

# LWD BEST PRACTICE GUIDE

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Table of contents	Page No.
1. INTRODUCTION	3
2. PURPOSE OF THE GUIDE	3
3. LWD APPARATUS SPECIFICATION	4
3.1. LWD – Components	4
3.2. Principle of LWD Test Method	5
3.2.1. Basic Procedure	5
3.2.2. Operability, Repeatability and Reproducibility	6
4. PRINCIPLES OF MEASUREMENT & ANALYSIS	6
4.1. Determination of ‘Surface Modulus’	7
4.2. Data Quality Issues	8
4.2.1. Correlations Between Devices	8
4.2.2. Test Quality	8
5. CALIBRATION REQUIREMENTS	9
6. USING THE LWD IN CONSTRUCTION ASSESSMENT	10
6.1. Introduction	10
6.2. Theory	10
6.3. Purpose of the LWD Testing	11
6.4. Construction Materials	12
6.5. Content of Test Protocol	14
7. REFERENCES	18
8. ACKNOWLEDGEMENTS	18
Appendix A – Test Protocol for IAN 73/06v1 (2009) and IAN7306 (2006)	

## 1.0 Introduction

Deflectometer devices are dynamic non-destructive testing tools commonly used in the field of pavement systems to measure a layer or surface modulus. Among the various testing devices used for non-destructive insitu assessment of pavement layers the Light Weight Deflectometer (LWD) has become the focus of increasing interest. In particular, the changes introduced in the Design Manual for Roads and Bridges (HD 26/06, and IAN 73/09 which superseded HD 25/94), introduced a potential requirement for field compliance testing of the surface modulus of constructed pavement foundations. In addition, other applications for deflectometers and the portable versions in particular include compliance testing for general highway investigation, (re)construction, highway utility trench reinstatements, and many other similar instances. The portable Light Weight Deflectometers (LWD) are considered in general to be relatively rapid and cost-effective tools, if used appropriately.

This Best Practice Guide has emerged from a working group (Pavement Foundations Group) to address the need for consistency in the implementation of LWD's into UK practice. However, the guide does reflect best practice for a range of applications. The guide is currently under the ownership of Highways Agency, with support from Transport Scotland, County Surveyors Society, Britpave, Minerals Products Association and other interested parties who have contributed.

The guide is seen as a statement of current knowledge, and includes recommendations for site operations. It is expected that this guidance will be updated periodically.

Feedback on its contents and comments for possible revision should be directed to Dr Paul Fleming ([p.r.fleming@lboro.ac.uk](mailto:p.r.fleming@lboro.ac.uk)) of Loughborough University, on behalf of the PFG working group.

*It is intended that this guide will be available from the FWD user group website (tbc), and will be updated bi-annually or more frequently as required.*

It should be noted that it is assumed that operators who use and interpret LWDs will have some form of appropriate training, in-house and /or external from the manufacturer, from other approved or competent operators or approved training bodies.

## 2.0 Purpose of the Guide

This guide aims to provide a useful reference to LWD users, specifically to explain three key aspects for their use in the UK: their principles of operation; their use for construction/materials testing; and Best practice protocols for field measurements and reporting.

The guide is divided into the sections 1-6, with the intention that the main document is read and understood by all users of the devices and those interpreting the data measured, whether for design or construction.

The field guidance document in Appendix A is intended for the field operators to provide clear consistency in measurement and reporting.

In this current Best Practice guide it is intended, that there are *three* field guidance testing protocols set out, that cover: Overseeing Organisation (OO) schemes (in accordance with IAN 73/09); general pavement (re)construction testing or other application specific testing such as trench reinstatements, and a general generic guide that can be amended and designed for site specific specifications.

### 3.0 LWD Apparatus Specification

The term Lightweight Deflectometer (LWD) is also loosely referred to as a Portable Falling Weight Deflectometer in some countries and documents.

In principle, the device imparts a transient load (pulse) through a loading plate and measures (directly or indirectly) the movement under load of the ground (or the loading plate). The measurements are interpreted as a ‘stiffness’ also termed the ‘**Surface Modulus**’ in the UK Road Design and Specification standards (IAN 73/09).

Terminology has not always been consistent and, previously, measurements may have been reported as surface stiffness, foundation stiffness or other similar terms.

There are several types of LWD in existence around the world, and many prototypes have been developed. In general, the devices in use in the UK are similar in specification and measurement method, detailed in Section 3.1, and shown in Figure 1.

### 3.1 LWD – Components



Figure 1. Three types of light weight devices commonly used in Europe.

LWDs a) and b) are similar, produced by CarlBro and Dynatest respectively. This equipment permits a variable drop height, and incorporates both a load measuring sensor (load cell) and a velocity sensor to measure deflection (also termed a 'geophone'). Note the velocity sensor in both a) and b) have a foot that rests on the ground – through a hole in the bearing plate.

LWD c) is of the type with a fixed drop height, and incorporates an accelerometer based sensor to measure deflection (mounted rigidly within the middle of the bearing plate) and the example shown is manufactured in Germany. It does not incorporate a load cell, and assumes a constant peak force on impact.

It should be noted that currently only LWDs a) and b) can be used for Overseeing Organisation (OO) schemes, in accordance with the requirements for dynamic plate testing specification set out in the IAN73/09.

It should also be noted that there are differences in manufacture specifications that can result in differences in the measured surface modulus when comparing data between the different LWD devices.

The apparatus system is described below, using Figure 1a as reference:

1. A loading plate, capable of approximately uniform distribution of the impulse load on the test surface. The diameter is adjustable, from 100mm to 300mm, constructed to allow the deflection measurements at the centre of the point of impact through a hole in the plate.
2. A load cell, used to measure the applied load of each impact, usually to a precision of 0.1 kN or better. The calibrated working range should, ideally, be 0 to 15 kN or greater, and is specified by manufacturer.
3. A deflection sensor, capable of measuring the maximum vertical movement, to a precision of +/- 2  $\mu\text{m}$ . The calibrated working range should, ideally, be 0 to 2000  $\mu\text{m}$  (2mm) or greater.
4. A drop weight, variable from 10 kg (standard) to 20 kg typically, capable of being raised to a predetermined (variable) height, and when dropped guided by a suitable low resistance rod, to impart a controlled force to the loading plate.
5. Spring element – to provide a controlled transient pulse length to the impact force, typically in the range 16 to 30 milliseconds. The spring element is typically a series of rubber cones/buffers, or cylindrical pad system as shown in Figures 1a and b.
6. A data capture system is required, with software to capture and display the impact test results and store them for later analysis or reporting. In addition the relevant site and position details can be logged along with the captured data. The data collection software is also required to permit the operator to vary the default values for the test to suit, such as plate size, plate rigidity factor and material Poisson's ratio. This is discussed further in section 6.

