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Original Research Paper

Comparative studies of lightweight deflectometer and Benkelman beam deflectometer in low volume roads

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ABSTRACT

A comparative subgrade moduli study is carried out by static and dynamic deflection methods using lightweight deflectometer and conventional Benkelman beam deflectometer on low volume road. Field and laboratory tests are performed at 40 test locations on in-service road of 2 km stretch that contains three common types of cohesive soils (CH, CI, and CL). Pavement static and dynamic responses are estimated to ascertain static, backcalculated, and composite moduli of subgrade. The backcalculated and composite moduli of subgrade is validated at given moisture content using repeated triaxial test. Static moduli values are on lower side as compared with dynamic moduli values whereas the composite, and laboratory moduli of subgrade are approximately consistent with 2% to 7% variation, respectively. Correlation analyses between static and dynamic moduli of different types of subgrade soils depict good correlation of determination (R^2) varies between 0.75 and 0.91. Subsequently, validation of static moduli with California bearing ratio (CBR) related subgrade moduli shows moderate correlation of 0.67 to 0.74 whereas dynamic moduli shows good correlation of 0.74 to 0.93 for different types of soils, respectively. Therefore, the comparative analysis shows that lightweight deflectometer provides reliable subgrade moduli values, and it can be used as a quick subgrade strength evaluating tool for low volume roads.

1. Introduction

The current method of structural evaluation system largely depends upon static deflection techniques for Indian low volume roads (Reddy and Veeraragavan, 1997). Recently, government of India estimated that, approximately for low volume roads (LVRs), the 5-year routine maintenance cost was in the range of 6%–13% of construction cost during the base year 2013 (Barodiya and Pateriya, 2014). The non-destructive testing techniques are recommended in road construction and evaluation practices for Indian highways to

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Table 1 – Summary of expressions for deformation modulus.

Name of the device	Expression for deformation modulus	Parameter
Static beam (press)	$E_v = 1.5r(\Delta\sigma/\Delta_s)$	E_v is the deformation modulus, E_{vd} is the dynamic deformation modulus, E_0 is the surface modulus in centre of loading plate, r is the radius of a loading plate, $\Delta\sigma$ is the change in stress under the beam in the centre, Δ_s is the change of soil deformation in the centre of the beam, k is the load transfer coefficient measured by deflection indicator and wheel ($k = 0.85$), P is the pressure of vehicle wheel on pavement, D is the reduced wheel path diameter, μ is Poisson's ratio ($\mu = 0.3$), I_p is the reduced pavement deflection, δ is dynamic load to 0.1 MN/m^2, s is the soil deformation under loading plate, l is the deflection, f is the stress distribution ratio (2-even segmented loading plate; π/2-rigid plate; 8/3-granular soils rigid plate; 4/3-cohesive soils rigid plate), σ_0 is the contact pressure under the loading plate.
Static Benkelman beam deflectometer (BBD)	$E_v = [kPD(1-\mu^2)]/I_p$	
Light dynamic devices (Zorn ZSG 02), LWD (Prima 100)	$E_{vd} = 1.5r(\delta/s)$	
Falling weight deflectometer (FWD)	$E_0 = [f(1-\mu^2)\sigma_0 l]/r$	

implement the mechanistic-empirical based analysis and design (IRC, 2012, 2014). However, for low volume roads various researchers suggested the estimation of deformation modulus with a constitutive equation and finite element programs (AASHTO, 1993; Fleming, 2000; Rajagopal and Justo, 1989; Zhou et al., 2010). But its applicability in India is very limited.

According to AASHTO guidelines, pavement evaluation measurements and analysis had a significant impact using static and dynamic devices in the context of mechanistic-empirical approaches (Bertuliene and Laurinavicius, 2008). In these mechanistic-empirical approaches, the structural integrity of pavement layers was primarily governed by the principle parameter widely termed as the resilient modulus (Senseney and Mooney, 2010; Solanki et al., 2011). The resilient behaviour of pavement layer materials was being assessed globally and in Indian National Highways using non-destructive field investigation tools such as falling weight deflectometer (FWD) and lightweight deflectometer (LWD) (Fleming et al., 2007).

Recently, LWD, a dynamic stiffness device, gained popularity as portable and cost effective tool for the determination of in-situ responses like deflections and surface modulus on thin bound, and unbound layers (Grasmick et al., 2014). These in-situ responses were being analyzed by a predominant technique known as backcalculation to estimate resilient layer moduli (ASTM, 2007; Senseney et al., 2010). Also, these in-situ responses were being used to estimate the residual life of in-service pavement and also defining various maintenance strategies such as overlays etc. (Zhou et al., 2010). LWD devices can also be used as quality control/quality assurance and structural evaluation tool by assessing in-situ compacted stiffness. However, use of portable dynamic deflectometers for structural evaluation of low volume roads is very limited in India (Senseney and Mooney, 2010; Tehrani and Meehan, 2010).

