COMPARISON OF DIFFERENT PROGRAMS FOR ANALYSING FALLING WEIGHT DEFLECTOMETER DATA

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प्रमाणपत्र

यह प्रमाणित किया जाता है कि **श्री शुभम मिश्रा** (अनुक्रमांक: 801723023) इंफ्रास्ट्रक्चर इंजीनियरिंग में विशेषज्ञता के साथ सिविल इंजीनियरिंग के क्षेत्र में मास्टर ऑफ़ इंजीनियरिंग के छात्र, थापर इंस्टीट्यूट ऑफ इंजीनियरिंग एंड टेक्नोलॉजी, पटियाला, पंजाब से, श्री राकेश कुमार श्रीवास्तव, वरिष्ठ प्रधान वैज्ञानिक और डॉ प्रदीप कुमार, प्रधान वैज्ञानिक एवं विभागाध्यक्ष (कृत्रीम मूल्यांकन विभाग) के मार्गदर्शन में 27 जुलाई, 2018 से 7 जुलाई 2019 तक की अवधि के दौरान "Comparison of Different Programs for Analysing Falling Weight Deflectometer Data" विषय पर अपना शोध कार्य हमारी संस्थान मे सफलतापूर्वक पूर्ण किया।

कार्यालय द्वारा सौंपे हुए सभी कार्यों को आपके द्वारा परिश्रम और ईमानदारी के साथ पूरा किया गया । हम भविष्य के सभी प्रयासों में आपकी सफलता की कामना करते हैं ।

This is to certify that **Mr. Shubham Mishra** (Roll No.: 801723023) a student of Master of Engineering in the field of Civil Engineering with specialization in Infrastructure Engineering, Thapar Institute of Engineering & Technology, Patiala, Punjab has successfully completed his dissertation work on **"Comparison of Different Programs for Analysing Falling Weight Deflectometer Data"** under the guidance of Mr. Rakesh Kumar Srivastava, Senior Principal Scientist and Dr. Pradeep Kumar, Principal Scientist and HoD (Pavement Evaluation Division) from 27 July 2018 - 7 July 2019, at our Institute.

He performed the task assigned to him with diligence and sincerity. We wish him success and luck in all his future endeavors.

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DECLARATION

I hereby declare that this work which is being presented in the thesis entitled **"Comparison of Different Programs for Analysing Falling Weight Deflectometer Data"** in partial fulfillment of the requirement for the award of degree of **Master of Engineering** in the field of **Civil Engineering** with specialization in **Infrastructure Engineering** submitted at **Thapar Institute of Engineering & Technology (Patiala)** is an authentic record of my own work carried out during the period from 27.7.2018 to 7.7.2019 under the guidance of Dr. Tanuj Chopra, Sh. Rakesh Kumar Srivastava and Dr. Pradeep Kumar.

The matter embodied in this thesis has not submitted by me for the award of any other degree or diploma.

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This is to certify that **Mr. Shubham Mishra** a student of M.E (Infrastructure Engineering), Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala, Punjab has successfully completed his M.E - Infrastructure Engineering thesis work entitled "Comparison of different programs for analyzing Falling Weight Deflectometer data" in this institute from **27.7.2018** to **7.7.2019**. During the above-mentioned period, he was found sincere, disciplined, dedicated and hardworking to the tasks assigned to him.

We wish him all the success in his life.

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LIST OF ABBERIVATIONS

BBD	Benkelman Beam Deflectometer
FWD	Falling Weight Deflectometer
NDT	Non Destructive Testing
ANN	Artificial Neural Network
CBR	California bearing Ratio
CCP	Constant Confining Pressure
VCP	Variable Confining Pressure
SHRP	Strategic Highway Research Program
IRC	Indian Road Congress
VG	Viscosity Grade
CTSB	Cement Treated Sub-Base
BC	Bituminous Concrete
DBM	Dense Bituminous Macadam
RAP	Reclaimed Asphalt Pavement
AASHTO	American Association of State Highway and Transportation Officials
WASHO	Western American State Highway Officials
CGRA	Canadian Goods Roads Association
PI	Plasticity Index
msa	Million Standard axles
cvpd	Commercial Vehicle Per Day
HWD	Heavy Weight Deflectometer
LWD	Light Weight Deflectometer
RWD	Rolling Weight Deflectometer
TSD	Traffic Speed Deflectometer
RMS	Root Mean Square
FEM	Finite Element Method
LET	Linear Elastic Theory
MET	Method of Equivalent Thickness
UTM	Universal Testing Machine
ASTM	American Society for Testing and Materials
SSD	Saturated Surface Dry
G_{mb}	Bulk Specific Gravity
ANOVA	Analysis of Variance

ABSTRACT

India has very large road network consisting of Expressways, National Highways, State Highways, District Roads and Rural Roads. In recent time, suitable maintenance and evaluation of road network is necessary requirement for any nation for its economic development. Evaluation of large road network is very difficult task for highway authorities. For the construction of expressways and highways huge amount of money is invested in India. There is need to evaluate these facilities regularly in terms of functional and structural performances to determine requirement for maintenance and rehabilitation measures. For structural evaluation, currently FWD is very popular because it simulates actual loading conditions of vehicles. As the use of the FWD is increasing the number of methods adopted for back-calculation of modulus values is also increasing. The use of these back-calculation methods without proper analysis may provide unreliable results.

Therefore in order to decide the appropriate back-calculation methodology, there is a need for evaluation of different programs. The purpose of this study is to summarise the literature available on evaluation of different programs for analyzing FWD data throughout the world. This study discusses the process followed by various researchers for selecting various programs, back-calculation procedure used and outcomes of the program evaluations. The focus of thesis work is mainly on analysis of FWD data to compute moduli values of different layers obtained from different programs. In this study five back-calculation methods; namely, KUAB, EVERCALC, KGPBACK, Elmod (Deflection Basin Fit and Radius of curvature methods) are evaluated for consistency and reliability. Some Analytical methods AASTHO (1993), Garg and Thompson (1999), Roque (1998) were also used for determination of subgrade modulus values. These back-calculated modulus values were compared with laboratory calculated modulus values. Modulus values from different programs are compared using Pearson correlations and Statistical analysis.

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CHAPTER 1
INTRODUCTION

1.1 GENERAL

India has second biggest road network (57 lacs km approx.) in world. Total lengths of the National Highways and State Highways are 1, 32,499 and 1, 76,166 kilometres respectively as per survey conducted by National Highway Authority of India. For the construction of expressways and highways huge amount of money is being invested in India. Pavements get deteriorated with age or time due to the effect of climatic conditions and due to repetitive applications of vehicular loads. To determine the need of rehabilitation measures, the highway infrastructure should be evaluated regularly. Pavements are mainly analysed for two types of performances that are functional and structural performance. The current road infrastructure in India which was built from 1990 to 2010 is reaching the end of its design life. There is a requirement for structural evaluation of these roads; i.e. identifying the existing structural condition of each and every layer of the pavement as well as analysing the overall pavement strength. Road should be maintained before it starts to show distresses. It is pavement engineer's responsibility to increase pavement performance as much as possible, while assessing and repairing pavements. Main reasons for failure of pavements are poor materials, poor design and faulty construction.

In Flexible pavement, vehicular loads are transmitted by grain-to-grain contact of aggregate. This pavement incorporates surface course laid over the sub-base and base course respectively. The flexible pavement experience deformation under action of the loads because of negligible flexural strength. The load from the vehicles is directly applied on surface course, and it is distributed from surface course to base, sub-base and the subgrade courses in form of a truncated cone. These stresses initiated by the loads carrying on the pavement are highest at top. Surface course has maximum stiffness which adds strength to pavement.

Destructive and Non-destructive testing are used for structural evaluation of roads. In destructive testing laboratory tests can be used for detecting the structural deficiencies in various layers of pavement. In these tests, samples of materials are excavated from different layers and taken to laboratory for assessment. Non Destructive testing is becoming popular in recent years because of their speed, low

cost, reliability, and non-disturbance of the pavement surface. There are mainly two NDT devices which are used in India; one is BBD (Benkelman Beam Deflection) which works under static loading and another is FWD (Falling Weight Deflectometer) which works under dynamic loading. For the last four decades, BBD had been popular in India but deflection values obtained in this method do not represent loading under moving vehicles. Moreover, its analysis is based on the empirical approach. FWD simulates the effect of moving vehicles on the pavement surface. Now FWD is gaining popularity because of its ease of use, representation of dynamic loading of vehicles, as well as the accuracy of its results. The analysis in FWD method is based on Mechanistic-Empirical Approach. Pavement strength is determined by processing deflection data (determined using FWD) in terms of layer modulus values.

1.2 NEED OF STUDY

As the use of the FWD is increasing the numbers of techniques adopted for back-calculation of pavement layers properties are also increasing. The use of these back-calculation techniques carelessly may provide unreliable outcomes which may not represent actual characteristics of the pavement layers. Back-calculated layer modulus plays very vital role in pavement engineering because it is not only used for design but also to compute remaining life of the pavement. Lower value of back-calculated modulus can result in over design of pavement thickness which will not be economical. If back-calculated modulus is greater than actual modulus it will over predict the remaining life. Therefore it is important to examine the reliability of back-calculated modulus to forecast the remaining life of pavement. A common problem with back-calculation program is the lack of consistency of the results which means that many a times back-calculated modulus values under different loads are not close to each other. It is necessary to understand the consistency of back-calculation programs. In this study effort was made to evaluate modulus values of surface, base and subgrade layers computed utilising different back-calculation methods under similar and variable loading conditions.