NOTE: It can be advisable to keep written records of field measured data, to limit the effect of subsequent data loss if the electronic storage unit becomes defective.

## 3.2 Principle of LWD test method

### 3.2.1 Basic Procedure

The operator selects the load bearing plate size to use. The operator then selects the drop height to control the maximum contact stress (maximum force divided by area of the bearing plate) OR can select a drop height by trial and error to control the range of peak deflection measured. These device variables are usually specified in the contract test protocol.

The weight is raised and held at the required height, and then released to impart the dynamic impact pulse.

The sensor readings, of force-time and deflection-time histories, are displayed on the readout unit. The calculated Surface Modulus is displayed, the theory is dealt with in Section 4.0 (Note: the operator must ensure the software settings match the mechanical parameters of the test set up) for plate size, plate rigidity factor, and Poisson's ratio.

The operator can repeat the test a number of times, either to a preset specification or to observe the behaviour under repeated load. It is often assumed that the initial 1-3 drops are used as 'seating' to ensure good contact, and that further drops are used to determine the surface modulus to be reported.

The quality of the measurements is affected by the suitable locating of the plate onto the material under test, in addition to the proper functioning of the equipment components and the operator competence.

The specific operation of the data collection, storage and downloading of test measurements is defined in manufacturer's guide to using their equipment.

### 3.2.2 Operability, Repeatability and Reproducibility

There is currently no British Standard or European Standard for the LWD. There exists an ASTM standard (E2583-07) that suggests required temperature ranges (-10 to 50 °C) for operation of LWDs, and also includes precision and bias recommendations, and reproducibility in terms of Coefficient of Variation for single operator and single equipment on a range of soil types under typical field conditions.

There is no UK published research or guidance on limits of LWD operability with respect to site (material) temperature, humidity or rainfall. In addition, there is no authoritative data or guidance currently for LWD repeatability or reproducibility in the UK, though some data has been published for the typical scatter found on site, expressed as Coefficient of variation, and is further discussed in Section 6.0.

It should be noted that the IAN 73/09 currently states that LWD testing should not be carried out at temperatures below 4 °C (upper material temperature).

## 4.0 Principles of Measurement & Analysis

The LWD has been used in a variety of applications, and in many cases used to evaluate the ‘relative’ stiffness of materials under test, although the philosophy of the guidance in IAN73/09 is to evaluate *absolute* stiffness (single point and rolling average) against the class of foundation for pass/fail quality assurance purposes.

### 4.1 Determination of ‘Surface Modulus’

Following on from Section 3.2, the LWD apparatus is used to impart a transient dynamic load pulse to the material under test and the proprietary software will display a ‘Surface Modulus’ value, which is calculated from equation 1 below.

The surface modulus should be computed at each point tested, using the following formula, usually preset in the proprietary software:

(Note: in many cases the term  $E_o$  is also termed  $E_v$ , or  $E$ )

$$E_o = f \cdot (1 - \nu^2) \cdot \sigma_o \cdot a / d_o \quad \text{Equation 1}$$

Where:

$E_o$	=	Surface modulus (MPa)
$f$	=	Plate Rigidity factor (2 is a standard value for a flexible plate)
$\nu$	=	Poisson’s Ratio, normally 0.35
$\sigma_o$	=	maximum contact stress (kPa)
$a$	=	Plate radius (m)
$d_o$	=	Maximum deflection (mm)

It is clear that the absolute value of surface modulus calculated, is affected by the input parameters of both plate rigidity and Poisson’s ratio (ratio of horizontal strain to vertical strain).

Assuming the sensors are all calibrated and working properly (see Section 5.0) then the variation in stiffness observed on site is generally attributed to material variations (such as water content, grading, compacted state etc.) and possibly poor uniformity of the contact between the bearing plate and the material under test.

It is not normally recommended, for any measurement technique, to either exceed the working range specified by the manufacturer or indeed work close to the limits of the sensor range where possible.

On materials that exhibit high surface modulus values the maximum deflection will be relatively small (for example surface modulus >260MPa with a 300mm diameter plate at 100kPa contact stress will measure a deflection <100µm). In some cases it may be prudent to carry out more tests to improve the statistical significance of the site test data, or where practicable increase the drop mass or height (or both), and/or reduce the plate size to promote larger (more reliable) deflections.

Similarly, on materials that exhibit very low surface modulus the maximum deflection will be relatively large and it may be prudent to reduce the drop height or drop mass where practicable (for example surface modulus <26MPa with a 300mm diameter plate at 100kPa contact stress will measure a deflection >1000µm).

Note: In the current IAN73/09 there is a requirement to ensure the measured deflections fall within a specified range for reasons of ‘accuracy’, and based on experience. This is dealt with further in Section 6.

It should also be noted that the ‘surface modulus’ represents the reaction to the impulse load of the layers beneath, and can represent the reaction of more than one layer under test. The LWD is not a layer test, although on higher class foundations (3&4) it is likely that the upper layer stiffness is the major factor in the surface modulus measured.

## 4.2 Data Quality Issues

In recent years there has been increasing emphasis on evaluating the ‘quality’ of the data measured by LWDs. This has in the main been via correlation trials with the larger Falling Weight Deflectometer (FWD), a trailer mounted device. In addition to this, investigations of the LWD test quality from evaluation of the deflection time history has developed into useful guidance on acceptability of a test based upon signal ‘shape’, explained further below.

### 4.2.1 Correlations between devices

It should be noted that the current technology used (sensors and software) in LWDs is similar or the same as that used in the relatively large FWDs, and that the two main producers of LWDs in Europe also manufacture FWDs.

The correlation between devices have, in general, been found to vary with the construction detail – i.e. the materials, type state and thickness, and thus are seen as site specific. This is the rationale behind the current IAN 73/09 guidance, wherein for ‘performance’ designs the LWD has to first be correlated with a FWD during demonstration trials, and the LWD surface modulus is thereafter corrected using the LWD:FWD correlation factor.