Although, structural evaluation using Benkelman beam deflectometer (BBD) for low volume roads is current regular practice in India. Significant limitations and various comparative studies are discussed by researchers focusing on identifying the limitations of static devices, such as: (1) stress condition evaluation in pavement layers from measured rebound deflection data is questionable; (2) variations in profile and magnitude of rebound deflection bowls from point to point (Rajagopal and Justo, 1989); (3) difficulty in extrapolating the deflections at transient loadings generating due to higher speeds of vehicles; (4) lack of stable zero reference led to erroneous values that resulted in underestimation of pavement deflections and unrealistic assessment of structural integrity (Meier and Rix, 1995); (5) slow performance, data uncertainty, and low reliability of results (Murillo Feo and Urrego, 2013).

A comprehensive comparative study was conducted by Bertuliene and Laurinavicius (2008) between static beam (Strassen test), light dynamic device (Zorn ZSG 02), LWD (Prima 100), and FWD (Dynatest 8000) by measuring resilient moduli named as deformation modulus of road subgrade and frost blanket course using the following expressions as shown in Table 1. Table 1 provides various expressions used to estimate deformation modulus based on the deflections measured by using different static and dynamic devices. The description of each variable used in the expressions is also summarized in Table 1. Bertuliene and Laurinavicius (2008) stated that for subgrade layer the mean deformation modulus estimated by light dynamic device (Zorn ZSG 02), LWD (Prima 100) were 14% – 17% lower than static beam values, and FWD (Dynatest 8000) values were 70% higher than the static beam values. Whereas, on frost blanket layer light dynamic device (Zorn ZSG 02), LWD (Prima 100) were 33% – 43% lower than the static beam values, and FWD (Dynatest 8000) values were 40% higher than the static beam values due to its differences in measuring methods and calculation methodologies.

Davies (1997) and Livneh et al. (1997) developed correlation between loadman portable falling weight deflectometer (PFWD) and BBD deflections on surface layers yielding poor correlations.

Zhou et al. (2010) carried out a comparative study of falling weight deflectometer (FWD) and Benkelman beam deflectometer (BBD) by developing correlation between BBD and FWD deflections for the junction of A30 and A12 in Shanghai as shown in Eq. (1).

$$\mathrm{FWD} = 4.39\,\mathrm{BB} - 15.8 \tag{1}$$

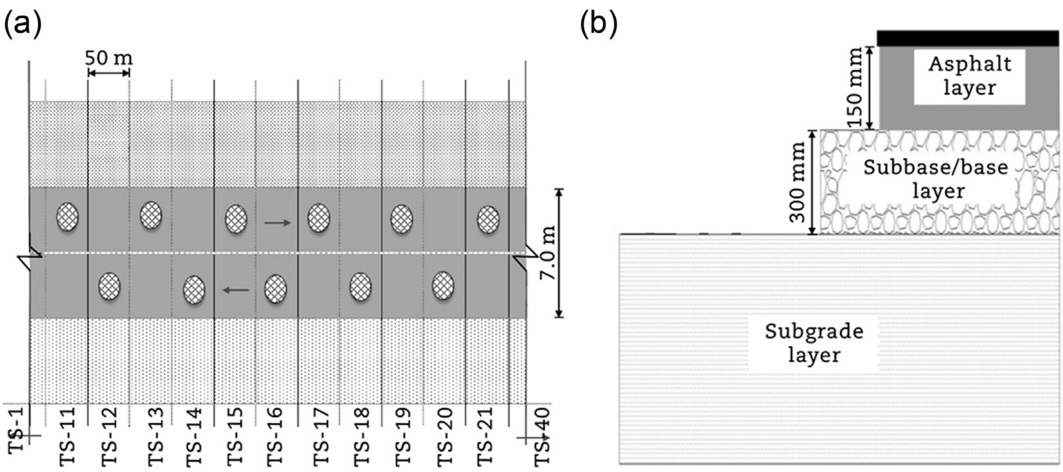

Fig. 1 – Condition of tested flexible pavement. (a) Test locations of LWD and BBD testing. (b) Average crust thickness and composition of project stretch.

where FWD is the deflection induced by FWD, BB is the deflection induced by Benkelman beam.

According to the study, the static modulus values were on lowerside as compared with dynamic modulus values. The tests results were interpreted, and the corresponding ratios were determined between static and dynamic modulus values. Thus, the previous studies mainly focussed on the use of FWD and PFWD/LWD as a replacement to BBD for subgrade strength evaluation on highways.

Considering the limitations of static BBD, there was a need for the prerequisite to carryout comparative studies of both regular dependency methods with new methods in order to eliminate the ambiguity in selection of resilient moduli and to establish as a reliable subgrade structural evaluation tool for low volume roads.

