Asset management innovation for rigid pavements

F Varela and R Pacheco-Torres
Department of Civil Engineering: Construction, Infrastructure and Transport, Faculty of Civil Engineering, Polytechnic University of Madrid, Madrid, Spain

E-mail: fernando.varela@upm.es

Abstract. Today, the new pavement management tools encourage preventive action, whereas more traditional approaches focus on acting on observed damage. An adequate initial evaluation is essential to properly manage pavement maintenance. In this regard, non-destructive tests such as deflection tests make it possible to obtain first-hand information without altering the condition of the pavement, and their use is becoming increasingly more common. This paper presents a study of the structural evaluation of rigid pavements based on measured deflections. Several aspects are identified which will make it possible to improve these procedures. A 62-kilometre stretch a motorway in Mexico has been used as a case study. A campaign of on-site measurements was carried out using a Falling Weight Deflectometer (FWD). The deflection values were used in several iterative methods with calculation programs and manual analytical methods, comparing the results obtained. The elastic moduli of the pavement layers were determined. These are the main parameters for calculating the remaining life of the structure, which facilitate decision-making around pavement management. The results obtained in this study demonstrate the usefulness of back-calculation methods for analysing the structural condition of rigid pavements as an initial stage in the development of pavement management systems. The conclusions validate the use of back-calculation programs in the structural analysis of rigid pavements, by comparing the results obtained with manual analytical methods.

1. Introduction
The current approach to road maintenance involves anticipating damage by monitoring and periodically evaluating the road surface and creating evolutionary models, thus identifying the areas that require action, scheduling their maintenance and assigning resources efficiently. Non-destructive tests make it possible to gather information about the condition of the pavement and process it using suitable software, in order to determine the actions to be taken to keep the infrastructure in optimum condition for use. These tests are generally faster and less expensive, and cause less inconvenience to users, compared to traditional techniques.

Among non-destructive tests, deflection analysis using a Falling Weight Deflectometer (FWD) has become popular due to its ability to estimate the properties of the pavement materials by measuring the deflections caused by an applied load. The data obtained using a FWD can be used in the structural evaluation of the concrete slab and support layers, respectively. These are required inputs for designing reinforcements during rehabilitation.

The main objective of this paper is to conduct a study on the rigid pavement management within a preventive approach, based on the current techniques for structural evaluation. The specific objectives are to: (i) identify the main parameters that allow an improvement on the current calculation
procedures; (ii) validate the results of automatic calculation programs by comparing them with those obtained by analytical methods.

Data obtained from a test campaign with a FWD is used to analyse the current condition of the road on a 62-kilometre stretch of motorway in Mexico. Based on these data, various methods were used to obtain the modulus of subgrade reaction and the elastic modulus of the concrete slab. The results obtained from several commonly used calculation programs and those obtained by analytical methods are then compared.

2. State of the art
An analysis of the state of the art has been made in terms of maintenance of rigid pavements, which is gathered below.

2.1. Management systems for road pavement maintenance
The basic aim of pavement management is to use reliable and consistent information to develop decision-making criteria, providing realistic investment alternatives and contributing to efficient decision-making [1]. Until not long ago, management was based on experience, assigning the resources available for network maintenance in the most effective manner possible. With current technology, more advanced road pavement management systems have been developed. These modern systems make it possible to classify and prioritise the actions to be taken, by studying changes in the structural and functional characteristics of the pavements.

In general, maintenance programmes should improve the long-term performance of the pavement, fulfilling the expectations of drivers. This goal is achieved through preventive maintenance, non-structural rehabilitation and routine maintenance. A management system must include road pavement performance models, making it possible to predict real changes and the condition of the road pavement at any given time.

Most efforts in this area have focused on developing management systems for flexible pavements. For this purpose, HDM-4 is the tool most commonly used for analysis, planning, management, maintenance assessment and investment decisions regarding roads. This tool can also be used to evaluate flexible road pavement. However, a recent study by the Washington State Department of Transportation (WSDOT) indicates that version 1.3 of HDM-4 does not provide meaningful analysis output for the rigid pavements studied by WSDOT [2].

