Correlative Studies of FWD, LDW and DCP Testing of Railway-Track Sub-Ballast Structures in Israel

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ABSTRACT: The performance of railway tracks depends to a large extent on the stiffness and strength of their subgrades and sub-ballast layers. Among the various methods of in-situ evaluation of stiffness, the Falling Weight Deflectometer (FWD) and some additional small-scale dynamic devices, such as the Light Drop Weight (LDW), have been gaining popularity in recent years. The LDW device substitutes in Israel for the German plate-bearing device by assuming that its surface modulus is equal to the static deformation modulus obtained from the regular plate-bearing test. The use of these various devices creates the need to study the correlation between results obtained with the LDW device and those obtained by using traditional approaches, such as FWD and the Dynamic Cone Penetrometer (DCP). The present work focuses on the correlation between these devices for local silty and clayey soils and local granular sub-base material. Studies have indicated that different types of equipment can produce different values for surface stiffness; furthermore, the experimental relationships between the different tests appear to be variable and perhaps site dependent. This paper also describes the DCP tests that were conducted together with the FWD and LDW tests in order to correlate stiffness results with CBR values. As a continuation of this line of investigation, the sensitivity of the depth of influence of the FWD device was then studied through (a) a theoretical analysis of a two-layered elastic model and (b) a correlative study of the FWD surface modulus results and the variation in CBR values with depth through DCP testing. The study concluded that although it is difficult (a) to determine a specific depth of influence and (b) to develop a unique relationship between stiffness and CBR values, approximated answers may be suggested.

KEYWORDS: CBR, DCP, FWD, LDW, railway track, sub-ballast, surface modulus.

1. INTRODUCTION

The thickness design of railway-track support in Israel is based on a recipe approach, in which the California Bearing Ratio (CBR) is applied to characterize the subgrade, capping, and sub-ballast materials. CBR is used as an index of both material strength and stiffness although it measures neither directly. Thus, performance-based specifications are required to control long-term functional and structural performance, in which quality-control testing is expected to include in-situ stiffness measurements on subgrade and sub-ballast layers, along with the conventional in-situ density measurements.

According to the Israel Railways design guidelines, the upper granular layer in the sub-ballast structure should comply with a limiting minimum value of the dynamic deformation modulus as measured by the German plate-loading. This limiting value is a function of six railway-design categories, each possessing unique elements, such as train speed, wheel loads, percentage of cargo trains, etc. In Israel, however, the Falling Weight Deflectometer (FWD) and the Light Drop Weight (LDW), which is one of the existing Light Falling Weight Deflectometer (LFWD) devices, and not the German plate-loading device, are employed for measuring in-situ stiffness. More specifically, the LDW device substitutes for the German plate-bearing device by assuming that its surface modulus is equal to the static deformation modulus obtained from the regular plate-bearing test.

The use of these various devices creates the need to study the correlation between results obtained with the LDW device and those obtained by using traditional approaches, such as FWD and the Dynamic Cone Penetrometer (DCP). In addition, the sensitivity of the depth of influence of the LDW and FWD devices should be explored. Finally, it is worth mentioning that the description of the various devices mentioned in this paper and their operational instructions can be found in [Nazzal, 2003], [Seyman, 2003] and [Phillips, 2005].

Given this background, the objectives of the present paper were formulated as follows: (a) to examine the comparative findings associated with FWD and LDW devices in local in-situ testing of prepared subgrades and upper sub-ballast layers; (b) to explore the sensitivity of the depth of influence of the LDW device through a correlative study of the LDW and FWD surface modulus results and the variation in CBR values with depth through DCP testing, accompanied by a theoretical study of a two-layered elastic model; (c) to correlate the LDW and the FWD surface modulus with the equivalent in-situ CBR value; and (d) to compare the required dynamic deformation modulus as defined by the German plate-bearing test (E_{V2}) with the target deflection values of FWD testing. The process of attaining these four major objectives is detailed in the present paper.