Thus the objective of this study is to carryout a comparative study between LWD and BBD as an in-situ subgrade strength evaluating tool by estimating static and dynamic moduli for low volume roads in India. The following tasks will be performed: (1) field investigations for estimating deflections using LWD and BBD, laboratory investigations for estimating basic soil properties and resilient modulus using conventional tests and repeated triaxial apparatus, (2) estimation of backcalculated composite and static moduli of subgrade, (3) development and validation of correlations between static and dynamic moduli of subgrade.

2. Experimental program and testing protocol

2.1. *Study area*

An experimental investigation was carried out on selected low volume flexible pavement stretch of 2000 m long and 7 m carriageway width during pre-monsoon season. The selected stretch carries average daily traffic volume of 1500 passenger car unit per day (PCU/d) in which commercial vehicles per day (CVP/d) are about 275 in the state of Gujarat, India. The entire project stretch was divided into 40 test sections of 50 m length in a staggered pattern as shown in Fig. 1(a). This figure emphasized test point indicated on each test section along the outer wheel path in both directions for BBD and LWD tests. The pavement was constructed in the year 2013, and the average existing crust thickness composition as per site conditions comprised of 150 mm bituminous layer, 300 mm base/subbase upon cohesive subgrade soil as shown in Fig. 1(b). Pilot pavement condition survey on the selected stretch was carried out, and ravelling, hungry surface, Hairline cracks on few sections was diagnosed.

2.2. *Field investigations*

Detailed field investigations were performed during the pre-monsoon season on the selected stretch using conventional BBD and LWD as Indian Road Congress (IRC) and American Society for Testing and Materials (ASTM) standards. Pavement responses such as deflections were collected using LWD and BBD followed by pavement core sample from test pits on 40 test sections for identifying in-situ crust composition which acted as seed values for backcalculation algorithms to estimate in-situ layer moduli. Pavement crust thickness along the study stretch was also explored from test pits as shown in Table 2.

2.2.1. *Static deflection tests (Benkelman beam deflectometer)*

Static pavement responses in terms of rebound deflections were measured on 40 test sections using conventional BBD as per IRC testing standards. Rebound deflections were

Table 2 – Section crust composition.

Crust composition	Average layer thickness (mm)		
	CH soil	CI soil	CL soil
Bituminous layer	150	152	149
Granular layer	289	294	293
Total	439	446	440

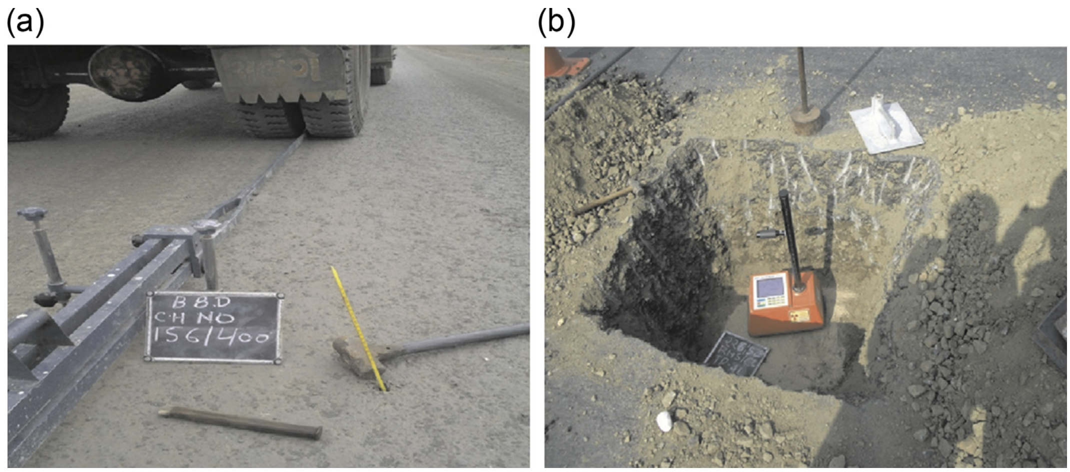

Fig. 2 – Construction site photo (a) BBD test scheme. (b) Field moisture content and density measurement at subgrade level.

measured along two parallel wheel paths at 0.9 m from carriageway edges. A standard loaded truck with a rear axle load of 80,126 N and tire pressure of 0.56 N/mm^2 was used (IRC, 1997; Wilkins, 1962) as shown in Fig. 2(a). Pavement surface temperature and subgrade moisture content had a significant influence on pavement performance and serviceability (Blight, 1974; Scrivner and Michalak, 1969). The pavement performance was designated in terms of in-situ responses and its elastic recovery obtained from in-situ deflection studies. The temperature and moisture content variations during different periods of field studied differs the in-situ deflection measurements to compare. Therefore, it was necessary to apply appropriate correction factors to the measured deflections (Reddy and Veeraragavan, 1997). The pavement temperature at the surface and 40 mm depth were recorded at every test section. Subsequently, moisture content of subgrade soil has been recorded by excavating test pits using nuclear density gauge (NDG) as shown in Fig. 2(b). The surface and 40 mm depth temperature were measured at each test section of entire stretch by excavating a small hole of 40 mm depth filling with glycerol (Reddy and Veeraragavan, 1997). The average surface and 40 mm depth temperatures were observed to be 45 °C and 38 °C. Thus the measured deflections were used to calculate static moduli of subgrade after applying necessary temperature and subgrade moisture content corrections as discussed in the subsequent section.