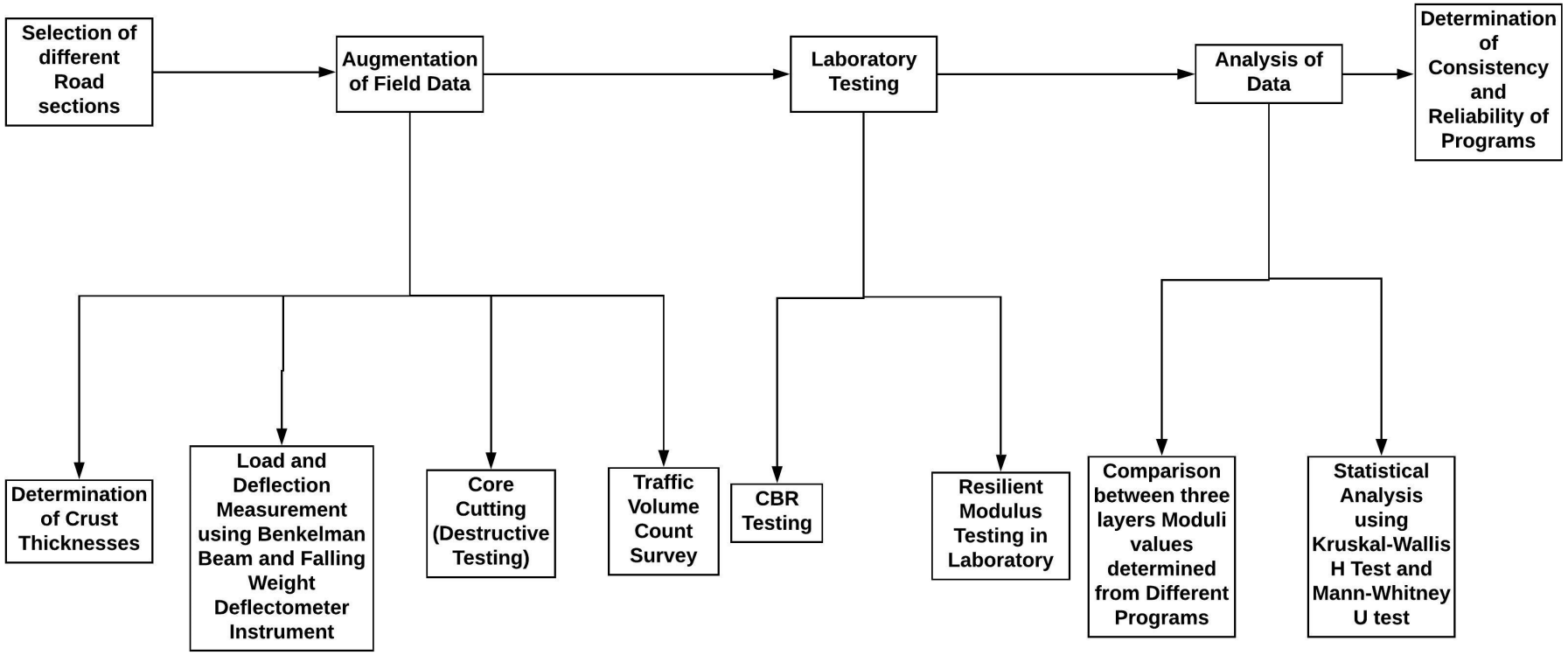
1.3 OBJECTIVES OF THE STUDY

- Analysis of Falling Weight Deflectometer data using different back-calculation techniques.
- Comparison of moduli values computed from KUAB, EVERCALC, KGPBACK, Elmod (Deflection Basin and Radius of Curvature) programs for analysing Falling Weight Deflectometer data.
- To find Pearson correlations and Statistical significant difference between modulus values of different layers computed from different programs.

1.4 SCOPE OF STUDY

- Literature Review of various Back-calculation Methods and Non-Destructive Techniques.
- Deflection data collection using Benkelman Beam and Falling Weight Deflectometer instruments on the selected road sections.
- To find the correlations between deflection values measured from Benkelman beam method and FWD.
- To compare the back-calculated subgrade modulus with different analytical methods.
- To determine Pearson Correlations between modulus values of different layers obtained from different programs.
- To perform the statistical analysis on modulus values of different layers obtained from different programs.
- Compare the back-calculated modulus at three different loads to determine the consistency of programs.
- To compare the back-calculated surface modulus determined from different programs with the laboratory resilient modulus to check the reliability of the program.

1.5 STRUCTURE OF THESIS



1.6 PRESENTATION OF THE STUDY

The work undertaken for the dissertation has been presented in following chapters.

Chapter I **'Introduction' -** The chapter broadly introduces the area of research and objective of the study. The advantages and limitations related to the research study have been discussed.

Chapter II '**Literature Review**' - In this chapter study of earlier work done related to the current work is discussed. It deals with review of relevant literature related to a variety of non-destructive testing of pavements, back-calculation methods and pavement material descriptions.

Chapter III '**NDT Techniques and Back-Calculation Programs**' – In this chapter various non-destructive testing equipments and various back-calculation programs used in this study are discussed.

Chapter IV '**Study Area**' – This chapter gives a concise overview of study stretches of roads and case study area under consideration.

Chapter V '**Methodology and Field work' –** This chapter present the particulars of structural evaluation carried out on in-service pavement. It also includes various laboratory tests performed in this study.

Chapter VI '**Data Analysis**' – Analysis of pavement evaluation data is explained in this chapter. Back-calculation modulus values determined from different programs are analysed statistically.

Chapter VIII '**Conclusions and Scope of Further Research**' – This chapter discussed conclusion and scope of further research in this study.

CHAPTER 2
LITERATURE REVIEW

2.1 GENERAL

Various national and international journals are reviewed so as to summarise the literature available on determination of modulus values using Falling Weight Deflectometer. The review includes different models utilised for analysis a of data acquired from the structural evaluation of pavements. The following section of this chapter presents an overview of different back-calculation procedures, evaluation of FWD data, and selection of layer modulus for the analysis of pavements. A few recently used mechanistic approaches for design of flexible pavements have also been reviewed.

2.2 BACK-CALCULATION OF LAYER MODULI

FWD measures the deflections of pavement surface at different distances from centre of load. The measured deflections and some other inputs are utilised to back-calculate pavement layer moduli or to compute the overlay requirement. A back-calculation is a process of working "backwards" for determination of elastic modulus for different pavement layers by using the measured deflections from FWD. Actually, in this process layer moduli is selected by using a suitable technique (Closed form solutions, database search, optimisation techniques, iteration, regression equations, Artificial Neural Network (ANN)) so that the deflection values calculated from assumed layer moduli should be close to the measured deflections.

2.2.1 Regression Equations

For back-calculating pavement layer modulus from the deflection values, various researchers have given regression equations. **Garg et al. (1999)** established regression equations to find out the subgrade modulus utilizing pavement deflection at 1097 mm from the middle of the loading plate. **Newcomb (1986)** proposed regression equations for various pavement layer systems for determining the subgrade modulus from FWD test. **Horak (1987)** also proposed regression equation for estimating the subgrade modulus utilizing pavement deflection measured at 2000 mm radial distance from middle of loading plate.

2.2.2 Optimization Method

It is a forward calculation program and also known as “Basin search method”. Different combinations of layer moduli, layer thickness values, properties of material, type of pavements and loading conditions are utilized to create a database of deflection basins. Then these deflection basins of the database are compared with measured deflection basins using a search algorithm. From the layer moduli the set of moduli are interpolated that produced the closest calculated deflection basins inside the database. The WESDEF back-calculation program is one program that utilizes this technique. It can manage up to five layers in which lowest layer is ‘fixed’ and to behave as a rigid layer.

Another back-calculation program which follows this method is MODULUS which utilizes the databases generated by the WESLEA program **Van et al. (1989) and Rohde et al. (1990)**. The numbers of layers and moduli ranges given by the user are responsible for the number of basins essential to achieve a suitable database. Then an algorithm is used for searching the generated deflection basins and numerous deflection basins are used for interpolating the moduli values **Baladi et al. (1994)**. To compute the probability of having converged to a local minimum a convexity test is performed by the program and it gives warning to the user if this test is not satisfied.

2.2.3 Iterative Method

Layer moduli are continuously varied in this approach until the computed deflection basin come equivalent to the measured deflection basin inside a particular tolerance. The difficulty related with back-calculating elastic moduli is that unknowns of equations for computing pavement surface deflection cannot be solved directly. In this manner, a careful iterative procedure including decision and convergence criteria is required. Iterative software are EVERCALC, CHEVDEF, MICHBACK and MODCOMP. Iterative back-calculation flow chart is presented in Figure 2.1.

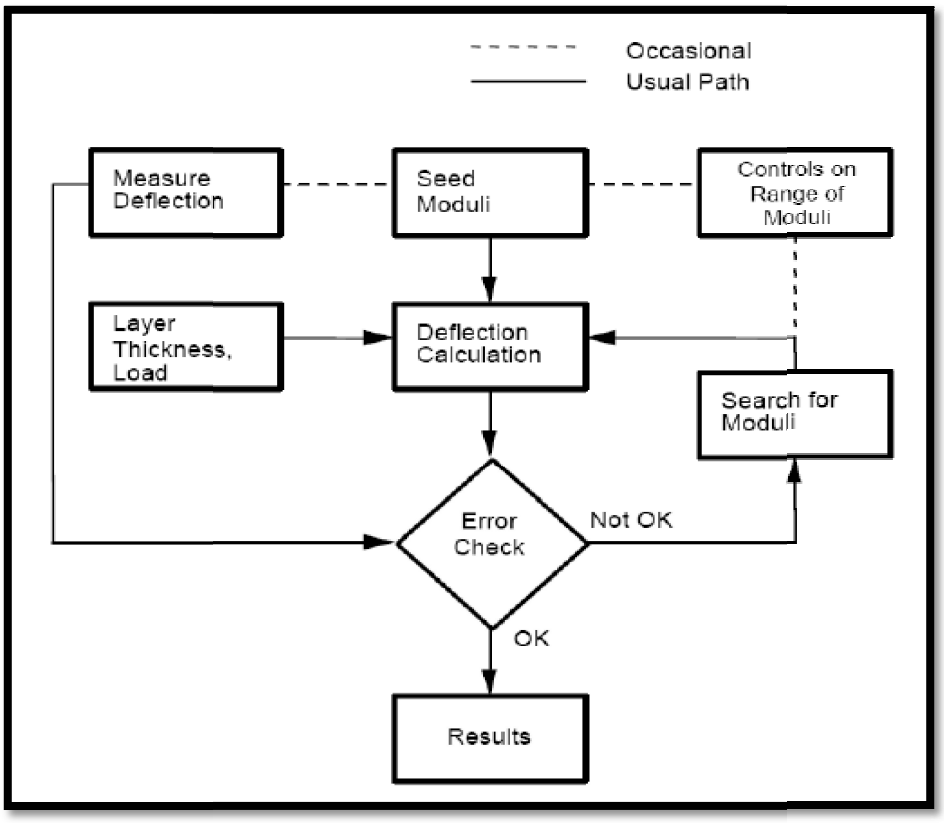


Figure 2.1 Iterative Back-Calculation Flow Chart (Lytton, 1989)

2.2.4 Dynamic Back-calculation Methods

In earlier discussed methods the load carried out to the pavement was considered to be a static load. Static back-calculation technique is very productive, when the thicknesses of layers are not unknown and their properties are mostly homogenous with respect to thickness values. When depths are unknown or moduli changes within a layer, the static back-calculation approach may not give consistent outcomes. Therefore to overcome the limitation of static approaches the development of dynamic approaches takes place to interpret the dynamic response of FWD deflections. DYNABACK-F and DIPLOBACK (based on Artificial Neural Network Analysis) are some examples of Dynamic back-calculation approach.

