 \quad (6)$$

Thus, by conducting LWD testing with a 300mm diameter plate, the CBR value can be estimated with the following procedure:

- Evd can be converted to Ev1 depending on the soil material by using equations 3 or 4 and/or the correlation presented in Figure 2 above.
- Convert the Ev1 to a spring stiffness K_{300} for a plate width B of 300mm by using the equation (Bowles, 1997):

  $$K_{300} = \frac{Ev1}{B\,(1-\nu^2)} \quad (7)$$

  Where ν is the Poisson's ratio of the tested material.

- Convert the K_{300} to a K_{762} by using the conversion factor shown in Figure 3. For converting from a 300mm plate to a 762mm plate, the factor is 0.44. Thus:

  $$K_{762} = 0.44\,K_{300} \quad (8)$$

- For estimating CBR, use equation 5 above by substituting the value for K_{762} obtained from the previous step.

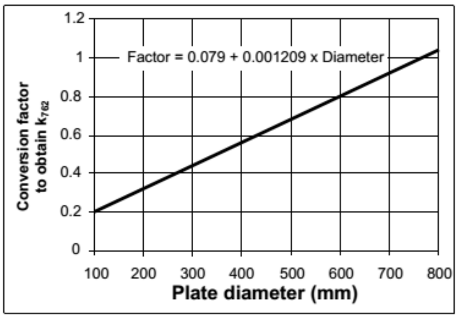

Figure 3: Conversion factor for smaller plate sizes (IAN 73/06, 2009)

The above suggests that by measuring the resilient modulus (Evd) on site, the static modulus (Ev1) and the CBR can also be estimated and thus the soil or the site can be characterised. The above correlations can be invaluable as the design engineer is then in a position to facilitate static settlement calculations for shallow foundations or to assess the capacity of a subgrade for accommodating a pavement.

4.2 General purpose characterisation of natural soils

An effort is made to compile a rough soil characterisation scheme for general use for cohesionless and cohesive soils. The intention of this effort is to classify naturally formed in-situ soils before being treated or compacted. The proposed scheme is shown in Tables 1 and 2. This characterisation scheme is completely uncoupled from compaction criteria which are presented in the next paragraph.
The soil characterisation scheme is based on the following:

- The modulus values provided by Bowles (1997), which correspond to Ev1 values
- The relative density of sands and the state of their packing as assessed by SPT
- The consistency of clays based on their undrained cohesion C_u
- By applying linear interpolation for the intermediate values for the above parameters and for Evd
- By considering Figure 2 and equations 2, 3 and 4

Variation is expected as this scheme is not based on the exact grain sizes present in the soil and their mass percentage.

Table 1: Soil characterisation scheme for cohesionless soils

Cohesionless soils	Very loose	Loose	Medium dense	Dense	Very dense
Evd (MPa)	0-12	12-24	24-34	34-50	50-90
Ev1 (MPa)	0-10	10-20	20-30	30-50	50-100

Table 2: Soil characterisation scheme for cohesive soils

Cohesive soils	Very soft	Soft	Firm	Stiff	Very stiff	Hard
Evd (MPa)	0-22	22-30	30-36	36-43	43-50	50-90
Ev1 (MPa)	0-15	15-25	25-33	33-41	41-50	50-100

Subgrade testing undertaken using LWD yielded various Evd values for different soil types. Table 3 provides examples of Evd values for a number of soil types measured in Christchurch, New Zealand. Tables 1 and 2 above can then be used to classify these soils based on their description and Evd measured using LWD.

Table 3: Example Evd values for various soils measured using LWD

Soil Type	Evd (MPa)	Soil characterisation
TOPSOIL (cohesive)	5	Very Soft
Clayey SILT (cohesive)	8 – 14	Very Soft
SILT (cohesionless)	17 - 27	Loose to Medium Dense
AP40 compacted GRAVEL (wet)	18 - 34	Loose to Medium Dense
AP40 compacted GRAVEL (moist – dry)	40 - 64	Dense to Very Dense

4.3 Compaction assessment based on modulus criteria

Table 4 presents target values for Evd and the reload modulus Ev2 for cohesionless soils extracted from the German standard ZTVE-StB 09. The reload modulus Ev2 is obtained by a static plate load test when the soil is first incrementally loaded to measure Ev1, then incrementally unloaded to zero stress and then incrementally reloaded to the same stress level as for when Ev1 was assessed. For well compacted soils, the ratio of Ev2 over Ev1 (Ev2/Ev1) is greater than one and usually smaller than 2.6. The classification of these soils is relying on the German soil classification system DIN 18196 and is somewhat similar to the U.S.C.S. classification system.

