Deflection Comparative Study on Subgrades between Falling Weight Deflectometer and Dynamic Load Plate

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ABSTRACT: Falling Weight Deflectometer (FWD) and Dynamic Load Plate (DLP) are two survey systems very similar in their concept. In both devices there is a load which falls from a certain height on a plate which is in contact with the ground. The deflection is measured by a sensor placed on the load point. The impact tries to reproduce the passing of a standard axis loaded truck, but in a dynamic and not static way, which is how loads are actually produced on roads. There are variations both in the load and the plate. Also, the FWD has additional sensors, which makes it possible to supply the necessary data to carry out back calculations. However, in the case of subgrades evaluation, the value that is used is the maximum deflection, thus the presence of more sensors does not improve the data acquisition when it comes to the evaluation of subgrades. There is another traditional test included in the Standards to evaluate subgrades which is based on a static load plate. There are several studies trying to establish a correlation between static and dynamic load plate tests. Nevertheless, the fact that there are different types of load (static and dynamic) makes it quite difficult. With regard to this, there are also studies that advise against the use of the static load plate test to evaluate subgrades. In this paper the comparison between these two systems using dynamic loads (FWD and DLP) is analyzed. The maximum deflection comparison has been sought in more than 1500 tests, performed by both devices at the same point and with equal moisture conditions. This number of tests has to be more than enough to find a correlation between the two tests.

KEY WORDS: Falling Weight Deflectometer (FWD), Dynamic Load Plate or Dynaplaque (DLP), maximum deflection, correlation, subgrade.

1. INTRODUCTION

The aim of the study is to establish a comparison between two of the most broadly used high-performance devices nowadays for the control of compacted materials. The values obtained through the sensor's deflection located on the center of the Dynamic Load Plate (DLP) comparing them with the ones obtained in the tests with Falling Weight Deflectometer (FWD) are analyzed in order to check whether there is a reliable correlation between both survey devices or not, and assess which factors can be essential for said relationship. To do so, we need to perform enough tests so as to enable the correlation to be representative.

In order to carry out this study, a high number of tests have been performed in Spain on the same day and same place with DLP and FWD. In fact, more than 1500 tests have been performed. Among them, 2/3 parts of the tests performed with FWD have been carried out with the 150 mm radius plate, and the rest with the 225 mm one. Regarding the applied load, approximately half of the tests were carried out by using 6.5 t (63.77 kN), and the other half by using 5.0 t (49.05 kN).

Moreover, in Mexico 173 tests have been performed with the same characteristics, but using only DLP and the FWD with a plate of a radius equal to 150 mm.

2. CONTROL OF COMPACTED MATERIALS. CURRENT SITUATION

Nowadays, the trends regarding construction works of the main infrastructure sites are focused on checking the real behavior of the work units being executed, regardless of the building process used, materials, etc. The aim of this is to know the characteristics of the finished product, thus being able to compare them with those assumed from the theoretical calculation processes. We seek to ensure the correct behavior of the entire infrastructure.

When accepting a subgrade, it is necessary to guarantee it fulfills these characteristics: enough bearing capacity and homogeneous behavior. Therefore, it is essential to have test control systems that enable to:

- Determine the compressibility moduli and/or the deflections and strains produced by the action of a load in a detailed way.
- Perform a high number of tests (homogeneity analysis).
- Evaluate the complex areas (for instance, cut-embankment transition zones).

The current Spanish regulations for the control of compacted materials and pavement subgrades establish in general terms the following tests:

- Humidity and density (NLT-109, 1987, ASTM D 1556, 2007, DIN 18125-1, 2010).
- Load plate test: compressibility modulus of the second load cycle (E_{v2}) and the relationship among moduli (k) (NLT-357, 1998, DIN 18134, 1990).
- Possibility to perform complementary tests (e.g. footprint test) (NLT-256, 1999, SNV 670365, 1972).
- In some standards the use of new control procedures based on high-performance tests has been already added (MTLT, 1997, SETRA, 1998, ADAR, 2004).

Therefore, the execution of the different layers that make up a pavement subgrade needs to be subject to the verification of their on-site conditions, which is called control tests. Once their construction is finished, it is necessary to perform acceptance tests on them, which aim to verify if the sought-after result has been obtained through the combination of those layers with the on-site conditions carried out.

The traditional control systems usually used show some limitations that make it difficult to perform a large number of tests, which prevents from an adequate control, especially regarding the homogeneity. Load plate tests require auxiliary resources, involve interruptions and delays affecting the works, and their performance (number of tests per day) is very reduced, which leads to an insufficient knowledge of the subgrade.