However, recent field trial work has shown some variability between the stiffness reported by the LWDs commercially available. This may be attributed, in part it is thought, to subtle differences between the exact specifications of the LWDs such as their total mass, load plate stiffness, the method of filtering the sensor raw data, spring stiffness and hence load pulse rise time. In addition, variability can arise from the materials under test, and this is further discussed in section 6.4 and set out (for guidance only) in Table 2.

There is also a concern that the testing methodologies of users can vary, leading to data variation, and that this requires better guidance and control via training, and standardisation via this ‘Best practice’ guide.



This guide cannot, however, give definitive guidance regarding the *expected* variation in absolute values between LWD devices, but it is suggested that where differences, and potentially disputes, arise then a correlation trial with an FWD, at the site, may be appropriate.

#### 4.2.2 Test Quality

Experience suggests that a 'stable' set up of the LWD is required to get the best data quality. The stability is affected largely by achieving a flat area to locate the load plate, which can be especially difficult on some occasions for the larger 300mm diameter plate. Users have reported the apparatus rocking, or moving during the test – and these represent instability. Experience also suggests that the 'noise' of impact during the test can be a useful additional guide to the efficiency of contact. It is not easy to make these acceptability criteria highly objective, however.

Investigation of deflection-time history for each individual test has in general highlighted issues relating to the effectiveness of the measurement of surface modulus in a series of scenarios.

These scenarios include: where the material under test is undergoing significant further compaction caused by the repeated drops; excess water under the test; or excessive rebound of the deflection sensor.

There has been some work done to provide guidance on acceptable and unacceptable deflection-time histories. The current state of knowledge in the industry is that this is, at present, considered to be advisory and requires further research, with collation of experience to determine the objectivity of accepting or rejecting test data based on deflection-time signal shapes. This is further discussed in section 6.0 and the latest thinking presented in simple graphical form for site operators in Appendix A.

## 5.0 Calibration Requirements

It is recommended that the manufacturer's guidance on calibration is followed and that this certificate is kept safe and made available for all schemes to provide evidence of a well maintained LWD.

The current guidance is that an annual calibration certificate is required, or more frequently if the LWD system fails the in-house consistency check as described below.

In addition, it is specified that an 'in-house' consistency check is developed, also recorded for internal QA purposes and made available as appropriate. The in-house check is to ensure, prior to field use (and weekly where the device is used infrequently), that the LWD and measurement system is responding in a repeatable manner on a consistent test surface. The test surface can be a marked area of competent concrete floor, with tests on rubber pads or similar to provide a suitable deflection range. Experience suggests a maximum variation in Surface Modulus between tests of 5% is acceptable for consistency.

## 6.0 Using the LWD in Construction Assessment

### 6.1 Introduction

This section of the Guide provides information on the relationship between Light Weight Deflectometer (LWD) testing, material types and how the LWD data outputs are used. It is intended the information will assist in selection of a suitable test protocol and developing an understanding of how the LWD can best be used. Advice given in this section should be read in conjunction with Sections 1-5 of the Guide.

The selection of an appropriate field test protocol (i.e. how the testing is undertaken) is dependent on several interrelated issues, including:

- Who requires the LWD test measurements?
- Why is the LWD testing being undertaken?
- What materials/constructions are being tested?
- What other factors (variables) may influence the LWD measurements?

In order to provide guidance on answering these four questions, the following sections provide some further detail to the theory behind LWD testing, purposes of LWD testing types and advice for specific construction materials, and the recommended content of a LWD test protocol for fieldwork.

### 6.2 Theory

Light Weight Deflectometer (LWD) tests are designed to determine the 'surface modulus' (often termed stiffness). The surface modulus is a response of the underlying structure, in terms of a transient deflection, to the dynamic stress applied through a circular bearing plate.

This deflection response is a composite response from the underlying structure within the test's zone of influence (also referred to as the zone of significant stress). A combination of the plate diameter (area loaded during the test), applied dynamic load and characteristics of the underlying materials will dictate the zone of influence of the test. Typically the zone of influence for the test may extend to a depth below the test level of between 1 and 1.5 times the plate diameter, i.e. testing undertaken with a 300 mm plate is likely to have a zone of influence between 300 and 450 mm depth. This is a simplification, however, and has been shown to vary dependent on the construction detail, specifically affected by the ratio of layer stiffness (Fleming at al., 2008).

The LWD surface modulus measured is considered, in general, to represent a composite value for the construction, rather than performance of an individual layer. However, for very thick layers or very stiff layers the surface modulus may approximate the layer stiffness (unconfined, and relative to time of testing for bound materials still curing). Changing the plate diameter to a smaller size may assist in evaluating specific upper layers, however.

The measured Surface Modulus (stiffness) is also dependent on non material specific variables such as:

- Equipment specific variables, for example location of the sensor used for measuring deflection and the rigidity of the test plate. The equipment specific variables are detailed in Sections 3 and 4.
- User defined variables (test frequency, magnitude and sequence of drop height/loading). The user defined variables are defined in the appropriate Test Protocol (Section 6.5).

### 6.3 Purpose of the LWD testing

The purpose of the LWD testing is dependent on the aim of the measurement exercise and its role in the construction process and contract specification. The role of testing can vary between research and performance testing, through to compliance or quality assurance testing. These different purposes have different drivers, related to the *value* being placed on individual readings (or averages of several test points) for a single test section and how the measurements are then subsequently used. The use of a LWD does not need to be limited to achieving only minimum values of surface modulus, for example the use of the LWD during some in situ road recycling schemes can have both upper and lower limits. The lower limit may be used to demonstrate adequate performance, and the upper limit can be used to help with site guidance on the effectiveness of compaction of the cold recycled material, whereby if too stiff compaction will be ineffective.

The link between Surface Modulus and a pavement design stiffness input is tenuous, and requires several assumptions which are likely to vary between construction material types. In the absence of a better method, however, the Surface Modulus can be taken as an immediate indication of construction quality assurance and the ability of the material tested to support the construction of the overlying structure.

Selection of the user defined variables, by the operator, in relation to equipment working ranges given within the Guide, is undertaken for a specific testing purpose. The main limitation of the LWD as a Surface Modulus testing device is its 'working range'. The working range for the load and deflection sensors are defined by the Manufacturer and will usually include an upper and lower limit for force and deflection. The force range is limited by the drop height and the mass which can be comfortably lifted and dropped in a controlled (safe) manner. The deflection range is constrained by the transducer design and associated electronics to process and digitise the signal. In brief, higher stiffness materials (generally anything that is bound) will generally require higher levels of contact stress to ensure the deflection generated is within the equipment working range (or the range specified in any test protocol). Achieving a suitable deflection can, by its nature, compromise maintaining a constant target stress, the area under load (i.e. plate size), and can have a consequence that the test method loses some of its simplicity.

