Uncertainty evaluation of deflection measurements from FWD tests on road pavements

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Abstract

The Falling Weight Deflectometer (FWD) is one of the most important non-destructive tests (NDT) used for field evaluation of pavement structural behaviour based on deflections survey. The paper aims to present the uncertainty evaluation of FWD deflections measurements based on a proficiency test scheme. This testing program has involved three devices from different manufacturers. The tests were performed in two full-scale pavement sections: asphalt pavement (flexible) and concrete pavement (rigid). The paper presents the methodology used in the testing protocol. Test results analysis has assessed the precision of deflections related to the repeatability and reproducibility of measurements. The experimental study confirmed a reasonable repeatability of the individual devices but it was observed a low reproducibility. Based on the precision analysis, the paper presents the uncertainty obtained from the FWD tests as a function of the deflection magnitude and the pavement structure stiffness.

Key words: non-destructive test, FWD, pavement, deflection survey, precision, uncertainty

1 INTRODUCTION

Road pavements are an important asset that should be maintain in adequate serviceability conditions in terms of surface and structural characteristics, and in accordance to the traffic exigencies (safety, comfort and loads) during life time. Non-destructive tests (NDT) are survey methods available to assess in a rapid and convenient manner the functional (texture, smoothness, friction) and structural (deflection) pavements condition. Pavement structural response is related to the bearing capacity and its evaluation is based on deflections testing. This is the principle of load NDT that is essential to achieve a mechanistic approach of the existing pavement structure for rehabilitation by backcalculation analysis of test results.

The Falling Weight Deflectometer (FWD) is the most widely used NDT device for pavement deflection testing (Fontul, 2004), although recent advances are in progress related to the development and implementation of a new generation of deflectometers, designated by Rolling Wheel Deflectometers (RWD) (Wilke, 2014). FWD consists of an impulse-loading device that measures the pavement's response to a load and the resulting surface curvature under that load. The usually machines are contained within a trailer to be towed by another vehicle, but other test apparatus are mounted inside a vehicle (mini van or truck). Other models of FWD are also available: the Light Weight Deflectometer (LWD), a portable model most commonly to test in situ pavement and subgrade layers during construction; the Heavy Weight Deflectometer (HWD) that it is a model adequate to apply higher loads in airfields.

The surface deflection measurements can have three main sources of error (Irwin, 2002):

(1) seating errors related to each time the device deploys to measure deflections. These errors are influenced by loose debris or irregularities from pavement surface and can be eliminated by performing sequential drops to guarantee the seating of the sensor;
(2) random errors derived from the signal conversion of the sensor. Averaging the measurement results can reduce these errors;
(3) systematic errors (bias) associated to sensor calibration.

Rocha et al. (2014) present a literature review on the accuracy and precision of FWD. Various FWD are commercially available and according to several authors each device presents a reasonable repeatability but, in general, it is reported a poor reproducibility amongst different devices. The main uncertainty sources of FWD deflections measurements most commonly reported in the literature are buffers and pavement stiffness. The shape, size, age and stiffness of rubber buffers impact the peak load, the rise time and the load pulse shape, and in consequence the magnitude of the deflections (Chen et al., 1999; Lukanen, 1992). The impact of buffers characteristics on deflections also depends on the pavement structure and it is particularly important in the case of weaker pavements (Chen et al., 1999).

ASTM D4694 and ASTM D4695 are standard documents related to deflection measurements by the FWD. These documents refer that precision is a function of both the characteristics of the pavement and the device used but any value is proposed related to repeatability or reproducibility. However, several studies were already performed with different devices to obtain FWD precision (Van Gurp, 1991; Choubane et al., 2006; Bentsen et al., 1989; Rocha et al., 2001 and 2014). Nevertheless, more studies are needed in order to improve the knowledge about FWD precision and the uncertainty evaluation is still a gap of the literature.

The paper presents uncertainty evaluation of deflections measurements based on the repeatability and reproducibility obtained in a proficiency test scheme (PTS) involving three different FWD devices. Series of tests were carried out on asphalt (flexible) and concrete (rigid) pavements following the requirements from ISO/IEC 17043. Statistical analysis of repeatability and reproducibility related to FWD measurements was based on the methodology proposed by ISO 5725-2.

