Pavement Foundation Stiffness Compliance Testing - A New Regime

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Abstract
Traditionally the construction of the foundations of paved infrastructure followed a recipe approach where specified materials are laid using specified plant in an approved away following a method specification. This approach is prescriptive and limits material use to those that meet the recipe assuming a given level of performance after completion.

To encourage sustainability the UK Highways Agency launched new pavement and foundation design guidance that is moving away from this prescriptive approach (IAN 73/06 revised in 2009, and HA 26/06). The guidance aims to allow a more flexible design and assessment of the required foundation performance parameters of strength and resistance to permanent deformation. This also introduced stiffness assessment of the constructed foundation to confirm compliance with design. In contrast to the previous regime, the actual performance of the foundation can influence (and provide savings to) the design of the structural pavement layers above.

The new guidance permits the use of Light Weight Deflectometers (LWDs) to assess stiffness compliance. LWDs are becoming increasingly common tools in the checking of foundations of paved infrastructure. This paper presents the background to the use of LWDs within the new guidance, and elements of a recently completed ‘Good Practice’ guide for their use.

INTRODUCTION

The materials and methods used in the construction of foundations of paved structures (such as ground bearing slabs, industrial floor slabs, local and main highways, heavy duty pavements and railways), have traditionally followed empirical approaches. The methods and design follow a recipe approach where if the natural underlying subgrade has a certain level of performance (normally measured via CBR or parameters correlated to it); then known materials, compacted in a known way, using specified plant, is assumed to have adequate performance.

These methods are normally derived from the specifications developed for the UK highway industry and included in the Manual of Contract Documents for Highway Works (MCHW, 2006). This typically specifies material grading and aggregate (or soil) properties relative to permitted uses of that material within a classification system (for example, general fills, subgrade improvement 'capping' layer Sub-base , or a procedure for stabilisation). The placement of materials is normally controlled by the layer thickness, plant to be used and a specified number of compaction passes.

Such a prescriptive approach does not necessarily make best use of the material properties achieved in compaction and does not encourage efficient use of materials for the correct application or encourage recycling or material reuse. However, if a more detailed measure of foundation material behaviour can be made insitu then more appropriate materials can be used in specific applications and the actual performance of those materials can be used to optimise the design of the layers themselves and any overlying paved structure (Rogers et al, 2004).

In a move to achieve this for the UK road infrastructure the Highways Agency has been working towards such a performance approach to pavement foundation design and specification.

In 2006 the HA introduced a new specification approach (IAN 73/09 and subsequent revision in 2009) which incorporates stiffness based design of foundations, and elements of performance appraisal during construction, including compliance testing of the pavement foundation prior to the construction of the overlying layers, using dynamic plate test devices. The dynamic plate tests include the Falling Weight Deflectometer (FWD) and the more portable Light Weight Deflectometer (LWD).

This paper presents the background to the introduction of the LWD testing and explains some of the issues associated with the use of LWDs. It then presents details of a recently produced good practice guide for the use of the LWDs, illustrating how device users and material suppliers and specifies can make best use of the data from tests.

PERFORMANCE REQUIRED OF PAVED INFRASTRUCTURE

The functions of the structure of any trafficked area are to reduce the applied stresses through the structure to a level that can be sustained by the underlying layers and subgrade over its life. This equates to a small number of high stress applications during construction, (due to the construction traffic and compaction of overlying layers), and a large number of small stress applications in service (where service loads are dissipated through the complete structure, Rogers et al, 2004). This loading is a function of the stresses applied, the design layer thicknesses and material and the subgrade properties. To achieve adequate performance the stresses must be dissipated sufficiently (by the provision of adequate thickness and load spreading ability of the pavement layers) so as to not over stress the subgrade leading to its failure due to plastic deformation or excessive resilient deformation affecting the structure above (Figure 1). In addition the materials themselves must not undergo internal deformation either. This means that the pavement materials must demonstrate adequate performance in terms of strength/resistance to permanent deformation, and stiffness, which are the fundamental pavement material performance parameters required. The consistency of foundation support along the site length is also considered important with regard to maintaining the long-term ride quality

TRADITIONAL DESIGN AND SPECIFICATION

The CBR test has been used as the measure of subgrade performance for pavement foundation design for many years. In essence, the test involves the slow compression of a 52mm diameter plunger into a (re)compacted (or insitu) sample of subgrade material . The force required to produce a standard penetration is measured and equated to a value from a 'standard' crushed rock, expressed as a percentage. The design CBR can also be estimated for design from correlation with simple plasticity index tests (related to suction and relative position of the water table). In situ it can be estimated indirectly from simple strength tests (such as the Dynamic Cone Penetrometer) or static plate bearing tests, and is accepted as a simple index test, but it clearly does not measure required material performance in terms of stiffness or strength, nor does it apply appropriate stress conditions to simulate the pavement loading applied.

