Pavement Structural Condition Evaluation - Residual Life Assessment and Rehabilitation Design using the Falling Weight Deflectometer (FWD)

- **Overlay Design**
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Introduction

Knowledge of the structural condition of a pavement is required to make effective decisions on the type of maintenance or rehabilitation to be carried out on a pavement section. Reliable quantification of the extent of necessary remedial work will ensure the design life is achieved with maximum benefit/cost ratio.

The Falling Weight Deflectometer determines the full dynamic deflection bowl beneath a standard wheel load. Using the associated analysis software, it is possible to quickly and accurately determine the structural condition of the pavement system. The remaining life and appropriate rehabilitation requirements of a pavement section are determined from calculated stresses and strains in each layer. Thus, by using non-linear layered elastic theory, a pavement structure is analysed in the same way as other civil engineering structures. From non-destructive FWD testing, the required overlay or other rehabilitation alternatives are quantified from soundly based principles, producing maximum pavement life at minimum cost.

FWD data are combined with environmental data, layer thicknesses, material response functions and traffic load information to determine remaining life, critical layer, failure mode and required treatment (if any), at each FWD test point. Determination of structurally uniform subsections is based on a statistical evaluation of remaining life for all test points along the design section of pavement.

More detailed information is contained in Transfund Research Report No. 117: Pavement Measurement and Interpretation for the Design of Rehabilitation Treatments.

Fundamental Principles

The shape of the deflection bowl allows detailed structural analysis of the pavement. Basically, the outer deflections define the stiffness of the subgrade while the bowl shape close to the loading plate allows analysis of the stiffnesses of the near surface layers. A broad bowl with little curvature indicates that the upper layers of the pavement are stiff in relation to the subgrade. A bowl with the same maximum deflection but high curvature around the loading plate indicates that the upper layers are weak in relation to the subgrade. With the critical layer identified in this manner, and residual life calculated, the most fitting treatment may be prescribed.

Reporting is normally carried out in two stages. At completion of the fieldwork, all raw data and a preliminary interpretation is provided on diskette with a graphical viewing programme for immediate appraisal. The final report includes colour presentation of all relevant parameters in a standard format:

Starting at the foot of the page, the lower graphs give the layer thicknesses used in the model (as found from back-analysis and/or as-builts, coring, penetration testing and test pitting) and the actual dynamic deflections (corrected to standard temperature for an 8.2 tonne equivalent design axle loading travelling at 60 km/hr). The overlying graphs are subgrade strain ratio and modulus non-linearity. The strain ratio is the strain at the top of the subgrade divided by the allowable strain for the proposed traffic. The modulus non-linearity allows identification of likely soil type in the subgrade and its susceptibility to moisture. The next graph shows the critical layer, i.e. the layer that governs the design life of the pavement according to the adopted strain criteria (usually that advocated by Transit NZ and specified in the Austroads Pavement Design Guide). The next set of graphs show the results of the structural analysis, giving the moduli for each layer: basecourse (if unbound granular chip seal, or asphalt if structural), subbase and subgrade. The resilient modulus scale is shown on the left, while the equivalent CBR (again using Transit NZ recommended relationships) is shown on the right margin. Colour coding is used to allow the various layers to be identified readily.