2 METHODOLOGY

2.1 EQUIPMENT

The evaluation of FWD precision was based on a PTS organized according to the ISO/IEC 17043. In December 2016, three laboratories have participated in the experimental series of FWD tests with the following devices:

- Carl Bro PRI 2100 FWD trailer (Figure 1a).
- KUAB 240 HWD trailer (Figure 1b).
- Dynatest 8002 FWD trailer (Figure 1c).

a) Carl Bro PRI 2100

b) KUAB 240

c) Dynatest 8002

Fig. 1 FWD equipment

Table 1 presents the main specifications of the equipment used in the experimental work, concerning the load (load range, load pulse time and diameter of load plate) and the sensors (type, deflection range and relative accuracy) characteristics. The load cells and sensors of the equipment were all calibrated at least a year ago.

Table 1 Main specifications of the FWD equipment

Manufacturer	Carl Bro	KUAB	Dynatest
Model	Carl Bro PRI 2100	KUAB 240	Dynatest 8002
Year of acquisition	(*)	2004	2002
Load range [kN]	7–250	30–240	7–120
Load pulse time [milliseconds]	20–30	30	20–30
Diameter of load plate [cm]	30 and 45	30 and 45	30 and 45
Type of deflection sensors	Seismometers	Geophones	Geophones
Deflection sensor range [μm]	2.2	(*)	(*)
Relative accuracy of deflection sensors	1 μm ± 2 %	(*)	2 μm ± 2 %

(*) Not available.

2.2 TESTING PROCEDURE

FWD tests were performed according the method described in ASTM D4694 and ASTM D4695. In general, FWD operates by applying a dynamic load on the pavement, generated by the vertical movement of a weight dropping along a guide system on a buffer, which is transmitted through a circular plate resting on the pavement surface. The resulting deflections on the pavement surface are measured using suitable instrumentation devices that use geophones or seismometers rested on the surface of the loaded pavement. The Figure 2 shows this scheme of FWD functioning adapted to the case of Dynatest 8002 FWD trailer (Figure 1c), similar to the equipment from others manufacturers.

