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RESEARCH ARTICLE

# Laboratory evaluation of B & C small-plate light falling weight deflectometer

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***Abstract***

*A new Light Falling Weight Deflectometer has been used in Hungary for a couple of years now. The B & C Small-plate Light Falling Weight Deflectometer developed by Andreas Ltd. has been used in the quality control process of subsoil, embankment and subgrade layers in road and railroad constructions. Apart from measuring the dynamic modulus, the device can determine the dynamic compaction of the tested layer based on a new theory. First results of the laboratory testing program carried out in the laboratory of the Department of Highway and Railway Engineering are presented in this paper. Detailed tests have been finished to determine the correlation to static and other dynamic moduli such as Light-Drop Weight Tester and to compare the measured dynamic compaction values to the values aquired by conventional soil sampling method.*

***Keywords***

*Light Drop-weight Tester · Light Falling Weight Deflectometer · B & C · compaction · subgrade modulus · dynamic compaction · static plate load test*

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## 1 Introduction

A new Light Falling Weight Device has been used in Hungary for years now. Development of the B & C Small-plate Light Falling Weight Deflectometer started in 2003 by Andreas Ltd., an independent QA/QC business company in Hungary, and the wider use of it has been started.

Apart from measuring the dynamic subgrade modulus value, the device is capable of determining the dynamic compaction of the tested layer. The device is portable, the measurement is fast, cost-saving and environment-friendly, because no nuclear isotopes are needed.

The evaluation of the device has been started in the laboratory of the Department of Highway and Railway Engineering at the Budapest University of Technology and Economics with the aim of detailed tests of the device, especially correlating to other available static and dynamic methods. First results of the laboratory testing program are presented.

## 2 Details of the device

The B & C Small-plate Light Falling Weight Deflectometer (B&C) consists of a 163 mm diameter steel plate and an 11 kg drop weight (Fig. 1). The drop height (72 cm) and the buffer characteristics are set to generate a stress intensity of 300-350 $kN/m^2$ under the plate. The device consists of a steel buffer to transmit the force to the ground in a pulse time of 18 ms. Modern electronic data collection system, LCD display and mini-printer are also part of the apparatus. Software for data storage, transfer and evaluation is also provided.

Determination of the dynamic subgrade modulus consists of three adjustment drops and other three consecutive drops for settlement measurement. Additional 12 drops are applied to obtain dynamic compaction. The option of simplified dynamic compaction measurement is also at the user's disposal [1, 2].

European standardization of the device and the dynamic compaction method has been started in the year 2007.

## 3 Basic theoretical background

The calculation of the dynamic subgrade modulus ($E_d$) is identical to that of the other Light Falling Weight Deflectometers, based on the well-known Boussinesq-theory [1, 2].

After determining the maximum vertical displacement under the load plate the device uses Eq.1 to calculate the dynamic modulus. Three primary drops are applied to ensure the proper contact between soil and plate. The next three consecutive drops are used to calculate modulus by using the mean value of the measured desplacement data ($s_d$). The stress under the plate is assumed to be constant ($p_{din}$=300 kN/m$^2$).

$$E_d = \frac{c}{s_d}\left(1-\upsilon^2\right)\cdot p_{din}\cdot R \tag{1}$$

where $c$ = Plate model coefficient (selectable: c = 2 or p/2); $\upsilon$ = Poisson's ratio (selectable: $\upsilon$ = 0,3 – 0,4 – 0,5); $R$ = Radius of the plate (81,5 mm)

**Fig. 1.** The B&C small-plate device

The basic idea of the dynamic compaction measurement method is "further compaction". It is assumed that the final compaction of the subgrade or earthwork ($T_{r\rho}$%) can be related to the volume change achieved by further compaction which is made by 18 drops of the weight.

The evaluation method is based on the assumption that during further compaction

- the residual settlement is arisen basically from the decrease of the air content,
- moisture content (w) is constant and,
- the residual settlement during further compaction and the air content at the end of the first compaction has a simple linear correlation.

