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**Applications for the ZFG 2000 Light-Weight Deflectometer
in Road Construction and Earthworking**

In earthworking, the dynamic plate load test using the Light-Weight Deflectometer according to TP BF-StB, Part B 8.3 [1] may be used for testing load-bearing capacity as an alternative to the static plate load test according to *DIN 18134*.

As this test procedure requires little effort, can easily be carried out by a single person and permits testing even in narrow conditions, it is widely employed in Germany both in earthworking, e.g. for backfilling in accordance with *ZTVE-StB* (Additional technical specifications and guidelines for earthworks in road construction) and, most importantly, in excavation work according to *TZVA-StB* (Additional technical specifications and guidelines for excavation in road traffic areas) (see Figures 1 and 2).

A loading vehicle is not required, which is an important advantage over the static plate load test.

Figure 1: Dynamic plate load test using the Light-Weight Deflectometer according to *TP BF-StB, Part B 8.3*
left: ZFG 2000 test unit; right: single-person operation

Figure 2: Dynamic plate load test using the Light-Weight Deflectometer according to *TP BF-StB, Part B 8.3* in narrow conditions

The short test duration of not more than 3 minutes per measurement permits the performance of a large number of measurements with reasonable effort and thus an assessment of the load-bearing capacity of a test section supported by statistical data.

Experimental and numerical investigations both yielded a measuring depth of 60 cm for the dynamic plate load test. This corresponds to twice the load plate diameter [2]. The measuring depth is thus at least the same or even slightly greater than that of the static plate load test even though the loading duration is only 17 ms ± 1.5 ms.

Another advantage of the ZFG 2000 test unit is the high precision of the data obtained from the measurements, which in contrast to the static plate load test are not affected by subjective factors. This high precision is illustrated, for example, by the exactly reproducible deflection curves plotted in Figure 3.

In calibration mode it is moreover possible to do a quick on-site function test of the entire measuring system without any additional calibration devices, using the acceleration due to gravity, by tilting the load plate by 90 and 180 degrees. This special feature reliably prevents faulty measurements on the construction site.

Another highly useful feature of the ZFG 2000 test unit is data storage on a chip card, which ensures proper data documentation.

To date, several thousands of Light-Weight Deflectometers have been employed in internal quality control as well as in field tests performed primarily for indirect compaction control (see Figure 3).