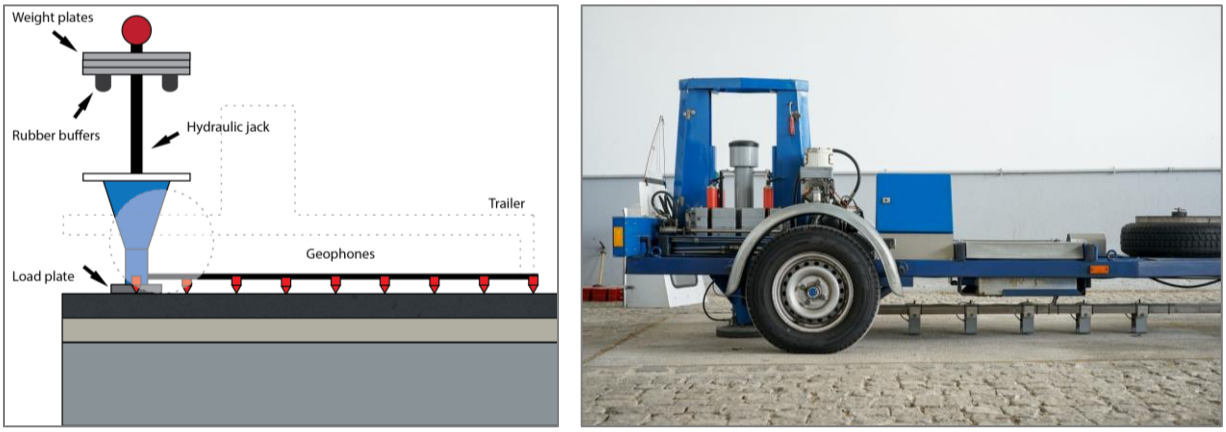


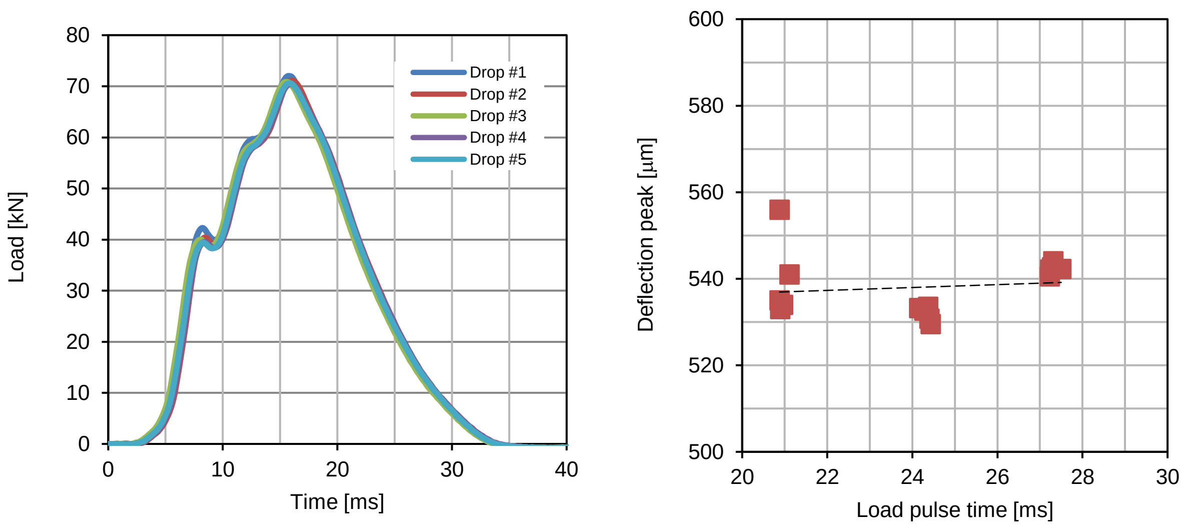
Fig. 2 Scheme of the FWD functioning

The deflections were measured by sensors in 8 points located at different distances from the load (including the centre of the load plate): 0, 30, 45, 60, 90, 120, 150, and 180 cm. The number of available sensors depends on the manufacturer and equipment model, and most equipment allows for the sensors to be repositioned as intended. As a result, the sensor spacing will depend on the number of available sensors and the length of the sensor bar. However, all the three devices have used the same sensors configuration. Peak of deflection at each location resulting from the force pulse was recorded in micrometres [µm] by two types of deflection transducers (see Table 1): seismic velocity transducer (geophones) and seismic displacement transducers (seismometers). The set of deflections measured in a testing point by all the sensors represents a deflection basin.

Five loading sequences were always performed and deflection average of last three ones was calculated, to minimize seating and random errors of deflection results. The load pulse of the dynamic load, measured by a load cell, was approximated to the shape of a half-sine wave (Figure 3a) and the load pulse time was the length of time between an initial rise until the load dissipates to near zero. The pulse duration was in the range of 20 to 30 milliseconds. In the case of Carl Bro PRI 2100, the load pulse time was controlled depending on buffer stiffness, drop and weights of the force-generating device and load plate diameter. The Figure 3b shows that in this case the load pulse time had not a clear impact on the deflection peak. The load peak was controlled in each device in order to obtain 65 and 90 kN.

Table 2 presents a summary of the main characteristics of protocol tests during PTS, concerning load peak, deflections sensors distance and load plate diameter. The series of tests were performed in two sites following the requirements of ISO/IEC 17043 (Table 3):

- Site 1 was a flexible pavement composed by asphalt concrete AC14 in the surface layer (5 cm), unbound granular material in the sub-base (20 cm) and a soil-cement and sandy soil in the subgrade (30 cm).
- Site 2 was a rigid pavement composed by concrete slabs (20 cm). This pavement was constructed on an existing pavement composed by paving stones (12 cm) and a subgrade of soil-cement and sandy soil.



a) Load pulse *b) Deflection*

Fig. 3 Sensitivity analysis to the load pulse time

Table 2 Protocol tests

Site	Load peak [kN]	Deflection sensors distance [cm]	Load plate diameter [cm]
1	65, 90	0, 30, 45, 60, 90, 120, 150, 180	30
2	90		

Table 3 Characteristics of experimental sites

Site	Pavement	Layer	Material	Thickness [cm]
1	Flexible	Surface	Asphalt concrete	5
		Sub-base	UGM(1)	20
		Subgrade	Soil-cement	15
			Sandy soil	15
2	Rigid	Surface	Concrete slabs	20
		Sub-base	Paving stones	12
		Subgrade	Soil-cement	(2)
			Sandy soil	(2)