The first closed-form solution for back-calculating the modulus values for two pavement layers were built up by **Scrivner et al. (1971)**. It was based on Burmister's Layer theory (1945). **Yih Hou (1978)** built up the first closed- form solution for back-calculation of modulus values for multi-layer pavements utilizing least squares method. **Swift (1972)** established the first graphical method for two layer pavement to determine the moduli. **Odemark (1949)** used the equivalent layer concept to get the

full use of Boussinesq's theory for analyzing pavement and for simplification of the pavement systems in some of the back-calculation models. **Lytton et al. (1979)** also used the Odemark's assumptions for converting the multi-layered pavement system into a single layer system positioned over a rigid base. **Anderson (1989)** had implemented database searching for back-calculation of pavement layer moduli. **Ioannides et al. (1989)** developed the model ILLIBACK based on the plate theory, which gives closed form solutions. BACK which is a back-calculation model developed by **Lin, P.S. et al. (1998)** is also based on plate theory. There are various back-calculation approaches and every approach has some advantages as well as some disadvantages as presented in Table 2.1 **(Sharma et al. 2008).**

Table 2.1 Some Back-calculation Approaches and their Limitations

Back-calculation Approaches	Limitations
Closed-form Solutions	Can deal with only restricted and ideal conditions **Lenngren (1991)**
Regression methods	Are quick but occasionally deliver false results
Conventional optimization techniques	Required more time to back-calculate layer moduli **(Harichandran et al. 1993, Sharma et al. 2008)**

The majority of above given approaches require crust details of each layer as input, for which cores are dug in the pavement which is a time-taking and tedious to measure the accurate value of thickness.

Sharma et al. (2008) used ANN for the back-calculation of pavement layer moduli. ANN is a tool which can give accurate result in less time. Authors compared the performance of ANN back-calculation with performance of other software which were EVERCALC and ExPaS. ExPaS is a back-calculation algorithm developed in-house; primarily based on a "search and expand" technique and EVERCALC is a back-calculation program downloaded from the internet. The remaining life of pavement was also estimated using ANN back-calculation without back-calculating layer modulus values. Subsequently, a reliability evaluation is carried out to find out the

performance of back-calculation by using ANN. In this study, author found that training of ANN is time-consuming and its performance relies upon on how effectively it has been trained. ANN model does not back-calculate layer modulus values outside the ranges given. This hassle can probably be treated by training ANN models over a bigger range of modulus values, which could encompass all viable practical values.

The correlation advanced by **Davies (1997) and Livneh et al. (1997)** between Loadman transportable FWD and Benkelman Beam deflections on top layers of pavements yields negative correlations. Back-calculation method will become crucial as the usage of deflection values to signify structural capacity of pavement and to decide the modulus of separate layers will increase**.** Correlation between BBD and FWD deflections was developed for the two junctions in Shanghai by carrying out comparative study of FWD and BBD as shown in equation (1):

$$FWD = 4.39\ BB - 15.8\ (R^2 = 0.9578) \quad \textbf{Zhou et al. (2010)} \qquad (1)$$

Ameri et al. (2009) compared four software three of them are used to do the static back-calculation and one of them is used for dynamic back-calculation namely, MODULUS 6.0, ELMOD 5.0, EVERCALC 5.0 and Dynamic Back-calculation with System Identification (DBSID). The FWD data utilised in the analysis was augmented on four different sites and analyzed by using the given software. Elmod 5.0 overvalued the moduli of the subgrade in a few cases. MODULUS 6.0 and EVERCALC 5.0 showed good consistency in outcomes for all the three layers. Results of them were compared, overall performances of each program were estimated and best software for the roads under study was recommended. They also found out the run time efficiency of the software. Subgrade moduli anticipated by DBSID changed into two and half instances more than the subgrade moduli computed by MODULUS 6.0. Base moduli calculated by MODULUS 6.0 had been almost 1.3 instances more than that of DBSID. Dynamic back-calculation is time consuming task. Overall they found that MODULUS 6.0 is most appropriate program for the study.

Ali and Khosla (1987) evaluated four programs for the analysis of deflection data with laboratory results. They used both destructive and Non-Destructive methods for evaluating material properties. Three sections of roads were selected and the test pits were excavated across the wheel path of traffic lanes at selected locations. Software

evaluated were ELMOD, OAF, MODCOMP2 and VESYS. ELMOD and VESYS models and laboratory testing values at different time of testing were in good agreement as compared to OAF and MODCOMP2. The researchers observed that Back-calculated modulus values using VESYS model had the least variation from laboratory values. At the end they concluded that VESYS and ELMOD were more suitable for prediction of pavement layer moduli.

Rada et al. (1993) compared four programs namely; ISSEM4, MODCOMP3, MODULUS, and WESDEF for developing a Strategic Highway Research Program (SHRP). Deflection data and other important information obtained from 16 SHRP pavement test sections were used for evaluating selected software by the different evaluators and at the end, their analysis was compared. Even though the ranking of the programs varied from one evaluator to another but the MODCOMP3, MODULUS, and WESDEF were ranked as the top three back-calculation software. Then the program to program comparison of the back-calculated moduli was conducted. It was found that MODCOMP3 program tends to envisage higher subgrade moduli but lower base and subbase moduli, when compared with WESDEF results. The modulus of surface layer appears to be consistent among all programs.

David A. Van Deusen (1996) compared the performance of several programs for selection of Flexible Pavement Back-calculation software for Minneosta road research project. Four programs were selected for this study EVERCALC v. 3.3, MODCOMP3 v.3.6, WESDEF and EVERCALC v.4.1. Five Mn/ROAD flexible pavement test sections were selected. Experiment was conducted, in which programs were run on deflection data; the moduli predicted from each program were compared to expected values and the percent error was calculated. After evaluating different programs it was found that the agreement between WESDEF and EVERCALC v. 3.3 was the best among the programs investigated. Output of MODCOMP3 program frequently have become unstable during analysis of field data. Large RMS percent error, unreasonable results and length computation times have been observed. The use of EVERCALC v. 4.1 as a "standard" back-calculation program should be implemented (at least for Mn/ROAD and research work).

Tarefder et al. (2012) found out the most consistent and accurate software for computing the layer modulus values of airport pavements in New-Mexico. In this study laboratory tests have been performed for determining the modulus of different

layers and soil samples were collected. Then the laboratory calculated modulus values were compared with those modulus values which were back-calculated from software. They also compared the back-calculated tensile stress using KENLAYER with laboratory tensile stress. Consistency and accuracy of software was computed by comparing the three sets of input data i.e three loads 40.03, 53.38 and 71.17 kN from FWD tests at same locations. In this study three programs were compared; BAKFAA, MODULUS and EVERCALC. Only Indirect tensile modulus of AC layer was determined in laboratory at any particular temperature. There was no triaxial modulus testing performed for determination of the Subgrade and base layer moduli. For surface modulus, difference in modulus and coefficient of variation of EVERCALC program were barely higher than those of MODULUS program. They found that EVERCALC is more consistent software for computation of layer moduli. Accuracy of back-calculated surface modulus was checked by comparing the laboratory calculated modulus with back-calculated modulus. It was found that EVERCALC gives closer value of modulus to laboratory calculated modulus in comparison to other programs. After comparing laboratory subgrade modulus with back-calculated subgrade modulus it was found that subgrade modulus calculated from EVERCALC was nearer to laboratory subgrade modulus. Overall it was found that EVERCALC has the best accuracy and consistency in comparison to other programs.

Priddy et al. (2015) compared back-calculation outcomes of selected programs by utilizing HWD data acquired during airfield pavement evaluations. In this study author used BAKFAA, ELMOD-6 and WESDEF programs for back-calculating the moduli for airfield pavements. WESDEF procedure was created during the 1980s and utilized by the Department of defence for back-calculation of layer moduli by utilizing measured HWD or FWD data. In this study total, 30 pavement sections from six airfields were selected for the back-calculation analysis and Dynatest Model 8082 HWD was used. Selected airfields were major U.S army deployment platform. BAKFAA determined similar back-calculated moduli to those computed by WESDEF. The ELMOD-6 program anticipated higher moduli for the subgrade among the sections analyzed. The forward calculated subgrade modulus values were nicely correlated to the back-calculated modulus values and the procedure was a simple check for reasonableness of subgrade outcomes when conducting back-calculation. It was suggested that the USAF continue utilizing WESDEF for back-calculation.