It can be derived that in this case the air volume ratio difference ($\Delta l$) of two states – which can be converted into settlement by further compaction – is in linear relationship with $T_{r\rho}$.

Assuming constant dry unit weight (construction condition):

$$\varepsilon_{\max} \approx \Delta l \; = (1 - T_{r\rho}) \tag{2}$$

Assuming constant volume (Proctor test condition):

$$\varepsilon_{\max} \approx \Delta l \; = (1 - T_{r\rho})\left(s^* + \upsilon^*\right) \tag{3}$$

where $s$, $\upsilon$ and $l$ are volume ratios of solid, water and air, * means an arbitrary reference state, $\varepsilon_{max}$ is the maximum vertical (and volumetric) strain which can be achieved by further compaction.

If $w$ is not optimal, then another point of the Proctor curve is used (instead of the Proctor optimum) as the reference state. Therefore Relative Compaction ($T_{rE}$) should be used instead of $T_{r\rho}$. The result for $T_{rE}$ is converted into $T_{rd}$ using Eq. 3. The basic theory supposes that $T_{rd} = T_{r\rho}$.

$$T_{r\rho} = T_{rE} T_{rw} = \frac{\rho_d}{\rho_d^w}\frac{\rho_d^w}{\rho_{d\,\max}} \tag{4}$$

where

$$T_{rw} = \frac{\rho_d^w}{\rho_{d\,\max}} \tag{5}$$

is called the "Moisture Correction Coefficient". It is a normalized Proctor curve.

The total settlement ($h_i$) upon the weight drop is measured in 18 drops. From the total settlements, the value of the Deformation Index ($D_m$) is computed as follows:

$$\begin{aligned} &S = (h_0 - h_1) + 2\,(h_1 - h_2) \,.... + 17\,(h_{16} - h_{17}) = \\ &s_1 + s_2 ... + s_{17} \\ &D_m = S/18 \end{aligned} \tag{6}$$

The total settlement $h_i$ is the sum of the residual and the elastic settlement. Therefore, the following secondary settlement variable $s_i$ is computed from Eq. 6.

$$s_i = \frac{(h_{i-1} - h_i)}{l} i \tag{7}$$

The elastic part can be eliminated from the calculations. The secondary residual settlement variable $s_i$ can be interpreted as the linear back-estimation of the total residual settlement until the $i$-th drop. The term $(h_{i-1} - h_i)/l$ is a numerical derivative at the $i$-th drop, which is multiplied by $i$. A kind of near-average $S$ is computed from these total residual settlements which is denoted by $D_m$ and is called Deformation Index.

Then the transformation of this settlement variable into strain should be done. This problem is approximately solved by the following empirical relationship:

$$T_{rE}\% = 100 - \Phi \cdot D_m \, [\%] \quad (8)$$

where $\Phi$ is an empirical constant developed on the basis of some experimental work. From the computed $T_{rE}$ and the known $T_{rw}$, calculation of $T_{rd}$ can be done by using Eq. 4.

For the application of the method, a laboratory Proctor curve with more points is needed to determine precisely the value of $T_{rw}$ in the case of different water content. The in-situ water content also needs to be measured for calculating $T_{rw}$.

## 4 International experiences with B&C device

Application and verification of the device has been started in Slovenia, Switzerland, Romania, Portugal and Germany. Further applications awaited in Thailand and Kazakhstan. Evaluation and comparative measurements to static and other dynamic methods have been initiated, but still few reports and papers are available.

Short research report has been published by the Technical University of Ljubljana in 2007. Comparative measurements to German Dynamic Plate modulus ($E_{vd}$) and Continuous Compaction Control moduli ($E_{CCC}$) were taken on three different materials with compaction difficulties. Their results are favourable [3].