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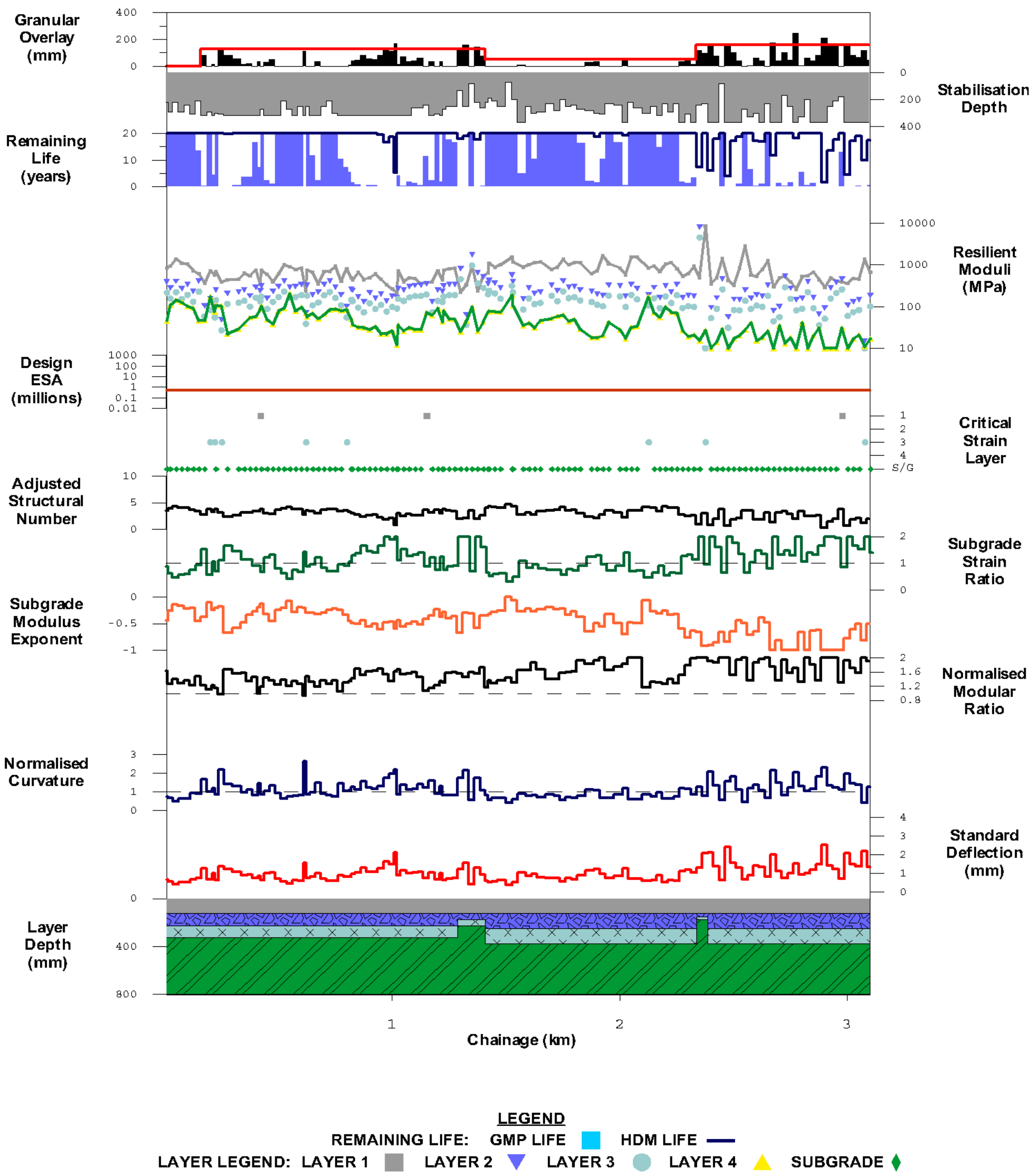
PAVEMENT STRUCTURAL ANALYSIS

FALLING WEIGHT DEFLECTOMETER SURVEY

A Granular Pavement



The adjoining graphs provide the interpretation and design guides. For each point is shown the remaining life and calculated overlay (where required to provide the design life). The individual results are then grouped into structurally uniform sub-sections to show practical intervals for which individual forms of treatment may be specified for construction. This vital step ensures a cost-effective approach to ensure the design life is achieved without superfluous overlay. The emphasis is placed on obtaining comprehensive in-situ test data so that sections which are structurally deficient can be clearly delineated from areas which require no strengthening, thus avoiding the over design that can result where a single form of treatment is applied to an extended length of pavement.