2.3 SELECTION OF LAYER MODULI FOR ANALYSIS OF FLEXIBLE PAVEMENTS

A few methodologies which are generally used for computation of material properties for analysis of pavements are given below:

2.3.1 Elastic Modulus of Subgrade

2.3.1.1 Laboratory Evaluation

The repeated tri-axial test in laboratory which simulates the tri-axial stress condition expected in pavements is carried out for the computation of elastic modulus of subgrade. Elastic modulus is also termed as 'Resilient Modulus (M_R)' which is calculated by using equation (2).

$$M_R = \frac{\sigma_1 - \sigma_3}{\varepsilon_{ra}} \quad (2)$$

Where, ε_{ra} = recoverable axial strain; σ_1, σ_3 = principal stresses

To characterise the elastic component of the total deformation the term 'Resilient deformation' was introduced by **Hveem (1955).** Non-linear behaviour of fine-grained soils was explained by **Shifley et al. (1968)** by utilising the bi-linear equations (3) and (4).

$$M_R = k_b + k_c(k_a - (\sigma_a - \sigma_c)) \text{ When } k_a > (\sigma_a - \sigma_c) \quad (3)$$

$$M_R = k_b + k_d\left((\sigma_a - \sigma_c) - k_a\right) \text{ When } k_a < (\sigma_a - \sigma_c) \quad (4)$$

Where, k_a, k_b, k_c and k_d = Material constants.

To determine stress dependent modulus of the fine grained soils, equation (5) is used.

$$M_R = k_1\left(\frac{\sigma_1 - \sigma_3)}{\sigma_3}\right)^{-k_2} \quad (5)$$

Where, k_1 and k_2 = Material constants.

Uzan (1985) developed a correlation between resilient modulus and a state of stress which is presented in equation (6).

$$M_R = k_1 P_a\left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\zeta_{oct}}{P_a}\right)^{k_3} \quad (6)$$

Where, ζ_{oct} = octahedral shear stress; P_a = atmospheric Pressure;

θ = bulk stress; k_1, k_2, k_3 = Material Parameters

2.3.1.2 Estimation of Subgrade Modulus

There are various relationships which are available for estimating the subgrade modulus. California Bearing Ratio (CBR) is the most common constraint which is used to estimate the elastic modulus of subgrade. Equation (7) is the general relationship used for estimation of subgrade modulus.

$$\text{Modulus of Subgrade} = k \times (\text{CBR}) \qquad (7)$$

The values of 'k' recommended by different Researchers and agencies are presented in Table 2.2.

Table 2.2 Values of k Recommended by Various Researchers

Design Method/ Investigators	**k (M_R in MPa)**
Skok et al. (1962)	13.4 for all soils
Wiseman et al. (1977)	20 for all soils
Freeme et al. (1982)	15 for CBR 3 to 15 %
Dauzats et al. (1982)	5 for CBR <15 %
Shell (1978), AASHTO (1993)	10 for all Soils
IRC : 37- 2018	10 for (CBR ≤ 5 %) 17.6 for (CBR > 5 %)

Some Non-linear relationships between M_R and CBR are also available. The general non-linear relationship used for estimation of subgrade modulus is given in equation (8).

$$\text{Subgrade Modulus} = k_1 \times (\text{CBR})^{k_2} \qquad (8)$$

Where, k_1 and k_2 are material constants.

The values of k_1 and k_2 recommended by different investigators and agencies are presented in Table 2.3.

Table 2.3 Values of k_1 and k_2 Recommended by Various Researchers

Design Method/ Researchers	Constants (M_R in MPa)	
	k_1	k_2
Bachelez et al. (1962)	6.5	0.67
Ullidtz (1987)	10	0.73
Lister et al. (1987)	17.6	0.64
IRC: 37	17.6	0.64

The subgrade modulus is determined as per IRC: 37-2018 guidelines, by using equation (9)

$$\text{Subgrade modulus } = 17.6 \times (\text{CBR})^{0.64} \text{ (For CBR > 5\%)} \quad (9)$$

To determine the resilient modulus of soil from CBR value and stress condition (θ) a relationship was developed and it is shown in equation (10) **(Cardoso et al. 1991)**.

$$M_R = 179.0412\ (\text{CBR})^{1.08774}\ \theta^{1.43833} / \sigma_1^{1.1859} \quad (10)$$

Where, M_R, θ, and σ_1 are in psi.

A simple chart was developed by using moisture density information for estimating the resilient modulus value of glacial silty soils **(Kirwan et al. 1976)**.

2.3.1.3 Structural Evaluation of Pavements

In past, subgrade modulus was calculated from the surface deflections which were measured during Non-destructive evaluation. Single deflection value was used for the back-calculation of subgrade moduli using equation (11).

$$M_R = \frac{0.24 \times P}{d_r \times r} \quad \textbf{(AASTHO 1993)} \quad (11)$$

Where,

M_R = back-calculated subgrade modulus (psi)

P = applied load (pounds)

d_r = deflection at a distance 'r' from the centre of the load (inches)

r =distance from the centre of load (inches)

Regression equation was developed for predicting the subgrade modulus using pavement deflection at a radial distance of 1097 mm from the middle of the loading plate. The equation is given below: **(Garg et al. 1999)**

Equation (12) is used to predict subgrade modulus for conventional pavements:

$$\text{Log } E_{Ri} = 1.51 - 0.19\, D_3 + 0.27 \log (D_3) \quad (12)$$

Equation (13) was proposed by **Roque et al. (1998**). Dual loading FWD system was used for measuring the deflections and to determine the subgrade modulus.

$$M_R(\text{ksi}) = 36.334 \left(\frac{D_x}{60}\right)^{-1.015} \quad (13)$$

Where,

$\frac{D_x}{60}$ = deflection (mils) measured at 60 inches radial distance from the middle of the dual plates.

Molenaar et al. (1982) presented the equation (14) for determination of subgrade soil modulus based on FWD deflections.

$$E_{sub}\ (\text{MPa}) = 6.614 \times 10^{-3} \times d_2^{\,-1.00915} \quad (14)$$

Where,

d_2 = deflection measured at a distance of 2000 mm from the middle of loading plate. (In meters)

Regression model developed by **Wimsatt (1999)** is given in equation (15).

$$E_{sub}\ (\text{MPa}) = \frac{0.24 \times P}{W_7 \times 1828.8} \quad (15)$$

Where,

W_7 (mm) = FWD deflection measured at a distance of 1828.8 mm radial distance from the centre of the loading plate.

The equation (16) was proposed by **Alexander et al. (1989)** for determining the subgrade modulus for an applied load of 111206 N and the deflection values (mils) taken at a radial distance of 1830 mm (D_{72}) from middle of loading plate.

$$Es\ (\text{psi}) = 59304.82\ (D_{72})^{-0.98737} \quad (16)$$

2.3.2 Granular Layer Modulus

2.3.2.1 Laboratory Tests

It is always been a difficult task to find out the resilient modulus value of granular layers because modulus value is highly stress dependent. Since 1960s, various efforts had been made to define the resilient behaviour of granular materials. To determine the modulus value of granular layer repeated triaxial test is conducted in the laboratory.

To consider the effect of shear stress on M_R value studies were conducted by **Uzan (1985)** and **May et al. (1981)** and equation (17) was given by these researchers to predict the M_R value.

$$M_R = k_1 \theta^{k_2} \zeta_{oct}^{k_3} \quad (17)$$

Where,

ζ_{oct}= octahedral shear stress

k_1, k_2 and k_3 = material constants

Trollope et al. (1962), Hicks (1971), and Kolisoja (1997) proposed that with increasing density M_R value generally increases. Effect of material density was included in the k-θ model by **Kolisoja (1997)** as shown in equations (18) and (19).

$$M_R = C\,(m_{max} - n)p_0\left(\frac{\theta}{p_0}\right)^{0.5} \quad (18)$$

$$M_R = D\,(m_{max} - n)p_0\left(\frac{\theta}{p_0}\right)0.7\left(\frac{q}{p_0}\right)^{0.2} \quad (19)$$

Where,

C, D are constants

m_{max}, m = maximum porosity and material porosity

The above equations are primarily depending on laboratory tri-axial tests carried out with steady confining pressure.

M_R values for CCP and VCP were proposed by **Nataatmadja et al. (1989)** as shown in equation (20) and (21)

For CCP $$M_R = \frac{\theta}{q\,(A+Bq)} \quad (20)$$

For VCP $$M_R = \frac{\theta}{\sigma_1 (C+Dq)} \quad (21)$$

Where A, B, C, D are constants.

A multiple regression equation (22) was proposed by **Itani (1990)** to develop a model which consists of confining stress, shear stress and bulk stress for determination of M_R.

$$M_R = k_9 \left(\frac{\sigma_\theta}{3}\right) k_{10}\, \sigma_d k_{11}\ \sigma_3\, k_{12} \quad (22)$$

Where k_9, k_{10}, k_{11}, k_{12} = regression constants

An equation (23) was developed by **Feliberti (1991)** in which axial strain is used in place of deviator stress for estimation of M_R.

$$M_R = k_{13}\, (\sigma_\theta)\, k_{14}\, \varepsilon_d\, k_{15} \quad (23)$$

Where k_{13}, k_{14}, k_{15} = regression constants

2.3.2.2 Estimation of Granular Modulus

The most commonly used equation for calculating granular layer modulus was given by **Shell (1978)** as shown in equation (24).

$$M_R\ (\text{Granular}) = 0.2 \times h^{0.45} \times M_R\ (\text{Subgrade}) \quad (24)$$

Where,

h (mm) = thickness of granular layer

M_R (Granular) and M_R (Subgrade) are in MPa

Equations (25) and (26) was given by **Smith et al. (1981)** for the determination of thicknesses of base and sub-base layer, layer moduli of subgrade, base and sub-base layer.

For base course material

$$E_b = E_{sg}\, (1 + 0.067 h_b) \quad (25)$$

For sub-base course material

$$E_{sb} = E_{sg}\, (1 + 0.003 h_{sb}) \quad (26)$$

Where,

E_b, E_{sb}, E_{sg} are modulus values of three layers of the pavement (MPa)

h_b , h_{sb} =base and sub-base thicknesses in mm

Equation (27) was proposed by **Smith et al. (1981)** for the determination of base modulus which is dependent upon thicknesses and moduli values of different layers.

$$\text{Log}(E_{\text{Granular}}) = 1.079 - 0.511 \times \log(h_1) - 0.008 \times \log(h_2) - 0.155 \times \log(E_1) + 0.279 \times \log(E_3) + 0.888 \times \log(k_1) \quad (27)$$

Where,

h_1 = thickness of asphalt concrete layer (inch)

h_2 = thickness of granular layer (inch)

E_1 = asphalt concrete layer modulus (psi)

E_2 = granular layer modulus (psi)

E_3 = subgrade modulus (psi)

k_1 = material constant for granular layer computed from repeated triaxial test.