2. NOTES ON LDW AND OTHER LFWD DEVICES

As mentioned, the FWD and the LDW are employed in Israel for in-situ measuring of the stiffness of subgrades and sub-ballast railway layers. The LDW device, which is described in [Livneh, 2007a], substitutes in Israel for the German plate-bearing device by assuming that the LDW surface modulus (M_{LDW}) is equal to the static deformation modulus (E_{V1}) obtained from the regular plate-bearing test during the first load cycle (see the Din No. 18 134). This equality has been verified recently by comparative tests as reported in [Sulewska, 2004]. According to [Tompai, 2008], however, this equality was not verified, and the experimental relationship yielded the $E_{V1}=0.83\times M_{LDW}$ relationship. Furthermore, according to [Kim et al., 2007], the experimental relationship was found to be $E_{V1}=1.20\times M_{LDW}$ with an R^2 value of 0.76, thus making the $E_{V1}=1.0\times M_{LDW}$ an average relationship for routine application.

As for the second cycle of this German plate-bearing test, the dynamic deformation modulus, E_{V2}, can be calculated from the above-mentioned M_{LDW} by using the relationship given by the expression [Zorn, 1995] in Equation 1 which yields almost the same outputs as those defined by the recent Zorn graphical display of 2011, given in the following web-site: http://www.ticservicegroup.com.au/wp-ontent/uploads/2011/11/ldwt_replaces_cbr.pdf:

$$E_{V2} = 600 \times \ln \frac{300}{300 - M_{LDW}} \tag{1}$$

where: M_{LDW} denotes the LDW surface modulus in MPa calculated according to Equation 2, and E_{V2} denotes the dynamic deformation modulus of the German plate-bearing device in MPa.

$$M_{LDW} = \frac{0.5 \times (1-\mu^2) \times P}{a \times \delta_0} = \frac{22.5}{\delta_0} \tag{2}$$

In Equation 2, P denotes the applied force at loading plate, in N; δ_0 denotes deflection at the center of the loading point, in mm; a denotes the radius of the loading plate, in mm; and μ denotes a Poisson ratio. It is worthwhile noting here that according to [Zorn, 1995], Equation 2 is based on Boussinesq's theory for rigid plates, whereas for some other LFWD devices, such as the Japanese PFWD, the Boussinesq theory for flexible plates is applied [Kavussi et al., 2010] (in this connection, see also Equation 3). The $22.5/\delta_0$ term is obtained for the following LDW data: a=150 mm, P=7,070 N and μ=0.2.

In continuation of Equation 1, Figure 1 depicts recent experimental relationships of E_{V1} and M_{LDW} with E_{V2}. It can be concluded from this figure that the relationship according to [Tompai, 2008] yields lower values of E_{V2} than those obtained from Equation 1. Moreover, this figure indicates that in the relationship according to [Sulewska, 2004], the calculated E_{V2} values are much higher than those obtained from Equation 1. Finally, according to the points taken from [Weingart, 1993], the E_{V2} values are much similar to those obtained from Equation 1. To conclude, Figure 1 indicates that Equation 1 yields average results, making this equation suitable for routine application.

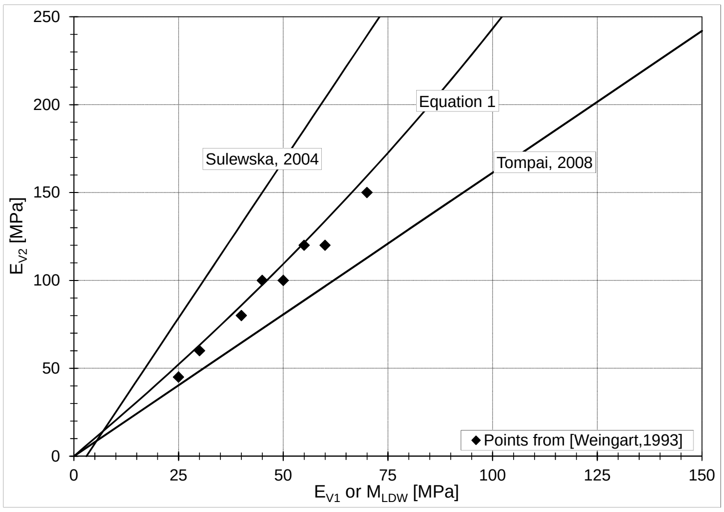

Figure 1: Relationships between the dynamic deformation modulus (E_{V2}) measured by the German plate-bearing device and the surface modulus (M_{LDW}) measured by the LDW device

This way of obtaining the dynamic deformation modulus, E_{V2}, is an important tool in the quality control process. As mentioned, the Israel Railways guidelines specify for each design category a limiting lower value of E_{V2} for the upper granular layer as measured by the German plate-bearing test.