The traditional design based the thickness of capping and sub-base on the subgrade CBR – the design value chosen as the lowest of the expected site CBR and the long-term equilibrium value. There was an assumption that all foundations were comparable in performance, and this was clearly erroneous but suitably simple to utilise the design charts and procedure. However, this approach made no allowance for better (or worse) performance achieved and meant that the materials used were not so readily optimised to save money or resources.

However, more flexible design and assurance of the level of performance of the foundation, in terms of stiffness and/or strength, permits a more pragmatic design of the pavement layers above. It also permits more options to the designer and constructor to choose from a range of materials in the foundation itself. This significant change in approach is in essence what is embodied in the new design and specification approach included in IAN 73/09 and the pavement design guide HD 26/06.

PERFORMANCE-BASED DESIGN

Many countries are also working toward performance led design. However, currently full analytical design is not achievable, and what is termed mechanistic empirical design is employed in many countries. Whereby the fundamental properties of materials and loading conditions are used to predict allowable stress and strains within the pavement structure. The UK guidance now fits into this approach.

In the revised pavement design guide HD 26/06 the upper pavement design is based on a foundation design meeting one of four classes, these based on long-term foundation stiffness (Classes 1 to 4, with Class 1 being for local low volume applications, Class 2 being a traditional foundation and 3 and 4 stabilised foundations; IAN 73/09 and HD26/06). The foundation is designed to achieve a required long-term stiffness, using the design charts or numerical procedures set out in IAN 73/09. A demonstration trial and continuous testing through the main works is required to demonstrate the subgrade design parameters are correct and that the design foundation performance will be achieved. The guidance sets short-term targets for stiffness, density and resistance to rutting under construction traffic wheel loads. This suite of construction tests is aimed to provide assurance that compliance with the long-term design values for the pavement foundation class will be met and test frequencies are specified (for example LWD tests are required every 20m per lane).

With regard to stiffness measurement, the target values comprise a rolling mean of five consecutive test results and an absolute minimum for any measurement of the foundation surface modulus. Foundation surface modulus is the composite modulus of all the layers assessed by the test (Figure 2).

LWD TESTING FOR STIFFNESS

To introduce this new stiffness based approach, suitable devices that can reliably measure the field stiffness of the completed foundation were required. As some pavement foundation materials exhibit stress and strain rate dependency, and to assess a suitable zone of material similar to a wheel loading, the device must apply an appropriate stress magnitude over a suitable area and at an appropriate rate. Traditionally such structural assessment has been undertaken with the FWD for completed pavements.

Devices

In recent years several portable light weight deflectometers (LWDs) have been developed, aimed at rapid on site evaluation of unbound and bound (slow and fast setting) materials. Currently there are two commercially available LWDs (the Grontmji-Carlbro Prima 100 and the Dynatest 3031, Figure 3) in the UK that satisfy the current specification set out in IAN 73/09. The two devices operate in very similar ways. In essence, a load is dropped onto a set of rubber buffers (to damp the impact and control the period of the load pulse) attached to a loading plate (typically 300mm in diameter, but interchangeable to various diameters). The bearing plate houses a load cell, and a geophone. The bearing plate has a hole in the base that allows a free moving geophone foot to rest on the ground, that measures the deflection of the ground under test (see Figure 4 for a schematic of the device). The geophone measures relative velocity, integrated by the software to provide a displacement, and the maximum contact stress is calculated from the measured peak load and plate diameter.

The stiffness of the foundation is then calculated assuming a Bousinesque elastic half space analysis (see Figure 4) allowing for plate flexibility/rigidity and the Poisson's ratio of the material under test. The devices collect load and deflection pulse against time traces for examination (Figure 5), which can be viewed on the hand-held PDA for data logging during testing, or stored for later viewing on a PC.

It should be noted that other LWD devices exist, in various forms but do not meet the requirements of IAN73/09. Additionally the FWD is considered in the UK as the gold standard dynamic plate test, and if an LWD is used it has to be correlated to the FWD in a site trial – at the same contact stress and bearing plate diameter for parity.

Experience with FWD and LWD devices has highlighted a number of issues with testing, data quality and reporting (Fleming et al, 2009). From sites trials a large variability of stiffness results has been observed, with larger variation on subgrades and smaller variation on well controlled sub-base materials. Variation in compatibility/correlations between LWD devices and correlations to FWD stiffness has been observed, and these are observed to be material and site specific, as a function of the type of buffers and pulse duration, depth of material stressed and the position and size of foot that contacts with the ground. In addition, issues with the consistency of good plate to ground contact, and variation in operator test methodologies and basic operator errors can also cause variation in the data collected (Fleming et al, 2009 and Fleming et al, 2007).