2.2. Non-destructive tests in pavement evaluation
Evaluating pavement condition is an essential step in assigning suitable maintenance actions and must be carried out from a functional and structural perspective. This can be done using destructive or non-destructive tests. Among non-destructive testing techniques, pavement deflection tests represent an extremely valuable engineering tool for evaluating the uniformity and structural condition of the existing pavement. Deflection is the structural response to the application of an extreme vertical load produced by vehicle traffic and can be related to the structural capacity of the pavement [3].

In rigid pavements, the deflections results obtained provide a great deal of information about the structure of the existing pavement, including variability in deflections, the efficiency of load transfer across joints and cracks, and the presence of voids under the slab. The information is also useful for back-calculating the main properties of the material, specifically the elastic modulus of the concrete and the modulus of subgrade reaction, thus making it possible to evaluate the structural condition of the pavement.

Currently, the most common device for measuring deflections is the Falling Weight Deflectometer (FWD). This device releases a known weight from a given height onto a plate resting on the structure of the pavement, producing a load similar in magnitude and duration to that of the wheel of a heavy vehicle [4]. The impact of the falling mass triggers a load wave which is transmitted to the pavement through a system of elastic buffers.
2.3. Analytical methods

There are several methods of analysing pavement condition based on deflections: the AASHTO 1993 Method, Lukanen’s Method, YONAPAVE Method and Rohde’s Method [3]. These methods make it possible to calculate the elastic modulus of the concrete slab and the modulus of subgrade reaction (k value), with which it is possible to determine the value for the effective structural number of an existing structure in order to design and evaluate stresses or rehabilitation based on the modulus of the subgrade and the concrete slab.

The recommended procedure for calculating the effective k value of non-destructive tests is based on the AREA concept, which was originally proposed by Hoffman and Thompson [5]. It consists of calculating the AREA parameter using the following expression, which describes the deflection basin (Eq. 1):

$$\text{AREA} = 150 \times [1 + 2 \times D_{30}/D_0 + 2 \times D_{60}/D_0 + D_{90}/D_0]$$

where $D_0$ is the surface deflection at the point of impact and $D_{30}$, $D_{60}$ and $D_{90}$ are the deflections at a distance of 30, 60 and 90 cm from that point. The AREA value is a good indicator of the pavement modulus, with high values corresponding to road pavements with good structural characteristics.

For a given load radius and sensor configuration, there is a unique relationship between the AREA parameter and the radius of relative stiffness in the pavement system. In the case of a load plate with a radius of 150 mm (5.9 inches), it is possible to apply the following equation by Hall (1991) (Eq.2):

$$l_k = [\ln((36 \times \text{AREA})/1812.279133)/( -2.559340)]^{4.387009}$$

With the AREA parameter calculated based on deflections measured by the FWD and the radius of relative stiffness, the effective k modulus can be obtained using Westergaard’s deflection equation (Eq.3):

$$k = [P/(8 \times d_r \times l_k^2)] \times \{1 + (1/2\pi) \times \ln[a/(2 \times l_k)] + (\gamma - 1.25) \} \times (a/l_k)^2$$

where $d_r$ represents maximum deflection, $P$ is the load, $\gamma$ is Euler’s constant and $a$ is the load radius. Finally, the k value of the subgrade can be used to determine the elastic modulus of the concrete, using Eq.4:

$$E_{\text{PCC}} = \frac{12 \times l_k^4 \times (1 - \mu_{\text{PCC}}^2) \times k}{h^3}$$

where $E_{\text{PCC}}$ is the elastic modulus of the concrete slab, $l_k$ is the radius of relative stiffness and $\mu_{\text{PCC}}$ is Poisson’s modulus for the concrete.