The LDW device is also termed the German Dynamic Plate (GDP) in the technical literature. Here it is important to mention some additional existing LFWD devices, such as the Transport Research Laboratory Foundation Tester (TFT), the Prima 100 tester (also called the Light Weight Deflectometer-LWD), the Loadman from Finland, all as listed in [Fleming et al., 2007], as well as the portable Japanese FWD (PFWD) as listed in [Kamiura, 2009]. (Note: For more details, see [Fleming et al., 2007].)

The aforementioned LFWD devices do not yield identical results. As reported in [Fleming et al., 2000], "results from different devices can be dramatically different." Field investigations of [Fleming, 2001] showed that the GDP, TFT and Prima (LWD) devices tested gave contrasting results on the same test constructions; they are also influenced by many test-related factors and site-specific martial factors. In this regard, it is important to note that the ASTM Standard, entitled "Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)" (Designation No. E2583-07), recognizes that different results can be obtained from different devices for the same given testing location. In addition, this ASTM Standard states that for the various LWD devices referred to in Note 4 in the standard, the approximate surface modulus of the tested layer has been estimated to lie between <u>0.50</u> and <u>0.75</u> times the surface modulus calculated using an LWD device that meets the precision and bias requirements of the standard.

The conclusions of the above finding is that reporting the name of the device used for in-situ testing is a must in order to provide physical meaning to the results obtained. To recall, for the LFWD devices, this paper deals only with the LDW measurements.

3. LOCAL AND OTHER COMPARATIVE LDW AND FWD TESTS

For the FWD tests, the FWD surface modulus (M_{FWD}) in MPa is calculated according to the following expression:

$$M_{FWD} = \frac{2 \times (1-\mu^2) \times P}{\pi \times a \times \delta_0} \quad (3)$$

where: P denotes applied force at loading plate in N, δ_0 denotes deflection at the center of the loading point, in mm; a denotes the radius of the loading plate, in mm; and μ denotes a Poisson ratio. It should be noted here that Equation 3 is based on Boussinesq's theory for flexible plates. For these FWD tests, the following data is applied: a=225 mm, P=32.4 kN and μ=0.5. Here it is worthwhile noting that Equation 3 (flexible plate) with μ=0.5 yields almost the same results as Equation 2 (rigid plate) with μ=0.2.

Now, to check the moduli ratio (M_{LDW}/M_{FWD}), direct comparative LDW and FWD tests were recently performed on five railway-construction sites in Israel (10 points for each site). The results of the correlative analysis of the results obtained are displayed in Table 1.

Table 1: Relationship between measured M_{LDW} and M_{FWD} values at 5 local sub-ballast sites [Livneh et al., 2008]

Site	Material	LL [%]	-200 [%]	R^2	Modular Ratio
1	Granular Sub-base	NP	7-14	+0.19	0.58
2	Compacted Silt	34-40	37-92	-3.83	0.73
3	Granular Sub-base	NP	13-15	-2.27	0.49
4	Compacted Heavy Clay	75-79	95-97	-2.34	0.63
5	Compacted Medium Cay	50-59	93-96	-0.71	0.44
All Sites	All the Above Materials	NP-79	7-97	0.55	0.52

In addition to Table 1, Figure 2 displays another set of LDW and FWD measurements, these performed on the surface of a chalky-marl embankment constructed for a major road alignment [Livneh, 2007b]. This figure and Table 1 indicate that it is difficult to develop relationships between the aforementioned two tests unless a comparison is conducted on a site-specific basis. Moreover, even with a site-specific basis, the scatter of the results is remarkable, leading to very low and even negative values for R^2. Note that negative values for R^2 are possible in a constraint-regression operation, indicating that the product obtained is not significant.