(1) Unbound granular material; (2) Unknown

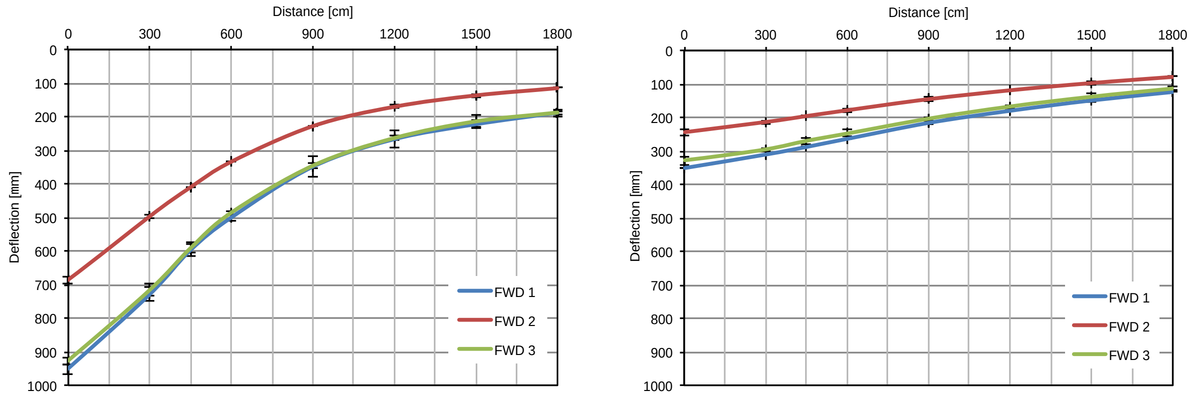
The ambient air temperature and pavement surface temperature were recorded always at the beginning of each test. In the case of pavement surface temperature, it was used an infrared thermometer. The sequence of tests was performed in order to minimize variations of the temperatures, mainly in the case of flexible pavement.

3 RESULTS AND DISCUSSION

3.1 REPEATABILITY AND REPRODUCIBILITY

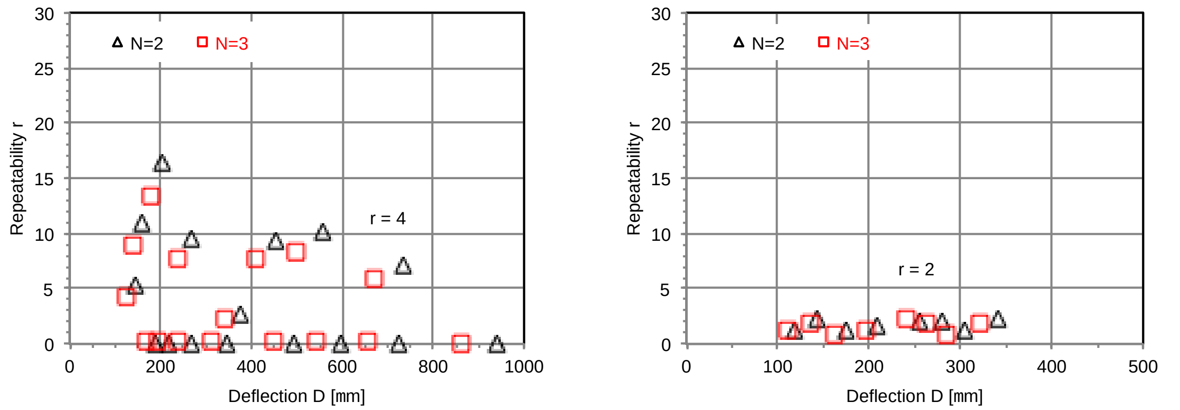
The precision of a test procedure is related to repeatability and reproducibility conditions of measurements. In general, repeatability includes the same measurement procedure and system, same operator and operating conditions and same location. In this case, repeatability was associated to the last three sequences of load tests. Reproducibility includes different locations, operators and measuring systems. In this case, reproducibility was related to the use of the three FWD devices. Prior to results analysis, the deflections were normalized to their appropriate nominal load levels, i.e., 65 kN and 90 kN (Table 2).