Moreover, different recent experiences with traditional load plate tests make it clear that there are some difficulties when assessing whether the compacting obtained with that test is the right one or not. In terms of this test, the current regulations establish:

- Demand of a minimum reload modulus value (E_{v2})
- Demand of a maximum k value; $k = E_{v2} / E_{v1}$ (E_{v1} is the initial modulus).

Presumably, a poorly compacted material has a low E_{v1} that increases during the reloading, which implies a high k. However, there are many tests that prove that the static load plate shows high E_{v2} values in many sections with poor compacted materials (Santiago et al., 2009). What is more, it is common to encounter well compacted soils with acceptable humidity and density control values and with a relationship between moduli during the static load plate test (k) higher than 3.

In addition to that, following the applying regulations, the verification of the subgrade characteristics must be performed with a frequency that implies the execution of a large number of tests. This makes it necessary to use high-performance devices. The objective is to have control systems that allow to carry out an exhaustive control, increasing the tests frequency, reducing the time of test execution, guaranteeing their repetitiveness and consistency and evaluating the compacted material response against dynamic loads.

3. MEASURING SYSTEMS USED

The systems used in this comparative study are Falling Weight Deflectometer -FWD- (ASTM D4694, 2009, NLT-338, 2007, Cost 336, 1999) and Dynamic Load Plate or Dynaplaque -DLP- (UNE 103807-1, 2005, NF P117-2, 2004). Both of them are high-performance devices using dynamic loads, which is how loads are actually produced on roads.

In the Standards there is another traditional test to evaluate subgrades which is based on a static load plate (NLT-357, 1998, DIN 18134, 1990). There are several studies trying to establish correlations between static and dynamic load plate tests (Chassaing, 1995), but usually these correlations refer to a certain type of materials under very specific conditions (Benatov et al., 2011, Ramos and Sánchez, 2011, De Hita and Sánchez, 2004, Sánchez and Ramos, 2005 and 2007). The fact that there are different types of load (static and dynamic) makes it quite difficult. Besides, there are different tests that prove that the static load plate is not the best test to evaluate compacted materials (Santiago et al., 2009).

Although broadly known, below there is a brief description of the general characteristics of both devices used in this research. If there are two survey devices that share a very alike concept, they are the FWD and the DLP. On both systems, the load falls from a certain height on a plate which is in contact with the ground. The deflection is measured by a sensor located at the load point. The impact tries to reproduce the passing of a standard axis loaded truck in a dynamic –and not static– way.

There are variations between both systems, regarding the load with which the impact is produced, and the diameter of the plate. In the case of the DLP, the mass weights around 120 kg when falling from a height of 500-700 mm, while the FWD makes it possible to choose among different loads and heights in order to generate the desired impact.

The plate’s diameters being transmitted to the ground by the load are also different. In the case of the DLP, the diameter is 600 mm, whereas with the FWD we can use two different plates, 300 and 450 mm in diameter respectively. With respect to the granular layers, usually wider diameter plates are used so that the stress provided to the granular layers is similar to the one produced by the passing of heavy vehicles. However, there are standards that require the use of a 300 mm plate for the FWD during the validation tests of granular layers.

The FWD also owns additional sensors that allow for it to obtain the necessary data to perform inverse calculations, which is very interesting in the case of in-service pavements. Nevertheless, with regard to the subgrades validation, the value usually used in the tests performed with FWD is the maximum deflection. Therefore, the presence of more sensors does not improve the decision making with reference to the validation of said subgrades.

The DLP not only facilitates the maximum deflections obtained during the load cycles, but also provides a dynamic strain modulus of all the underlying layers being affected by the load that is produced during the test.

4. THEORETICAL STUDY

4.1. Elasticity Theory. Semi-Infinite Space

First of all, a theoretical study has been carried out in order to know what could be the relationship between the deflections obtained by the DLP and the ones obtained by the FWD. The value of the elasticity modulus of a semi-infinite space shall be identified following the Elasticity Theory (Boussinesq, 1885), by the equation (1).

$$Es(0) = f \cdot (1- \mu^2) \cdot a \cdot q(0) / d(0) \quad (1)$$

Theoretically, the moduli obtained by both systems should be equal (equation (2)). For this reason equation (3) establishes the relationship between DLP and FWD deflections.

$$a_p \cdot q(0)_p / d(0)_p = a_d \cdot q(0)_d / d(0)_d \quad (2)$$

$$d(0)_d = a_d \cdot q(0)_d \cdot d(0)_p / [a_p \cdot q(0)_p] \quad (3)$$

Given the fact the data usually provided is N(0) and not q(0), equation (3) would have to be changed, based on equations (4) and (5). Equation (6) shows the obtained relationship.