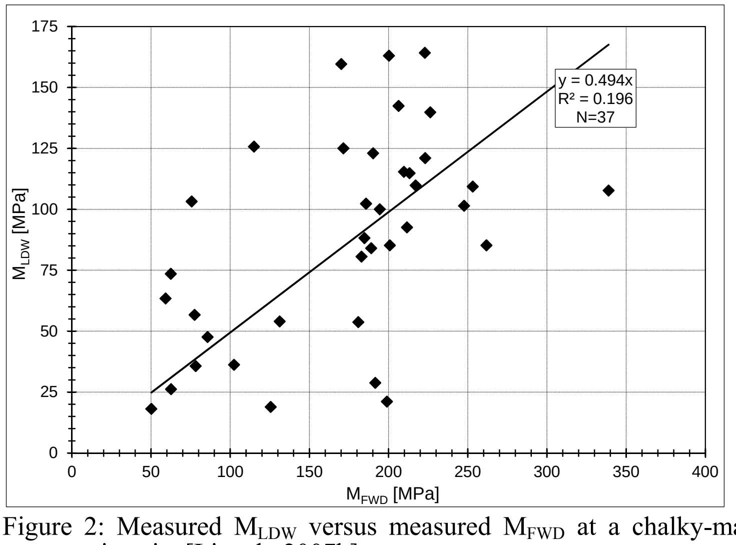

Figure 2: Measured M_{LDW} versus measured M_{FWD} at a chalky-marl embankment construction site [Livneh, 2007b]

At this juncture, it should be pointed out that similar correlative measurements have been reported in the technical literature. They are shown in Figure 3, which indicates that the values of M_{LDW} are equal to a range of 0.47 to 0.61, multiplied by M_{FDW}. This figure displays, once again, a considerable scatter in the results, especially those that yield a negative coefficient of determination (R^2) of -0.01.

Plate-loading tests (PLT) and Falling Weight Deflectometer (FWD) test were performed by [Loizos et al., 2003] in order to evaluate the subgrade modulus of three tested sections. A comparison of the mean values of these subgrade moduli is presented in Table 2. Because of the limited amount of data available, the comparison shown in Table 2 is simply made in terms of mean values in order to provide a gross evaluation of the subject matter.

Now, assuming that the PLT surface modulus (E_{V1}) values of Table 2 are equal to the surface modulus (M_{LDW}) values measured by the LDW device, as suggested at the beginning of Section 2, the modular ratio values given in this table can be regarded as the ratio values of M_{LDW} to M_{FWD}. These modular ratio values are of the same order of magnitude as all the values associated with Table 1, Figure 2 and Figure 3.

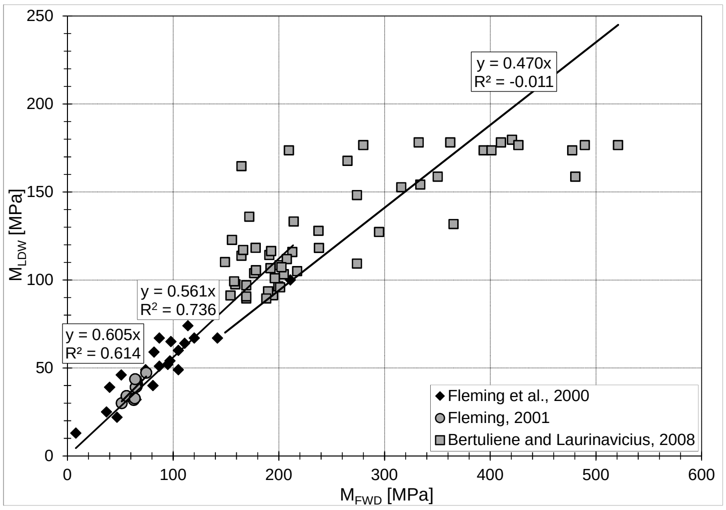

Figure 3: Measured M_{LDW} versus measured M_{FWD} according to [Fleming et al., 2000; Fleming, 2001; Bertulienė and Laurinavičius, 2008]

Table 2: Mean values of surface modulus measured by Falling Weight Deflectometer (FWD) and L-Loading Tester (PLT) after Figure 10 of [Loizos et al., 2003]

Section	Surface Modulus [MPa]		Modular
No.	FWD	PLT	Ratio
1	485	215	0.44
2	179	138	0.77
3	162	108	0.67

To sum up, the ratio values of M_{LDW} to M_{FWD} obtained above lie in the range of 0.44 to 0.77. Thus, for reasons of coefficient-of-safety, it is suggested that the $M_{LDW}=0.44\times M_{FWD}$ relationship be applied, which will lead to the following relationship:

$$E_{V2} = 600 \times \ln \frac{300}{300 - 0.44 \times M_{FWD}.} \approx 1.0 \times M_{FWD} \qquad (4)$$

Here, it should be noted that Equation 4 acquires experiential verification through the data of Table 6.1 in [Nazzal, 2003], for which the multiplier factor equals 1.03, R^2=0.74, and N=22.