Whilst there are many sources for potential variability in the device readings on site, the new designs have accounted for many of these issues by the careful setting of the target values required, with the rolling average (mean) target helping to smooth out much of the variation expected. For larger projects the requirement of an initial foundation site trial and validation of the LWD measurements to the FWD is intended to address many of the variability issues prior to the main works.

However, although the LWD device and an outline test method is specified within IAN73/09, there is no current British or European standard governing LWDs. Neither is there a site operating procedure for consistency of measurement between users and devices. To ensure that any test device, measurement or operator issues are minimised, a LWD test protocol was clearly required (Fleming and Edwards, 2009).

Good Practice Guide

The authors, with the support of the HA, Britpave and a number of contractors and consultants, have now produced a UK LWD 'Good Practice' guide (Fleming and Edwards, 2009). The guide provides an overview of the LWD test and measurement methods, details current state of practice knowledge on their use and interpretation, and includes a 'test protocol' specifically aimed at meeting the requirements of the IAN73/09 compliance testing.

The protocol for undertaking testing in accordance with IAN73/09 allows users to test appropriately and minimise many of the issues that can affect the test, advises what to do if the test goes wrong, and presents some guidance on setting up and testing before going to site (Figure 6). It also presents some guidance as how to identify poor tests or material issues by interrogation of the test data (Figure 7). These issues are further discussed below. While the protocol is very much geared towards IAN73/09 the test methodology is equally valid to use when testing non IAN73/09 foundations.

PRACTICAL EXPERIENCE AND ISSUES WITH LWD TESTING

The following section briefly describes the tests and identifies some of the issues with testing.

The IAN Protocol

The protocol following IAN73/09 requires the LWD device is calibrated annually and checks are done to confirm its proper working. On site, after setting up the device at the test location three seating drops are given at a target contact stress of 100kPa to seat the plate properly, followed by a further three measurement drops. (It should be noted that on bound materials the target stress increases to 200kPa). The average of the three measurements is recorded as the stiffness modulus for that position. If the plate is not seated correctly, or the data appears erroneous a new test location is required.

Test Quality Evaluation

Operators with experience may observe obvious problems with poor quality tests from the device moving or shaking during the test. This is usually from poor seating of the device. For a good quality impact the deflection trace that can be expected is shown in Figures 7a and b, whereby the deflection curve is smooth and returns to 0 or has a slight rebound.

It is not uncommon to experience some rebound from the load pulse (Fleming and Edwards, 2009). The diagrams in Figure 7 show a range of possible responses that have been observed in research trials and are include in the Good Practice guide as simple visual aides to site operators. For example, whilst slight rebound of the velocity curve is permissible, excessive rebound may demonstrate issues with the test such as poor seating or saturation of the ground.

When undertaking the drops (both seating and test drops) it is normal to expect a small amount of variability between the readings (usually more so with the seating drops) due to bedding in of the plate. However, where a progressive change (reduction) in the peak deflection occurs, and as shown in Figure 7c the unloading deflection is far below the 0 line but consistently moves towards it, this is indicative of a poorly compacted material or shearing on a weak material, showing progressive compaction and an increase in stiffness (i.e. decrease in peak deflection) caused by the loading of the device itself.

In addition when positioning the device the location of the geophone foot is important, as shown in Figures 7d and 8. The foot may be resting on one large particle, or on a thin layer of mobile fines, or be subject to punching shear on weaker materials (as shown in Figure 9), This can also lead to an uneven trace (Figure 7d).

Soft Spots

Although the IAN only sets a requirement to test on top of the completed foundation it is good practice to test on sub-layers as they are installed to give assurance that the final targets will be met on the finished foundation.

The data in Figure 10 was obtained from an area of compacted sub-base and highlights measurements which have not obtained the required minimum target for the site. On further investigation and excavation down through the layers (Figure 11) the problem areas were found to be caused by the sub-grade, which had to be excavated and then refilled. If testing had been performed on the layers during construction the spots could have been identified and treated rather than afterwards.

CONCLSIONS

The Highways Agency is introducing stiffness compliance testing to give assurance of pavement foundation performance during construction to feed into more analytically based pavement designs. The aim of this is to encourage better use of materials and their achieved properties and to help foster sustainability. This approach replaces the traditional empirical recipe approach to pavement foundation design and construction.

The LWD has been identified as a suitable tool to evaluate insitu stiffness of materials via a composite short-term foundation stiffness measurement. The data must meet a rolling average value and a minimum value for different classes of foundation, to provide assurance on site that the long-term pavement design expectations have been met during construction.

