# Advanced Backcalculation of FWD Data on Asphalt Pavements

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## ABSTRACT

Backcalculation of pavement layer moduli is a way to assess mechanical properties needed for mechanistic design. This practice has been around for about three decades and has worldwide use. Usually, a linear elastic approach is used, due to the speed and efficiency of the software. Occasionally, finite element modelling is applied for research purposes, but rarely for production work. To assess non-linear properties, the input is sometimes varied, like employing multi load levels repeated a number of times. Changing the shape of the load pulse and testing at different temperatures are other means of getting data for e.g. the master curve of asphalt pavements.

The present paper discusses ways to cope with non-linear properties, like visco-elastic behaviour, that were tried and used over the past 30 years. Further, utilizing time histories, and what the implications are regarding the sampling of such is discussed. Finally, suggestions are made on how to proceed with research leading to a practical and useful method for assessing better data on fatigue of pavements, rolling resistance et cetera.

**Keywords**: Falling Weight Deflectometer, Pavement Moduli, Dynamic Response.

## 1. INTRODUCTION

The Falling Weight Deflectometer (FWD) is by now one of the most common devices to assess bearing capacity on major highways. Since the 1980:ies backcalculation software has been used to derive elastic moduli of the pavement materials. These properties are then used to assess stresses and strains that are indeed valid for pavement structural and fatigue analysis and design.

If non-linear elastic properties are prevailing the signal to noise ratio decreases and the RMS increases. There are several reasons for this to occur, such as anisotropic stress sensitivity, permanent deformation, temperature gradients, viscoelasticity, damping in unbound layers only to mention some of the more common properties affecting the deflections.

The present paper presents a strategy to cope with these effects during testing and how to use the information for the analyses. Thus, better and more sustainable pavements can be constructed, and the FWD can be used for construction control. The results also serve to a better assessment of asset management for pavements.

## 2. HISTORIC OVERVIEW

The 1980:ies can be regarded as the decade of introduction of mechanistic design to pavement engineers. After the publication of numerous papers dealing with the American Association of State Highway Officials (AASHO) Road Test and other similar field experiments, and the introduction of mainframe computer software such as BISAR; there was by 1972 a framework available for the design of pavements regarding the actual strain from live loads. This became useful for practitioners and was wider used by 1985 with the introduction of personal computers and software like ELSYM5.

Further, more field tests were needed to verify the response from loads. There were Benkelman Beam Tests, Plate Load Tests, Various Vibrating Loads, and Impulse Devices.

In the laboratory, strain could be measured under controlled conditions, but it was soon learnt that a "calibration" was needed between tests. Hence, wisely the term mechanistic-empirical design was introduced as to cover for the influence of unknown data, such as climate and local variability, overloads et cetera. Some of these factors can be handled by statistical measures and, more recently, neural networks, but in some cases, the cost for retrieving a material property is exceeding by far the benefit of doing something about its implications.

Anyway, by the late 1980: ies there were a number of computer programs on the market that were able to backcalculate the material stiffness of pavement layers from Falling Weight Deflectometer load and deflection data. The programs assumed a linear elastic response, and utilized the peak load and peak deflections from an array of sensors at various distances from the load center. The important requirement here is that the load is normalized in such a way to represent a passing wheel at a certain speed. Thus, the derived moduli are valid at this load at the ambient temperature and other weather-related issues such as pavement and subgrade moisture. Obviously, by sticking to the same machine, the shape of the impulse load is constant.

## 2.1 FEM to cope with stress-sensitivity

It is a known fact that unbound materials are stress-sensitive, i.e. the modulus is varying by the stress state. The bulk stress has been used for granular materials, and the deviator stress for cohesive materials. Bonaquist et al. showed a relation between the octahedral shear stress and the deformation properties, [1]. For adhering shear to field testing, one should assume a Poisson's ratio though, as it is difficult to assess any shear stress from the FWD test itself.

For the linear layer elastic solutions, a homogenous layer can be subdivided into many thin layers to accommodate the effect of stress sensitivity by depth, albeit it is not possible to adjust for such properties in the horizontal plane. A thin pavement resting on a cohesive soil, would be particularly difficult to solve with the linear elastic software. The outermost sensors used to assess the subgrade modulus would react and measure a low stress-state soil. This would result in overestimating the subgrade stiffness. The program would then compensate for all too stiff subgrade, so that the unbound materials would appear as softer than they really are. Rather early there was software available to handle this predicament, e.g. ILLIPAVE. Later neural networks were employed to speed up the process [2,3]. Even if the FEM programs were wide-spread, they did not replace the linear layer ones, as the latter are much faster and easier to set up and use.