According to local specifications, the required limiting central deflection measured on a subbase surface is 400 micron, for which the measuring FWD device is characterized, as previously mentioned, by P=32.4 kN and a=225 mm [Livneh, 2008; Livneh et al., 2008]. Thus, for μ=0.5 and Equation 3, M_{FWD}=172 MPa; and for the same data and Equation 4, E_{V2} is also equal to 172 MPa. This latter value is higher than the required maximum for E_{V2} (120 MPa) as defined by the design guidelines issued by Israel Railways Ltd.

Finally, it is important to note that the technical literature contains entirely deferent values for the M_{LDW}-M_{FWD} ratio than those previously mentioned. For example, according to [Fleming et al., 2007], this ratio can reach a value of 2.26; and according to [Livneh, 2007a], it can even reach 2.94, both of which far exceed the maximum value of 0.77 previously mentioned. However, these exceptional ratio values were obtained for measurements conducted on the surface of asphaltic pavements. According to [Fleming et al., 2007], too, the ratio of M_{LWD} (i.e., the surface modulus of another device, the LWD) to M_{FWD} ranges between 0.8 and 1.4. Thus, when adopting a ratio value from any published information, attention should be paid to (a) the extent to which the material quoted resembles the material under consideration and (b) whether the measuring device specified in this information is the same as the present LDW.

4. CORRELATIVE RELATIONSHIPS AND DEPTH OF INFLUENCE

Correlative relationships between recorded M_{LDW} values (in MPa) or recorded M_{FWD} values (in MPa) and interpreted CBR_e values from the associated recorded DCP are conducted according to the following equations:

$$M_{LDW} = \alpha \times CBR_e^{1/1.41} \tag{5a}$$

$$M_{FWD} = \beta \times CBR_e^{1/1.41} \tag{5b}$$

$$CBR_e = \left(\frac{\Sigma[\Delta Z_i \times \sqrt[3]{CBR_i}\,]}{\Sigma \Delta Z_i} \right)^3 \tag{6}$$

where: CBR_e denotes the equivalent CBR value of the interpreted CBR values (from the DCP test) that vary along a depth with a predefined maximum value (Zo), measured from the surface of the LDW test or the FWD test; CBR_i denotes the CBR value (interpreted from the DCP test) existing along a strip at a given depth and with a thickness of ΔZ_i; and $\sum \Delta Z_i$ denotes the total depth of Zo.

Equations 5 and 6 assume that the character of the stratum along this predefined depth (Zo) has a major influence on the M_{LDW} or M_{FWD} results. It should be noted that (a) the use of the 1.41 power function in Equation 5a or 5b was suggested previously in [Livneh, 1988], based on local experience; and (b) the equivalent CBR value (CBR_e) expression of Equation 6 is quoted from [Livneh and Ishai, 1987].

The predefined depth (Zo) in Equation 6 actually denotes the depth of influence (also termed the measurement depth or the impact depth) of any given LFWD or FWD device. Existing observations concerning this depth of influence are reported in the technical literature. According to [Fleming, 2001; Moony and Miller, 2009; Fleming et al., 2009, among others], the LWD depth of influence is 0.9-1.5 times the plate diameter. According to [Heczko, 2009], on the other hand, the LWD depth of influence may amount up to twice the plate diameter.

In order to derive a theoretical evaluation of the values of Zo, a two-layered elastic model was postulated. In this model, E_1 denotes the modulus of elasticity of the upper layer, which possesses H_1 thickness; E_2 denotes the modulus of elasticity of the lower layer, which extends to infinite depth; a denotes the radius of the flexible bearing plate; a Poisson ratio for both layers is equal to 0.5, and the α factor of Equation 5a and the β factor of Equation 5b are taken as equal to 1.0. If the Odemark-Ulidtz approximation is applied, the surface modulus (M) can then be calculated for various values of E_2/E_1, H_1 and Zo. Figure 4 displays an example of such a calculation, in which E_2=25 MPa, E_1=200 MPa and a=150 mm. This figure indicates that various values of Zo lead to various values of the calculated α or β factor, ranging from 0.42 for Zo=300 mm up to 1.21 for Zo=1,000 mm.