$$N(0) = q(0) \cdot \pi \cdot a^2 \quad (4)$$

$$q(0) = N(0) / \pi \cdot a^2 \quad (5)$$

$$d(0)_d = a_p \cdot N(0)_d \cdot d(0)_p / [a_d \cdot N(0)_p] \quad (6)$$

Since the load would have to be equal, the simplified equation would be the following (equations (7) and (8)). If the load is different, equation (9) would be obtained.

$$d(0)_d = a_p \cdot d(0)_p / a_d \quad (7)$$

$$d(0)_p / d(0)_d = a(0)_d / a(0)_p \quad (8)$$

$$d(0)_p / d(0)_d = [N(0)_d \cdot a(0)_p] / [N(0)_p \cdot a(0)_d] \quad (9)$$

Considering that the plate radius of the DLP is equal to 300 mm, whereas the FWD one can be 150 or 225 mm, the relationships shown below are obtained.

$$d(0)_p / d(0)_{d150} = 0.50$$

$$d(0)_p / d(0)_{d225} = 0.75$$

where:

$Es(0)$	Modulus of a semi-infinite space
f	Distribution coefficient of the applied stress
μ	Poisson coefficient
a	Radius of the used plate
a_p	Radius of the plate used in the DLP
a_d	Radius of the plate used in the FWD
$q(0)$	Applied stress
$q(0)_p$	Applied stress by the DLP
$q(0)_d$	Applied stress by the FWD
$d(0)$	Deflection on the center of the plate
$d(0)_p$	Deflection on the center of the DLP plate
$d(0)_d$	Deflection on the center of the FWD plate
$d(0)_{d150}$	Deflection on the center of the FWD plate (150 mm radius)
$d(0)_{d225}$	Deflection on the center of the FWD plate (225 mm radius)
$N(0)$	Applied load
$N(0)_p$	Applied load by the DLP
$N(0)_d$	Applied load by the FWD

4.2. Multilayer System

The Elasticity Theory considers that materials have an elastic, linear, homogeneous and isotropic performance. the multilayer theory was developed following such hypothesis, (Burmister, 1943). This theory allows to simulate a pavement structure as a multilayer system, composed of several materials over a Boussinesq semi-infinite space.

The relationships that are obtained when simulating the tests by means of a multilayer model are also analyzed. The calculations have been carried out by using the hypothesis of two different semi-infinite spaces, one of a 900 kg/cm^2 (88.29 MPa) resilient modulus and another one of 1800 kg/cm^2 (176.58 MPa), with the same Poisson coefficient (0.4). Table 1 includes the obtained deflections. In both cases (150 and 225 mm FWD plate radius) the theoretical relationships of the previously obtained 0.50 and 0.75 are confirmed.

Table 1. Obtained theoretical deflections

Es(0) (MPa)	$d(0)_{d150}$ (mm)	$d(0)_{d225}$ (mm)	$d(0)_p$ (mm)
88.29	2.58	1.72	1.29
176.58	1.29	0.86	0.65

When we put this into practice, a problem arises. The ground being tested is not homogeneous from the surface to several meters down. On the contrary, its features usually change. The difference on the plate radius used in these tests makes the affected ground's thickness to be different, thus, there can be variations on the obtained theoretical correlations.

The results obtained by using the multilayer model are also analyzed. In this case, it is assumed a subgrade in which the first 600 mm have the previously used modulus, with a different modulus for the semi-infinite space. As an example, the study is carried out with elasticity moduli that result from multiplying the upper modulus by 0.75 and 0.50 respectively. That is, in the case of 88.29 MPa, 66.22 and 44.15 MPa are used as semi-infinite space moduli. Table 2 shows the results obtained in this case.

Table 2. Theoretical deflections obtained in a bilayer system (E_{sup} = 88.29 MPa)

E_{inf} (MPa)	$d(0)_{d150}$ (mm)	$d(0)_{d225}$ (mm)	$d(0)_p$ (mm)
66.22	2.71	1.85	1.42
44.15	2.97	2.10	1.67

where:

E_{sup} Elasticity modulus of the upper layer
E_{inf} Elasticity modulus of the below layer (semi-infinite space)

The calculated results show that the deflection obtained by the FWD using a 150 mm radius plate changes from 2.58 mm (Table 1) to 2.71 and 2.97 mm deflections (Table 2) for this model with worse underlying layers. Likewise, in the case of FWD using a 225 mm radius plate it changes from 1.72 mm to 1.85 and 2.10 mm deflections respectively for the bilayer model. Also, in the case of DLP, it changes from 1.29 mm to 1.42 and 1.67 mm deflections respectively.