2.2.2. *Dynamic deflection tests*

2.2.2.1. *Lightweight deflectometer characteristics*. Dynatest 3031 LWD test was performed on selected pavement test locations by generating impulse load using 20 kg drop mass, from a maximum drop height on top of circular plate having a 300 mm plate diameter as ASTM protocols (ASTM, 2007). The drop of 20 kg induced an impulse load of 13.2–16.5 kN was observed on the pavement surface. The higher drop mass of weight of 20 kg was used in this study instead of 5, 10, and 15 kg as the modulus is directly proportional to higher drop mass (Kavussi et al., 2010). Various researchers carried out extensive studies on identifying the inherent factors influencing the LWD measurements, these factors were categorized in two distinct ways, such as: (a) LWD equipment characteristics such as drop height, plate size, radial sensor spacing and drop weight (Benedetto et al., 2012; Stamp and Mooney, 2013), (b) soil index and volumetric properties susceptible to environmental conditions (Tehrani and Meehan, 2010). Thus, the maximum drop height, drop mass and plate diameter induced an average stress range of 185–235 kPa on the pavement surface. This average contact stress range simulated the stress level when induced due to the standard vehicular loading (Fleming, 2001). As the LWD load influence depth was governed by two important cases, (a) for plate diameter, depth of influence was approximately 1.5 times the plate diameter (Nazzal et al., 2007), (b) influence depth of LWD with radial geophones was 1.8 times of plate diameter whereas, depth of influence of LWD without geophones was 1.0–1.5 times of plate diameter (Senseney and Mooney, 2010). Thus the selected plate diameter and LWD with radial geophones in this study affirms appropriate load influence depth for the pavement stretch to estimate backcalculated layer moduli in a multilayer system.

The responses were collected using three transducers, including center and offset velocity transducer geophones fixed at distances of 0, 300, and 600 mm and were mounted to the load plate which was also isolated from direct impact force. The 300 or 600 geophone configuration captured deflections and produced most reliable layer moduli backcalculation results (Senseney and Mooney, 2010). The frequency ranges of geophones used were 0.2–300 Hz with a resolution of 1 μm (Vennapusa and White, 2009).

2.2.2.2. *Deflection measurements*. Deflections obtained from all transducers were recorded and compared using personal data assistant (PDA). In this study, the mean load impulse time history was varying from 17 – 25 ms. However, the only center transducer was selected for the analysis of measured deflections as center transducer generates maximum deflection beneath the load. In this study, LWD test was performed

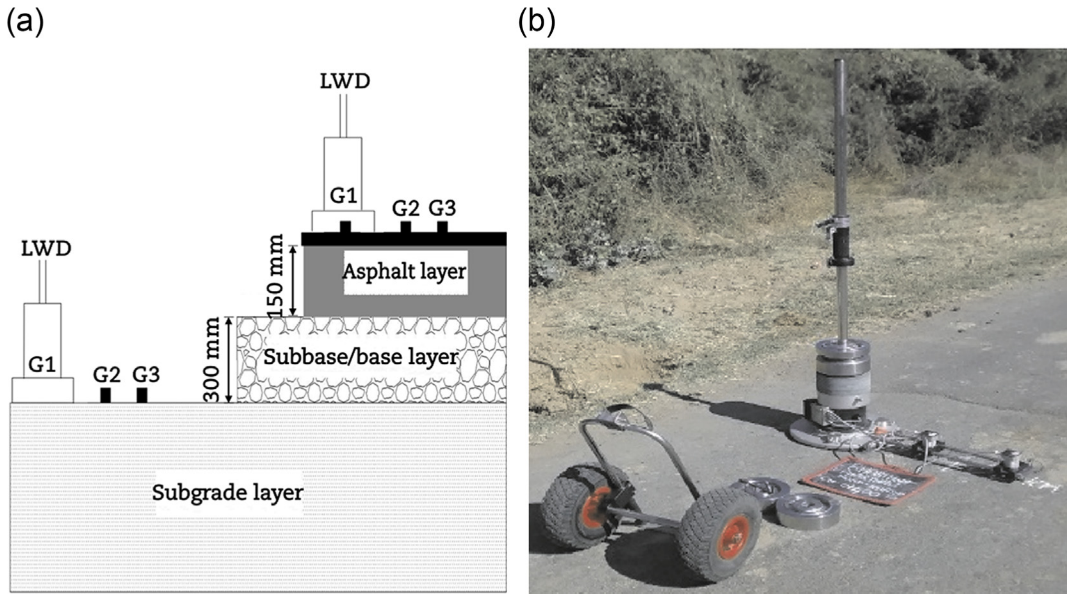

Fig. 3 – Work schematic of LWD. (a) LWD experimental program. (b) Dynatest LWD 3031 with transducers.