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┌─────────────────────────────┐   ┌─────────────────────────────┐
│ Dynamischer Platten-        │   │ Dynamischer Platten-        │
│ druckversuch                │   │ druckversuch                │
│ LEICHTES FALLGERÄT          │   │ LEICHTES FALLGERÄT          │
│ nach TP-BF-StB Teil B8.3    │   │ nach TP-BF-StB Teil B8.3    │
│ Prüfgerät: ZORN ZFG-2000    │   │ Prüfgerät: ZORN ZFG-2000    │
│ Platte: 300 mm              │   │ Platte: 300 mm              │
│ Gerätenummer: #2815         │   │ Gerätenummer: #2815         │
│                             │   │                             │
│      (deflection curves)    │   │      (deflection curves)    │
│                             │   │                             │
│ s: 0,2 mm/cm  t:10ms/cm     │   │ s: 0,1 mm/cm  t:10ms/cm     │
│ Karte: #050704103828/64     │   │ Karte: #050704103828/85     │
│ Do 12.08.04  10:12:24       │   │ Mo 16.08.04  13:25:02       │
│ ----------------------      │   │ ----------------------      │
│ Nr.  v(mm/s)    s (mm)      │   │ Nr.  v(mm/s)    s (mm)      │
│ ----------------------      │   │ ----------------------      │
│  1.   233,2     0,836       │   │  1.   113,6     0,292       │
│  2.   230,0     0,785       │   │  2.   110,1     0,284       │
│  3.   216,8     0,728       │   │  3.   111,5     0,285       │
│ ----------------------      │   │ ----------------------      │
│ i.M.  226,7     0,783       │   │ i.M.  111,7     0,287       │
│ ======================      │   │ ======================      │
│ s/v= 3,454 ms               │   │ s/v= 2,569 ms               │
│ Evd= 28,7 MN/m²             │   │ Evd= 78,4 MN/m²             │
│ ===============             │   │ ===============             │
└─────────────────────────────┘   └─────────────────────────────┘
 Unzureichend verdichteter         Gut verdichtete Schotter-
 gleichkörniger schluffiger        tragschicht B1 0/32
 Feinsand SU
```
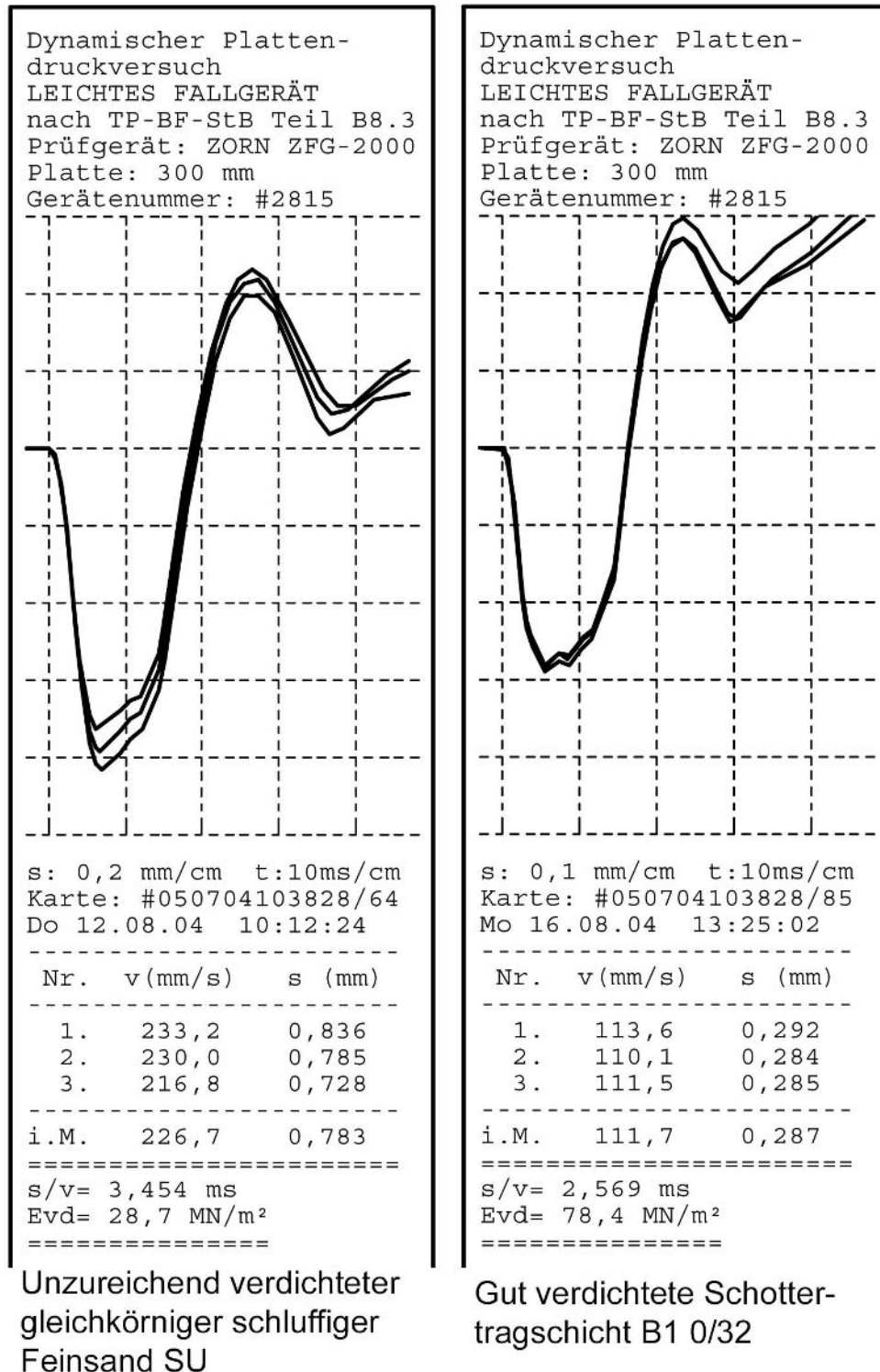
Figure 3:   Indirect compaction control using the Light-Weight Deflectometer

The inadequate compaction of the sand layer in Figure 3 is reflected, on the one hand, by the low E_{vd} value of 28.7 MN/m² and, on the other hand, by the decrease in individual deflection amplitudes from s_1 = 0.836 mm to s_3 = 0.728 mm. The fall in the