The same requirements apply to all the roles for LWD testing, in that the data sets are required to be collected in a robust manner. The robustness of the testing is defined as understanding the repeatability and reproducibility of the test. The Best Practice Guide and Test Protocols are written to assist with achieving such a robust testing methodology that is consistent between all experienced operators/users. This should

provide data that is trustworthy for any specific project, and enable direct comparison between projects.

## 6.4 Construction Materials

LWDs are becoming accepted across a wide range of construction materials and applications. The design of LWD equipment was initially undertaken with the purpose of testing lower stiffness materials (such as subgrade clays and unbound aggregates); however, several drivers have meant that it is also desirable to use the same device for testing other materials. These other materials include:

- Treated soils,
- Stabilised soils,
- Hydraulically bound mixtures; and
- Cold recycled mixtures which contain bitumen.

The above material types cover a wide range of potential combinations and, therefore, stiffness characteristics.

The link between the Surface Modulus measured (i.e. stiffness of the composite foundation under test) and the layer Moduli (stiffness of individual layers within the foundation) is complex. Prediction of surface modulus for different materials/combinations of material is challenging, complicated further by site effects and test related factors including:

- stress sensitivity of unbound capping materials, unbound sub-base mixtures and for clay subgrades. This can be investigated, see Appendix B (to be completed).
- curing time (strength/stiffness gains) for a diverse range of bound materials and also the influence of discontinuities in bound layers (induced or naturally occurring cracking). This can be investigated by testing at intervals.
- Water sensitivity of material stiffness behaviour (particularly for natural soils and mixes with high fines content. This can be investigated in any site or laboratory trials.

Testing across the typical range of stresses achievable with a LWD and the nature of the materials likely to be tested, mean that Surface Modulus measured on site is likely to be relatively variable. Guidance on typical variations within material specific data sets is given in Table 2. A simplistic view is that the more controlled and specified the material/mixture, the lower the variation in surface modulus; however, the values in Table 2 are given for general guidance only. The variation is expressed as the 'coefficient of variation' (CoV), which is the ratio between the standard deviation and the mean for a data set – used to help 'normalise' the expression of variability.

Table 2. Guidance on typical variations of Surface Modulus results

Material type and layer in pavement	Typically range of coefficient of variation (COV)
Cohesive subgrade clay soils	25 to 60%
Granular capping materials	10 to 40%
Granular subbase mixtures	5 to 20%
Bound subbase mixtures	5 to 30%*
* a larger COV may be expected for testing stiffer materials, dependent on the Working Range of the equipment and Test Protocol adopted	

In order to minimise data variations and allow ready comparison of LWD data sets, LWD testing should ideally be done with both comparable equipment and user defined variables, and supported by appropriate training for LWD test specifiers and the LWD operators. Figure 2 and Table 3 outline the range of user defined variables which should ideally be specified prior to site testing being undertaken. This is based upon current knowledge and it may require updating following feedback on its implementation.

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## 6.5 Content of Test Protocol

The following sections outline the content and guidance required to be given in a LWD test protocol. The test protocol can either be adopted on a site or contract specific basis. Standard test protocols have been produced for IAN73 (2006 and 2009) for both unbound and bound foundations (Appendix A), testing of unbound materials where the investigation of stress sensitivity is required and general use within specific projects such as utility reinstatement works (not completed). In addition, a blank proforma test protocol is provided for adaptation by an intended user or test specifier (not completed). In the absence of further protocols, Figure 2 and Table 3 can be used to assist in the specification of any LWD testing requirements (Note: a full set of protocols are yet to be produced).

The test protocols have been produced as a decision support tool for the operative and include guidance on deciding whether the measurement is acceptable based on the deflection signal response. Some aspects of the testing protocol will require subjective assessment by the LWD operator; therefore there is an inherent reliance on the experience and training of the LWD operator.

The main objectives for any test protocol are to ensure that the testing undertaken is fit for purpose and that all the information that is pertinent to its purpose is recorded for subsequent interrogation and presentation.

A prescriptive flow diagram summarising the variables and decision points involved in LWD testing is shown in Figure 2. Its purpose is to define all the variables which need to be specified during the production of a LWD test protocol. Table 3 details the variables that require specification and gives appropriate guidance. Note: this guidance is based upon current knowledge and may be refined following implementation and feedback.

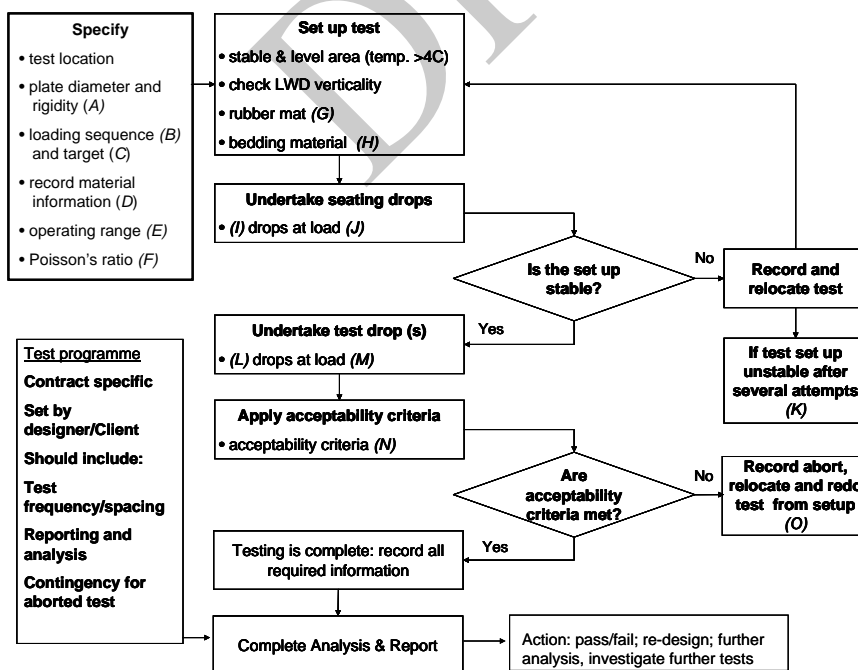


Figure 2: Outline flow diagram for generic LWD testing Protocol (see Table 3 for codes)