both at top of the bituminous layer to estimate subgrade layer moduli by adopting backcalculated techniques hereafter designated (M_{r_Back}) and at the top of subgrade layer to estimate composite subgrade layer moduli hereafter designated (M_{r_Comp}). The detailed schematic of LWD experimental program is shown in Fig. 3(a). LWD test was repeated at each test location by dropping six multiple drops (deflections) of which three drops were considered as seating drops and remaining were used for backcalculating pavement layer moduli. Fig. 3(b) shows the LWD setup along with transducers employed in this study.

2.2.3. *Test pits and sample collection*

Test pits were dug at 40 test sections soon after the surface deflection measurements for soil sample collections and crust thickness profile. The average existing crust thickness profile for each type of subgrade soil is shown in Table 2. The collected soil samples at each section in test pits were used for laboratory investigations as discussed in subsequent sections.

2.3. *Laboratory investigations*

Laboratory investigations, including conventional index, volumetric properties along with conventional California bearing ratio (CBR) test and repeated triaxial test, were performed on soil samples collected from test pit excavated at each test section.

2.3.1. *Subgrade soil properties*

Tests pits data were used to assess the variations in soil characterization, which associated properties were collected to perform laboratory investigations. Laboratory investigations were performed as the Indian standard specifications to determine conventional index and volumetric properties such as liquid limit, plastic limit, average dry density, and average moisture content as shown in Table 3. CBR test was also performed for soil samples collected at all the test sections to determine subgrade moduli hereafter designated as M_{r_CBR} in order to validate in-situ estimated moduli. Table 3 presents the type of soil and a wide range of its associated properties for 120 test samples measured by the laboratory investigations. For each test, three samples were prepared, and an average of three test results was considered as shown in Table 3.

2.3.2. *Repeated triaxial tests*

Laboratory moduli of subgrade (M_{r_Lab}) was experimentally determined in the laboratory by applying repeated axial load on three soil samples collected from each test pit at each test section in a triaxial cell. Resilient modulus test in this study

Table 3 – Soil properties of test sections.

Parameter	Subgrade soil		
	High plasticity (sample number: 36)	Medium plasticity (sample number: 48)	Low plasticity (sample number: 36)
Indian soil classification	CH	CI	CL
Liquid limit (W_L) (%)	57	42	33
Plastic limit (W_p) (%)	25	23	21
Plasticity index (I'_p) (%)	32	19	13
Free swell index (FSI)	49	22	5
Field dry density (γ_{df}) (kN/m^3)	1.818	1.849	1.948
Field moisture content (W_{cf}) (%)	13.56	12.17	10.36
California bearing ratio (%) (CBR value)	2.5	3.0	5.8

Table 4 – Summary of repeated triaxial test results.

Type of soil	Number of samples	Axial stress (kPa)	Confining pressure (kPa)	Field moisture content (%)	Field dry density (γ_{df}) (kN/m^3)	Laboratory resilient moduli (M_{r_Lab}) (MPa)
CH	36 (12)*	13.8–68.9	13.8–41.4	13.56	1.818	36.7
CI	48 (16)*	13.8–68.9	13.8–41.4	12.17	1.849	52.9
CL	36 (12)*	13.8–68.9	13.8–41.4	10.36	1.948	75.9

Note: "*" means number of test locations.

was performed as the test procedure suggested by AASHTO standard for 120 soil specimens (AASHTO, 1998). The sample deformations were monitored using two linear variable differential transducers (LVDTs) mounted to the chamber. In the view of simulating the in-situ conditions in terms of representative stress levels on subgrade soils, the level of confining stress induced by 80 kN equivalent single axle load (ESAL) on the subgrade top would be about 13.8–27.6 kPa (Elliott and Thornton, 1988). The application of load repetitions during conditioning stage and post conditioning stage of prepared specimen for each load sequence for subgrade soils were as Table 1 suggested in AASHTO standard for subgrade soil (AASHTO, 1998). Three specimens were prepared for one test section by maintaining moisture content and density levels similar to the in-situ conditions that were previously observed at each test section. The prepared test specimens were tested under repeated triaxial test apparatus. The corresponding mean deviator stress and mean recovered deflection/strain were recorded, and subsequently M_{r_Lab} was calculated using the constitutive model as shown in Eq. (2).

$$M_r = \sigma_d / \epsilon_r \tag{2}$$

where M_r is the resilient modulus, σ_d is the repeated deviator stress, ϵ_r is the recoverable axial strain.

The measured M_{r_Lab} values for all test specimens along with the study stretch are shown in Table 4. The range of axial stress and confining pressure values are shown in Table 4 as AASHTO (1998) guidelines. These measured M_{r_Lab} values were further used to validate the back calculated M_r values estimated from LWD test as discussed in the subsequent section.