deflection amplitudes indicates additional compaction occurring under the impact of the Light-Weight Deflectometer.

Where compaction is adequate, as e.g. in the right-hand diagram in Figure 3, the dynamic deformation modulus E_{vd} is significantly higher than in the left-hand diagram shown in Figure 3. Also, the individual deflection amplitudes fluctuate only slightly about the mean value and do not decrease continuously with each impact of the measuring device. Also noteworthy is the lower relative penetration speed s/v = 2.569 ms, which is below the recommended limit of 3.5 ms [4].

Comparability of the test results obtained with the Light-Weight Deflectometer is, however, conditional upon the use of calibrated test equipment.

As the Light-Weight Deflectometer is used in field tests it is of particular importance to ensure the required test accuracy with regard to the impact force and the required measuring accuracy of the deflection measuring device over the entire temperature range from 0°C to 40°C, regardless of the frequency range of the material being tested. These requirements are largely covered by the calibration regulation [1]. For this purpose, a reference calibration stand was set up for the Light-Weight Deflectometer at Bundesanstalt für Straßenwesen in Bergisch Gladbach. This calibration stand permits calibration of both the impact force and the deflection measuring device of Light-Weight Deflectometers. Thus, a key prerequisite has been provided for the certification of calibration organisations operating in Germany. This measure also contributes to increasing the acceptance of dynamic plate load testing among both clients and contractors.
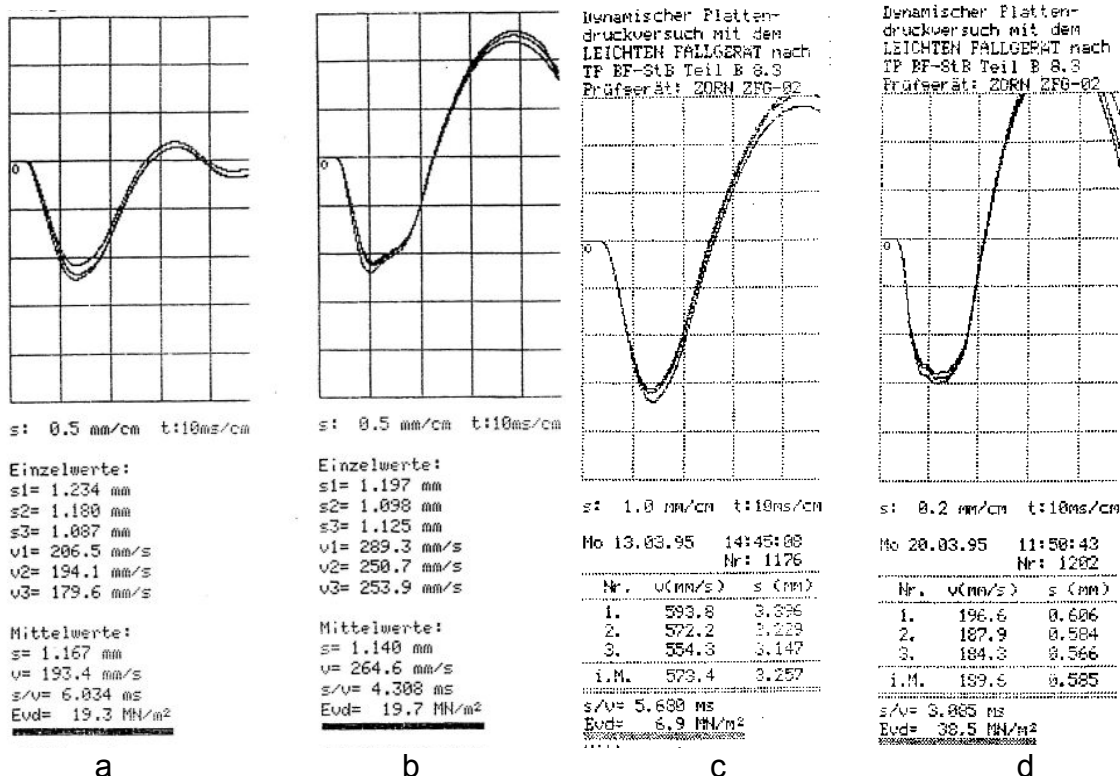

| a | b | c | d |

Figure 4   Site investigation using the Light-Weight Deflectometer
          a: Example: 1: sand fill
          b: Example: 2: cohesive soil
          c: Example: 3: fill, riverside clay, sand
          d: Example: 4: fill, clayey sand

The dynamic plate load test according to *Technische Prüfvorschrift für Boden und Fels im Straßenbau TP BF - StB, Teil B 8.3, Ausgabe 2003* (Technical test code for soil and rock in road construction TP BF – StB, Part B 8.3, edition 2003) may also be used beyond the scope of application of *ZTVE* and *ZTVA* for **site investigation** and for **estimating the required thickness of unbound base courses** (see examples in Figure 4).