The overlay refers in each case to the same material as is present in the surface layer of the existing pavement (i.e. an overlay of asphaltic concrete for structural asphaltic pavements, or unbound M/4 overlay with chip seal in the case of existing unbound granular pavements). For the case of unsealed roads or for seal extensions, the overlay requirement assumes M/4 basecourse overlay with reduction factors (discussed below) to compensate for any crustal effects (wetter or drier than normal) in an unsealed road. Alternative designs (including stabilisation, reconstruction or widening if appropriate) can also shown be presented where required. These allow comparative costings (using local unit rates) to enable the most economic design to be adopted.

A concise report is prepared for each project, along with the graphical and tabular summaries including:

- Summary of overlay requirements to meet the design loading
- Discussion of the layer strengths, critical layers and implications for the most cost-effective rehabilitation
- All field data and interpretation for each test point, with adopted parameters
- Recommendations setting out how the pavement can most economically be sectionalised for individual types of treatment

A CD can be provided with the final report, giving all results, formatted for incorporation with the RAMM database where required.

Details Of Field Testing And Analysis

The Falling Weight Deflectometer (FWD) has been developed from the "déflectométre à boulet" originally devised by Bretonniere (1963). A force pulse is applied to the road surface by a specially designed loading system, which represents the dynamic short-term loading of a truck axle. This produces an impact load of 25-30 ms duration, and a peak force of up to 120 kN (adjustable). The deflection bowl response of the pavement is measured with a set of 7 precision geophones at varying distances from the loading plate.

Comparison To Heavy Wheel Load

The duration of the load corresponds to a wheel velocity of 60- 80 km/hr for the upper layer. This is important because of the visco-elastic characteristics of the asphalt layers and the elastoplastic response of the subgrade. The response of pavement structures both to the FWD and to loading by a heavy truck wheel has been compared on several instrumented test roads (Ullidtz, 1973). Stresses, strains and deflections were measured under both the FWD and moving wheel load. The response is practically identical. On the other hand, Ullidtz has shown that no simple correlation exists between the Benkelman beam and the moving wheel load. The relation is very dependent upon the specific visco-elastic responses governed by the dynamic characteristics of the pavement layers and subgrade.

These experiments indicate that the stress (and strain) conditions during an FWD test are very similar to the conditions under a heavy wheel load. Theoretical computations of pavement response to the impact load of the FWD are very close to the response to a rolling wheel load.

It may, therefore, be concluded that if the deflection bowl is measured under an FWD test and the theory of elasticity is then used to determine the moduli of the individual layers that would produce the same deflection bowl. Then the resulting layer moduli will be representative of the pavement materials under heavy traffic loading.

Accuracy and Capacity

Because no reference point (or support) is needed for the deflection bowl measurement (the "reference point" is the centre of gravity of the earth) the deflections can be measured with high accuracy. A typical accuracy is 0.5% ± 1 m. This accuracy is necessary because the subgrade modulus must often be determined from deflections of only 20-30 m. The total test sequence is controlled from the driver's seat and the results are automatically stored on disk, for later uploading and processing. Measurements are repeated generally 3 times at each point to assess repeatability, allow the effects of different loading to be evaluated and identify any external factors such as passing vehicles which may have affected results. 200-300 points may be tested during one day, depending on the distance between the test points.

Surface Moduli

Before calculating the layer moduli, the deflection data may be checked by plotting the "surface modulus". With the Dynatest FWD this may be done automatically immediately after the test. The surface modulus is the "weighted mean modulus" of the half space calculated from the surface deflection using Boussinesq's equations:

$$E_o(0) = 2 * (1-u^2) * \Phi_o * a/d(0)$$

$$E_o(r) = (1-u^2) * \Phi_o * a^2/(r * d(r))$$

where:

$E_o(r)$ = surface modulus at a distance of r from the centre of the loading plate

u = Poisson's Ratio (usually set equal to 0.35)

Φ_o = contact stress under the loading plate

a = radius of the loading plate

$d(r)$ = deflection at the distance r

E_o versus r plot allows immediate determination of whether the subgrade conditions are linear elastic or non-linear.