Favourable results were also reported by Boujlala (2007) [4]. Comparison to static plate load test on a test location in Switzerland is reported. A sandy gravel subgrade layer of a sideway was tested by B&C and conventional plate load test. After parallel tests on 4 spots, a correlation of $E_d \approx 0{,}6 \cdot M_{E2}$ was found, where $E_d$ is the B&C dynamic modulus and $M_{E2}$ is the modulus obtained by the second load cycle of the static load test.

## 5 Laboratory tests

A rectangular steel box of 1,4 × 1,4 m area and 1,0 m depth was used in the research. The bottom of the box was the reinforced concrete floor of the building and one side of the box was substituted by wooden boards for easy access and handling of the material. Soil placed in the box was compacted by an electric vibrator. All soil layers reached a thickness of 8-13 cm after compaction.

A typical soil widely available in Hungary was applied. It can be qualified as silty fine sand („loess"). Prior to the beginning of the tests, a modified Proctor test was carried out to determine the maximum dry density (1,85 g/cm$^3$) and optimum moisture content (10,8 %) of the tested material.

The $E_d$ dynamic subgrade modulus was determined by the device at variable compaction ratios (~82-92 %) for eleven different layer thicknesses. Four $E_d$ measurements were taken for each layer thickness. The moisture content of the moulded material was set near to the optimum moisture content. The achieved compaction ($T_{r\rho}\%$) and moisture content ($w$) were checked for each layer during the test by using conventional specimen sampling and drying method. Dynamic compaction measurements of 18 drops were also taken on each layer.

## 6 Test results

Measured values are presented in Table 1. Four measured $E_d$ values, $w$, and layer thickness values are included, together with calculated $\rho_d$ and $T_{r\rho}\%$ compaction values after undisturbed soil sampling.

Results of B&C dynamic compaction measurements are also provided. Values of the moisture correction coefficient ($T_{rw}$) for each moisture content values were determined with the help of the modified Proctor curve. Mean values were calculated for each measured data.

Comparison results show that the dynamic modulus values measured by the B&C device ($E_d$) is about 2,5 times higher than the ($E_{vd}$) moduli of the German Dynamic Plate (Fig. 2). Still few measurements have been evaluated, but the correlation is relatively good ($R$=0,86).

The stress under the B&C device is assumed to be 0,30-0,35 MPa, which is about 3-3,5 times the stress under the German device, but the measured moduli is only about 2,7-2,8 times higher.

The final dynamic compaction ($T_{rd}$) of the layer measured by the B&C dynamic method resulted considerably higher than measured by conventional methods ($T_{r\rho}$). The obtained differences are detailed in Table 2 and Fig. 3.

The measuring depth of the device was also examined. Values of the dynamic modulus in the function of layer thickness are presented on Fig. 4. Exponential regression shows a relatively good fit ($R^2$= 0,97). Single (D) and double plate diameter (2·D) lines are also shown.

The shape of the curve shows that the measuring depth of the B & C device is about as high as 18-26 cm, appr. 1,5-times the plate diameter.

## 7 Summary

First laboratory evaluation results of the B&C Small-plate Light Falling Weight Deflectometer are presented in this paper. A typical Hungarian soil (silty fine sand) was compacted in a sand box of 1,4 × 1,4 m area. Eleven layer thicknesses were compacted and tested. Dynamic modulus values were determined on the surface of each layer, together with water content and compaction values. Dynamic compaction measurements were also taken on each layer.