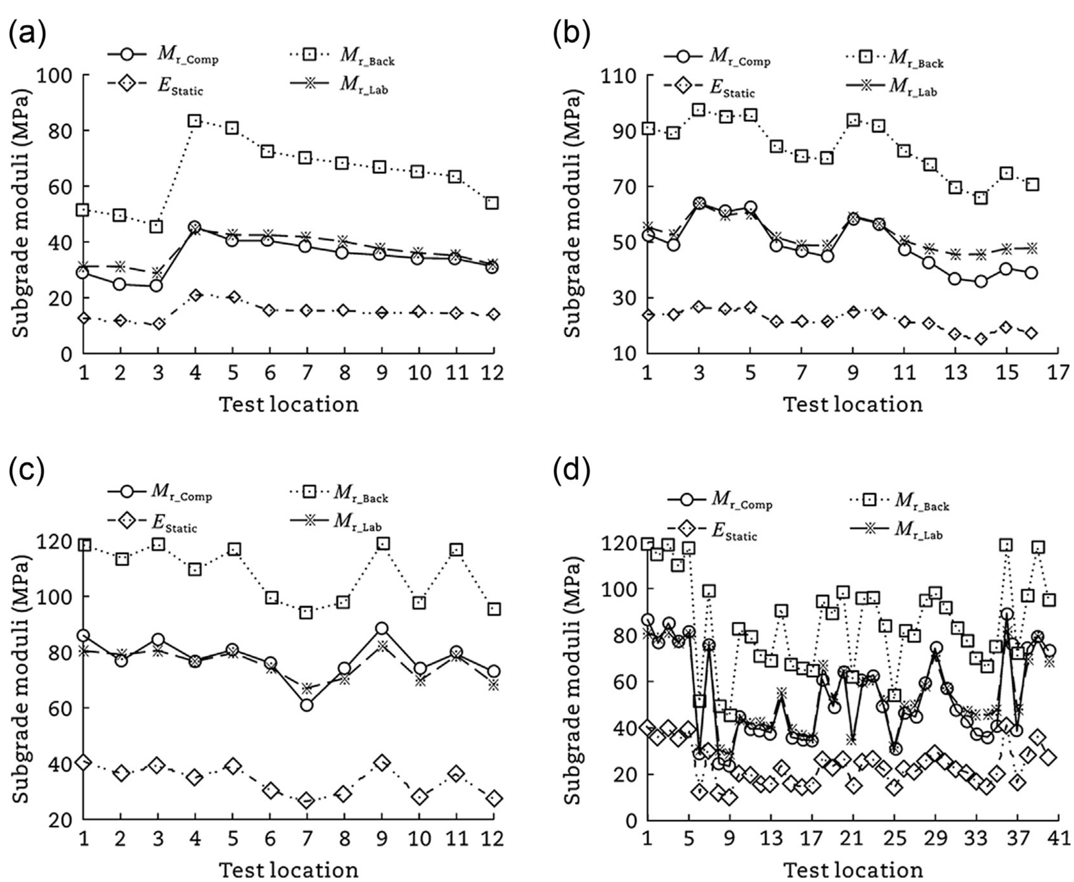

Fig. 4 – Static and dynamic moduli of subgrade. (a) CH soil. (b) CI soil. (c) CL soil. (d) All types of soils.

Table 5 – Summary of static and dynamic subgrade moduli analysis.

Subgrade moduli	Type of soil	CH	CI	CL
M_{r_Comp} (MPa)	Number of test locations	12	16	12
	Mean	34	49	78
	Standard deviation	6.2395	9.2229	7.3526
M_{r_Back} (MPa)	Number of test locations	12	16	12
	Mean	63	84	108
	Standard deviation	11.6888	10.1026	10.5775
E_{Static} (MPa)	Number of test locations	12	16	12
	Mean	15	22	34
	Standard deviation	3.1111	3.5838	5.4073
M_{r_Lab} (MPa)	Number of soil samples	36	48	36
	Mean	37	53	76
	Standard deviation	5.1227	5.8019	5.3336

3. Analysis of static and dynamic moduli of subgrade

3.1. *BBD test results*

In this study, based on the estimated temperature and moisture content along with the study stretch, appropriate corrections were applied to the deflections as per Canadian goods road association CGRA procedure (Wilkins, 1962; IRC, 1997). The static deflection values measured on 40 test sections of a study stretch were analyzed to determine true rebound deflection values as the CGRA procedure (Wilkins, 1962; IRC, 1997).

3.1.1. *Estimation of Static moduli of subgrade*

The seasonally corrected rebound deflection values were further processed to determine static subgrade moduli (E_{Static}) as the constitutive equation suggested in AASHTO (AASHTO, 1993; Fleming, 2000; Zhou et al., 2010) as shown in Eq. (3).

$$E_{Static} = 0.24P'/d_r R \tag{3}$$

where E_{Static} is the static moduli of subgrade value, P' is the applied load, d_r is the surface deflection measured at a distance r from the centre of the loading plate, R is the distance from the center of load.