Examples 1 and 2 in Figure 4 are both soils with approximately the same relatively low load-bearing capacity ($E_{vd} \approx 19$ MN/m²). In the case of fill sand a, the low load-bearing capacity is due to inadequate compaction; in the case of soil b, by contrast, it is not attributable to insufficient compaction but to an excessively high water content, as can be seen from the lines plotted for deflection and penetration speed.

Examples 3 and 4 are undefined fills which, however, differ substantially in terms of load-bearing capacity.

Based on the dynamic deformation modulus determined, the minimum thickness of unbound base courses can be estimated in accordance with Figure 5, based on the reference values given in Table 8 of RStO.

For Example 3, according to Figure 5, a minimum thickness of ≥ 23 cm is required for an unbound base course with a CBR of $\geq 40\%$ to obtain a deformation modulus of $E_{v2} \geq 45$ MN/m².

In Example 4, by comparison, the load-bearing capacity of the fill is already so high that according to Figure 5 a minimum thickness of ≥ 16 cm of the base course material with a CBR of $\geq 60\%$ is enough to attain a desired deformation modulus of $E_{v2} \geq 120$ MN/m² on the surface of the unbound base course.

Mindestschichtdicke von Tragschichten ohne Bindemittel

Ev2 Soll = 150 MN/m², CBR = 60 %
Ev2 Soll = 120 MN/m², CBR = 60 %
Ev2 Soll = 100 MN/m², CBR = 60 %
Ev2 Soll = 45 MN/m², CBR = 40 %
Beispiel 3: Evd = 6,9 MN/m²
Beispiel 4: Evd = 38,5 MN/m²

Mindestschichtdicke der ToB Ic

Dynamischer Verformungsmodul der Unterlage unter der ToB E_{vd} - Ist [MN/m²]
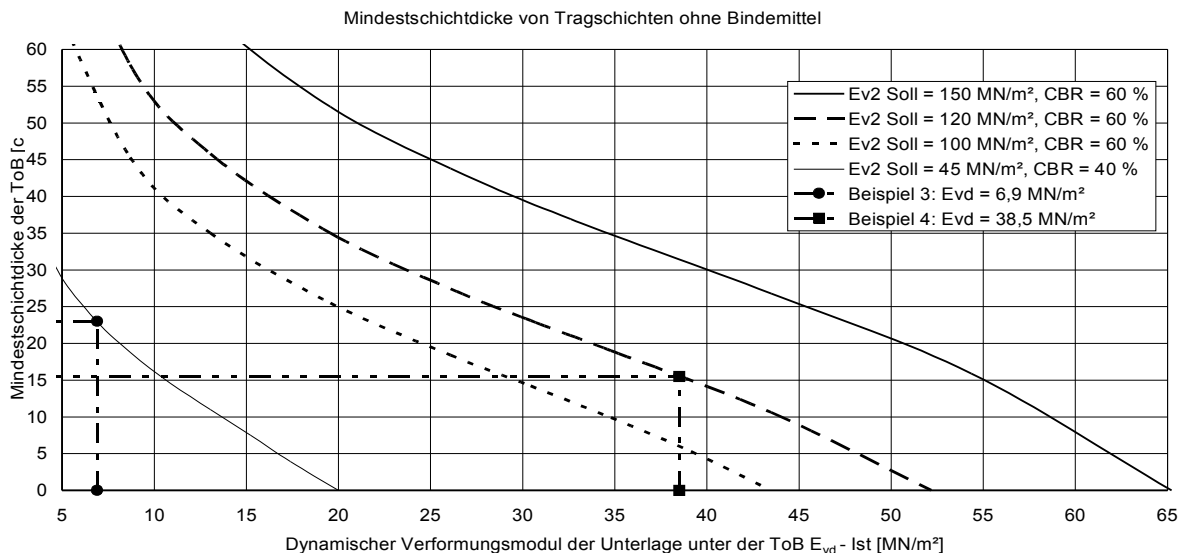
Figure 5: Reference values for the required thickness of unbound base courses plotted against the dynamic deformation modulus E_{vd} of the subgrade and the CBR of the base material.

The dynamic plate load test thus permits an immediate assessment of load-bearing capacity and the structural measures required to provide the required deformation modulus on the subgrade or the unbound base course, without any need for time-consuming additional investigations.

The Light-Weight Deflectometer according to TP BF-StB, Part B 8.3 [1] may also be used for testing load-bearing capacity in **road pavements**, e.g. on cold-recycled pavement courses with $E_{vd} \geq 80$ MN/m² [3], even though under Technical Test Code TP BF-StB, Part B 8.3 [1] use of the Light-Weight Deflectometer would not be permitted if $E_{vd} \geq 70$ MN/m².