**Tab. 1.** Laboratory test results

| Nr. | Layer thickness (cm) | Layer thickness (cm) average | w (%) | w (%) average | $r_d$ ($g/cm^3$) | $T_{rr}$ (%) | $T_{rr}$ (%) average | B&C $T_{rd}$ (%) | B&C $T_{rd}$ (%) average | B&C $T_{rw}$ | B&C $T_{rr}$ (%) | B&C $T_{rr}$ (%) average | B&C $E_{vd}$ (MPa) | B&C $E_{vd}$ (MPa) average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | *2,60* | ***2,35*** | 9,20 | 9,04 | 1,62 | 87,50 | 82,11 | 94,20 | 96,10 | 0,99 | 93,53 | 95,22 | 268,90 | 280,80 |
| | *2,50* | | 8,90 | | 1,46 | 78,90 | | 96,10 | | 0,99 | 95,12 | | 251,00 | |
| | *2,20* | | 9,40 | | 1,51 | 81,41 | | 96,70 | | 0,99 | 96,17 | | 289,60 | |
| | *2,10* | | 8,60 | | 1,49 | 80,63 | | 97,40 | | 0,99 | 96,07 | | 313,70 | |
| *2* | *4,10* | ***4,08*** | 8,60 | 8,94 | 1,72 | 93,04 | 90,74 | 97,50 | 97,40 | 0,99 | 96,16 | 96,44 | 188,20 | 187,30 |
| | *3,80* | | 8,80 | | 1,73 | 93,71 | | 96,80 | | 0,99 | 95,71 | | 163,70 | |
| | *4,00* | | 9,00 | | 1,63 | 88,38 | | 97,70 | | 0,99 | 96,81 | | 188,20 | |
| | *4,40* | | 9,40 | | 1,62 | 87,83 | | 97,60 | | 0,99 | 97,07 | | 209,10 | |
| *3* | *5,50* | ***5,53*** | 9,70 | 9,48 | 1,75 | 94,75 | 92,57 | 98,10 | 97,63 | 1,00 | 97,77 | 97,12 | 150,60 | 152,43 |
| | *5,00* | | 9,00 | | 1,77 | 95,73 | | 97,20 | | 0,99 | 96,32 | | 144,80 | |
| | *5,30* | | 9,30 | | 1,66 | 89,60 | | 97,50 | | 0,99 | 96,89 | | 163,70 | |
| | *6,30* | | 9,90 | | 1,67 | 90,19 | | 97,70 | | 1,00 | 97,48 | | 150,60 | |
| *4* | *7,30* | ***7,40*** | 9,50 | 9,56 | 1,72 | 93,08 | 91,13 | 96,90 | 97,60 | 1,00 | 96,45 | 97,18 | 150,60 | 146,35 |
| | *7,50* | | 10,20 | | 1,68 | 90,72 | | 98,00 | | 1,00 | 97,91 | | 150,60 | |
| | *7,20* | | 9,30 | | 1,67 | 90,25 | | 97,50 | | 0,99 | 96,89 | | 144,80 | |
| | *7,60* | | 9,40 | | 1,67 | 90,47 | | 98,00 | | 0,99 | 97,47 | | 139,40 | |
| *5* | *8,60* | ***8,45*** | 8,90 | 8,77 | 1,75 | 94,37 | 91,35 | 97,40 | 97,15 | 0,99 | 96,41 | 96,00 | 129,80 | 121,75 |
| | *8,50* | | 8,10 | | 1,67 | 90,54 | | 96,60 | | 0,98 | 94,58 | | 117,60 | |
| | *8,70* | | 9,00 | | 1,64 | 88,58 | | 97,20 | | 0,99 | 96,32 | | 125,50 | |
| | *8,00* | | 9,20 | | 1,70 | 91,90 | | 97,40 | | 0,99 | 96,70 | | 114,10 | |