Table 3: Guidance for completion of a LWD test protocol

Variable		Guidance
A	Plate diameter	<p>For unbound materials, the larger the plate size, the larger the nominal aggregate size that can be representatively tested, and the increased depth of influence beneath the test. For a given force, the contact stress will be greater for a smaller plate.</p> <ul style="list-style-type: none"> <li>• The standard diameter specified for testing pavement foundation materials is 300 mm (IAN73, 2009).</li> <li>• The zone of significant stress below the test plate is typically between 1 and 1.5 times the diameter.</li> <li>• A maximum aggregate size to plate diameter ratio of between 7:1 and 10:1 should ensure individual particles do not unduly influence individual tests.</li> </ul> <p>For (stiff) bound materials, the diameter may be changed to achieve the required contact stress.</p>
B	Loading sequence	<p>The loading sequence is comprised of seating (I and J) and test drops (L and M). A drop is defined as a single drop of the weight and recording of the deflection response. The response of certain materials may be influenced by the loading sequence, especially if significant secondary compaction (unbound materials) or significant shearing/remoulding (clays) occurs under the repeated drops.</p>
C	Targets	<p>LWD testing can either be specified to target a specified load and/or a deflection. These should be selected on the basis of the equipment operating range (E) and can be refined dependent on the intended use of the LWD test outputs.</p>
D	Material information	<p>Several aspects of the material and environment should ideally be recorded to allow for full reporting and any subsequent interrogation of the LWD data sets, these include:</p> <ul style="list-style-type: none"> <li>• Material type – record not only the top layer tested, but its thickness and the underlying construction.</li> <li>• Weather (general)</li> <li>• Temperature (ambient, on occasion test material)</li> <li>• Duration post-compaction. Along with temperature this may indicate the strength/stiffness gain of a bound material. Unbound aggregates and cohesive fills can also benefit from a hiatus post compaction.</li> <li>• Surface condition of the material – visible signs of segregation in unbound materials, surface water or water pumping during the test, size and length of cracks, a dry crust, curing coat, open/closed texture and uneven/even surface, are all possibly relevant.</li> </ul>
E	Operating range	<p>The equipment operating range includes environmental and physical factors. The most common ranges that require specification are the range of acceptable deflections, pulse time (or rise time), and temperature. Data sets determined outside of the LWD Working Range are less reliable than those determined within it. Acceptance of testing outside of the LWD working range is dependent on data use and limits of acceptability, and should be specified in the Test Protocol.</p> <ul style="list-style-type: none"> <li>• The typical LWD working deflection range is between 100 µm and 1500 µm, with a maximum value of 2000 µm. However, reference should be made to the manufacturer's guidelines.</li> </ul>

		<ul style="list-style-type: none"> <li>• A working range for deflection down to 50 <math>\mu\text{m}</math> may be acceptable for stiffer materials, dependent on the use of the LWD data sets and surface modulus variability.</li> <li>• A standard pulse duration of 16 to 30 milliseconds is normally recommended (or a pulse rise time of 8-12 milliseconds). Adjusting pulse duration can influence the zone of influence of the test and measured data.</li> <li>• Ground temperature, which may influence material response and performance.</li> <li>• Air temperature – reference should be made to equipment supplier's guidance on how air temperature may influence the equipment.</li> </ul>
F	Poisson's ratio	<p>The Poisson's ratio is a fundamental material property which describes the relationship between horizontal and vertical strain, during compression. It is an input into the equation for Surface Modulus and, therefore, should be specified for any LWD testing.</p> <ul style="list-style-type: none"> <li>• The default Poisson's ratio recommended for adoption is 0.35. This is generally realistic for unbound mixtures, asphalt and HBMs prior to any strength/stiffness gain.</li> <li>• The Poisson's ratio for clays is around 0.45.</li> <li>• The Poisson's ratio for HBMs is around 0.20.</li> <li>• Materials at high levels of water content (approaching saturation) may theoretically be incompressible and have a Poisson's ratio approaching 0.5.</li> </ul>
G	Rubber mat	<p>The use of a thin foam or rubber mat provided by the equipment supplier and used in accordance with their instructions may improve contact between the plate and material surface.</p> <ul style="list-style-type: none"> <li>• The influence on LWD test outputs across a range of materials is not understood. Therefore, it is not recommended to alternate between the use with or without a rubber mat.</li> <li>• Not all LWDs have the option for using a mat.</li> </ul>
H	Bedding material	<p>Use of bedding materials is not currently considered to be good practice.</p> <ul style="list-style-type: none"> <li>• However, controlled work in the laboratory has indicated that sand can improve LWD plate contact with the underlying material but is subjective re thickness of the layer.</li> <li>• The use of bedding materials will significantly slow down the rate at which testing can be undertaken.</li> </ul>
I	Number of drops during seating	<p>Selection of seating drops is important assist in improving the contact between the LWD load plate and test material.</p> <ul style="list-style-type: none"> <li>• Equipment producers generally recommend three drops to seat the plate.</li> <li>• Plate contact on bound material (for example HBMs that have gained significant strength/stiffness) does not generally improve with seating drops. The use of a single seating drop can be used to confirm stability of the equipment.</li> </ul>
J	Target load during seating	<p>The target load during seating should be selected to ensure that the LWD plate is bedded onto the material.</p> <ul style="list-style-type: none"> <li>• A load in excess of the test load is not recommended, in order to avoid producing an unrepresentative result.</li> </ul>