2.4. Back-calculation process

In pavement design, stresses, deformations and deflections are calculated based on defined traffic loads, layer thicknesses and the structural contribution of the materials. Back-calculation is the opposite procedure, making it possible to describe the mechanical resistance of the layers that make up the structure of an existing pavement, based on the deflections measured on the surface [6]. This enables us to calculate the elastic modulus of the concrete that is used to evaluate the structural condition of the slab, and the effective modulus of subgrade reaction (k value) used to evaluate the support layer [7]. The ASTM D5858 standard provides an approach to back-calculation based on deflection measurements [8]. Figure 1 shows the flow diagram for the back-calculation process.
Figure 1. Flow diagram of the back-calculation process.

The back-calculation process is sensitive to the seed moduli and the more realistic these are, the better the results obtained in the process of iterations. For each deflection basin measured, the required input data are entered. These include the load characteristics of the FWD device, Poisson’s coefficient, layer thicknesses, deflections and locations, and possibly, the initial estimates of the layer moduli (seed moduli). The materials classification and approximate layer thicknesses can be obtained from construction records, non-destructive tests or a core extraction programme.

3. Methodology
The following describes the methodology applied to the analysis of a specific road in which deflection measurements have been taken in recent years.

3.1. Case study
A 62-kilometre stretch of motorway in Mexico was used as a case study. Each year, goods with a transported value on the order of 25% of the country’s gross domestic product travel along the section which the object of study.

3.1.1. Initial data
The current pavement structure was put into service in 1995. It is made up of concrete slabs resting on an asphalt layer, which in turn rests on a base with an average thickness of 20 cm. In order to obtain the thicknesses of the layers that make up the pavement along the lane under study, a field exploration programme was conducted, which involved taking test borings or bore holes every kilometre. This made it possible to determine the stratigraphic profile of the pavement, which is shown in figure 2. Two different structures can be identified. The first is made up of a layer of concrete, followed by asphalt mix and a layer of hydraulic base. The second type of structure identified consists of a layer of concrete, asphalt mix and a cement-stabilised base layer.

Figure 2. Stratigraphic profile of the pavement (KP 207+000 to KP 148+000) and types of structure identified.
3.1.2. Deflection measurement
Pavement deflection measurement was carried out in March 2017, using a Dynatest 8082 Falling Weight Deflectometer. The equipment sensors are located at a distance of -30, 0, 30, 60, 90, 120, 150 and 180 cm, measured between the system’s load axis and the location of each sensor. The radius of the load plate is 15 cm (5.9”). The deflection measurements were taken every one hundred metres, in the centre and at the edges of the slab, recording the temperature of the pavement surface and the air at the time of measurement. The distance travelled and location of each measurement point were also recorded using GPS. Three blows were used at each point, gradually increasing the load. Lastly, an output file was generated, containing this information and the deflection measurements. Figure 3 shows the measurement scheme of an FWD and the arrangement of the geophones.

![Figure 3. Measurement scheme of an FWD and arrangement of the geophones.](image)

3.2. Analysis
This section studies the deflections from the stretch of motorway between KP 148 and KP 210 using the Elmod and Rubicon programs and analytical methods (AREA Method and YONAPAVE Method). The purpose is to obtain values for the elastic modulus of the concrete slab and the subgrade, the main parameters in the structural analysis of rigid pavements, and to determine its remaining structural capacity. Only the deflections measured at the centre of the slab were used.

3.2.1. Using software
Today there is a range of software programs available to perform back-calculation. However, there is no standardised criterion for choosing the most suitable in each case study [9]. Of the available programs, in this study the deflection analysis was performed using Elmod software and Rubicon software.

Elmod version 6.1.8.2, developed by Dynatest Consulting, was used for the analysis. This program is capable of analysing large batches of FWD data, a valuable characteristic when analysing long stretches of road. The Elmod program standardises the deflections for a pressure of 700 kPa. Lastly, it provides the elastic modulus of each layer, including the subgrade. Calculations made with the Rubicon Toolbox program used version 2.4.1., developed by the company Rubicon Solutions. The program has a back-calculation module that makes it possible to perform an automated back-calculation of the elastic moduli of the layers, based on FWD data. It uses an effective search method to find the rigidity of the layer which will produce a calculated deflection basin which is close to the FWD deflection basin measured. This program allows for a maximum of 50 iterations. The initial elastic moduli for the calculation were established based on the ASTM D5858 - 96 Standard, as indicated in table 1, depending on the material in each layer.
### Table 1. Elastic modulus and Poisson’s Modulus for different types of material.