The equations (28), (29), (30) and (31) were recommended by AASHTO 1993 which are used for determination of modulus of granular layer from CBR values.

M_R (Granular, psi) = $740 \times CBR$ for $\theta = 100$ psi (28)

$440 \times CBR$ for $\theta = 30$ psi (29)

$340 \times CBR$ for $\theta = 340$ psi (30)

$250 \times CBR$ for $\theta = 10$ psi (31)

Where, θ = summation of principal stresses

It recommends some other options also for the determination of modulus of granular layer.

- Triaxial testing in laboratory
- Back-calculation from deflection profiles (NDT)
- Presumed values if data is not available

2.3.3 Bituminous Layer Modulus

The estimation of bituminous layer modulus is somewhat complicated because its value is influenced by an enormous number of components. Bituminous layer modulus can be resolved either destructively or Non-destructively. In destructive method it is computed by core extracted from field and carry out laboratory testing. The laboratory tests are performed under repetitive load conditions in constant strain or constant load mode.

To estimate the bituminous layer modulus equation (32) was developed using SHRP (Strategic Highway Research Program) data. This equation was developed by **Rada et al. (1991).**

$$E_{ac}= 0.553833 + (0.28829\ P_{200})\ (f\ -0.17033\ -0.03476)\ (V_a + 0.07037)\ (\eta_{70.10}{}^{6} + 0.000005)\ [t_p{}^{0.3+\ 0.49825\ \log (f)} \times (P_v)^{0.5}] - 0.00189[t_p{}^{0.3+\ 0.49825\ \log (f)} \times P_v{}^{0.5} \times f^{4.4}] + 0.931757\ f^{0.02774} \quad (32)$$

Where,

E_{ac} = modulus of surface layer (10^5 psi)

P_{200} =percentage of aggregate weight passing 200 sieve

f = test frequency

V_a = percentage of air voids in mix

η = asphalt viscosity at 70^0F

t_p = surface layer temperature at mid-depth (^{o}F)

P_v = percentage of asphalt content by volume of mix.

The values of resilient modulus of bituminous mixes suggested by IRC for different average annual pavement temperature are presented in Table 2.4.

Table 2.4 Indicative Values of Resilient Modulus (MPa) of Bituminous Mixes (IRC: 37-2018)

Material Type	Elastic/Resilient modulus (MPa)	Poisson's Ratio
Bituminous layer with VG40 or Modified Bitumen	3000 or tested value (whichever is less)	0.35
Bituminous layer with VG30	2000 or tested value (whichever is less)	0.35
Cement treated base	5000	0.25
Cold recycled base	800	0.35
Granular interlayer	450	0.35
Cement treated sub-base	600	0.25
Unbound granular layers	Use equation 24	0.35
Unbound granular base over CTSB sub-base	300 for natural gravel 350 for crushed aggregates	0.35 0.35
Subgrade	Use equation 7	0.35

Table 2.5 gives the details of different inputs to be considered for the analysis of pavement as per IRC: 37-2018 guidelines.

Table 2.5 Recommended Material Properties for Structural Layers (IRC: 37- 2018)

Material Type	Elastic/Resilient modulus (MPa)	Poisson's Ratio
Bituminous layer with VG 40 or Modified Bitumen	3000 or tested value (whichever is less)	0.35
Bituminous layer with VG 30	2000 or tested value (whichever is less)	0.35
Cement treated base	5000	0.25
Cold recycled base	800	0.35
Granular interlayer	450	0.35
Cement treated sub-base	600	0.25
Unbound granular layers	Use equation 24	0.35
Unbound granular base over CTSB sub-base	300 for natural gravel 350 for crushed aggregates	0.35 0.35
Subgrade	Use equation 7	0.35

The Poisson's ratio values adopted by various investigators for the analysis of flexible pavements are presented in Table 2.6.

Table 2.6 Poisson's Ratio Values Assumed by Various Investigators

Design Method/Researchers	Layer	Range	Typical Value	Remarks
Uzan et al. (1992)	Granular	0.60-0.70		Examined non-linearity of poisson's ratio value of Granular material
Allen et al. (1974)	Granular	0.35-0.40		
Monismith et al. (1967)	Clayey subgrade	0.40-0.50	0.4	For wet condition, poisson's ratio value of 0.5 is considered.
	Saturated clays		0.5	
	Sands		0.35	
Pell (1987)	Asphalt	0.35-0.50	0.5	For higher temperatures
AASHTO (1993)	Asphalt	0.15-0.45	0.35	It is affected by temperature; Lesser value for cold temperature (< 30°F) Higher value for warm temperature (< 120°F)
	Granular	0.30-0.40	0.35	For Crushed material value is lower For uncompressed rounded gravel/sand value is high
	Subgrade	0.30-0.50	-	Non-cohesive soil -0.3 cohesive soil -0.5
Austroads (1992)	Asphalt	0.35-0.50	0.4	
	Granular	0.10-0.50	0.35	For cemented material value is 0.2
	Subgrade	0.35-0.45	-	Non-cohesive soil -0.35 Cohesive soil -0.45

Table 2.7 Salient Characteristics of Some Back-Calculation Programs

Program Name	Developer	Forward Calculation Method	Forward Calculation Subroutine	Back-calculation Method	Nonlinear Analysis	Layer Interface Analysis	Maximum Number of Layers	Seed Moduli	Range of Acceptable Modulus	Ability to Fix Modulus	Convergence Scheme	Error Weighting Function
BISDEF	USACE-WES	Multilayer Elastic Theory	BISAR	Iterative	No	Variable	Number of deflections; best for 3 unknowns	Required	Required	Yes	Sum of squares of absolute error	Yes
BOUSDEF	Zhou et al. (Oregon State)	MET	MET	Iterative	Yes	Fixed (rough)	At least 4	Required	Required	N/A	Sum of percent errors	N/A
CHEVDEF	USACE-WES	Multilayer Elastic Theory	CHEVRON	Iterative	No	Fixed (rough)	Number of deflections; best for 3 unknowns	Required	Required	Yes	Sum of squares of absolute error	Yes
COMDEF	USACE-WES	Multilayer Elastic Theory	BISAR	Database	No	Fixed (rough)	3	No	No	N/A	Various	No
DBCONPAS	Tia et al. (University of Florida)	Finite Element	FEACONS III	Database	Yes	Yes	N/A	No	No	N/A	N/A	N/A
ELMOD/ ELCON	Ullidtz	MET	MET	Iterative	Yes (subgrade only)	Fixed (rough)	4 (exclusive of rigid layer)	No	No	Yes	Relative error of 5 sensors	No
ELSDEF	Texas A&M, USACE-WES	Multilayer Elastic Theory	ELSYM5	Iterative	No	Fixed (rough)	Number of deflections; best for 3 unknowns	Required	Required	Yes	Sum of squares of absolute error	Yes
EMOD	PCS/Law	Multilayer Elastic Theory	CHEVRON	Iterative	Yes (subgrade only)	Fixed (rough)	3	Required	Required	Yes	Sum of Relative squared error	No
EVERCALC©	Mahoney et al.	Multilayer Elastic Theory	CHEVRON	Iterative	Yes	Fixed (rough)	3 (exclusive of rigid layer)	Required	Required	Yes	Sum of absolute error	No
FPEDD1	Uddin	Multilayer Elastic Theory	BASINF	Iterative	Yes	Fixed (rough)	N/A	Program Generated	N/A	N/A	N/A	No
ISSEM4	Ullidtz	Multilayer Elastic Theory	ELSYM5	Iterative	Yes (finite cylinder concept)	Fixed (rough)	4	Required	Required	Yes	Relative deflection error	No

Table 2.8 Salient Characteristics of Some Back-Calculation Programs

Program Name	Developer	Forward Calculation Method	Forward Calculation Subroutine	Back-calculation Method	Nonlinear Analysis	Layer Interface Analysis	Maximum Number of Layers	Seed Moduli	Range of Acceptable Modulus	Ability to Fix Modulus	Convergence Scheme	Error Weighting Function
MICHBACK	Harichandran et al.	Multilayer Elastic Theory	CHEVRONX	Newton method	No	Fixed (rough)	Number of deflections; best for 3 unknowns	Required	Required	Yes	Sum of relative squared error	N/A
MODCOMP5	Irwin, Szebenyi	Multilayer Elastic Theory	CHEVRON	Iterative	Yes	Fixed (rough)	2 to 15 layers; maximum of 5 unknown layers	Required	Required	Yes	Relative deflection error at sensors	No
MODULUS	Texas Transportation Institute	Multilayer Elastic Theory	WESLEA	Database	Yes	Fixed	4 unknowns and stiff layer	Required	Required	Yes	Sum of relative squared error	Yes
PADAL	Brown et al.	Multilayer Elastic Theory	N/A	Iterative	Yes (subgrade only)	Fixed	N/A	Required	N/A	N/A	Sum of relative squared error	N/A
WESDEF	USACE-WES	Multilayer Elastic Theory	WESLEA	Iterative	No	Variable	5	Required	Required	Yes	Sum of squares of absolute error	Yes

N/A = Not applicable

(Source: Using FWD Data with Mechanistic- Empirical Design and Analysis, Volume I: Final Report)

2.4 SUMMARY OF LITERATURE REVIEW

Throughout the years, various diverse testing equipments have been utilized to acquire pavement deflection data and presently FWD has turn out to be the globally accepted device. A large number of back-calculation methodologies and their equivalent programs for flexible pavements are comparable, despite the fact that the outcomes got from the programs do vary because of innate suppositions, iteration methods and forward and back-calculation techniques incorporated with programs. Every technique is having some limitations. Various regression equations have been developed by the researchers over the time. But it is difficult to tell that which equation can be used for particular study.