K	Action if unable to get a stable test setup	The assessment of whether a test set up is stable is subjective and reliant on the training and experience of the LWD operator. The surface level tolerance and/or nature of the material being tested may mean that achieving a stable set up is not feasible. If several unsuccessful attempts at adjacent locations occurs, further advice should be sought.
L	Number of drops during test	The number of drops to achieve a representative surface modulus value, needs to be balanced against the potential for altering the underlying material and also the speed of testing. <ul style="list-style-type: none"> <li>• Current guidance is that three drops are undertaken and the mean value recorded. Additional testing could be specified, dependent on variation around the mean.</li> </ul>
M	Target load/stress during testing	A standard target load/stress can be specified, along with an acceptable range of deflections (based upon the working range) or the load/stress can be adjusted to target a specific range of deflections. <ul style="list-style-type: none"> <li>• A target stress of around 100 kPa is often specified, for sub-base, unbound aggregates and in general hydraulically bound mixture (before they gain any strength or stiffness via curing). A minimum of 200 kPa for hydraulically bound mixtures which have begun to gain strength/stiffness is often recommended.</li> </ul>
N	Acceptability criteria	The shape of the Deflection and Force Signal Responses are considered to represent an indication of the interaction between the material under test and the LWD test. Specific shapes of the Deflection Signal Response have been observed by various parties, and reported anecdotally. At this stage, the current knowledge suggests that some 'generic' signal shapes may be indicative of problems. Examples of different signal curves and potential factors they may highlight are shown in Figure 3 below: Experience upon implementing this Guide is expected to help refine the advice given here.  If the Test Protocol includes a review of the Deflection Signal Response, then decision support must also be provided (N).
O	Action of acceptability criteria (N) is not met	If the test measurement quality is deemed unacceptable, i.e. for deflections outside the acceptable working range or for concerns over data quality from analysis of the deflection-time signals, the test failure should be reported and repeated at a new location.
(Link to M)	Multiple loading regimes	Multiple loading regimes may be specified to assess material response over a range of stresses. <ul style="list-style-type: none"> <li>• Drops over a range of low to high loads have been used to assess the stress dependency of unbound aggregates and clays.</li> <li>• Assessing the stress dependency of materials can be of value, see Appendix B (<i>to be completed</i>), and can be useful for material evaluation purposes.</li> </ul>

Note: No accepted form of standard reporting has yet been established, this is under review.

## 7.0 References

IAN 73/06. Design Guidance for Road Pavement Foundations (Draft HD 25), Interim Advice Note 73, Highways Agency, London, February 2006.

IAN 73/06 v1. Design Guidance for Road Pavement Foundations (Draft HD 25), Interim Advice Note 73 (second issue), Highways Agency, London, February 2009.

ASTM E 2583-07. Standard Test method for Measuring Deflections with a Light Weight Deflectometer (LWD), 2007, ASTM International, Philadelphia, USA.

Fleming P. R., Frost M. W., Lambert J. P., “A Review of the Lightweight Deflectometer (LWD) for Routine Insitu Assessment of Pavement Material Stiffness”, Transportation Research Record No. 2004, Soil Mechanics, 2007, pp. 80–87. ISSN 0361-1981

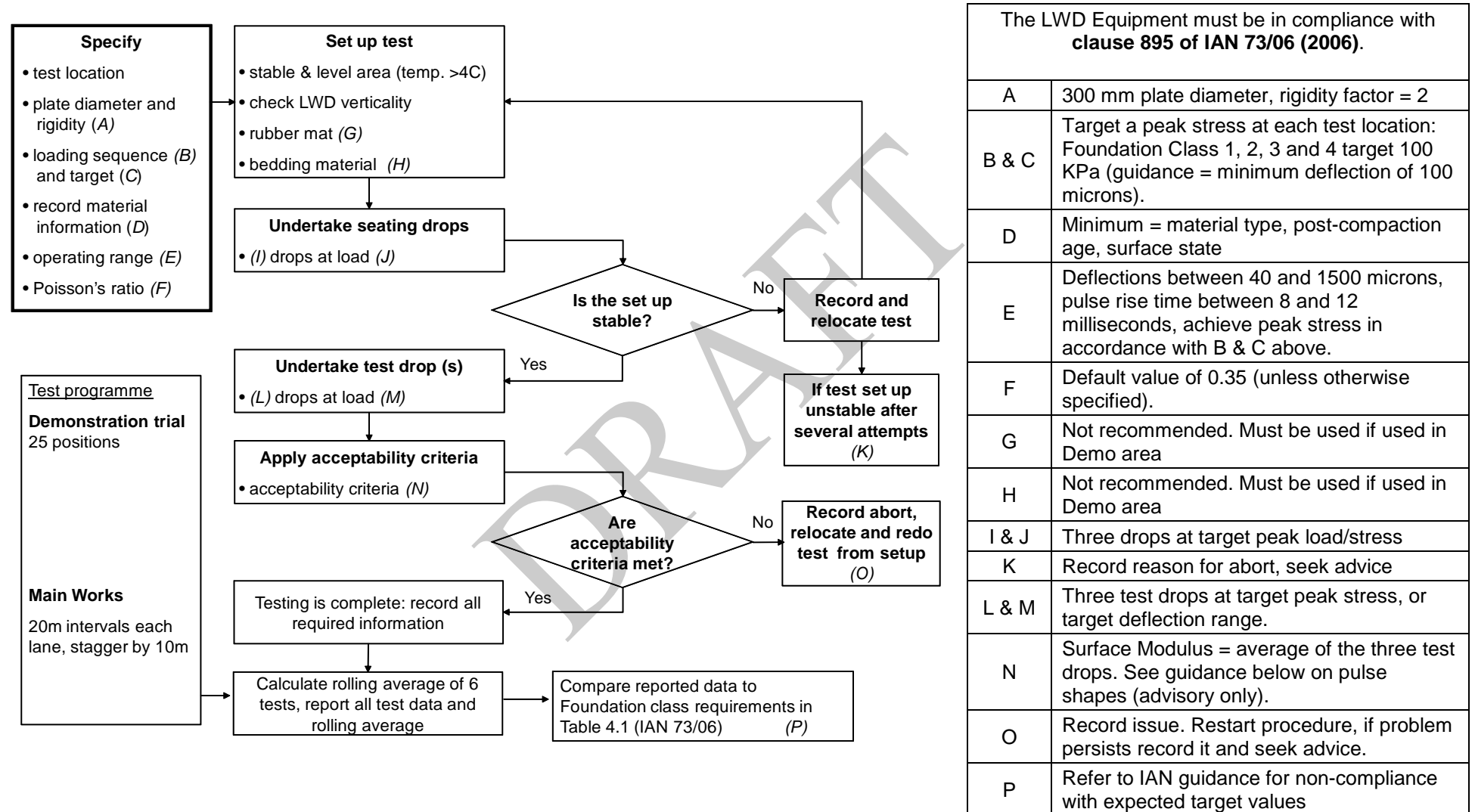
## 8.0 Acknowledgements

This Best Practice Guide was prepared by Dr Paul Edwards (Lafarge A & C UK) and Dr Paul Fleming (Loughborough University), on behalf of, and with input from, the ‘Pavement Foundation Group’ (PFG). The PFG group activity is coordinated and minuted by Peter Langdale of the TRL, and was established by Wyn Lloyd of the Highways Agency, and is now chaired (since January 2010) by Donna James of the Highways Agency. Additional thanks are due to Transport Scotland, Transport Research Laboratory, Britpave, Materials Products Association (MPA), Grontmij Carlbro, Dynatest and Scott Wilson (Dr Jo Edwards).