| Material                     | Elastic Modulus [MPa] | Poisson’s Coefficient |
|------------------------------|-----------------------|-----------------------|
| Asphalt concrete             | 3500                  | 0.30–0.40             |
| Hydraulic cement             | 35000                 | 0.10–0.20             |
| Cement-treated bases         | 4100                  | 0.10–0.30             |
| Granular bases               | 350                   | 0.20–0.40             |
| Lime-stabilised soils        | 200                   | 0.10–0.30             |
| Granular sub-bases           | 140                   | 0.20–0.40             |

#### 3.2.2. Analysis of the deflections using the AREA Method

In the second part of this methodology, the AREA Method is used to perform a numerical analysis of the deflections in order to obtain the elastic modulus of the concrete slab and compare these values with those generated by the software programs. The deflections were not corrected for temperature, as the existing literature does not indicate how to apply this correction to rigid pavements. Using Eq. 1, the AREA parameter was calculated for each blow, and with this, the radius of relative stiffness, utilising Eq. 2. With these parameters and knowing the maximum deflection, the applied load and the radius of the load plate, the effective k modulus was calculated using Westergaard’s equation (Eq. 3). Lastly, the elastic modulus of the concrete slab was determined using Eq. 4. The YONAPAVE Method was used to estimate the elastic modulus of the subgrade.

#### 4. Results

Figure 4 shows the standardised deflections for the project. It is possible to see that along some sections, the deflections are highly variable, with high values. In contrast, others are uniform and remain within the same range. Uniform and low deflections indicate good structural capacity, while very high and variable values indicate weaker pavement with the presence of damage.

![Figure 4. Variation in standardised deflections in the project.](image)

The results of deflections back-calculated by the Elmod software are shown in figure 5. It can be observed that at KP 179 the deflections are mostly uniform in all the measurements taken, and that the elastic moduli also show little variation.
Figure 5. Deflections plotted by Elmod and standardised to 700 KPa, KP 179.

The elastic modulus of concrete slab E1 was calculated using the AREA Method. The resulted are compared to those obtained using Elmod and Rubicon in figure 6. It is possible to see a similarity between the values obtained by Elmod and the AREA Method, demonstrating the same behaviour throughout the route. In contrast, the values obtained with Rubicon show greater variations and smaller magnitudes along some sections, compared to those found using the AREA Method.

Figure 6. Comparison of the elastic modulus of the concrete subgrade according to calculation method.

Figure 7 compares the results obtained when calculating the modulus of subgrade E4 using the YONAPAVE Method with those calculated with Elmod and Rubicon. It can be seen that there is a relationship between the values obtained with Elmod and the AREA Method. The values obtained demonstrate similar behaviour in both cases. In contrast, the values obtained with Rubicon are lower than the others and almost constant throughout the project, with few and slight variations.
The residual deflection values were calculated as the y-intercept for the linear regression line in a graph of deflection vs. load. Figure 8 shows the graph of residual deflections to detect voids for KP 148, calculated using Elmod.

The residual deflection values are plotted for the entire project (see figure 9). The red line indicates the limit of 50 mm$^3$. According to this, there are a large number of sections in which there are indications of the presence of voids under the slab.

**Figure 7.** Comparison of the elastic modulus of concrete subgrade E4 for each calculation method used.

**Figure 8.** Graph of residual deflections for detecting voids using Elmod, KP 148.

**Figure 9.** Graph of residual deflections for the project.

5. **Discussion of results**

The Elmod and Rubicon results differ with regard to the elastic moduli. In the case of Elmod, an iterative method based on the seed moduli entered is used, with the iterations ending when the
maximum permissible error is reached. In the case of Rubicon, a database search method is used, whose result is also limited by the seed moduli and restricted by the maximum number of iterations permitted by the program (50 iterations).