Regarding the last three sequences of load tests obtained by each FWD device, the average and standard deviation of deflections were calculated. In the case of the load peak of 90 kN, Figure 4 represents the average deflection basins obtained on the flexible pavement, Site 1 (Figure 4a), and the rigid pavement, Site 2 (Figure 4b) for the three FWD devices, designated by FWD 1, 2 and 3. In each sensor point it is represented the standard deviation of measured deflections. Taking into account the vertical scale of the graphics, the standard deviations are represented with an amplification of ten times because these values were in general very small. In general, it could be concluded that there was a tendency for one of the FWD devices – FWD 2 – obtain lower deflection values. Regarding this scattering, repeatability (r) and reproducibility (R) limits of deflections (95%) were estimated in accordance with ISO 5725-2 (Figure 5 and Figure 6 respectively) and considering two cases depending on the number of laboratories (N): all the three devices (N=3); and only the two devices FWD 1 and FWD 3 (N=2). From Figure 5 and Figure 6 it could be concluded that: (a) repeatability and reproducibility limits were a function of the deflection magnitude (D) and of the pavement stiffness; (b) a reasonable repeatability but a low reproducibility was observed due to FWD 2 device regarding the differences observed for both cases (N=3 and N=2); (c) and a general improved repeatability and reproducibility were achieved in the case of the rigid pavement.



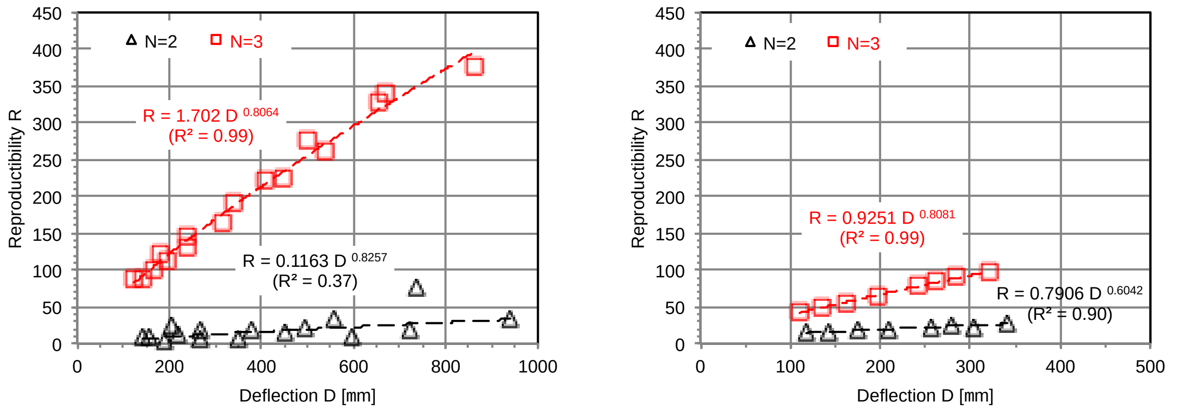
a) Flexible pavement *b) Rigid pavement*

Fig. 4 Deflection basins (90 kN)



a) Flexible pavement *b) Rigid pavement*

Fig. 5 Repeatability limits of the deflections



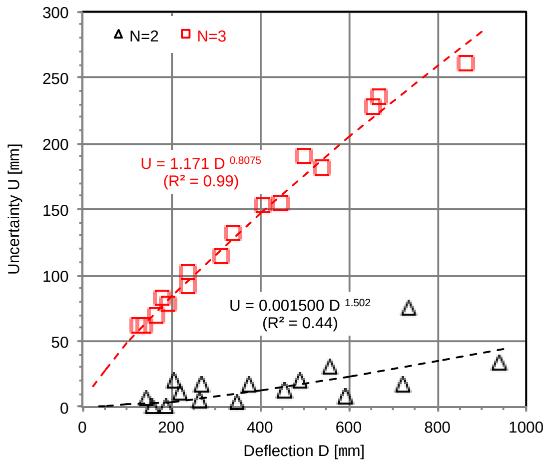
a) Flexible pavement *b) Rigid pavement*