## 2.2 Time histories

The original FWD sensors readings were monitored by means of a voltmeter. A larger deflection created a higher voltage, and the top reading was stored as the output. Thus, one could derive the highest deflection per sensor. By the mid 1980:ies electronics improved and data could be stored on a personal computer, which facilitated the data collection quite considerably. A nice side-effect was the ability to record the output over time, hence the entire deflection (and load) history could be stored. This could be illustrated and the time lag between sensors could be studied. Peter Sebaaly et al. suggested instantaneous backcalculation, rather using the top values, that were shifted in time [4]. Whether the method gave a better subgrade response or not was not thoroughly investigated.

### 2.3 Shapes of deflection-load diagrams

Usually, a time history is presented in the time domain, i.e. load and deflection sensor readings are displayed along a time line lasting during load pulse or longer to accommodate for echoes or bounces, see Figure 1.

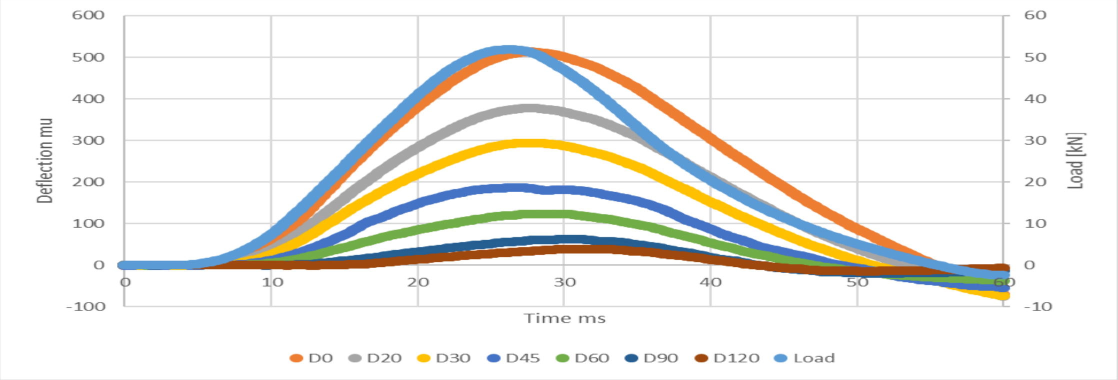

**FIGURE 1** Load and deflections over a 60 ms window. Load is leftmost curve in kN on the right scale. Deflections from seven sensors µm on the left scale.

If the load and deflections are plotted instead; one would see how the shape of the curve may differ by the material properties. It is rather common in presenting geotechnical applications, but also for studying dissipation in materials. The shape of the load-deflection diagrams varies substantially, due to circumstances. A normal shape can be seen in Figure 2. Over the years many time histories have been sampled by many agencies. They are rarely used for the design, perhaps due to the tedious work to analyze the data.

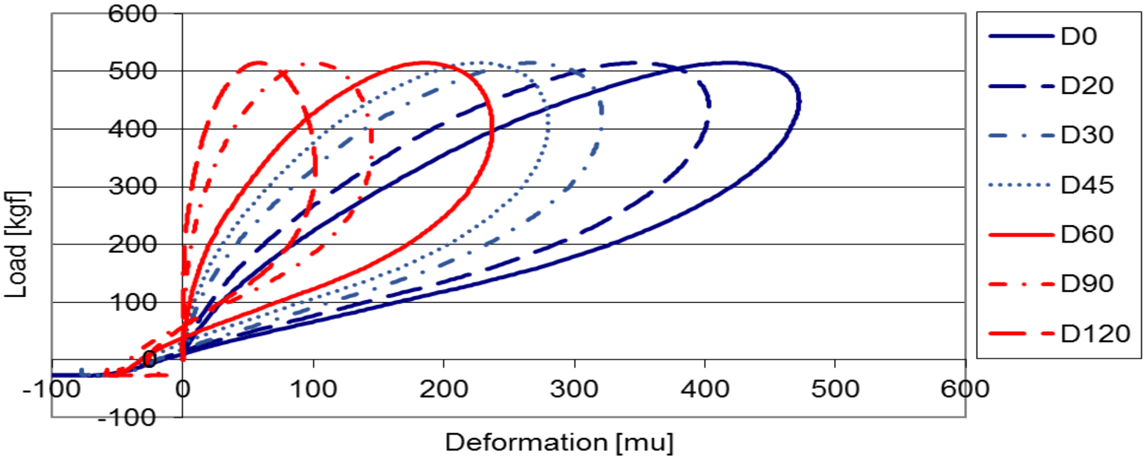

**FIGURE 2** Load Deflection Diagram showing seven sensors at 0, 20, 30, 45, 60, 90 and 120 mm offsets.

# 3 CHARACTERISTICS OF LOAD AND DEFLECTIONS

The following pavement and soil properties have been identified to affect the shape of the time history curves.