The E_{Static} calculated from Eq. (3) for each test section of entire stretch was further used to compare with the estimated dynamic moduli of subgrade using LWD, and repeated triaxial apparatus as discussed in the subsequent section. The estimated E_{Static} values were categorized according to the soil type. The results are presented in Fig. 4(a)–(c).

3.2. *LWD test results*

3.2.1. *Estimation of composite moduli of surface and subgrade layer*

The dynamic deflections obtained from LWD test both on top of bituminous and subgrade layer at were processed to estimate composite moduli of surface and subgrade layer by considering Boussinesq's static linear-elastic half space theory by using the constitutive equation as shown in Eq. (4) (Fleming, 2000; Fleming et al., 2007; Livneh and Goldberg, 2001).

$$E_0 = f'(1-\upsilon^2)\sigma'_0 a/d_0 \tag{4}$$

where E_0 is the composite moduli of surface/subgrade layer, f' is the plate rigidity factor (2 is a standard value for a flexible plate), ν is Poisson's ratio, normally 0.35, σ'_0 is the maximum contact stress, a is the plate radius, d_0 is the maximum deflection.

These estimated composite moduli of surface layer for 40 test samples was further processed to estimate back-calculated moduli of subgrade (M_{r_Back}) using appropriate backcalculation technique. Further, composite moduli of subgrade (M_{r_Comp}) were estimated to validate the M_{r_Back} considering the potential influencing parameters as discussed in Section 2.2.2 that governed the deflection and moduli values while performing LWD test. In this study, all LWD equipment related factors were taken into consideration as discussed earlier and the effect of variation in moisture content upon LWD measurements were considered under controlled laboratory conditions while performing repeated triaxial test for the tests samples. The M_{r_Comp} values were validated and compared with M_{r_Lab} values according to the soil type as shown in Fig. 4(a)–(c).

3.2.2. *Backcalculated moduli of subgrade*

The deflections measured at each test section was used in Dynatest's LWDmod program which forward calculated based on the Odemark's layer transformation approach along with constitutive Boussinesq's equations. Backcalculation procedures adopted in this study include comparison of calculated deflections considering the non-linearity stress dependent with measured deflections by considering three layer system. These calculated and measured deflections along with seed moduli values were adjusted with an iterative procedure to obtain layer moduli. Thus, based on the iterative process, pavement layer moduli was estimated by using LWDmod program based on the deflection bowl approach which required layer thickness values as input (Sharma and Das, 2008). The estimated M_{r_Back} for all the 40 test sections were further calibrated and validated with M_{r_Lab} values according to the soil type as shown in Fig. 4(a)–(c). According to the soil type, the estimated M_{r_Lab}, M_{r_Back}, M_{r_Comp} and E_{Static} values were compared. The results are presented in

Table 6 – Summary of correlation analysis.

Type of soil	Independent variable / Dependent variable / Parameter	M_{r_Comp} / E_{Static} / M_{r_Comp} E_{Static}	M_{r_Back} / E_{Static} / M_{r_Back} E_{Static}	M_{r_Lab} / E_{Static} / M_{r_Lab} E_{Static}
CH	Coefficients	1.8446	3.5734	1.4509
	Intercept	5.6772	7.7335	14.1925
	R^2	0.8459	0.8045	0.7764
CI	Coefficients	2.4514	2.7700	1.4690
	Intercept	−5.3822	21.9950	20.0879
	R^2	0.9074	0.7655	0.8233
CL	Coefficients	1.2056	1.9191	0.9620
	Intercept	36.1088	41.9316	42.7572
	R^2	0.7861	0.7639	0.7512

Fig. 4(a)–(d). Table 5 presents the summary of estimated static and dynamic moduli of subgrade values.

3.3. *Comparative analysis of static and dynamic moduli of subgrade*

Comparative analysis was carried out in two distinct ways: (1) development of correlations, and (2) analysis of static and dynamic subgrade moduli values.

3.3.1. *Development of correlations*

The detailed comparative analyses were carried out for the estimated static and dynamic moduli of subgrade by developing correlations. According to the soil type, correlations were developed between E_{Static} and M_{r_Lab}, M_{r_Back}, M_{r_Comp} values. The summary of the correlation analysis for each soil type is shown in Table 6.

3.3.2. *Validation of Correlations*

The developed correlations were validated with the calculated M_r value as equation suggested in Indian standard specification as shown in Eq. (5) (IRC, 2012). The subgrade moduli estimated from the equation was designated as M_{r_CBR}. The CBR value used in this equation was obtained from the laboratory investigations as shown in Table 2.

$$M_r = \begin{cases} 10 \times \text{CBR} & \text{CBR} = 5 \\ 17.6 \times (\text{CBR})^{0.64} & \text{CBR} > 5 \end{cases} \tag{5}$$

where M_r is the resilient modulus of subgrade soil, CBR is California bearing ratio.

