# Laboratory evaluation of new B&C Light Falling Weight Deflectometer

## Evaluation en laboratoire d'un déflectomètre de pois de chute neuf (B&C)

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ABSTRACT

A new Light Falling Weight Deflectometer of 163 mm plate diameter has been developed in Hungary by Andreas Ltd.
Along with measuring the dynamic load bearing capacity of engineering fills and subgrade layers, the B&C device is capable of measuring the compaction of the tested layer on the same spot.

Basic theoretical background and calculation of the dynamic compaction are presented, together with laboratory evaluation results. Correlation to static plate load test and German Dynamic Plate moduli are presented. Comparisons of conventional and dynamic compaction results are also discussed. Additional laboratory test results are presented for the estimation of the measuring depth.

RÉSUMÉ

Un déflectomètre de poids de chute d'un diamètre 163 mm était développé en Hongrie par Andreas Ltd.
En mesurer la capacité portante des remblais artificiels et des couches sous-sol le dispositif B&C est capable de mesurer le tassement au même lieu.

On présente les bases théoriques et le calcule du tassement dynamique avec l'évaluation de laboratoire. On pressent aussi les comparaisons aux essais de plat statiques et les modules de German Dynamique Plate. On discute les résultats d'essais de tassement conventionnel et de compaction dynamique. Des résultats d'essai de laboratoire additionnels sont présentés pour estimer la profondeur de mesure.

Keywords : Light Drop-weight Tester, Light Falling Weight Deflectometer, LFWD, B&C, German Dynamic Plate, compaction, subgrade modulus, dynamic compaction, static plate load test

## 1 INTRODUCTION

A new Light Falling Weight Deflectometer (LFWD) 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. The wider use of the device has been just 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 environmental 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 correlating to other available static and dynamic subgrade moduli. 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 a 10 kg drop weight (Figure 1.). The drop height (72 cm) and the buffer characteristics are set to generate a stress intensity of 300 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 the dynamic compaction of the tested layer. The option of simplified dynamic compaction measurement is also at the user's disposal (Andreas Ltd. 2007, Subert 2006).

European standardization of the device and the dynamic compaction measurement method has been finished in 2008.

Figure 1. The B&C small-plate device

## 3 BASIC THEORETICAL BACKGROUND

### 3.1 *Calculation of the dynamic subgrade modulus*

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

After determining the maximum vertical displacement under the load plate, the device uses Equation 1. to calculate the dynamic modulus.

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

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

*Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*
*M. Hamza et al. (Eds.)*

*doi:10.3233/978-1-60750-031-5-1088*

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 displacement data ($s_d$). The stress under the plate is assumed to be constant ($p_{din}$=300 kN/m$^2$).

### 3.2 *Calculation of the dynamic compaction value*

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):

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

where s, v 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 dynamic compaction ($T_{rd}$) using Equation 4.

The theory supposes that $T_{rd} = T_{r\rho}$.

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

where

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

is called the "moisture correction coefficient". It can be defined as 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:

$$S = (h_0 - h_1) + 2(h_1 - h_2) \dots + 17(h_{16} - h_{17}) = s_1 + s_2 \dots + s_{17} \tag{6}$$
$$D_m = S/18$$

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 Equation 7.

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

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.

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

$$T_{rE}\% = 100 - \Phi \cdot D_m \ [\%] \tag{8}$$

where $\Phi$ is an empirical constant developed on the basis of experimental work ($\Phi$=0,365±0,025). From the computed $T_{rE}$ and the known $T_{rw}$, calculation of $T_{rd}$ can be done by using Equation 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 the precise calculation of the coefficient

## 4 INTERNATIONAL EXPERIENCES WITH B&C DEVICE

Application and verification of the device has been started (among others) 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 published results 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 modulus ($E_{CCC}$) were taken on three different materials with compaction difficulties (e.g. slag). Their results are favorable. (Majes & Petkovsek 2007)

Favorable results were also reported in Switzerland (Boujlala 2007). A sandy gravel subgrade layer of a sideway were tested by B&C device and by conventional plate load test. After parallel measurements on 4 spots, a correlation of $E_d \approx 0{,}6 \bullet ME_2$ was found, where $E_d$ is the B&C dynamic modulus and $ME_2$ is the modulus obtained by the second load cycle of the static load test.

## 5 LABORATORY TESTS

A rectangular steel box of 1,4 x 1,4 m area and 1,0 m depth was used in this research program. 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 in 3-12 cm thick layers by an electric vibrator. Soil layers reached a thickness of 8-13 cm after compaction. The total built-in layer thickness resulted in 68 cm.

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 on the top of each layer. The moisture content of the soil was set near to the optimum moisture content. The achieved compaction ($T_{r\rho}$%) and moisture content (w) were determined for each layer during the test by conventional specimen sampling and drying method. Dynamic compaction measurements of 18 drops were also taken on each measurement spot.

## 6 TEST RESULTS

After performing the drop-weight tests on each layer, four measured $E_d$, w, and layer thickness values were determined, together with calculated $\rho_d$ and $T_{r\rho}$% compaction values after undisturbed soil sampling.

B&C dynamic compaction measurements were also determined. 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.

### 6.1 *Correlation between dynamic moduli*

Comparison results show that the dynamic modulus values measured by the B&C device ($E_d$) is about 2,4 times higher than $E_{vd}$ modulus values of the German Dynamic Plate (GDP) (Figure 2.). Still few measurements have been evaluated, but the correlation is good (R=0,90).

The stress under the B&C device is assumed to be 300 kPa, which is about 3-3,5 times the stress under the German device, but the measured moduli is only about 2,4 times higher.