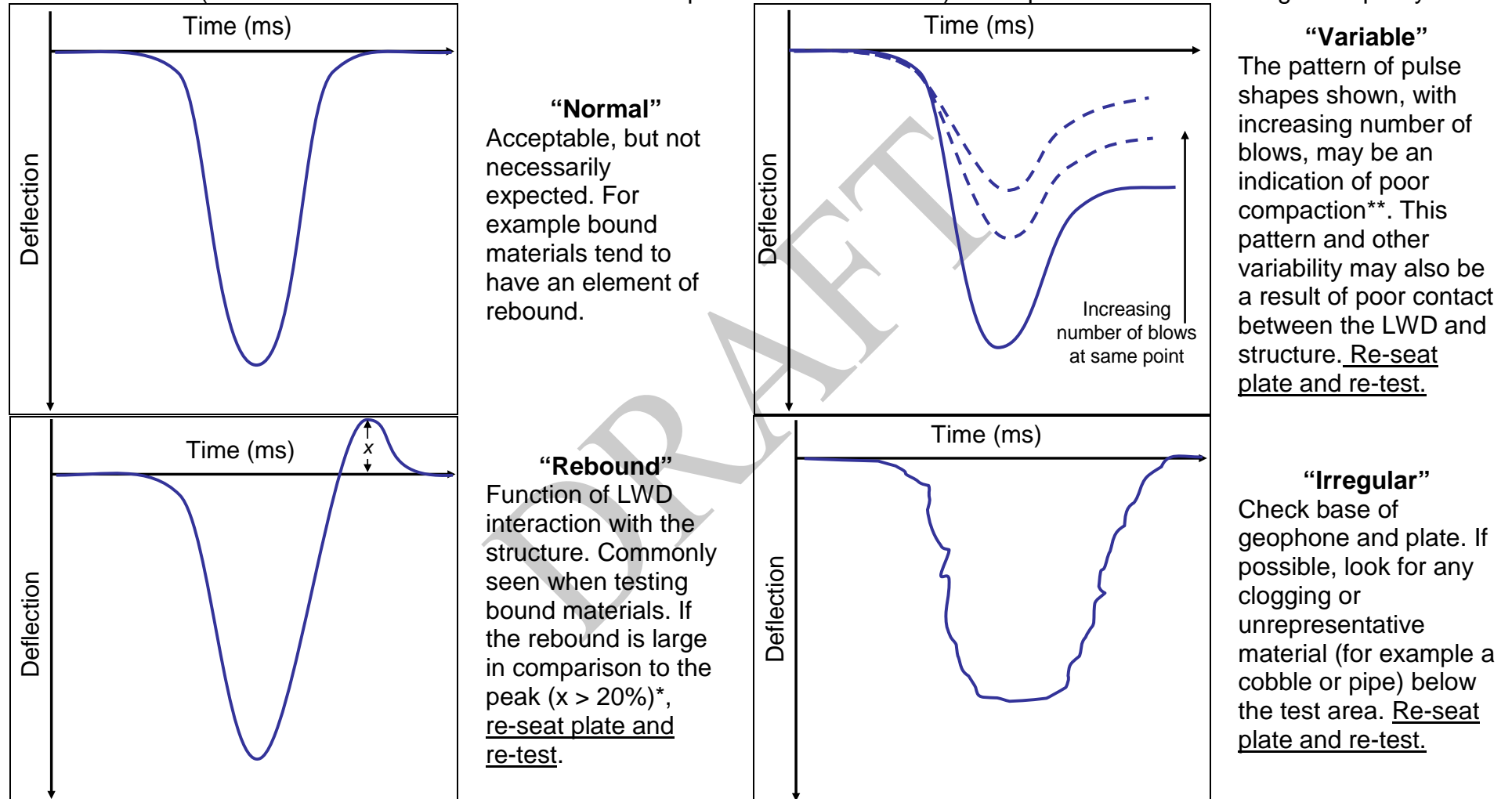
APPENDIX A – TEST PROTOCOLS for IAN 73/06 (2006) and IAN 73v1 (2009)

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Light weight falling deflectometer (LWD) testing protocol developed for use in accordance Highways Agency Design guidance **IAN 73/06**. 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.