Table 4: Modulus based compaction criteria for Evd and EV2 (ZTVE-StB 09)

Soil group	Evd (MPa)	Ev2 (MPa)	Compaction degree (%)
GW, GI, GE (gravels)	≥50	≥100	≥100
SW, SI, SE (sands)	≥40	≥80	≥98

5 BENEFITS FROM THE USE OF LWD

5.1 Potential benefits to New Zealand construction and economy

The LWD has become an internationally recognised test method for many areas of construction following its use in Europe and the United States over the last 30 years. The major benefits of using the LWD from a practical perspective are:

- It relies on sound principles of geotechnical engineering
- It is fast, portable and easily operated by one technician
- It produces repeatable results and is cost effective
- The geotechnical parameters measured allow a more robust performance based approach to be adopted in the design and construction monitoring phases

Additionally, specific benefits for New Zealand can potentially be the following:

- It is environmentally safe and does not have the safety and transport issues of a nuclear density meter (NDM)
- It offers a 600mm investigation depth below plate level (Adam and Kopf, 2004) which is substantially deeper than other well established methods. This 600mm thickness can be the same uniform soil layer or a composite section made of subgrade, subbase and base materials.
- Compared to NDM, it provides a more reliable assessment tool when checking materials coarser than 40mm for assessing degree of compaction; CETANZ Technical Guide TG3 recommends caution when interpreting test results from NDM for granular materials coarser than 40mm
- Assessment of the soil modulus as per AS/NZS 2566.1:1988 when flexible pipes are installed in trenches, becomes more straightforward for both designers and contractors, leaving less room for disputes over construction quality acceptance
- Looking at several of the more common test methods utilised in New Zealand practice (Clegg hammer, CPT, DCP/Scala penetrometer, shear vane, CBR), it is clear that none of them actually measure the soil modulus

If CBR tests are also conducted in conjunction with LWD, then a correlation between Evd and CBR can be established. Currently, there is significant discussion and research occurring in the American geotechnical community on the development of modulus-based construction specification for acceptance of compacted geomaterials (NCHRP 10-84, 2014). However, modulus-based construction specifications are already well-established and accepted in European practice as presented in paragraph 4.3.

5.2 Potential cost savings for highway projects

The LWD was used for assessing the stabilisation process of the founding aggregates on the A556 improvement scheme in Cheshire, UK (Ground Engineering, 2016). The ground conditions along the route were very challenging and variable with CBR values as low as 1.5%. The finished pavement was required to meet Foundation Class II with greater than 100MPa modulus as per Highways England's Interim Advice Note 73/06. One of the main tests used for demonstrating compliance with the design was LWD. The performance based design required a mean Evd modulus of 50MPa for the geogrid reinforced capping layer. By achieving this requirement for the capping layer, it was ensured that the Foundation Class II (100MPa) was achieved on the finished pavement surface. It was found that surface moduli of up to 700MPa were achieved using this construction and quality assurance methodology. The contractor and the designer succeeded to save £2M ($NZD3.5M) when compared to soil excavation and replacement. From the above example, it can be concluded that more efficient designs and hence cost savings could be achieved if New Zealand Standards are introduced on the use and interpretation of LWD.

6 CONCLUSIONS

The Light Weight Deflectometer (LWD) is an internationally recognised and utilised test method that has been gaining in popularity following its use in European countries (for example, Germany and UK on a performance design basis) and the USA for over 30 years. However, its utilisation in New Zealand for both design and construction has been limited to date for various reasons. With modern and robust test equipment now available, and internationally accepted standards readily available, utilisation of the LWD in New Zealand is likely to become more prolific.

The LWD provides many advantages over other in-situ and laboratory test methods by quickly and easily measuring the resilient modulus (Evd), and allowing it to be easily incorporated into the design process or utilised at the construction monitoring phase.

Utilisation of the LWD in the design and construction process allows the creation of a performance based design with a more robust construction monitoring process. This in-turn creates more resilient infrastructure through the use of performance based acceptance criteria. The LWD equipment also reduces construction timeframes due to its portability, speed of testing and ease-of-use for technicians.

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