- Inertia
- Visco-elastic (asphalt bound materials)
- Fracture mechanics (bending in curling slabs)
- Damping in unbound materials
- Pore pressures in finer soils
- Plastic Deformation

## 3.1 Inertia

In most cases the influence of inertia on the Load-Deflection curve is relatively small. The load is a known parameter, but the amount of pavement and soil affected, thus the weight of the affected volume must be estimated. Overall, the range of the work is relatively small compared to other parameters. Figure 3 shows an example of an elastic response for three deflection sensors at 0, 30 and 120 cm from the load center. The $D_{120}$ displays a straight line and the peak load and peak deflections occur simultaneously. The dissipated work is about 3 Nm.

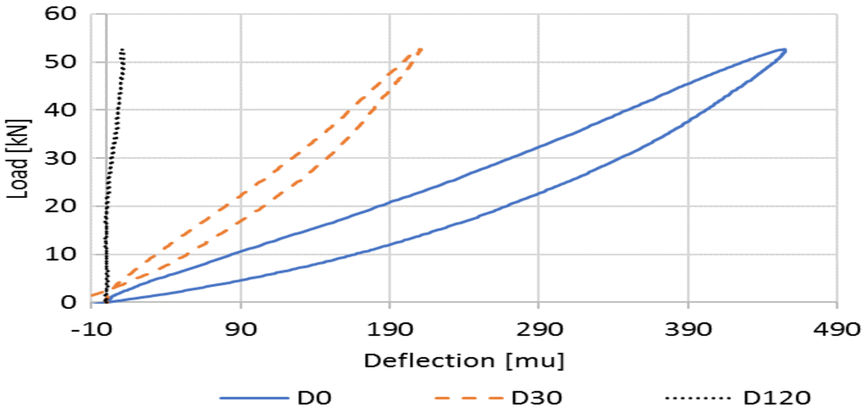

**FIGURE 3.** Load-Displacement Diagram Displaying an Elastic Response

## 3.2 Visco-Elastic Properties

At Texas A&M Allen Magnuson et alia put together a software for time history (TH) evaluation for assessing master curves of the asphalt materials [5]. The software was marketed for a while, but was not widely used. Part of the problem was that the entire deflection history had to be used and that the deflection sensors drifted with time. A tedious calibration of the sensors was needed to achieve an accurate output. There was also a way of handling “the tail” by various techniques of data treatment. Under the right circumstance, and a relatively thick asphalt pavement, indeed the parameters could be derived. Most asphalt pavements consist of layers with different kinds of mixes though, so it would be a tremendous task to backcalculate each layer separately.

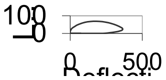

**FIGURE 4** Load-Deflection Diagram from a hot, thick asphalt concrete pavement. The lag from peak load to peak deflection is about 25 ms.

### 3.3 Strain Energy for fatigue

The work related to fatigue was addressed early by VanDijk and Visser [6]. Later work of dissipated energy was presented by Vargas-Nordcbeck et al [7]. In 2014, the present author investigated the bending stress and the associated energy dissipation from curling concrete slabs, [8]. Figure 5 shows the difference between a test near the center of a Portland cement concrete slab and its edge when curling upwards from the study. The work assessed seemed to be near that of equations derived from earlier research.