Due to the natural variability of materials there is normally a degree of scatter in any data collected with LWD devices however there are also issues with variability due to the devices themselves and the testing methods used. To accommodate these a Good Practice guide has been launched to allow operators to use consistent methods of testing to provide suitable high quality data.

However the users of the devices require an understanding of the issues associated with the devices and they can not simply be used to collect "a number". During testing operators need to assess the efficacy of drops via inspection of the collected load pulse trace and be able to identify issues with the materials and the drops from the traces inspected.

The devices also present useful information for non main highway applications for identification of soft spots and foundation consistency checks, for a range of pavement applications including trench reinstatements, foundations for ground bearing slabs and subgrade checks, as well as applications in heavy duty paving and railways.

The use of such devices within a range of construction applications will allow material suppliers constructors and owners to have better assurance of the potential performance of their paved assets from construction onwards.

References

1. FLEMING P.R. AND EDWARDS J. P. :2009, LWD Good Practise Guide Available at web address www.lboro.ac.uk/lwd

2. FLEMING, P.R., FROST, M.W. and LAMBERT, J.P., 2007. Review of Lightweight Deflectometers for Routine In-situ Assessment of Pavement Material Stiffness. Transportation Research Record : Journal of the Transportation Research Board, 2004, pp. 80-87 [DOI:10.3141/2004-09]

3. FLEMING P.R., FROST, M.W., LAMBERT, J.P., 2009. Lightweight Deflectometers for Quality Assurance in Road Construction. IN: Tutumluer, E. and Al-Qadi, I.L. (eds). Bearing Capacity of Roads, Railways and Airfields: Proceedings of the 8th International Conference (BCR2A'09), June 29 - July 2 2009, Unversity of Illinois at Urbana - Champaign, Champaign, Illinois, USA, pp. 809-818

4. HD26/06 : Highways Agency, Design Manual for Roads and Bridges, Volume 7 Section 2. Pavements Design (HD 26/06), Highways Agency, London, 2006.

5. IAN 73/09: Interim Advice Note 73 Revision 1 (IAN 73), Highways Agency, London, 2009. Highways Agency, Design Guidance for Road Pavement Foundations (Draft HD 25),

6. MCHW 2006: Manual of Contract Documents For Highway Works MCHW, Volume 1, Specification for Highways Works.

7. ROGERS, C.D.F., FLEMING, P.R. and FROST, M.W., 2004. A Philosophy for a Performance Specification for Road Foundations. Proceedings of ICE, Transport, 157 (3), pp. 143-151