Calculating Layer Moduli

The layer moduli may be determined using the program ELMOD (acronym for Evaluation of Layer Moduli and Overlay Design). As indicated by the name the program can also calculate the residual life and the needed overlay of a given material for a given traffic loading and design life. The program can be operated in the field with the same microcomputer that controls the FWD and will accept the output from the FWD, stored on a floppy disk, as input to the program.

ELMOD models the pavement as a layered elastic system using the Odemark-Boussinesq method, which suitably accommodates non-linear properties (commonly exhibited by cohesive subgrades). The FWD deflection bowl is initially analysed in conjunction with measured layer thicknesses to determine moduli, stresses and strains in each layer. The program then uses the existing pavement condition, the prescribed failure criteria and design traffic loading to determine existing residual life, required overlay thicknesses and the most critical layer.

In calculating the moduli the program first makes use of the outer deflections. They are almost completely controlled by the subgrade modulus. The change with distance from the centre of the load is used to check whether a stiff layer at some depth is likely. If that is the case then the depth to the stiff layer is determined (assuming it to be infinitely stiff). If a stiff layer is not detected the deflections are used to calculate C and n in the subgrade modulus relationship:

$$E = C * (\Phi_z/\Phi)^n$$

where:

C and n are constants

Φ_z = vertical stress

Φ = reference stress

The reference stress is introduced to make the equation correct with respect to dimensions. E and C then both take dimensions of stress.

The exponent n is a measure of the non-linearity. If n is zero the material is linear elastic (eg hard granular materials). Soft cohesive soils may be markedly non-linear with n being between -0.3 and -1. A strongly non-linear subgrade modulus (n less than -0.4) in a firm or stiff soil, often indicates a moisture problem with poor drainage affecting the performance of the subgrade. This is not always the case, but where n values are low, the potential for subsurface drainage improvement should be checked.

The moduli of an upper stiff layer and of an intermediate layer, if present, are then determined through an iterative process using the total central deflection and the shape of the deflection bowl under the loading plate. The subgrade modulus at the centre line is adjusted according to the stress level. The outer deflections are then checked and a new iteration carried out if necessary.

For the layer modulus to be determined from the deflections it must have a significant influence on the deflection basin. In practice the method is limited to three or four structural layers: a stiff upper layer, an intermediate layer and a subgrade (which may be infinite or of limited depth). The intermediate layer may be sub-divided into two layers (to model granular base and subbase) by using established criteria for the modular ratio of these layers. Certain limitations also apply to layer thicknesses and modular ratios.

Residual Life And Overlay / Reconstruction Design

Adjustment for Seasonal Variations

The moduli determined by the ELMOD program for a given test point naturally correspond to the climatic conditions that happened to prevail during the testing. These conditions are not likely to be representative of the full range of design conditions, and the moduli must therefore be adjusted.

The modulus of asphalt is adjusted according to temperature and the moduli of the unbound layers according to season. For the unbound layers two different kinds of seasonal variations may be specified, or the seasonal variation may be input season by season. If desired the modulus of each layer in each season may be printed out in a table.

The asphalt temperature susceptibility, the yearly temperature variation and the seasonal variation of unbound materials are input in a special sub-routine. This includes parameters for locality specific input data concerning the design criteria, the design wheel loads (up to 12 different types in one analysis), the seasons of the design procedure, the desired design life, the desired input and output formats etc.

Residual Life and Needed Overlay

When the moduli corresponding to each season in the design procedure have been calculated, the critical stresses or strains caused by the wheel loads may be determined. The design wheel loads may be single wheels, equivalent single wheels, dual wheels (standard 8.2 tonne axle) or two dual wheels in tandem (particularly useful for airfields).