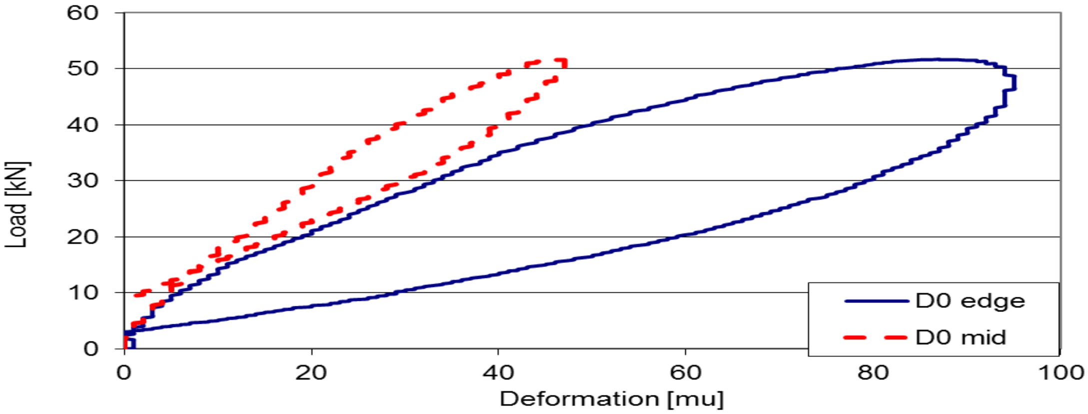

**Figure 5** Load-Deflection diagrams showing mid-slab and edge tests

### 3.4 Damping is Soils

The damping occurring in granular materials has not been thoroughly investigated in the field. Many tests have been done in tri-axial cells, but those seem to suffer from difficulties in simulating the right confining pressure, which is varying not only by depth, but also due to several other factors, e.g. degree of compaction, moisture et cetera. Perhaps damping in soils by a wave function suggested by Uglova and Tiraturyan [9] can be used for an analytical approach. From the Load-Deflection diagrams we can assume that the dissipation caused by damping is relatively high on roads with thin bound layers, and a dissipation of 5-10 Nm is to be expected.

### 3.5 Pore Pressures and Plastic Deformation

High pore pressures will push the other sensors upward and thus, heaving of the surface may occur. This phenomenon is often seen from active design projects, and here the dissipation should not be derived from anything but the center $D_0$ sensor. The plastic deformation is often occurring on new roads, and the dissipation from the compaction energy can be derived. If plastic deformation occurs, repeated loads will reveal this circumstance. The second drop will follow the same plot as the first in the deflection diagram, but at the peak load it the deformation will return somewhat earlier; it will follow the same path back, but the curve is slighted shifted to the left.

## 4 DISCUSSION

When going further with pavement analytical tools there are basically two approaches or methods you can take. These are (a) Pragmatic and (b) Analytical.

One pragmatic approach is already in use, namely the linear layer elastic one. It works fine for many road agencies, due to several reasons. First, the testing procedure is standardized to a load pulse, with the maximum near the legal wheel load, 50 kN in most countries. The second issue is that the derived moduli are adjusted to a design procedure, based on the field moduli. This may be regarded as a calibration. In the pavement design world, this would be the empirical part of the ME (Mechanistic-Empirical) design.

The analytical approach takes a different course. In this case, more parameters are added, like pavement inertia, visco-elastic properties, damping in soils, and pore pressures in soils. The visco-elastic effects could be handled by the scheme suggested rather early by Magnuson et al [4] and Kutay et al, [10]. More recent work on effects of temperature and ageing, correlated in the field was carried out by Lee at al., [11]. They found that the complex modulus could be backcalculated, but differed from the ones in the LTPP data base.

Unless, one aspect is totally dominating over the others, one must regard all factors influencing the dynamics. Ceylan et al. were looking into using neural networks to derive visco-elastic parameters [2] and Wang and Li included more parameters in their study, [12].

In this case one must know what the impacts are from each parameter. During dry conditions, one may ignore pore pressures in coarse soils, but the problem in the field is the constantly varying factors not only from weather, but also from the fact that you are moving to a new situation for each testing point.

To improve on the input Madsen and Levenberg suggested using different load pulses as input to improve the dynamic evaluation, [13]. Such testing was also carried out by the present author, [14].

## 5 CONCLUSIONS

The rather rational way of using top load and deflections only for a linear elastic model has been around for thirty some years. The model is rather robust, and certainly very useful, which is probably why it remains as the first choice for pavement structural evaluation. However, sampling of data has improved, and in addition there are many more elaborate models that can be used for deriving more parameters than elastic properties. The use of recycled materials and additives must be evaluated in the field for asset management. Thus, the present author suggests going forward with analytical and pragmatic models as well. The analytical models would handle specific properties, like e.g. viscoelasticity. However, considering all aspects of dynamics in one single model could pose problems, as with all multi-variable models. The pragmatic approach would be aimed to production work for the pavement engineer as a robust method for employing many different aspects of pavement deformation.

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