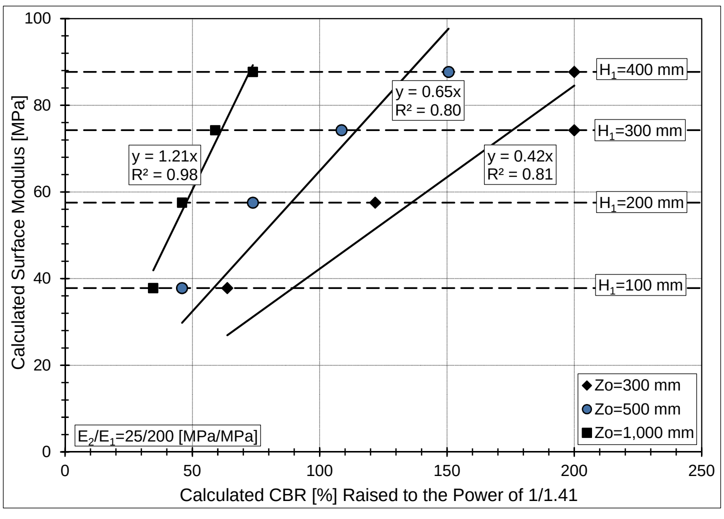

Figure 4: Calculated M_{LDW} versus calculated CBR_e for a theoretical two-layered elastic model.

The aforementioned calculations assist in finding the Zo value for which the calculated α or β factor is equal to the original value; i.e., 1.0. For the example of Figure 4 (i.e., where E_2/E_1=25/200=0.125), this value is equal to 762 mm; for other values of E_2/E_1, the corresponding Zo values (for which calculated α or β equals 1.0) are as shown in Figure 5. This figure indicates that these Zo values are essentially (a) higher than twice the bearing plate diameter for E_2/E_1 smaller than 1.0; (b) about the same as the bearing plate diameter for E_2/E_1 larger than 1.0. Thus, if these Zo values denote the depth of influence (i.e., the measurement depth or the impact depth), the theoretical findings match the aforementioned experimental values, indicating that no single value can be assigned for a depth of influence. This conclusion is in compliance with the following quotation [Fleming et al., 2009]: "…there is a clear argument to suggest that for layered road foundations the depth of significant stressing is likely to be affected by the stiffness modulus ration of adjacent layers, especially if the upper layer is less than one plate diameter in thickness."

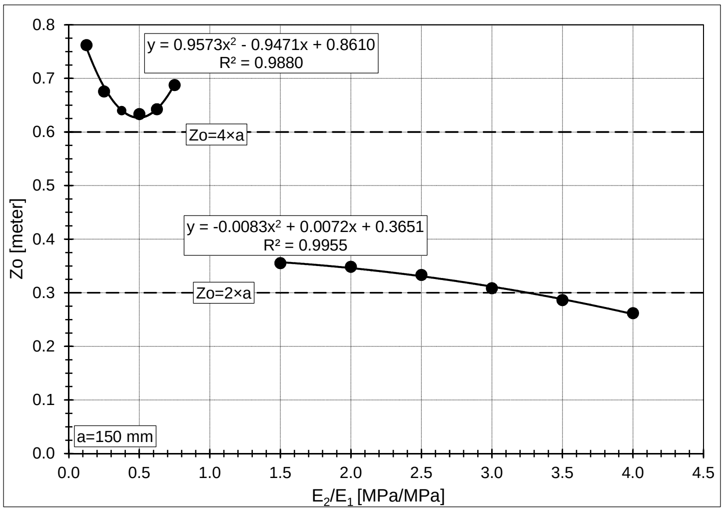

Figure 5: Zo as a function of E_2/E_1 for which the α factor is equal to he α original factor (i.e., 1.0) in a theoretical two-layered elastic model

5. COMPARATIVE LOCAL LDW, FWD AND DCP TESTS

In order to evaluate the α factor of Equation 5a as a function of Zo, test-pits were excavated at three different locations, all of which contained an undisturbed silty and silty-clay stratum. Comparative LDW and DCP tests were carried out on staggered surfaces, arranged at depths of approximately every half meter. The α factors obtained for these measurements, utilising three values of Zo (i.e., 0.25, 0.50 and 1.00 meter), are shown in Table 3.