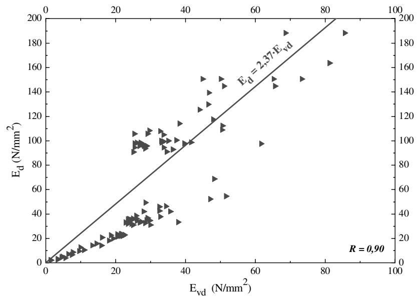


Figure 2. Correlation between B&C and GDP moduli

### 6.2 *Correlation between B&C dynamic modulus and static plate load test modulus*

Also good correlation was found between the static plate load test modulus $E_2$ and B&C modulus $E_d$ (Figure 3.).

This case the dynamic modulus is about the same order of magnitude than plate load test modulus, as the stress is the same under the loading plate in case of both methods.

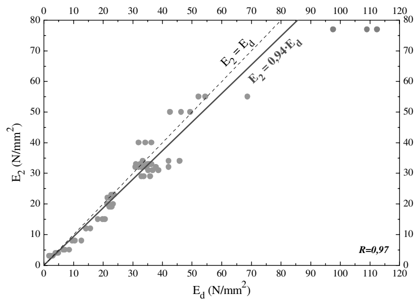


Figure 3. Correlation between B&C and static plate load test moduli

### 6.3 *Correlation between conventional and dynamic compaction values*

The final dynamic compaction ($T_{rd}$) measured by the B&C dynamic method resulted considerably higher than measured by conventional soil sampling method ($T_{r\rho}$) in case of lower compactions than 90 %. Around 95 %, the dynamic values more or less scatter around the equality line.

The differences between the results are detailed in Figure 4. and Table 1.

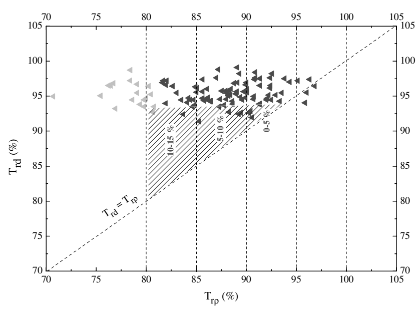


Figure 4. Compaction values measured by B&C ($T_{rd}$) and by conventional method ($T_{r\rho}$)

Table 1. Difference between compactions by conventional and B&C dynamic methods

| Compaction range by conventional method | Difference of B&C dynamic compaction method |
|---|---|
| $T_{r\rho} \leq 85$ % | + 10-15 % |
| $85 < T_{r\rho} \leq 90$ % | + 5-10 % |
| $90 < T_{r\rho} \leq 95$ % | + 0-5 % |
| $T_{r\rho} > 95$ % | no significant difference |

### 6.4 *Measuring depth*

The measuring depth of the B&C device was also examined.

Values of the dynamic modulus ($E_d$) in the function of layer thickness (h) are presented in Figure 5. Exponential regression shows a relatively good fit (R=0,97). Single (D) and double plate diameter (2·D) lines are also shown.

The shape of the curve shows the clear effect of the underlying concrete floor in case of low layer thicknesses. When reaching the measuring depth of the device, the effect of the stiff underlying surface disappears and the obtained modulus values tend to a more or less constant value.

Result show that the measuring depth of the B&C device is about as high as 18-26 cm, approx. 1,5-times the plate diameter.

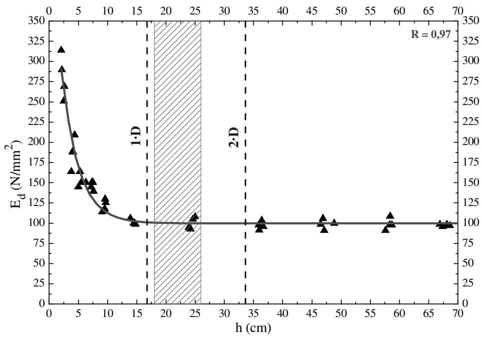


Figure 5. Measuring depth of B&C device

## 7 CONCLUSIONS

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 or "loess") was compacted in a sand box of 1,4x1,4 m area. All together 68 cm of soil has been compacted and tested in eleven layer thicknesses.

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.

Correlation to the German Dynamic Plate (GDP) and static plate load test modulus was determined. Results show that B&C dynamic modulus is approx. 2,4 times higher than GDP modulus.

Correlation to static plate load test modulus gave an $E_2 = 0,94 \cdot E_d$ formula.

Dynamic compaction values measured by B&C device was found to be considerably higher than compaction determined by conventional soil sampling method, but only in case of lower compaction percentages. At higher compaction ratios, the difference tends to decrease gradually until 1-5 %. In case of compactions around 93-95 %, no significant difference was measured.

A measuring depth of 18-26 cm was found in case of silty fine sand. Therefore the effective layer thickness resulted in approx. equal to 1,5-times the plate diameter.

## REFERENCES

Andreas Ltd, 2007, B&C Main Page, www.andreas.hu/ENG/bcmain.htm

Boujlala, S. 2007. Relation entre l'essai de plaque ME et l'essai dynamique B&C, Projet de semestre, Département de la Construction, Filliére du génie civil, Ecole d'ingénieurs et d'architectes de Fribourg, Suisse

Majes, B. & Petkovsek, A. 2007. Usage of Andreas dynamic load bearing capacity and compactness deflectometer, Research Report, Faculty of Civil and Geodetic Engineering, Technical University of Ljubljana, Slovenia

Subert, I. 2006. Measuring Compaction-rate and Bearing Capacity with Small Disk Light Falling Weight Deflectometer, Presentation at 13th Danube-European Conference on Geotechnical Engineering, Ljubljana, Slovenia, 29-31. May 2006.