In the asphaltic layer, the induced horizontal tensile stresses and strains at or near the base of the layer determine the fatigue life to the onset of significant cracking. The number of repetitive loadings may be defined in terms of the critical strain in an equation of the form:

$$N = ae^{-b}$$

where:

a and b are constants depending on the stiffness of the asphaltic concrete

N = number of loadings to cause cracking failure

e = critical strain

In the unbound layers (notably the subgrade) the fatigue life is governed by the compressive vertical strain induced by repetitive loadings which lead to progressively increasing deformation.

The allowable strain at the top of the subgrade can be expressed in an equation of a similar form to that for asphalt fatigue strain where:

$$N = ce^{-d}$$

where:

c and d are constants

N = number of loadings to induce unacceptable deformation (standard 8.2 tonne dual tyred axle load)

E = critical strain at top of the subgrade. Dependent on the stiffness of the structural layers

(Transit New Zealand advocate the Austroads Design Manual which is derived from parameters of c=0.0085 and d=0.14 for all grades of granular pavements.)

ELMOD allows specification of either critical stress or strain criteria depending on site conditions, asphalt composition and climate. All parameters used, including the values in the equations above, are reported for each analysis.

For each season the critical stresses or strains are determined in each layer for the design load, and the damage is summed using Miner's Law. The residual life may then be calculated, when the present condition is known. Finally the required overlay thickness to extend the design life is calculated. This will depend on the type of overlay material and the required design period, both of which are specified for local conditions.

The structural evaluation is carried out at each test point. The moduli, residual lives and needed overlays are printed in tables and are also plotted for the full length of the road. Finally the output is sectionalised into practical sub-sections for uniform construction.

Interpretation and Design Application

The sets of graphs and tables giving the pavement model, structural condition and design (discussed earlier) are generated for each section of highway evaluated.

Tabulations for structural asphaltic pavements show overlays for 3 different design methods, all widely accepted internationally, namely:

a AUSTROADS

b AASHTO-92

c TRRL

Tables for unbound granular pavement profiles are usually based on the Austroads (1992 and 1994), Pavement Design Guide. Transit NZ provide additional methods in the August 1997 Supplement to the Austroads Guide.

The alternative treatments for unbound granular pavements are:

a unbound granular (M/4) overlay

b asphaltic concrete or friction course overlay

c digouts or reconstruction

d cement stabilisation of existing basecourse

Austroads identifies 3 methods for determining unbound overlay thicknesses. The simplest method uses only the central deflection (Austroads, 1992, Chapter 10). The Austroads (1994) method termed the Austroads Simplified Mechanistic Overlay (ASMOL) Procedure, uses 3 points from the deflection bowl and statistical correlation’s to determine probable strains. The most rigorous method uses all 7 points determined on the FWD bowl, and specific determination of actual strains in each layer. Transit NZ provides two additional methods for unbound granular pavements, which are exhibiting distress from excessive subgrade strain. These are based on past performance, hence requiring knowledge of the past traffic. The precedent subgrade strains are calculated and used as the basis for subsequent design. It is important to note that these methods are not applicable to cement stabilised basecourses or cases where distress is not related to subgrade deformation. Details are provided in the Transit NZ July 1997 Supplement to the Austroads Guide.

All alternative overlay methods are normally made available on diskette with a graphical viewing programme to enable comparisons to be made readily.

The analyses will generally identify whether stabilisation is worthy of further consideration. If so locations for test pit sampling and associated laboratory testing may be readily identified from the deflectometer results. When the laboratory results are available a check of the preliminary stabilisation design can be carried out, including economic appraisal in relation to overlay options.