Initial experiences in testing unbound base courses in road pavements were reported as early as at Mineralstofftagung in Nuremberg in 1993 [4].

The example of the well-compacted crushed rock base course in Figure 3 shows, for example, that the Light-Weight Deflectometer permits determination of the deformation modulus of road pavement base courses with sufficient accuracy even at $E_{vd} \geq 70$ MN/m² ($E_{v2} \geq 150$ MN/m²).

Measuring accuracy may be regarded as adequate if – on a sufficiently compacted test area – the duration of impact is > 16 ms and the individual deflection curves are similar in shape or even approximately congruent.

Example 5 in Figure 6 clearly meets this requirement. The individual deflection curves demonstrate good reproducibility of the measurement even though $E_{vd} \gg 70$ MN/m².

In Example 6, on the other hand, measuring accuracy is approaching the limit. Where bearing capacity is that high, the Light-Weight Deflectometer must be expected to yield incorrect readings.

Example 7 shows such an incorrect reading as the condition that duration of impact ≥ 16 ms was not met. The normal stress of 0.10 N/mm² produced under the load plate by the impact of the 10 kg drop weight is not enough to generate a measurable deflection amplitude.

In such a case, the deformation modulus has to be determined by means of a so-called **medium-heavy falling-weight deflector** producing a normal stress of 0.15 N/mm² under the load plate [5].

This test device differs from the Light-Weight Deflectometer by featuring a drop weight of greater mass (15 kg) compared with the 10 kg of the Light-Weight Deflectometer. In addition, it employs a stiffer spring on the test unit to ensure the same duration of impact as is obtained with the Light-Weight Deflectometer (see Figure 7, left).
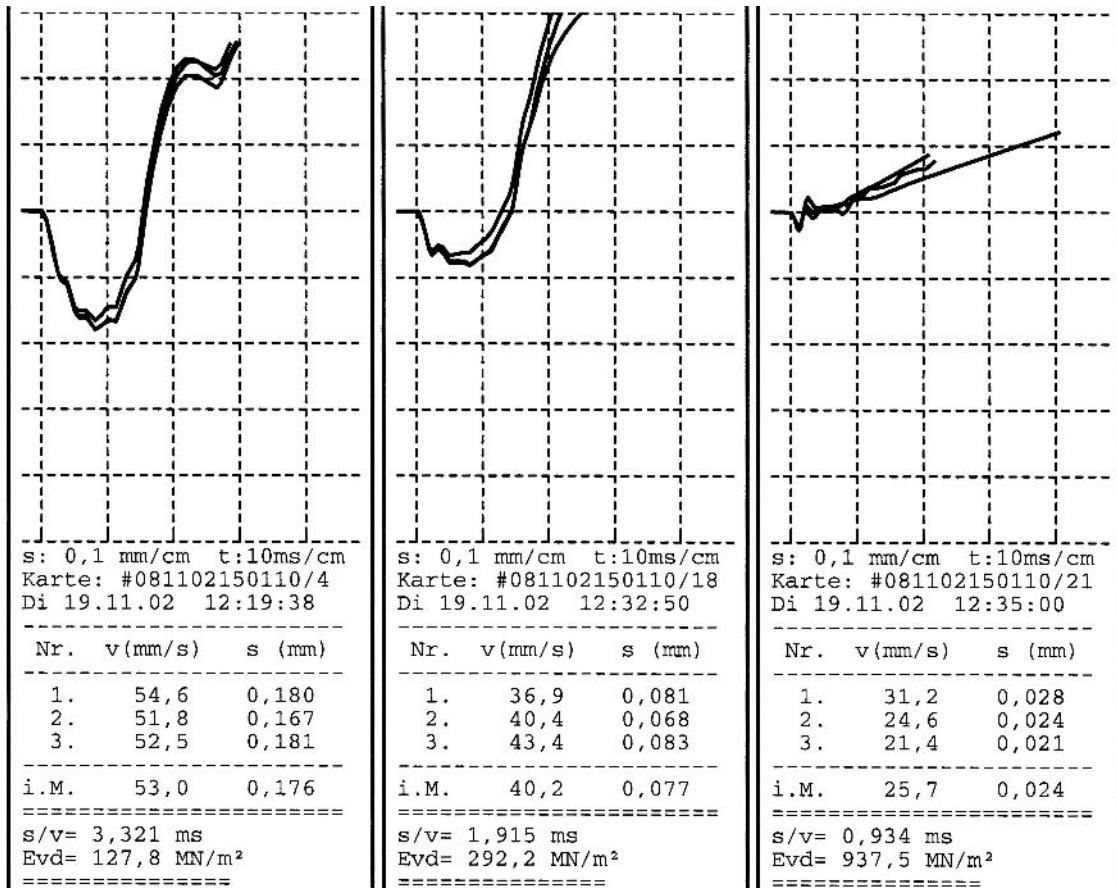
```
s: 0,1 mm/cm  t:10ms/cm
Karte: #081102150110/4
Di 19.11.02  12:19:38
----------------------
Nr.  v(mm/s)   s (mm)
----------------------
 1.    54,6     0,180
 2.    51,8     0,167
 3.    52,5     0,181
----------------------
i.M.   53,0     0,176
======================
s/v= 3,321 ms
Evd= 127,8 MN/m²
================
```