Table 3: Calculated α and β factors and R^2 values for different Zo values as measured at 5 construction sites.

Material	Device (No. of Measurements)	Zo [mm]	Regression Outputs		
			α Factor	**β Factor**	**R^2**
Silt and Silty-Clay	LDW (N=169)	250	3.28	---	---
		500	3.07	---	-0.60
		1,000	3.04	---	-0.53
Existing Sub-Ballast	LDW (N=14)	900	4.01	---	0.76
		1,200	4.04	---	0.72
Compacted Silt	FWD (N=29)	500	---	5.85	0.19
		1,000	---	5.63	0.12
Existing Sub-base(*)	FWD (N=10)	600	---	9.78	0.57
		900	---	9.91	0.42
Existing Sub-base(**)	FWD (N=10)	600	---	9.51	-0.17
		900	---	9.87	-0.16

(*) Dry (before rainfall); (**) Wet (after rainfall at the same sub-base location).

Table 3 indicates that the Zo value for the sites tested does not significantly influence the α or β factor, which means that, from a practical point of view, these sites can be regarded as homogenous. The values obtained for the α factor of Table 1 range between 3.04 and up to 4.04, and those for the β factor range between 5.85 and 9.87. These values are to be supplemented with the findings given below.

Various additional correlative local studies are given by [Livneh, 2007b]. These studies indicate that the values obtained for the α factor range from 3.07 to 6.02, with R^2 values ranging from a negative value of -0.56 to a considerably high value of 0.78. For the present study, all the aforementioned local tested data from all previous references (including the new ones from Table 3) were divided into these two groups: (a) silty and clayey materials, for which the design CBR is lower than 15%; (b) granular and sandy materials, for which the design CBR is higher than 15%. For the first group, the α factor obtained is given in Figure 6, in which it is equal to 3.99 and R^2=0.32. In a similar manner, the α factor obtained for the second group is given in Figure 7, in which it is equal to 5.01 and R^2=0.74.

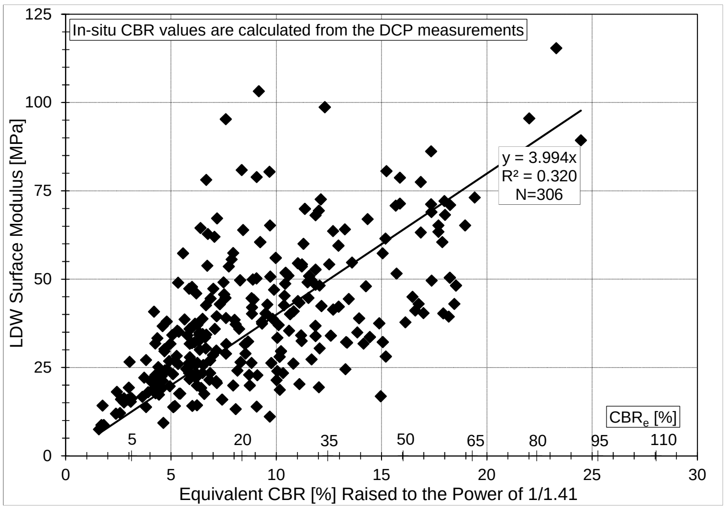

Figure 6: Surface modulus from LDW testing versus in-situ CBR as obtained for local silty and clayey materials