Optimization method uses forward calculation program. This sort of methodology is most appropriate for situations when an enormous number of pavements with a comparable arrangement required to be tested in sequence. For these circumstances, the generated database can be utilized over and again to back-calculate the pavement layer moduli for all comparable pavements. This method can be utilized with a database created from any linear or non-linear program. Iterative approach is used for back-calculation of pavement layer moduli. The main limitation of this method is that unknowns of equations which are used to calculate pavement surface deflection cannot be solved directly. On the roads of different countries, various studies were performed to evaluate the different programs for analysing Falling weight Deflectometer data.

CHAPTER 3
NDT TECHNIQUES AND BACK-CALCULATION PROGRAMS

In this chapter various commonly used non-destructive methods have been discussed with mainly focus on impulse loading equipments such as FWD. IRC: 81-1997 (Strengthening of Flexible pavement using Benkelman Deflection technique) and IRC: 115-2014 (Structural evaluation of flexible pavement using FWD technique) procedures have been deliberated in this chapter. Some commercially available FWD models and various back-calculation programs used in this study are also discussed.

The NDT instruments are classified as static and dynamic loading equipment depending on duration of application of load.

3.1 STATIC LOADING EQUIPMENT

The deflections are measured at any location by applying static or slow moving load. BBD, California travelling Deflectometer and Lacroix deflectograph are some popular devices which can be considered in this category. Benkelman Beam is a 3.66 m lengthy equipment which is used to measure response of a pavement in terms of surface rebound deflection under static standard axle truck loading. When the front leg of the BBD is fall in the region of deflected bowl due to wide deflection bowl area the movement of beam support resting in deflection bowl can result in erroneous deflection measurements. To measure deflections at different radial locations under slow moving load condition Double, Multiple and Modified Benkelman beam have been utilised **(Zube et al. 1966).** BBD was one of the first methods developed for measuring deflections on pavements and was economical, easily available and widely used in the world. However, it does not simulate the effects exerted by moving vehicles because it operates under static loading, its performance is slow and there is high degree of uncertainty in taking data **(Murillo et al. 2013).** Lacroix Deflectograph was manufactured in France and mostly utilised in Europe. It is faster equipment as compared to Benkelman beam. It is a truck mounted Benkelman beam. California division of highways developed the Travelling Deflectometer which was used to compute the deflections between each set of dual wheels **(Zube et al. 1966).** The CEBTP Curviameter device was originally developed by France

(Paquet 1978). It works at a speed of 18 km/h and measures surface deflections of pavement as well as determines pavement deflection bowl.

Though, it is simple to measure deflections under static load but the evaluation of pavement by using these equipments is generally slow and does not replicate the actual loading conditions created by the running vehicle.

3.1.1 Benkelman Beam Deflection Method

Benkelman beam is an instrument utilised for measuring the surface deflection of the pavement under standard axle truck loading. Only maximum surface deflection (actual or rebound) is determined by using this method. It is simple, inexpensive and reliable equipment. Structural response is measured under static loading condition which does not represented the loads which are applied on pavements by fast moving traffic. Therefore, the loading applied by this procedure is not realistic. The profile of entire deflection bowl is not measured as per IRC: 81-1997 guidelines. Two pavements with same maximum deflection can have different deflection bowls which indicate that strain in asphalt pavement depends on the stiffness of individual layers of pavement. Therefore, to compute strength properties of individual layers, measurement of entire deflection bowl is important. Benkelman Beam apparatus is shown in Figure 3.1.



Figure 3.1 Benkelman Beam Test Apparatus

Maximum deflection is measured using two different procedures:

3.1.1.1 WASHO Method

WASHO stands for Western American State Highway Officials method. In this method deflection noted, as wheel load approaches the point as depicted in Figure 3.2.

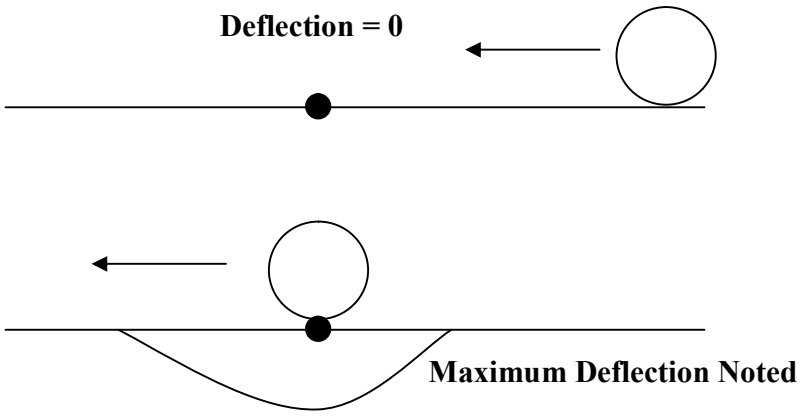


Figure 3.2 WASHO Method

3.1.1.2 CGRA Method

CGRA stands for Canadian Good Roads Association. In this method, after the removal of the load from the point rebound deflection is measured as shown in Figure 3.3.

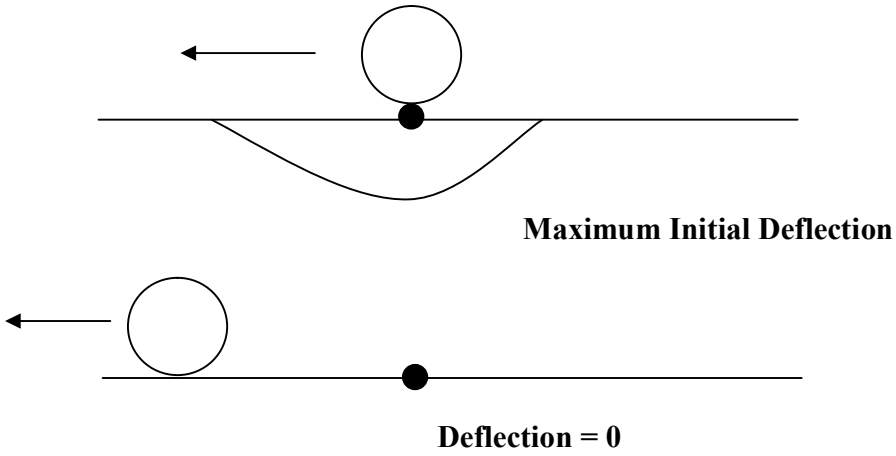


Figure 3.3 CGRA Method

The deformation of pavement under applied load depends upon type of subgrade soil, moisture content of soil, compaction, thickness of pavement layers, surface temperature etc. Pavement deflection is determined by BBD which includes 3.66 m lengthy slender beam hinged at a distance of 2.44 m from the tip, by properly setting the probe among the dual wheels of loaded truck; it is viable to measure rebound and residual deflections of the pavement structure. Rebound deflection is mainly used for overlay design. IRC: 81-1997 guidelines suggested that CGRA procedure to be used for deflection measurements.

According to CGRA Method

Equipment includes:

1. **Beam Details:**

Length of beam from Hinge to Probe = 2.44 m

Length of beam from Hinge to Dial = 1.22 m

Distance from Hinge to front legs = 0.25 m

Distance from Hinge to rear legs = 1.66 m

Lateral spacing of front support legs = 0.33 m

2. **Loading Details:**

5 tonne truck is recommended to apply 8170 kg rear axle load (uniformly distributed over the two dual wheels).

1. Spacing between tyres walls = 30 – 40 mm
2. Tyre Pressure = 5.6 kg/cm^2
3. Tyre pressure measuring gauge
4. 4.5 cm deep hole in pavement for temperature measurement.

3.1.1.3 Procedure for Deflection Survey

This survey mainly includes two operations:

1. Pavement condition survey for gathering the basic information of pavement
2. Actual Deflection measurement

Pavement Condition Survey

By using 3 m straight edge simple measurement for rut depth is performed based on this, road length is classified in to section of equal performance according to criteria given in Table 3.1.

Table 3.1 Classification of Various Road Lengths

CLASSIFICATION	PAVEMENT CONDITION
Good	If there is no Cracking, Rutting < 10 mm
Fair	If there is no Cracking or it is limited to single crack in the wheel track with rutting between 10 mm and 20 mm
Poor	Large cracking and Rutting > 20 mm Sections with cracking > 20% shall be considered failed.

Information acquired during this survey shall be noted in Performa given in the code IRC: 81-1997.

Deflection Measurements

- In every road section minimum of ten points need to be marked at same distance in each lane of the traffic.
- Staggered points should be marked on adjacent lane for roads having more than one lane**.**
- In transverse direction, mark the Point on the pavement at a 60 cm distance from pavement edge for single lane roads (Lane width < 3.5 m) and at a 90 cm distance from the edge of the pavement for wider lanes (Lane width > 3.5 m)
- For divided four lane highways, point should be selected at 1.5 m from edge.
- Wheels of truck are centred above the particular point. One end of Benkelman beam is put in between dual wheels.
- When the rate of deformation of the pavement ≤ 0.0025 cm/minute the first reading (D_0) is taken.

- Similarly an intermediate reading (D_1) is taken at a distance of 2.7 m, truck is gradually moved to this distance
- Then the last reading (D_2) is taken by moving the truck to a distance of 9 m.
- Rebound deflection value at any point is computed by the equations (33) and (34)

1) If $(D_1 - D_2) \leq 0.0025$ cm,

   Then rebound deflection = $2 (D_0 - D_2)$ (33)

2) If $(D_1 - D_2) > 0.0025$ cm,

   Then rebound deflection = $2 (D_0 - D_2) + 2.91 [2 (D_1 - D_2)]$ (34)

- Pavement temperature is measured by inserting thermometer in the standard hole which is filled with glycerol as shown in Figure 3.4.



Figure 3.4 Temperature Measurement at the Site

- Tyre pressure is also checked at every 2-3 hours intervals during the day.
- Deflection readings measured by BBD method are affected by pavement temperature. Therefore, for designing purpose all deflection readings should be

linked to standard temperature. Hence readings taken at different temperature should be corrected for standard temperature which is 35° C.

- Correction applied on deflection readings for temperature difference should be 0.01 mm for each degree Celsius variation from standard temperature of 35° C.