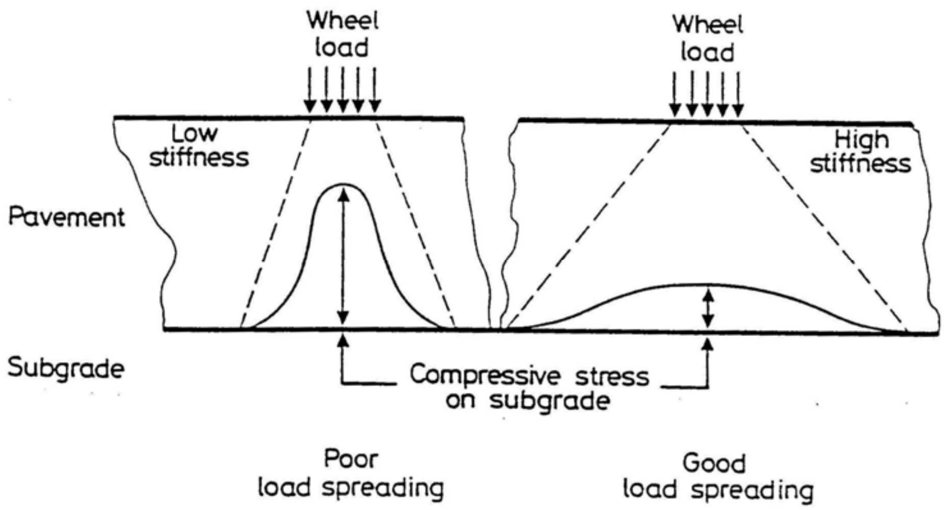


Figure 1, Pavement Load Dissipation and the Importance of Stiffness

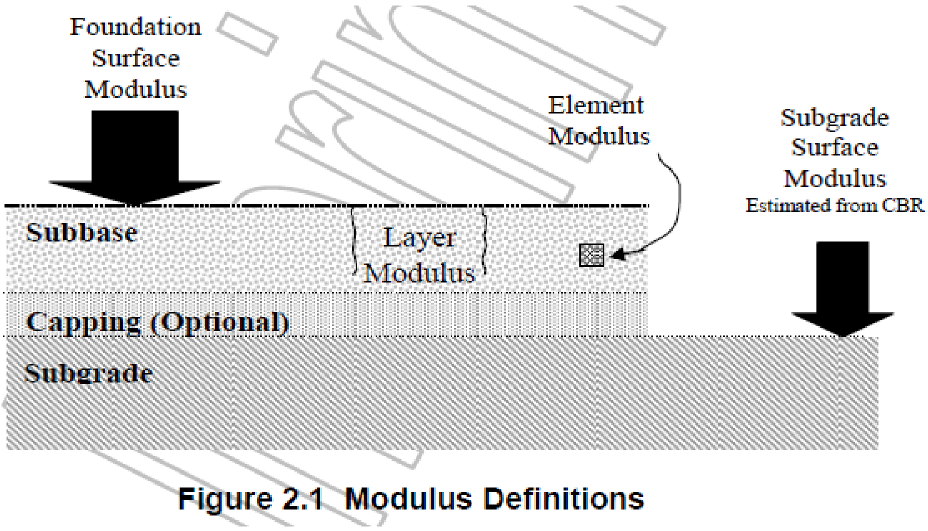


Figure 2 Foundation Stiffness Definitions, (after IAN 73/09)

Figure 3 The Grontmji-Carl Bro Prima (left) and the Dynatest LWD (Right).

Surface Modulus

$$'E' = \frac{2.\ \text{Pressure.}\ \text{radius.}\ (1 - \nu^2)}{\text{deflection}}$$

Note: Buffer stiffness/number affects load pulse length.