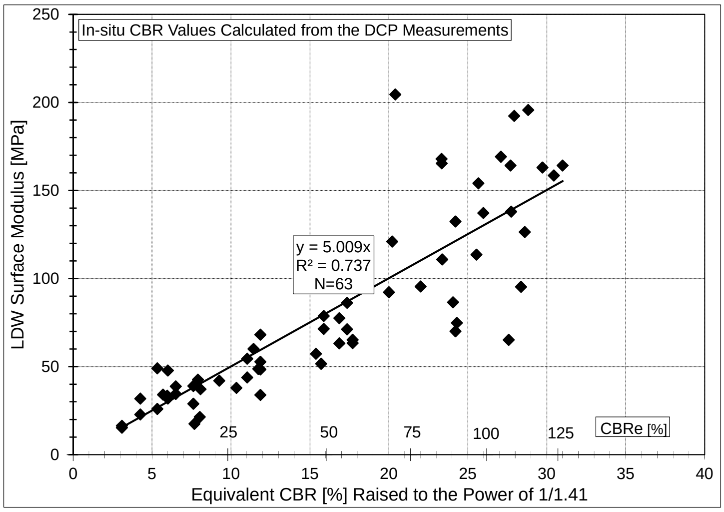

Figure 7: Surface modulus from LDW testing versus in-situ CBR as obtained for local granular and sandy materials

Here, it is important to note that the two values of the α factor are entirely diffident from those reported earlier by the author [Livneh, 2000]. Those reported values were 6.02 for a clayey stratum [N=13] and 4.35 for a sandy stratum [N=29], both, in fact, being values in an opposite direction to the two mentioned above. However, as the data given in Figures 6 and 7 already include the [Livneh, 2000] data, it seems that the outputs of these two figures are more relevant. Furthermore, the average value of these two α factor values coincides with that given by Zorn on the internet, α=4.45. This latter value is different from that given in the past by [Zorn, 1995].

As for the FWD device, it is suggested that the empirical relationship mentioned earlier in this paper (i.e., M_{LDW}=0.44×M_{FWD}) be utilized. The β factor can be calculated from this relationship: 9.08 for the first group and 11.34 for the second group. Here it is interesting to note that the β factor obtained for the total data of Table 1 (N=50) yielded the value of 10.42, which is the average value of the two values mentioned previously (i.e., 9.08 and 11.34). The accompanying R^2 yielded a value of 0.65. According to [Seyman, 2003], [Nazzal, 2003] and [Phillips, 2005], the β value equals, respectively, 10.47 (R^2=0.86), 10.86 (R^2=0.35) and 13.50 (R^2=0.29).

6. CONCLUSIONS

The performance of railway tracks depends to a large extent on the stiffness (surface modulus) and strength of their subgrades and sub-ballast layers. Among the various methods of in-situ evaluation of stiffness, the Falling Weight Deflectometer (FWD) and some additional small-scale dynamic devices, such as the Light Drop Weight (LDW), have been gaining popularity in recent years

Various studies have indicated that different types of falling-weight equipment can produce different values for subgrades and sub-ballast layer stiffness. This is not surprising, as some of this equipment is used for measuring very different resonances. For the same reason, the reported R^2 values obtained for the various correlative equations reported in the present paper are sometimes very low, even negative.

Nevertheless, for design purposes, the following findings are derived from this study: (a) It seems that LDW surface modulus outputs are of the same magnitude as those obtained from the first loading cycle in German static plate-bearing tests (i.e., E_{V1}); thus, the LDW device can be used as a substitute for the German static plate-bearing. (b) The ratio of LDW surface modulus (M_{LDW}) to FWD surface modulus (M_{FWD}) ranges from 0.44 to 0.77, so that the design ratio is taken as 0.44. (c) For design purposes, the FWD surface modulus (M_{FWD}) is of the same magnitude as that obtained from the second loading cycle in German static plate-bearing tests (E_{V2}). (d) Theoretical analyses indicate that the depth of influence of the measuring device is higher than twice the bearing plate diameter for E_2/E_1 smaller than 1.0, and about the same as the bearing plate diameter for E_2/E_1 higher than 1.0, where E_1 is the modulus of elasticity of the upper layer and E_2 is the modulus of elasticity of the lower layer; this result indicates that no single value can be assigned for the depth of influence. (e) The aforementioned range of depth-of-influence theoretical values coincides with that of experimental values reported in the technical literature; however, for the experimental measurements in the present study, the depth of influence behaved as an independent variable. (f) It is difficult to develop a unique relationship between LDW or FWD surface modulus and CBR values; nevertheless, general approximate answers can be suggested, one for silty and clayey materials (α=3.99) and second for granular and sandy materials (α=5.01).

Finally, it should be noted that the above findings lead to the conclusion that the FWD central deflection criterion specified by Israel Railways Ltd. leads to higher E_{V2} values as is indeed required by its design guidelines. The present paper's conclusions substitute for the previous results published by the author elsewhere on the same matters.

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