| *6* | *11,80* | ***11,65*** | 14,00 | 13,04 | 1,53 | 82,95 | 89,19 | 98,10 | 97,53 | 0,97 | 95,51 | 95,99 | 105,70 | 101,03 |
| | *12,10* | | 14,00 | | 1,53 | 82,84 | | 98,00 | | 0,97 | 95,42 | | 100,30 | |
| | *11,40* | | 12,30 | | 1,81 | 97,71 | | 96,70 | | 0,99 | 96,12 | | 98,70 | |
| | *11,30* | | 12,00 | | 1,73 | 93,26 | | 97,30 | | 1,00 | 96,92 | | 99,40 | |
| *7* | *24,60* | ***24,43*** | 13,60 | 12,74 | 1,61 | 86,93 | 87,06 | 97,60 | 97,93 | 0,98 | 95,61 | 96,74 | 104,80 | 100,00 |
| | *23,90* | | 13,00 | | 1,67 | 90,13 | | 98,10 | | 0,99 | 96,85 | | 94,50 | |
| | *24,20* | | 13,20 | | 1,64 | 88,79 | | 98,00 | | 0,98 | 96,52 | | 92,80 | |
| | *25,00* | | 11,10 | | 1,52 | 82,41 | | 98,00 | | 1,00 | 97,97 | | 107,90 | |
| *8* | *35,90* | ***36,25*** | 12,50 | 13,10 | 1,60 | 86,66 | 89,93 | 96,40 | 97,20 | 0,99 | 95,66 | 95,84 | 97,80 | 96,78 |
| | *36,00* | | 13,00 | | 1,61 | 87,12 | | 97,30 | | 0,99 | 96,06 | | 93,60 | |
| | *36,40* | | 13,40 | | 1,68 | 90,97 | | 98,30 | | 0,98 | 96,56 | | 100,00 | |
| | *36,70* | | 13,40 | | 1,76 | 94,96 | | 96,80 | | 0,98 | 95,09 | | 95,70 | |
| *9* | *46,50* | ***47,33*** | 13,20 | 12,43 | 1,64 | 88,50 | 86,21 | 98,00 | 97,85 | 0,98 | 96,52 | 97,08 | 98,50 | 98,78 |
| | *46,90* | | 12,40 | | 1,56 | 84,17 | | 96,70 | | 0,99 | 96,04 | | 105,80 | |
| | *47,10* | | 11,90 | | 1,56 | 84,24 | | 98,30 | | 1,00 | 97,98 | | 91,00 | |
| | *48,80* | | 12,30 | | 1,63 | 87,94 | | 98,40 | | 0,99 | 97,81 | | 99,80 | |
| *10* | *58,40* | ***58,25*** | 10,40 | 11,36 | 1,50 | 81,24 | 83,58 | 96,20 | 97,08 | 1,00 | 96,16 | 96,66 | 108,40 | 98,70 |
| | *58,30* | | 10,20 | | 1,52 | 82,15 | | 98,10 | | 1,00 | 98,01 | | 97,80 | |
| | *57,60* | | 11,80 | | 1,55 | 83,90 | | 96,70 | | 1,00 | 96,44 | | 90,80 | |
| | *58,70* | | 13,00 | | 1,61 | 87,01 | | 97,30 | | 0,99 | 96,06 | | 97,80 | |
| *11* | *68,60* | ***67,75*** | 11,00 | 10,45 | 1,49 | 80,52 | 84,02 | 96,80 | 97,28 | 1,00 | 96,79 | 97,22 | 99,70 | 95,53 |
| | *67,40* | | 10,10 | | 1,52 | 81,91 | | 95,60 | | 1,00 | 95,47 | | 96,40 | |
| | *66,90* | | 10,40 | | 1,53 | 82,62 | | 98,40 | | 1,00 | 98,36 | | 90,20 | |
| | *68,10* | | 10,40 | | 1,68 | 91,03 | | 98,30 | | 1,00 | 98,26 | | 95,80 | |