An interesting point is whether the relationships obtained for a semi-infinite space are kept when varying the condition of the underlying ground. Table 3 shows that such relationships are not the same as the ones assumed in the case of a semi-infinite space (one-layer model).

Table 3. Relationships between theoretical deflections obtained during the multilayer analysis

	One-layer	Bilayer (E_{sup} = 88.29 MPa)	
	Es (0) = 88.29 MPa	E_{inf} = 66.22 MPa	E_{inf} = 44.15 MPa
$d(0)_{d150}$ (mm)	2.58	2.71	2.97
$d(0)_{d225}$ (mm)	1.72	1.85	2.10
$d(0)_{p}$ (mm)	1.29	1.42	1.67
	Es (0) = 88.29 MPa	E_{inf} = 66.22 MPa	E_{inf} = 44.15 MPa
$d(0)_{d225}$ / $d(0)_{d150}$	0.67	0.68	0.71
$d(0)_{P}$ / $d(0)_{d150}$	0.50	0.52	0.56
$d(0)_{P}$ / $d(0)_{d225}$	0.75	0.77	0.80

Table 4. Relationships between theoretical deflections obtained during the multilayer analysis

	One-layer	Bilayer (E_{sup} = 176.58 MPa)
	Es (0) = 176.58 MPa	E_{inf} = 44.15 MPa
$d(0)_{d150}$ (mm)	1.29	1.48
$d(0)_{d225}$ (mm)	0.86	1.05
$d(0)_{p}$ (mm)	0.65	0.83
	Es (0) = 176.58 MPa	E_{inf} = 44.15 MPa
$d(0)_{d225}$ / $d(0)_{d150}$	0.67	0.71
$d(0)_{P}$ / $d(0)_{d150}$	0.50	0.56
$d(0)_{P}$ / $d(0)_{d225}$	0.75	0.80

Additionally, it is studied whether these variations are equally obtained for the case of E_{sup} = 176.58 MPa or -on the contrary- are different. Specifically, this is tried with the hypothesis of E_{inf} equal to 50% of E_{sup}, in order to check if they match the ones obtained.

The calculated deflections and the obtained results are summarized in table 4. As it can be seen, the relationships among the three systems are exactly the same as the ones found in the case of 88.29 MPa.

4.3. Non-linear Models

Different authors establish that the resilient modulus of the granular layers depends on the stress the granular layer has on the considered area. Two types of non-linearity are normally considered in North American literature, one for granular materials and another one for cohesive materials (Ullidtz, 1998).

Dynamic deflection testing (FWD or a similar device) often shows a variation of deflections with a distance that could be due to a non-linearity. Equation (10) is proposed (Ullidtz, 1987).

$$E = C \cdot (\sigma_1/p)^n \qquad (10)$$

where:

E	Resilient modulus
σ_1	Mayor principle stress from the external loading
p	Reference stress
C, n	Constants

σ_1 is the mayor principle stress from the external loading excluding any static stresses due to the weight of the material, p is the reference stress, often taken equal to 1 kg/cm^2 (0.0981 MPa), and C and n are constants. The n value usually varies from 0 to -0.5. A mean value (-0.3) is adopted and then it is observed how this affects the theoretical results previously obtained. Equation (10) will take the simplified form (Equation (11)).

$$E = C\cdot(\sigma_1)^{-0.3} \quad (11)$$

The C value will not have any effect on the study since what is going to be established is a comparative study between the different cases.

The values of the modulus for the different systems are obtained in the following way:

FWD (plate radius: 150 mm)	C·0.51
FWD (plate radius: 225 mm)	C·0.66
DLP (plate radius: 300 mm)	C·0.78

If the moduli are considered equal to the response of the ground under the applied loads produced during the test, the previously deducted theoretical relationships must be corrected by this factor. Therefore, in short the following would be the available relationships:

$$d(0)_p / d(0)_{d150} = 0.50\cdot(0.78/0.51) = 0.76$$

$$d(0)_p / d(0)_{d225} = 0.75\cdot(0.78/0.66) = 0.88$$

In case the granular layer worked with the -0.5 n value, which is the range indicated limit, the values would be:

$$d(0)_p / d(0)_{d150} = 0.50\cdot(0.66/0.33) = 1.00$$

$$d(0)_p / d(0)_{d225} = 0.75\cdot(0.66/0.49) = 1.01$$

5. EXPERIMENTAL STUDY

In a first study conducted in Spain in the province of Badajoz, 1382 comparative tests were performed at the same place (each FWD test point was separated no more than 3 m from the DLP test point in order to ensure the same subgrade structure) and on the same day (to ensure identical test conditions on each test point, removing any effects from other factors, e.g. subgrade moisture), using the FWD with the 300 mm diameter plate as well as the DLP. Another 236 comparative tests were also performed, again at the same place and on the same day, using the FWD with the 450 mm diameter plate, as well as the DLP.