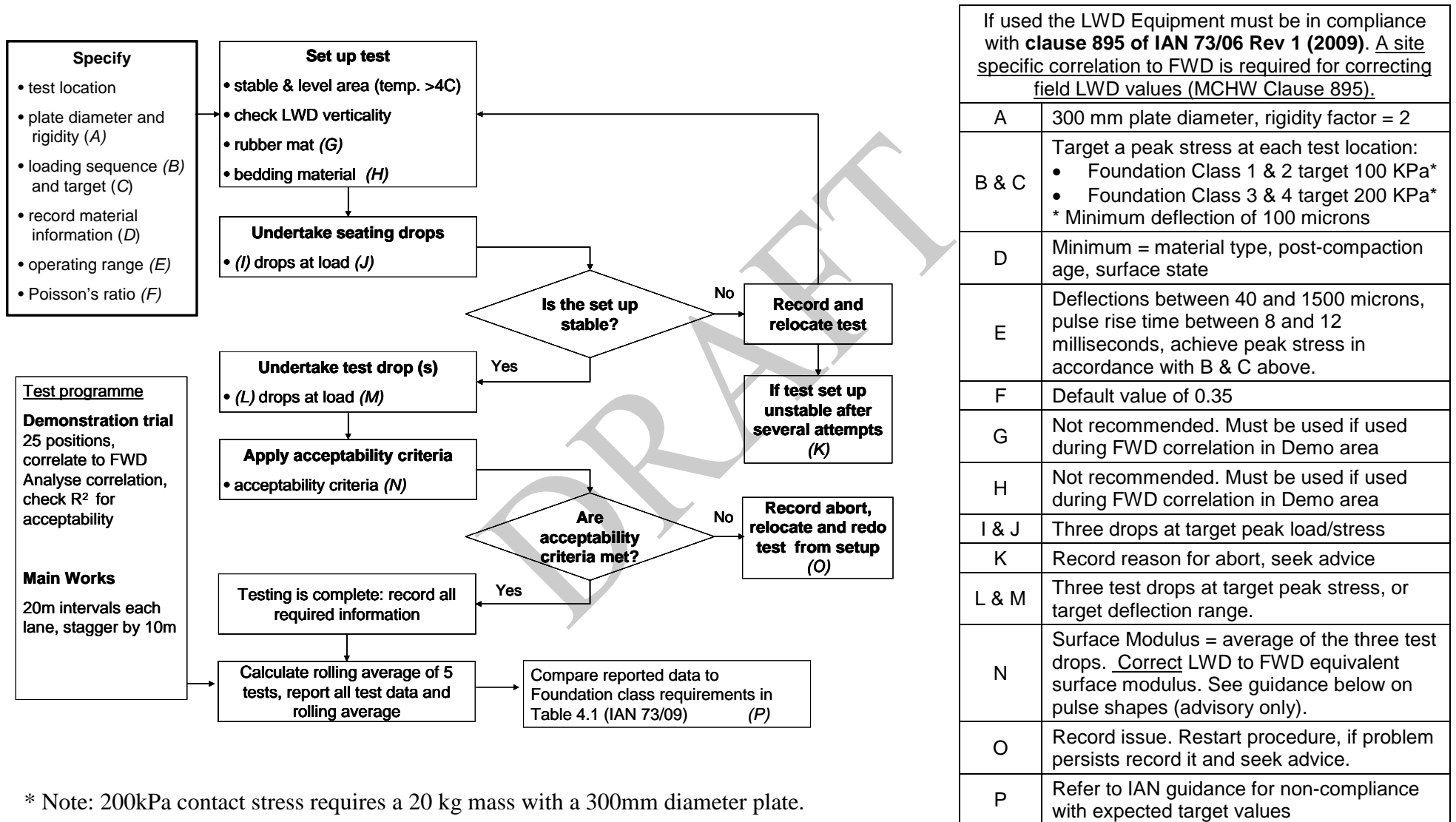
Pulse shape is a potential indicator of testing issues. It is a function of the interaction between the LWD (geophone) and the underlying structure. This covers several variables, which can only realistically be assessed on site. Pulse shape must not be taken in isolation, site observations (water content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



\* 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).

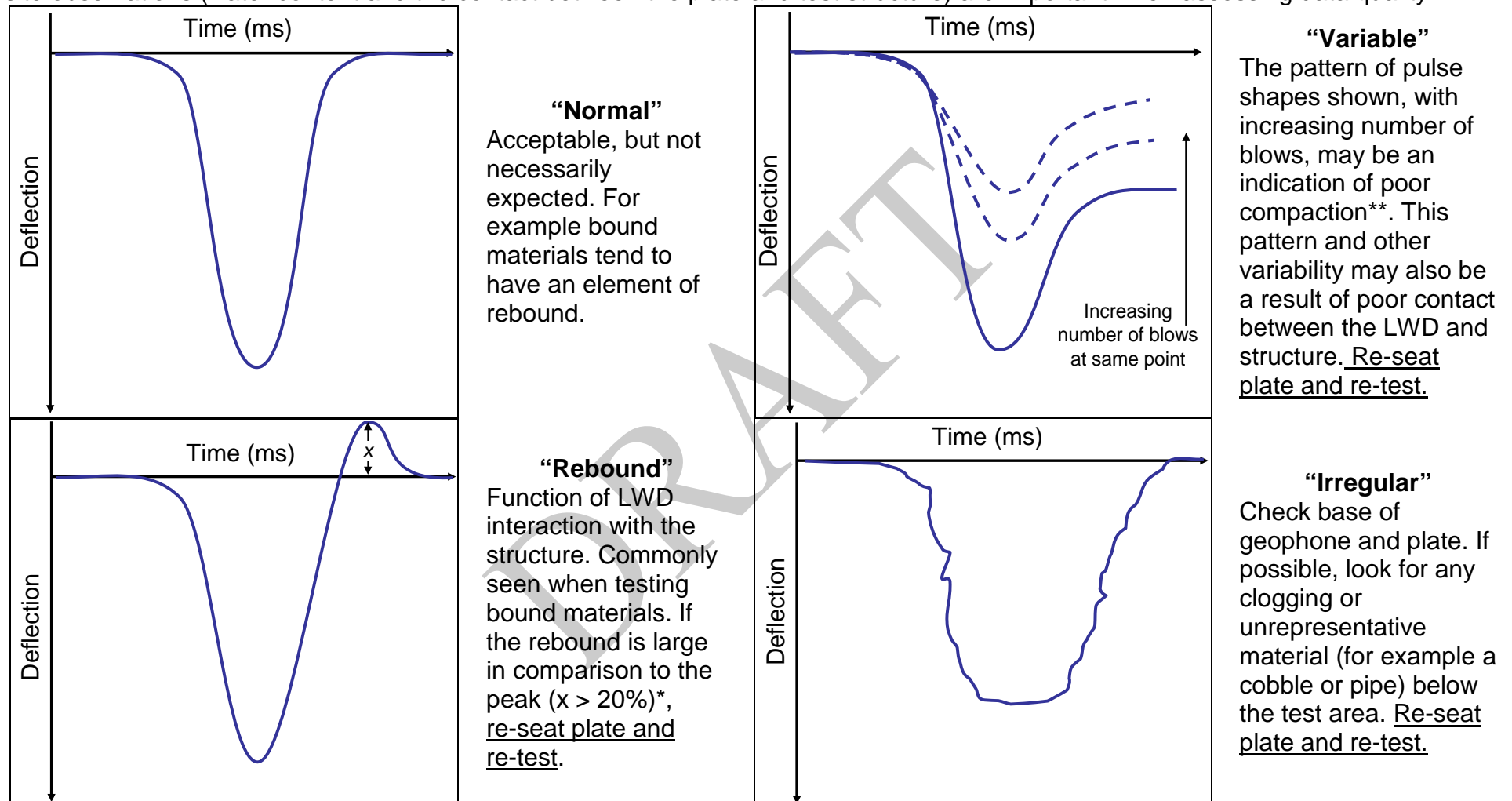
\*\* LWD testing is not a proxy for measurement for adequate compaction (density), but can be used to highlight areas for further investigation.

Light weight falling deflectometer (LWD) testing protocol developed for use in accordance Highways Agency Design guidance **IAN 73/09**. 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.



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

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.



\* 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).

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