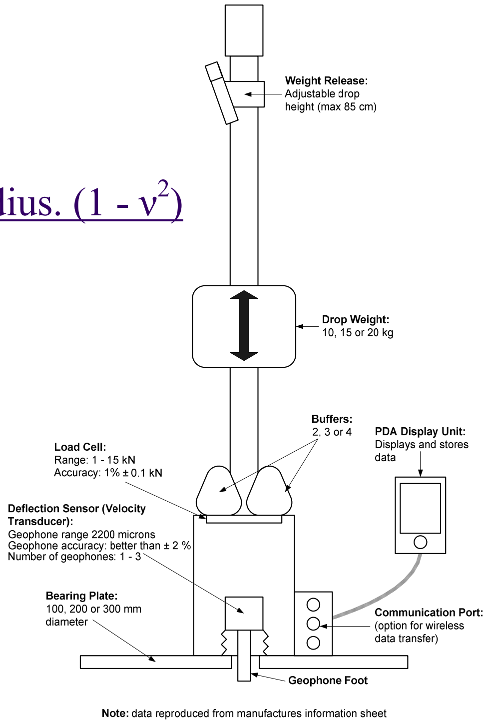


Figure 4 Schematic of and LWD Device, and the Bousinessque Equation

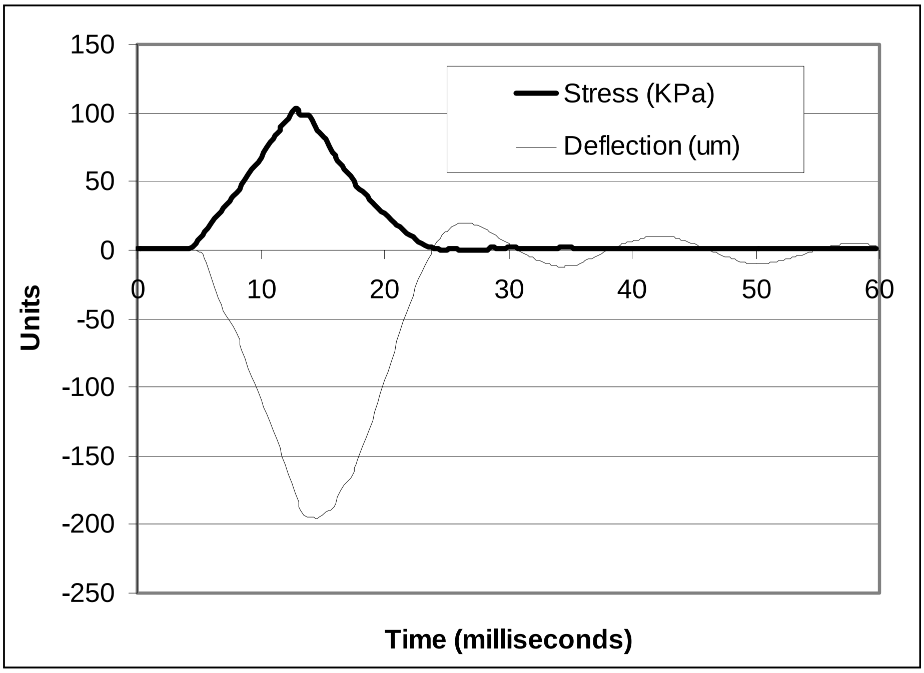
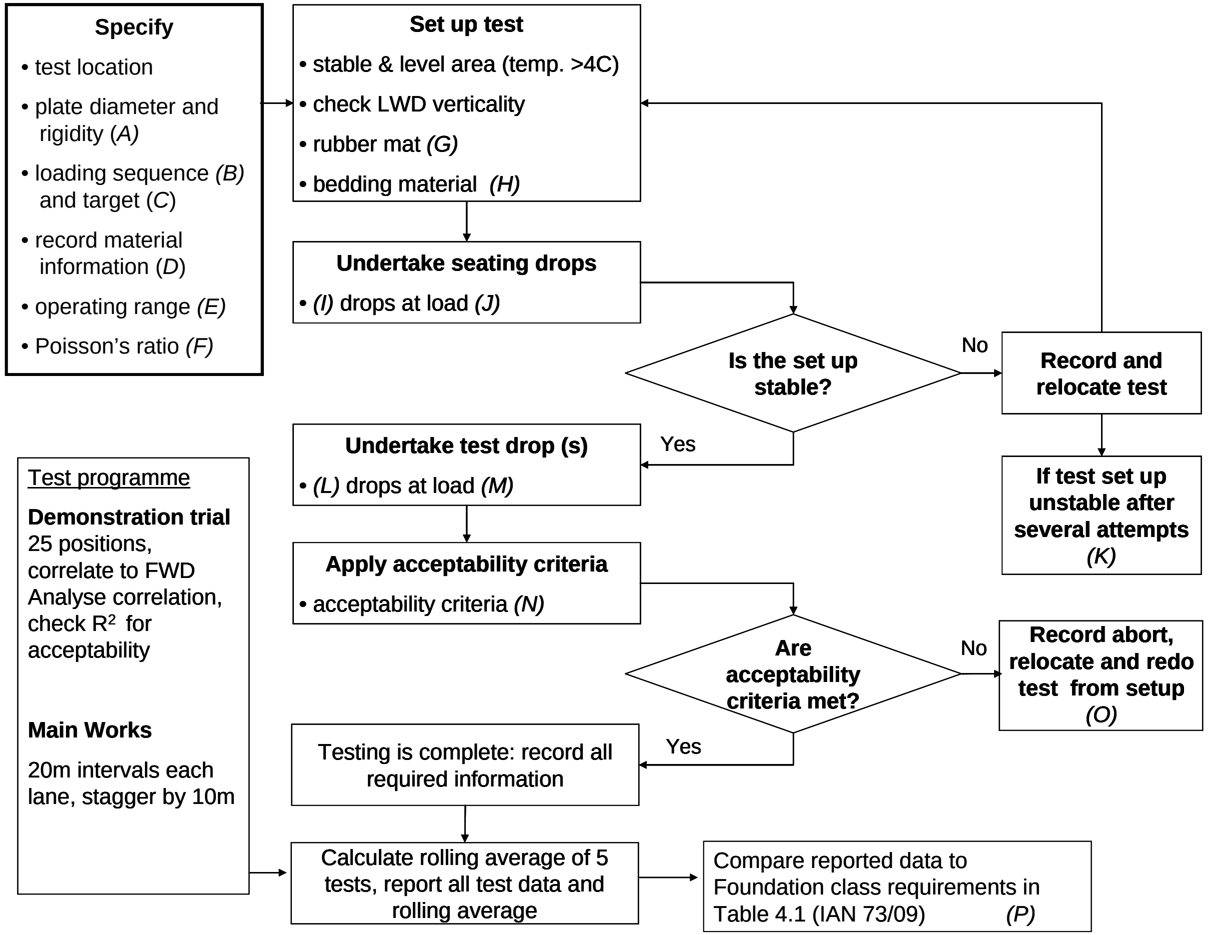


Figure 5, A Typical (good) Test Trace of Load and Deflection. (Note the small amount of rebound in the deflection trace and that deflection lags slightly behind load).

Light weight falling deflectometer (LWD) testing protocol developed for use in accordance Highways Agency Design guidance. The function of the LWD is for specification compliance, against set criteria, which are both material and design (Foundation Class) dependent. Testing is required on the top of foundation only. Assessing the intermediate layers is advisable, but optional.