In the process of the DLP test three deflections are obtained, corresponding to each of the three load cycles to be applied. The first study that needed to be carried out was to check which of the three matched better with the deflection obtained by the FWD. Results show that the best correlation is obtained for the third deflection, with lower deviation values and coefficient of variation. Focusing only on working with this third deflection, the results obtained are the ones shown in tables 5 and 6.

An average value of 0.971 and a coefficient of variation of 0.128 have been obtained in the case of the third deflection of the DLP, and the deflection of the FWD with a 150 mm radius plate. This shows that there is a strong correlation between said values. When performing the tests with the 225 mm radius plate on the FWD, the obtained correlation is 1.235 with a coefficient of variation of 0.138.

At a later stage, a campaign of 173 tests was carried out in Jalisco State, Mexico. In this campaign the DLP and the FWD with a 150 mm radius plate were used. Four sections were tested during this last campaign. However, as opposed to the first one where the characteristics of all the sections were very homogeneous, on this second campaign the sections showed slight differences among them. Table 7 shows the statistical summaries of said tests, grouped by tests sections. All the same, the obtained results produced an average correlation of 0.854 and a coefficient of variation of 0.174.

Table 5. Statistical summary $d(0)_P$ / $d(0)_{d150}$

Section	Number of tests	Average (m)	Coef. of variation (s/m)
1	96	1.00	0.14
2	232	0.92	0.13
3	226	0.92	0.12
4	150	0.94	0.15
6	116	1.03	0.12
7	156	0.98	0.15
8	132	1.04	0.11
9	120	0.98	0.11
10	60	1.01	0.12
11	10	0.99	0.12
12	24	0.94	0.13
13	24	1.07	0.11
14	24	1.04	0.11
15	12	1.10	0.12
Weighted average and c. of variation		0.971	0.128

Table 6. Statistical summary $d(0)_P$ / $d(0)_{d225}$

Section	Number of tests	Average (m)	Coef. of variation (s/m)
1	20	1.15	0.08
2	24	1.26	0.19
3	24	1.25	0.26
4	24	1.30	0.16
5	12	1.30	0.14
6	20	1.19	0.10
7	24	1.12	0.13
8	12	1.22	0.08
9	12	1.26	0.14
10	6	1.31	0.24
13	24	1.24	0.09
14	24	1.26	0.10
15	10	1.32	0.10
Weighted average and c. of variation		1.235	0.138

Table 7. Statistical summary. Relationships $d(0)_P$ / $d(0)_{d150}$

Section	Number of tests	Average (m)	Coef. of variation (s/m)
1	52	0.87	0.14
2	55	0.88	0.21
3	40	0.84	0.18
4	26	0.78	0.12
Weighted average and c. of variation		0.854	0.174

6. SUMMARY OF THE STUDY AND CONCLUSIONS

The following conclusions have been drawn from the performed study:

- Both the FWD and the DLP, two of the most used high-performance devices in the control of compacted materials, are systems based on the same principle, so that the deflections obtained by both devices should have a very good correlation. On this matter, the conducted study corroborates that there is in fact a good correlation in the measurings performed by both control systems.
- The deflection obtained in the third cycle with the DLP is the best one correlating with those recorded by the FWD.
- The plate's diameter used for the application of the load -keeping a constant load- has an effect on both the stress that is induced on the ground, and the thickness affected by the load, which can cause variations during the comparative study.
- The different sensitivity that the modulus of the granular layer has against the applied stress -non-linear behavior- can also introduce variations when comparing the values.
- The results of the different performed theoretical studies show certain differences among them, mainly due to the hypothesis adopted in each case.
- The results of the experimental tests have great similarity with the ones obtained through the theoretical studies based on non-linear models. This clearly corroborates the non-linear behavior of the granular materials, according to what is pointed out by many authors.
- Given the necessary limitation of this study, we suggest to continue with this line of research, by carrying out new tests on different subgrades' structures that show different materials compositions. This should serve as a way to check the correlations and conclusions drawn in this research, as well as to keep developing the knowledge of the dynamic systems behavior and their application on granular layers.

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