  If pavement temperature < 35° C

  Then Correction = +ve

  If pavement temperature > 35° C

  Then Correction = -ve

  For example, if deflection is measured at 39 ° C

  Then the value of the correction factor should be 0.04 mm which will be deducted from deflection reading to get corrected value with respect to temperature of 35°C.
- Since, pavement deflection is affected by the yearly variation of the season hence, pavement deflection readings should be taken when the pavement is in its worst situation.
- Since, in India time just after monsoon season pavement is in weakest condition so deflection readings should take during this period.
- Correction on seasonal variation is mainly affected by nature of subgrade soil, its field moisture content during BBD survey and average yearly precipitation in that region.
- Subgrade soils are divided in to three groups namely, Sandy/gravel, Low Plastic Clay (PI≤ 15) and High Plastic Clay (PI > 15)

  Similarly rainfall also divided in to two groups, namely Low rainfall area (yearly rainfall ≤ 1300 mm) and High rainfall area (yearly rainfall > 1300 mm)

  Seasonal correction factor shall be determined from figures given in IRC: 81-1997 for given field moisture content, nature of the subgrade soil and yearly rainfall. Figure 3.5 is the graph for moisture correction factor and taken from IRC: 81-1997.

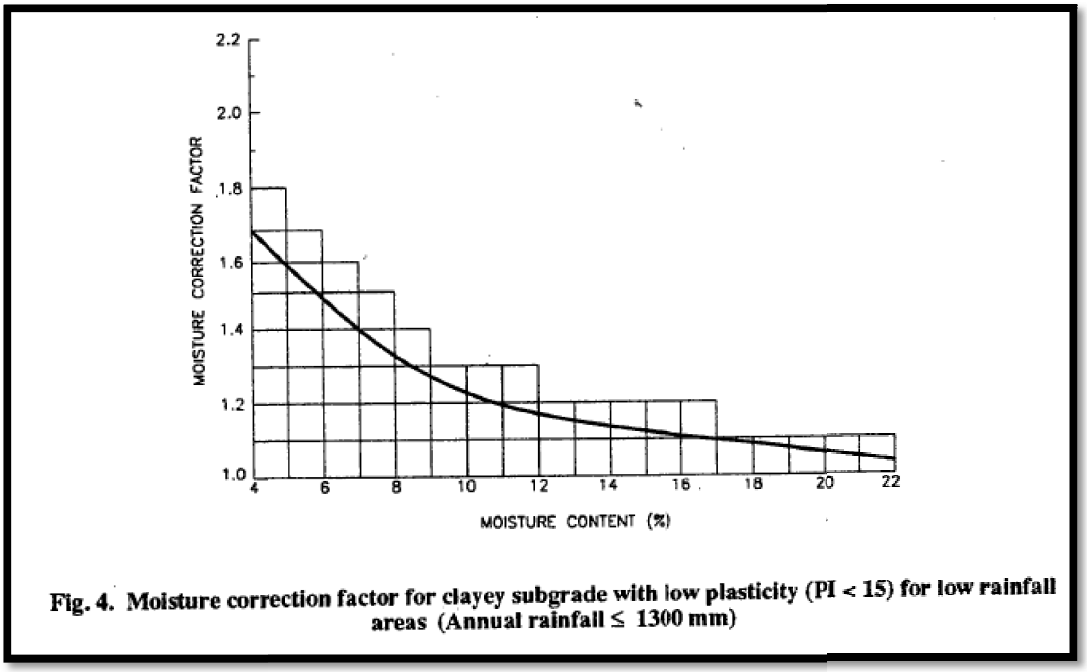


Fig. 4. Moisture correction factor for clayey subgrade with low plasticity (PI < 15) for low rainfall areas (Annual rainfall ≤ 1300 mm)

Figure 3.5 Graph for Moisture Correction Factor (IRC: 81-1997)

- Deflection readings corrected after application of temperature correction should be multiplied by moisture correction factors to get corrected deflection readings.

3.1.1.4 Analysis of data for overlay design

Characteristics deflection

Thus to calculate characteristic deflection for design purposes mean deflection and standard deviation are required. The formulas are specified in IRC: 81-1997 to determine characteristics deflection for arterial roads and for all other roads.

Design of Overlay

Bituminous macadam overlay is calculated from the design curves (given in IRC-81) relating characteristics deflection to the design traffic (in msa) as .presented in Figure 3.6.

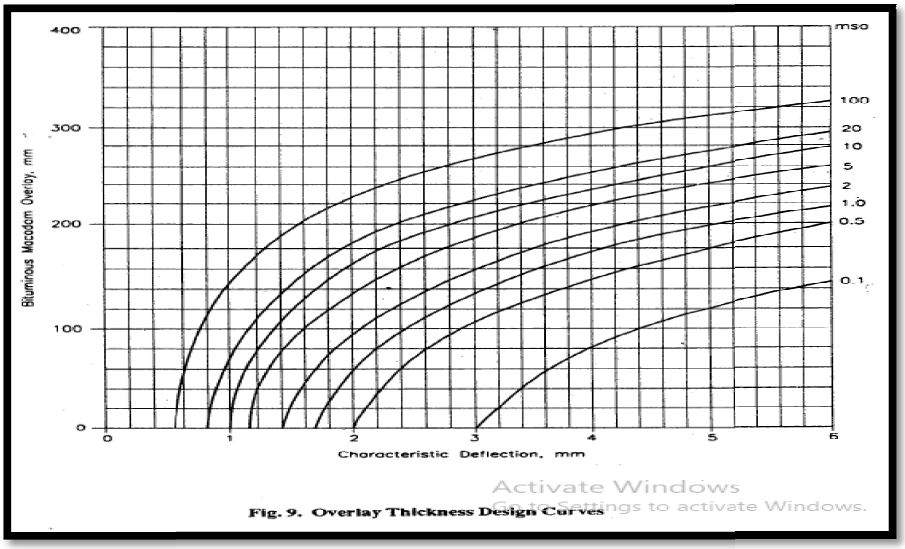


Figure 3.6 Overlay Thickness Design Curve (IRC: 81-1997)

Calculation of Design Traffic

During design life of road the cumulative number of standard axles to be carried is represented the design traffic. Equation (35) is suggested by IRC for the determination of design traffic.

$$N_S = \frac{365 * A\,[(1+r)^x - 1]}{r} * L * F \qquad (35)$$

N_s = Cumulative number of standard axles

A = Initial traffic in the year of completion of construction in terms of number of cvpd

r = Annual growth rate of commercial vehicles

x = Design life in years

F = Vehicle damage factor

L = Lane distribution factor

Design curves shown in Figure 3.6 calculate the thickness in terms of BM overlay. If other compositions are to be placed on the pavement then overlay thicknesses can be determined by using suitable equivalency factors given in IRC: 81-1997.

1 mm of BM= 15 mm of Water Bound Macadam / Wet Mix Macadam

1 mm of BM = 7 mm of Dense Bituminous Macadam

3.2 DYNAMIC LOADING EQUIPMENT

Dynamic loading equipments are mainly of two types one is vibratory loading equipment and another one is impulse loading equipment. A few of the vibratory equipments which are used for pavement evaluation are Heavy Vibrator, Road Rater and Dynaflect. Impulse loading equipments are Light weight Deflectometer, FWD, Loadman portable FWD and Rolling weight Deflectometer.

Nijboer et al. (1962) and Heukelom et al. (1962) had used Shell heavy vibrator for the research. By using this equipment, the elastic moduli for each layer can be calculated by utilising the wave velocity and wavelength from a continuum of frequencies of oscillation. The sinusoidal vibrations are produced by Dynaflect pavement testing device at a frequency of 8 Hz. In this device five geophones (velocity transducers) are fitted each at a distance of 305 mm. Output produced by these transducers is used to measure pavement Deflection **(Scrivner et al. 1966).**

Road raters are available in different models and load magnitudes vary for different models. Both trailer mounted and vehicle mounted device types of road raters are obtainable. Four or more geophones are used for deflection measurement **(Hoffman et al. 1982)**.

The vibratory equipments have certain disadvantages because of that they are not commonly used. The major limitation of Heavy vibrator is that it is very slow and works at slow frequency rates. In Dynaflect device the extent and frequency of load shall not be changed and maximum peak force that can be bear by this device is 1000 pound. The technical limitation of Road rater is that material stiffness changes and deflections produced are not simulate the moving wheel load due to application of large static load for heavy models.

The impulse loading equipments which nearly replicate the timing and amplitude of a rolling wheel load, their development was started in sixties. **Isada (1966)** studied the change in the strength of flexible pavement due to seasonal changes by using the falling mass device. Evaluation of pavements by using FWD was discussed by (**Bohn et al.**

1972). Falling Weight Deflectometer has undergone several improvements over the years. Current FWD's have various features such as Global Positioning System (GPS) and electronic distance measurement system.

3.3 FALLING WEIGHT DEFLECTOMETER (FWD)

FWD is a Non-destructive type instrument used for assessing load carrying ability of pavements. FWD is trailer mounted device which measures the surface deflections of pavement surface by applying impulse loading to the pavement surface by dropping a weight. The weight is fallen on a spring system, which conveys the load to the pavement surface through a loading plate. The applied load can be changed by varying the magnitude of the dropping mass and the height of drop. Velocity transducers or sensors are installed at different radial locations from the middle of loading plate which are utilised to determine the vertical surface deflections of pavement. It provides the deflection bowl which is examined and used for the back-calculation of moduli values of pavement layers. FWD data is mainly used for:

- Finding layer moduli values
- Pavement Overlay Design
- Estimation of remaining life
- Determining the Load transfer efficiency of joints in cement concrete pavements

Figure 3.7 is showing the deflection profile measured at different sensor locations.