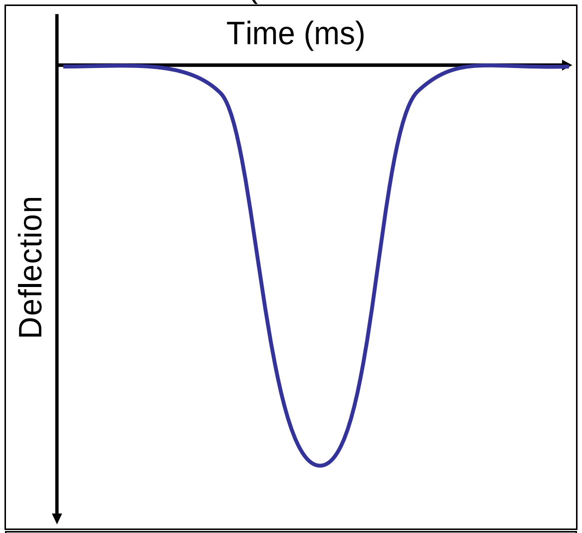


The LWD Equipment must be in compliance with clause 895 of IAN 73/06 Rev 1 (2009). A site specific correlation to falling weight delfectometer is required.	
A	300 mm plate diameter, rigidity factor = 2
B & C	Target a peak stress at each test location: • Foundation Class 1 & 2 target 100 KPa* • Foundation Class 3 & 4 target 200 KPa* * Minimum deflection of 100 microns
D	Minimum = material type, post-compaction age, surface state
E	Deflections between 40 and 1500 microns, pulse rise time between 8 and 12 milliseconds, achieve peak stress in accordance with B & C above.
F	Default value of 0.35
G	Not recommended. Must be used if used during FWD correlation in Demo area
H	Not recommended. Must be used if used during FWD correlation in Demo area
I & J	Three drops at target peak load/stress
K	Record reason for abort, seek advice
L & M	Three test drops at target peak stress, or target deflection range.
N	Surface Modulus = average of the three test drops. Correct to FWD equivalent. See guidance below on pulse shapes (advisory only).
O	Record issue. Restart procedure, if problem persists record and seek advice.
P	Refer to IAN guidance for non-compliance with expected target values

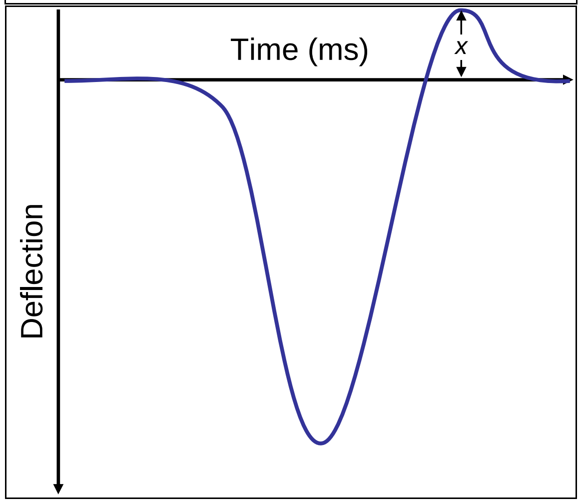
- Note: 200kPa contact stress requires a 20 kg mass with a 300mm diameter plate.

Figure 6 Flow Chart of LWD Best Practice Testing Protocol (after Fleming and Edwards, 2009)

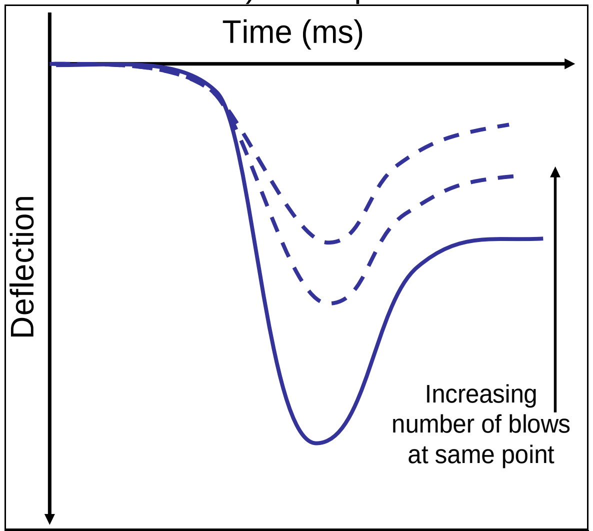
Pulse shape is a potential indicator of testing issues. It is a function of the interaction between the LWD (geophone) and the underlying structure. This covers several variables, which can only realistically be assessed on site. Pulse shape must not be taken in isolation, site observations (water content and the contact between the plate and test structure) are important when assessing data quality.