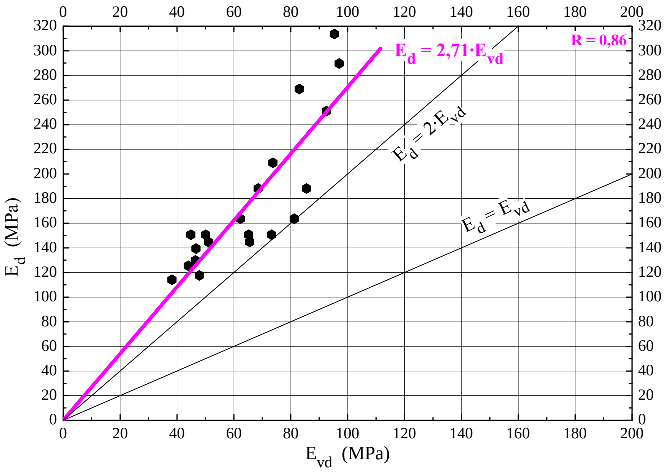


**Fig. 2.** Correlation between B&C and GDP moduli

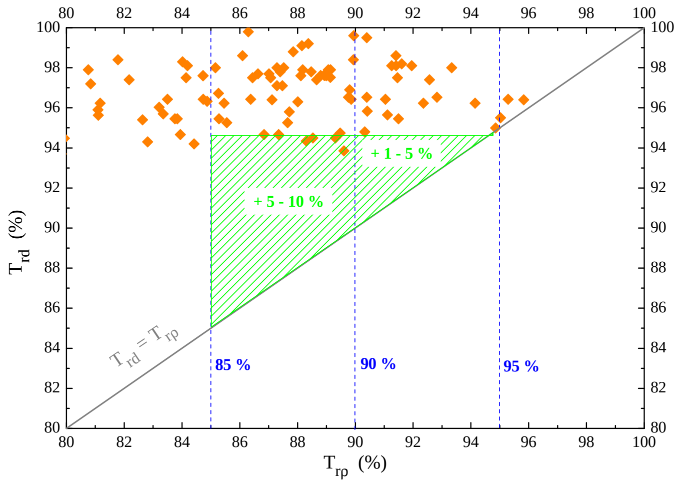


**Fig. 3.** Compaction values by B&C and conventional method

**Tab. 2.** Difference between compactions by conventional and B&C dynamic methods

| Compaction range by conventional method | Difference of B&C dynamic compaction method |
|---|---|
| $T_{rp} \leq 85$ % | + 10-15 % |
| $85 < T_{rp} \leq 90$ % | + 5-10 % |
| $90 < T_{rp} \leq 95$ % | + 1-5 % |
| $T_{rp} > 95$ % | no significant difference |

Correlation to the German Dynamic Plate modulus was determined. Results show that the B&C dynamic modulus is appr. 2,7 times higher than GDP modulus.

Dynamic compaction values by B&C method was found to be considerably higher than compaction determined by conventional method. In case of lower compaction percentages, the difference can reach +10 %. At higher compaction ratios, the difference tends to decrease gradually until 1-5 %. In case of compactions higher than 95 %, no significant error was measured.

A measuring depth of 18-26 cm was found in case of silty fine

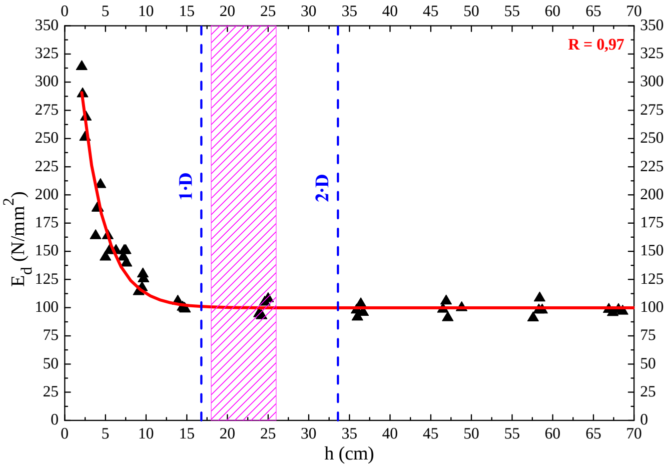


**Fig. 4.** Measuring depth of B&C device

sand compacted at different ratios. The effective layer thickness resulted in appr. equal to 1,5-times the plate diameter.

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