The average M_{r_CBR} value for CH, CI and CL soils is 25, 30 and 54 MPa. Based on the calculated M_{r_CBR} values, the estimated static and dynamic moduli of subgrade was validated by estimating the correlation index as shown in Table 7.

3.3.3. *Analysis of Subgrade moduli values*

Subgrade moduli estimated from static and dynamic devices were compared, and the ratio was determined according to soil type. Based on the tests results and analyses carried out in estimating of static and various dynamic moduli of subgrade, the ratios of static and dynamic moduli of subgrade obtained in this study is shown in Table 8.

4. Discussion

The test results and analyses of subgrade moduli from static and dynamic devices illustrates that the static moduli of subgrade estimated from BBD test is on a lower side as compared with the dynamic moduli of subgrade estimated from LWD and repeated triaxial tests for all the soil types. Further, the composite moduli of subgrade values estimated from LWD test are approximately consistent with laboratory estimated moduli of subgrade using repeated triaxial test with an average percentage variation of 7% for CH and CI type soils whereas 2% for CL type soil respectively.

The backcalculated moduli of subgrade values estimated by LWD test is on the higher side as compared with the other subgrade moduli values. However, the convergence of backcalculated subgrade moduli values is closely dependent upon the type of backcalculation technique being adopted. Pavement backcalculation process is mathematically an indeed complex inverse problem that can be approached deterministically or probabilistically. Current backcalculation techniques adopts several optimization techniques like artificial neural networks (ANN), generic algorithm, etc. (Sharma and Das, 2008). LWDmod program adopts static backcalculating algorithms in which the data converges to the local minima.

Table 7 – Summary of validation analysis.

Type of soil	Independent variable / Dependent variable / Parameter	M_{r_Comp} / M_{r_CBR} / M_{r_Comp}: M_{r_CBR}	M_{r_Back} / M_{r_CBR} / M_{r_Back}: M_{r_CBR}	E_{Static} / M_{r_CBR} / E_{Static}: M_{r_CBR}
CH	R^2	0.8452	0.8370	0.6691
CI	R^2	0.9279	0.8855	0.7195
CL	R^2	0.9306	0.7430	0.7399

Table 8 – Analysis of static and dynamic moduli of subgrade.

Parameter	Type of soil		
	CH	CI	CL
E_{Static}: M_{r_Comp}	0.45	0.45	0.44
E_{Static}: M_{r_Back}	0.25	0.27	0.32
E_{Static}: M_{r_Lab}	0.42	0.42	0.45

The correlation analysis between static and dynamic moduli of subgrade values demonstrates good correlations for each soil type. However, the validation results of estimated static and dynamic subgrade moduli with M_{r_CBR} depicts poor correlation between E_{Static} and M_{r_CBR}. Therefore, this states that the E_{Static} values are conservative to determine the realistic subgrade structural integrity.

The interpretations of estimated static and dynamic moduli of subgrade are carried out by estimating ratio of static and dynamic moduli of subgrade in this study as shown in Table 8. The calculated values were on higher side as compared with the findings in AASHTO (1993) and the ratios calculated in other studies using BBD and FWD varies from 0.2 – 0.33 and 0.18 – 0.27 (Ali and Khosla, 1987; Von Quintus and Killingsworth, 1998; Zhou et al., 2010). However, in this study the ratio between E_{Static} and M_{r_Back} is less than the previous studies. The ratios between E_{Static} with M_{r_comp} and M_{r_Lab} are on the higher sides respectively. The less ratio values are due to over estimated M_{r_Back} values which can be improved by adopting more realisting backcalculation techniques.

5. Conclusions

A comprehensive comparative study is carried out between Benkelman beam deflectometer and lightweight deflectometer in estimating the subgrade moduli for pavement structural evaluation of low volume roads in India. Experimental investigations are performed to estimate static moduli of subgrade using Benkelman beam deflectometer, backcalculated and composite moduli of subgrade using lightweight deflectometer. In-situ results are validated with repeated triaxial results. The test results and analysis illustrates the following conclusions.

- Although correlation analysis between static and dynamic moduli of subgrade exhibits good correlation. Though, validation analysis with calculated CBR based moduli of subgrade shows the inability of adopting static moduli of subgrade as design strength parameter. Whereas the other measured and backcalculated dynamic moduli of subgrade values can show better results.
- The LWD backcalculated and composite dynamic moduli of subgrade values are validated effectively with laboratory measured dynamic moduli of subgrade values. This depicts the feasibility of LWD device.
- This study helps engineers and researchers to initiate and extend mechanistic-empirical techniques using dynamic non-destructive testing devices for the design and preservation of low volume road.
- Therefore, based on this study, it is concluded that LWD can be used as subgrade strength evaluating tool for the phases construction and maintenance of the pavement.

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