```
s: 0,1 mm/cm  t:10ms/cm
Karte: #081102150110/18
Di 19.11.02  12:32:50
----------------------
Nr.  v(mm/s)   s (mm)
----------------------
 1.    36,9     0,081
 2.    40,4     0,068
 3.    43,4     0,083
----------------------
i.M.   40,2     0,077
======================
s/v= 1,915 ms
Evd= 292,2 MN/m²
================
```

```
s: 0,1 mm/cm  t:10ms/cm
Karte: #081102150110/21
Di 19.11.02  12:35:00
----------------------
Nr.  v(mm/s)   s (mm)
----------------------
 1.    31,2     0,028
 2.    24,6     0,024
 3.    21,4     0,021
----------------------
i.M.   25,7     0,024
======================
s/v= 0,934 ms
Evd= 937,5 MN/m²
================
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Figure 6:   Measurements using the Light-Weight Deflectometer on concrete screed
left: Example: 5: sufficiently accurate measurement
middle: Example 6: Measurement close to the limit (incorrect measurement)
right: Example: 7: obviously incorrect measurement

8

Figure 7: Alternative configurations of falling-weight deflectometer
left: Medium-heavy falling-weight deflectometer using a 15 kg drop
load and a load plate diameter of 300 mm.
right: Medium-heavy falling-weight deflectometer with a load plate
diameter of 150 mm.

Alternatively, the dynamic deformation modulus may also be tested by means of a
falling-weight deflectometer with a 150 mm load plate (see Figure 7, right). Here,
the impact on the soil increases from 0.1 N/mm² to 0.4 N/mm² and, in combination
with the 15 kg weight, even to 0.6 N/mm². This falling-weight device is therefore
suitable for testing pavement courses with a very high deformation modulus.
It must be borne in mind, however, that measuring depth is reduced to about 30 cm
as compared with the 60 cm that are obtained with a load plate diameter of 300 mm.