When the results from the Elmod and Rubicon Toolbox programs were compared with analytical methods for estimating the elastic modulus of the concrete slab and the subgrade, Elmod came closer in both cases. The Rubicon results were less similar to those of the analytical methods and it is likely that the limited number of iterations may have affected these results.

The deflections obtained by the FWD were highly varied, indicating low capacity and/or the presence of damage. When the elastic moduli of the concrete slab and subgrade were back-calculated, abnormal values were found. This fact can be attributed to three main factors: the presence of voids, warping of the slab due to thermal gradient, and damage (primarily in the form of cracks).

It is reasonable to infer that the estimated values of the moduli are affected by the condition of the surface, producing lower values where the deflections are higher or close to the areas with more severe damage. Consequently, the low moduli imply damaged areas which warrant special attention in maintenance programmes. In the case of the data analysed, it is possible that the majority may be affected by the surface degradation of the slabs, based on the visual inspection performed using photographic records.

6. Conclusions
Non-destructive tests on pavements offer advantages over traditional methods. These include greater speed and ease in performing them, cost savings and fewer requirements, and an increase in the amount of data obtained, with the possibility of evaluating the project as a whole and making fewer changes in the infrastructure. Such tests make it possible to identify structural deficiencies before these manifest in the form of damage.

This research has compared the results obtained by analytical methods and calculation programs in order to estimate the elastic modulus of the concrete slab and the subgrade based on the deflections obtained. The following specific conclusions are noteworthy:

- The Elmod program came closest in calculating the elastic moduli.
- The results of the Rubicon program were less similar to those of the analytical methods, with these differences being primarily attributed to the limited number of iterations allowed by this program.

The deflections obtained in the FWD tests must be carefully analysed, as these may be affected by a range of factors and alter the results. The person performing the analysis must be knowledgeable about the typical values of each material in order to make reasonable suppositions and use their judgment in the back-calculation process.

When tests are performed using the FWD, under ideal conditions, the slabs to be tested would not have any cracks. Additionally, it is advisable refrain from performing the tests in the middle of the day in order to avoid warping due to thermal gradient.

It was determined that in areas with very limited layer thicknesses, the back-calculation of the elastic moduli is affected. Estimating the moduli for layers of pavement less than five centimetres thick is a common difficulty in back-calculation.

The loss of support from the soil under rigid pavements associated with voids entails an increase in stresses and deflections, causing a significant reduction in pavement life and contributing to its premature breakage. Any maintenance programme for rigid pavements must include measuring deflections for the purpose of detecting early voids and planning injections, saving on later rehabilitation and reconstruction costs.
7. References

[1] Solminihac H 2001 Gestión de infraestructura vial (Chile: Pontificia Universidad Católica)

[2] Washington State Department of Transportation 2004 Application of HDM-4 in the WSDOT highway system (Washington: Washington State Department of Transportation)

[3] Higuera C 2009 Caracterización de la resistencia de la subrasante con la información del deflectómetro de impacto Revista Facultad de Ingeniería UPTC 19

[4] Smith K, Harrington D, Pierce L, Ram P and Smith K 2014 Concrete Pavement Preservation Guide (USA: National Concrete Pavement Technology Center)

[5] Hoffman MS and Thompson MR 1981 Mechanistic Interpretation of Nondestructive Pavement Testing Deflections (Illinois: University of Illinois at Urbana-Champaign)

[6] Noriega MH 2011 Relación entre el módulo resiliente hallado por retrocálculo y el encontrado en ensayos de laboratorio (PhD dissertation, Universidad Nacional de Colombia)

[7] American Association of State Highway and Transportation Officials (AASHTO) 1993 Guide for Design of Pavement Structures (United States: AASHTO)

[8] ASTM International 2015 ASTM D5858 – 96. Standard Guide for Calculating In Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory (ASTM International)

[9] Tarefder R and Ahmed M 2013 Consistency and accuracy of selected FWD back calculation software for computing layer modulus of airport pavements Int. J. Geotech. Eng. 7 21–35