Unsealed roads (eg forestry or seal extension projects) are ideal for FWD/ELMOD design because the equipment is well suited to measurement on granular surfacing. Even where loose gravel is present on the surface, recordings are simply repeated until consistent readings (within 2 microns on the outer geophones) are obtained. The modelling procedure differs from that used for surfaced pavements in order to allow for possible changes in average moisture content (and hence stiffness) of the upper layer, after sealing. The existing pavement is modelled as a multi-layer structure to determine existing moduli in the usual manner. The existing crustal layer will often show either unusually high stiffness if well trafficked and tested under dry conditions, or may be softened during wet periods. Therefore, to make due allowance for design purposes (i.e. accommodating likely changes in stiffness due to moisture equilibration), the modulus of the existing upper layer may be factored depending on observed conditions during testing. The minimum thickness M/4 basecourse required to accommodate the total design traffic is then determined using the standard Transit NZ recommendations for vertical strain limits depending on the total design traffic loading. Suitability of the existing surface layer to act as subbase is then evaluated from field inspection of drainage conditions, precedent (including FWD testing of adjacent sealed sections if appropriate) and laboratory testing where marginal materials are encountered.

When evaluating rehabilitation options for any type pavement, evaluation of the respective layer moduli from the structural model is particularly valuable to the designer. Low moduli in an unbound granular surface layer indicate that the basecourse may be degrading or is being intruded by fines, ie shoving may be expected soon (if not already apparent) and in alpine regions, frost heave and the associated decrease in chip protrusion (leading to loss of skid resistance) can be expected. Quantitative comparison may be made of the in situ stiffnesses with those achievable after lime (or sometimes cement) stabilisation and the economics compared with those for unmodified granular overlay. An important benefit is that the limits of the area requiring treatment are accurately defined, thus limiting needless expenditure while maintaining serviceability and safety.

All methods are reliant on the moduli determined from FWD testing and, to a lesser degree, the coring and DCP results. If pavement layer thicknesses differ between coring points, the calculated equivalent stiffness will still be valid, but the corresponding moduli will appear anomalous because the equivalent stiffness is determined by the product of the modulus and the cube of the layer thickness. However because stiffness is the main governing variable, the calculated overlay requirements will be affected minimally. The frequency of coring and DCP testing is determined after sensitivity analysis and examination of as-built information, but some form of depth control is required at about 300 to 1000 m intervals.

The analysis does not address economic aspects directly; therefore overlay thicknesses are generated irrespective of any upper bound. In practice, large overlay thicknesses will usually indicate that reconstruction rather than overlay, which should be considered by the designers. Other aspects, which will require specific attention of the design team, are level constraints, drainage improvement options, and the extent of cracking (requiring local patching, or partial reconstruction before applying overlay). Areas of local reconstruction or dig-out can be accurately defined because the full extent of the problem area including latent zones can be evaluated beyond the perimeter of the visibly distressed area - precluding a major cause of rehabilitation failure.

The critical layer identified at each point is used as a design aid to confirm the severity of visually identified cracking (low moduli in the asphalt layer) or positions where the potential drainage improvement should be considered (critical subgrade). Where the overlay thicknesses are large and the base layer is critical, reconstruction may be indicated. Judgement is required throughout the interpretation and confirmation with test pits is essential in all sections which require reconstruction or stabilisation.

Where reconstruction or widening is proposed, a preliminary guide to in situ CBR values can be determined from established CBR-subgrade modulus relationships (Ullidtz, 1986). These have been studied for local conditions and estimated in situ CBR values are tabulated. Depending on drainage and watertable fluctuations, adoption of appropriate (soaked or unsoaked) CBR values will need to be considered. The accuracy of CBR-modulus predictions is generally found to have considerable variance, i.e. within a factor of 2. The advantage of subgrade modulus determinations from the FWD is that the uniformity of the foundation can be determined effectively and the critical areas confidently identified. Where results from the alternative methods of overlay are the same, destructive testing can be eliminated, or perhaps limited to a minimal number of CBR tests which can be precisely positioned at the most appropriate sites where deflectometer testing has identified critical subgrade conditions.

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