Fig. 6 Reproducibility limits of the deflections

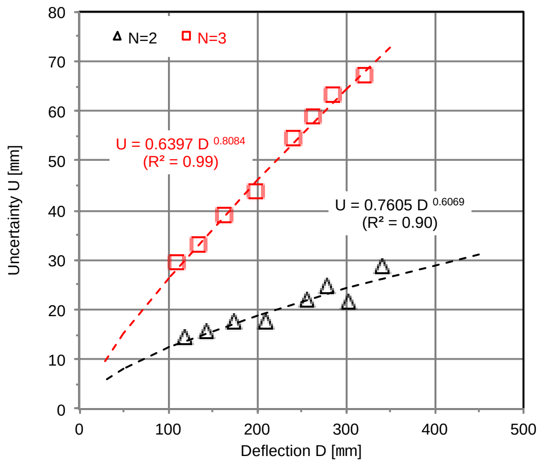
Figure 5 also shows that the repeatability was less dependent of the deflection magnitude (almost constant): r=4 (flexible pavement); r=2 (rigid pavement). In the case of the reproducibility (Figure 6), an exponential tendency was observed between the variables. As an example, if a deflection magnitude of D=300µm was measured and considering N=3, correspondent reproducibility would be: R=169 (flexible pavement); R=93 (rigid pavement).

3.2 UNCERTAINTY

Uncertainty of a measurement is the dispersion of the values that could be attributed to the measured parameter. The estimation of the uncertainty was based on the standard deviations of the repeatability and reproducibility. Figure 7 presents the uncertainty (*U*) in function of the deflection magnitude (D) for confidence level of 95%. In consequence of precision analysis, the uncertainty also depends on the pavement stiffness. As expected and according the precision results, the relative uncertainty was higher for the flexible pavement (Figure 7a) than to the rigid pavement (Figure 7b).



a) Flexible pavement



b) Rigid pavement

Fig. 7 Uncertainty of the deflection measurements

Considering the previous example for a deflection magnitude of *D*=300µm and a confidence level of 95% (N=3), the uncertainty would be ±117µm and ±64µm for flexible and rigid pavements respectively. These values correspond to a relative uncertainty of 39% and 21%.

4 CONCLUSIONS AND RECOMMENDATIONS

The FWD is the most widely used NDT device for pavement deflection testing. This test is essential to achieve a mechanistic approach of the existing pavement structure for rehabilitation by backcalculation analysis of test results. FWD consists on applying a dynamic load on the pavement surface through a circular plate, generated by a weight dropping on a buffer system, and the resulting pavement deflections are measured using suitable sensors rested on the pavement surface of the loaded area.

The main purpose of the paper is to present the uncertainty evaluation of deflection measurements obtained from FWD tests performed on road pavements according the procedure of ASTM D4694. Assessment of uncertainty was based on the repeatability and reproducibility obtained in a proficiency test scheme (PTS) involving three different FWD devices: Carl Bro PRI 2100, KUAB 240 and Dynatest 8002. A series of tests were carried out on flexible and rigid pavements following the procedures of ISO/IEC 17043. Statistical analysis of repeatability and reproducibility was based on ISO 5725-2. The paper describes the equipment and testing procedures of the experimental study.

From the analysis of results presented along the paper, the following main conclusions could be pointed out:

- The study confirmed that the deflection measurements had a reasonable repeatability but a low reproducibility, mainly due to one of the devices. A general improvement of precision was obtained in the case of the rigid pavement.
- Precision of deflections depended on the deflection magnitude and of the pavement stiffness (flexible or rigid). The paper proposes constant values and regressions models for limits (95%) of repeatability and reproducibility respectively.
- The estimation of the uncertainty was based on the standard deviations of the repeatability and reproducibility. The paper purposes regression models to the uncertainty estimation in function of the deflection magnitude and pavement stiffness (flexible or rigid) for confidence level 95%. As expected and according the precision analysis, the relative uncertainty obtained in the experimental study was lower for the case of rigid pavement.

Some recommendations could be important for further studies:

- Precision and uncertainty should be confirmed on PTS involving a large number of equipment and also other pavement structures.
- Load pulse time is one of the main uncertainty sources of FWD tests. So, a recommendation is given in the sense of a further analysis of the influence of the buffer system stiffness on the load duration and, consequently, on the peak deflection.
- A very satisfactory precision of load peak was observed. However, it could be important the analysis of the influence of this parameter.
- A complementary study to evaluate the influence of the uncertainty of deflections measurements on the backanalysis of mechanical properties of the pavement is also recommended.

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