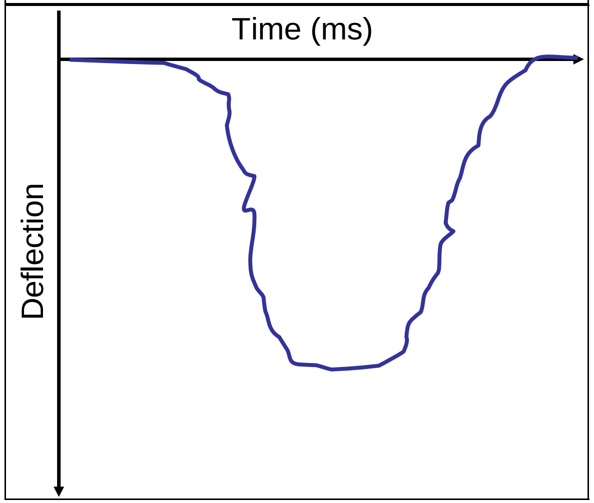
(a) "Normal"
Acceptable, but not necessarily expected. For example bound materials tend to have an element of rebound.



(b) "Rebound"
Function of LWD interaction with the structure. Commonly seen when testing bound materials. If the rebound is large in comparison to the peak (x > 20%)*, <u>re-seat plate and re-test</u>.



(c) "Variable"
The pattern of pulse shapes shown, with increasing number of blows, may be an indication of poor compaction**. This pattern and other variability may also be a result of poor contact between the LWD and structure. <u>Re-seat plate and re-test.</u>



(d) "Irregular"
Check base of geophone and plate. If possible, look for any clogging or unrepresentative material (for example a cobble or pipe) below the test area. <u>Re-seat plate and re-test.</u>

* This arbitrary value is selected in the absence of other guidance. A lower value of x may be suitable for Foundation Class 1 and 2 (Unbound).
** LWD testing is not a proxy for measurement for adequate compaction (density), but can be used to highlight areas for further investigation

Figure 7 Evaluation of Testing Traces to Assess Suitability of Test Data Collected (after Fleming and Edwards, 2009)

Figure 8 Testing on Large Particle Size Materials

Figure 9 Shearing of Ground During Testing

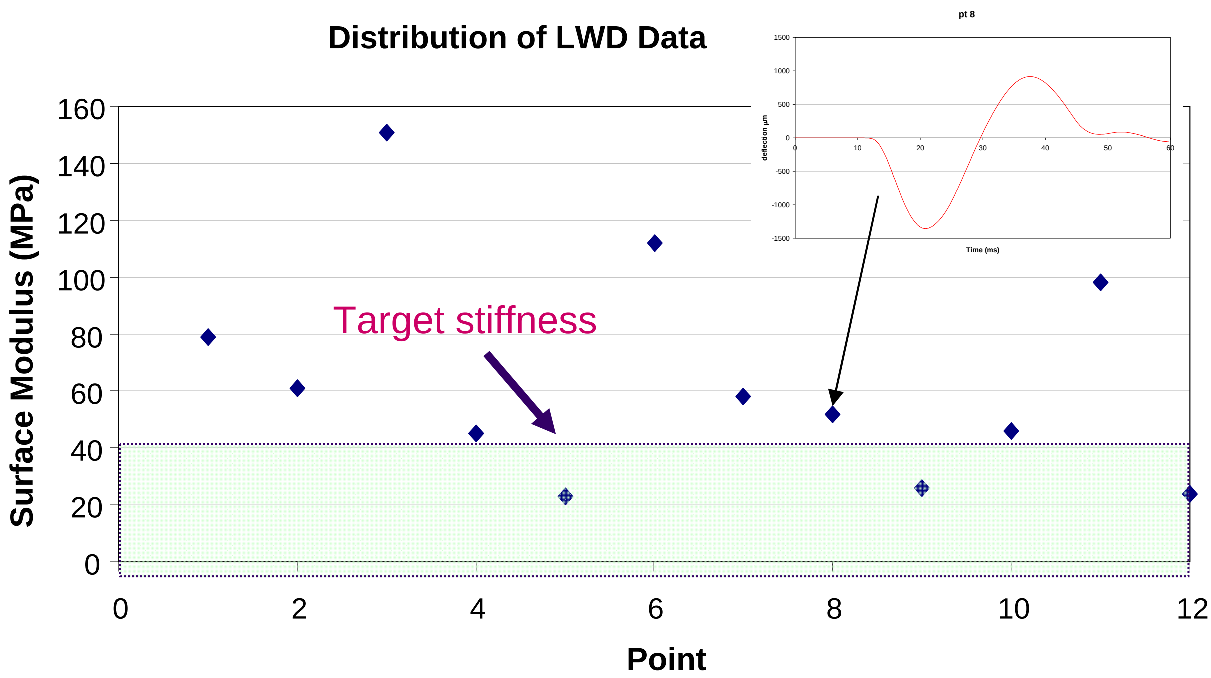


Figure 10 Sample Test Data (Note Failures at areas 5, 9 and 12, and although Point 8 is above the target stiffness examination of the signal response shows large rebound and therefore has failed)

Figure 11 Soft Spots Identified from LWD Testing, Marked Up On Site and Undergoing Proof Rolling