The various configuration variants of the falling-weight deflector were tested on a
crushed rock base of very high load-bearing capacity.

The results of this test have been compiled in Table 1.

Table 1: Static and dynamic deformation moduli on crushed rock base of very high load-bearing capacity

| Contact pressure | Static deformation modulus | | | Dynamic deformation modulus E_{vd} [MN/m²] | | | |
	0.5 N/mm²	0.33 N/mm²		0.1 N/mm²	0.15 N/mm²	0.4 N/mm²	0.6 N/mm²
Measurement No.	E_{v1} [MN/m²]	E_{v2} [MN/m²]	E_{v2}/E_{v1} [-]	$\varnothing$ 300 mm m = 10 kg	$\varnothing$ 300 mm m = 15 kg	$\varnothing$ 150 mm m = 10 kg	$\varnothing$ 150 mm m = 15 kg
1	272	538	1,98	83	98	78	112
2	262	403	1,54	88	96	104	100
3	196	408	2,08	116	104	107	110
4	154	337	2,19	98	99	125	131
5	190	401	2,12	95	90	82	86
6	219	449	2,05	95	116	103	86
7	151	302	2,00	118	128	135	117
8	233	510	2,19	107	116	127	138
9	191	471	2,46	94	87	110	113
Mean value	**208**	**424**	**2,07**	**99**	**104**	**108**	**110**
Standard deviation	42,8	76,5	0,24	12,1	13,7	19,3	17,7
Variation coefficient	21 %	18 %	12 %	12 %	13 %	18 %	16 %
E_{v2}/E_{vd}				4,27	4,08	3,93	3,85
Mean deflection amplitude				0.23 mm	0.33 mm	0.43 mm	0.63 mm
Contact pressure relative to σ =0.1 MN/m²				1,0	1,5	4,0	6,0
Factor by which mean deflection amplitude increases relative to σ =0.1 MN/m²				1,0	1,44	1,88	2,74

The measurements show that if the plate rests fully on the ground, the dispersion of measurements obtained with the falling-weight deflector on a crushed rock course with very high load-bearing capacity will not be greater than when the static load plate test is used. Depending on the equipment configuration, the variation coefficient ranges between 12% and 18%. By comparison, the variation coefficient of the static deformation modulus lies between 18% and 21 %.

In the subject case, the static deformation modulus is extremely high. This is attributable to the fact that the crushed rock course spreads loads very effectively and the measuring stand of the plate load unit is therefore located in a deflection bowl. This results in a higher E_{v2} value and a very high ratio of $E_{v2}/E_{vd} \approx 4$.

The dynamic deformation modulus depends, however, to a minor extent on contact pressure and the load plate diameter.
When contact pressure increases from 0.1 N/mm² to 0.15 N/mm², the deflection amplitude rises from 0.23 mm to 0.33 mm, i.e. by 44%, while the dynamic deformation modulus goes up only from E_{vd} = 99 MN/m² to 104 MN/m², i.e. by about 5%.

Even more pronounced is the difference with contact pressures of 0.4 N/mm² and 0.6 N/mm². The deflection amplitude increases by 88% and 174%, respectively, relative to the contract pressure of 0.1 N/mm², while the deformation modulus increases only by 9% and 11%, respectively.

There is thus no linear relationship between contact pressure and load plate diameter on the one hand and the deflection amplitude and the dynamic deformation modulus on the other.

Requirements therefore have to be specified for the contact pressure that exists when a specific equipment configuration is used. For this reason it is indispensable to develop a test code also for the medium-heavy falling-weight deflectometer.
Here it must be noted that for pavement courses contract pressures should be chosen that closely approximate actual traffic loads. For this reason, it is recommended to use a falling-weight deflectometer with a 150 mm load plate diameter. The measuring depth of this unit is 300 mm and also adequate for common pavement thickness. Another advantage of the smaller load plate diameter is that with this smaller plate solid contact can be ensured more effectively on coarse-grained material than with a load plate of 300 mm diameter.

By way of summary it can be said that the dynamic load plate test can be used universally in road pavement construction and, by selecting an appropriate falling weight and load plate diameter, can be adapted to any test task, with the loading speed of the test unit closely approximating actual traffic loads.

Literature

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