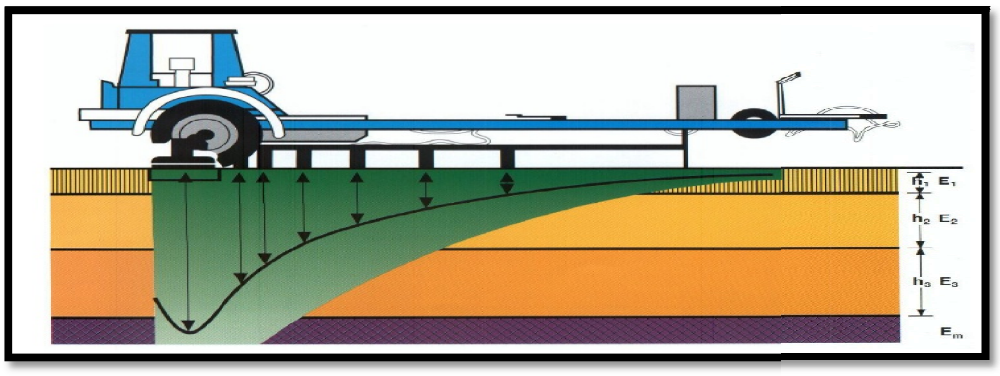


Figure 3.7 FWD Trailer Showing Deflection Profile Recorded At Different Sensor Locations

(Source: https://rims2019.co.nz/)

The Falling Weight Deflectometer used in this study is shown in Figures 3.8 and 3.9.



Figure 3.8 Trailer Mounted FWD Used In This Study



Figure 3.9 Another View of FWD Used In This Study

3.3.1 Components of Falling Weight Deflectometer

The major components of FWD are illustrated below:

1. **The Vehicle**

   The vehicle is customized for accommodating the complete FWD system including hydraulic and electronic circuits. A vehicle is modified so that personal laptop, electronic wirings and vehicle operator should be accommodated inside the vehicle. For charging the batteries an alternator is installed to get a power from the engine of the vehicle. A sine wave inverter is utilised to deliver power to computer and electronic circuit.

2. **Force – Generating Device (Falling 'weight')**

   The force-generating is capable of being raised to one or more predetermined heights and dropped.

3. **Guide System**

   It is designed to operate with negligible friction or resistance so that weight falls perpendicular to the pavement surface.

4. **Loading Plate**

   Loading plate uniformly distributed the load on the surface of pavement. Typically the diameters of the loading plate are 300 and 450 mm for measurements on roads and airfields. The plate should be properly placed to measure pavement deflection at centre of plate.

5. **Deflection Sensor**

   The maximum vertical movement of pavement is measured by using deflection sensor and mounted in such a way to the measuring plane so that it minimizes angular rotation at the maximum expected movement. The number and spacing of sensors depend upon the purpose of the test and pavement layers characteristics. Displacement transducers, Velocity transducers or accelerometer are the sensors which are used. Mostly the 300 mm sensor spacing is used.

6. **Data Processing and Storage System**

   Air temperature, pavement surface temperature and distance measurement data for each test point can be recorded manually or automatically. Load and Deflection data is recorded on a personal computer.

7. **Load Cell**

   Load cell measures the applied impact load and is positioned in such a manner that it does not obstruct the process of deflection measurements under the centre of the load plate. Load cell should be water proofed and resist the mechanical shocks due to road impacts during testing or travelling or both.

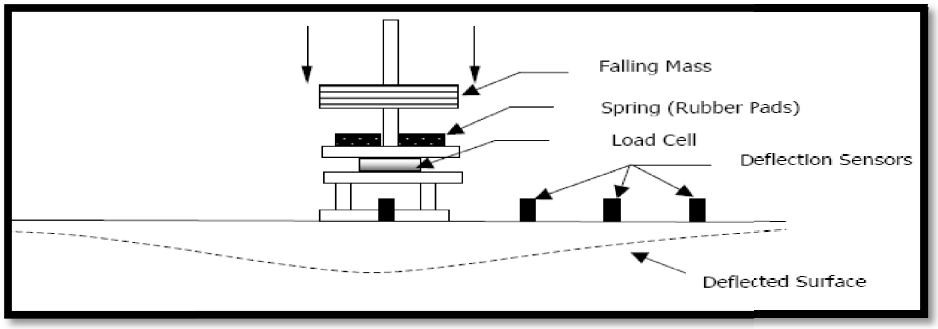


Figure 3.10 Working Principle of FWD (IRC: 115-2014)

Figure 3.10 is representing the working principle of the FWD. Before starting the structural evaluation of pavement it is important that different transducers installed in FWD, such as geophones and load cell are calibrated. The general operation of instrument, battery and data acquisition system are to be checked before testing. It is also important to have proper planning to curb traffic and safety of the workers.

3.3.2 Deflection Measurements

For the augmentation of FWD data steps which are followed are illustrated below:

1. For controlling the traffic a suitable arrangement is made.
2. For future references paint is used to mark the test points.
3. Pavement and air temperatures are recorded.
4. The FWD is placed properly over the test point so that loading plate is placed directly above the test point. Figure 3.11 is showing the load pulse generating system of FWD.

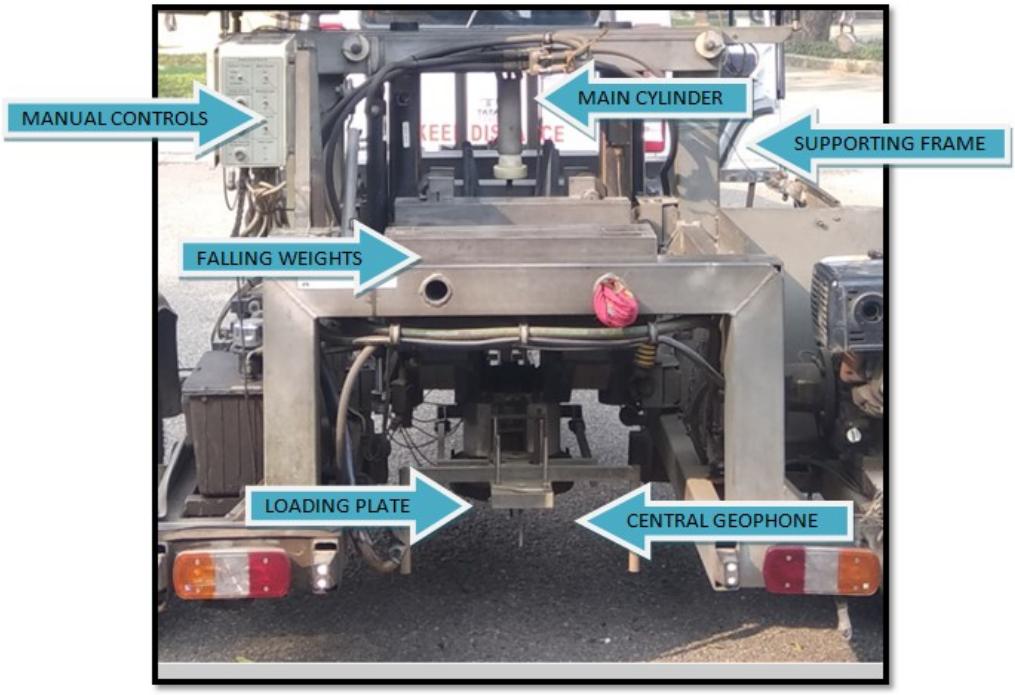


Figure 3.11 Load Pulse Generating System

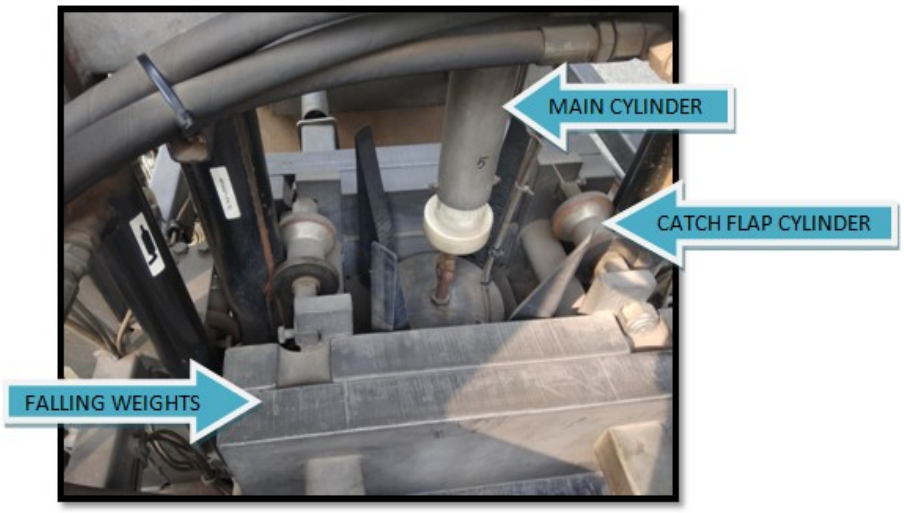


Figure 3.12 Falling Weight System

The falling weight system is shown in Figure 3.12. It consists of main cylinder, catch flap cylinder and falling weights. The geophones (sensors) attached in FWD are presented in Figure 3.13.



Figure 3.13 Geophone Overview

5. Frame on which sensors are attached is straightened and moved down on the surface of road so that probes of the sensors come in contact with ground. Then loading plate is positioned on the pavement surface as depicted in Figure 3.14. Then falling weights are lifted to the desired height.



Figure 3.14 Sensor Bar In Contact With the Pavement Surface

6. The data acquisition software is started with entering suitable configurations.
7. The signals from load cell and sensors are recorded in laptop when falling weights are dropped.
8. Firstly, one seating load is dropped on the pavement surface. Load and deflection data is not to be recorded for the seating load.

9. The height of fall is customized in such a way so that the applied impulse load matches the desired load.

3.3.3 Determination of Pavement Layer Thickness

Pavement crust detail is necessary input for back-calculation process of layer moduli, for predicting remaining life and overlay requirement for pavement. Layer thickness can be determined from past data and by excavating test pits. A non-destructive technique which is a Ground Penetrating Radar can also be used to measure layer thickness. It is difficult to get the accurate thickness of constructed pavement layer, most effective method for determining the thickness is the excavation of test pits at suitable spacing and measure the layer thickness. The test pits can be excavated along the outer lanes starting from the outside edge of the lane and exposing pavement layers sufficiently to note the sign of distresses, defects and thickness of each layer. After collecting necessary data, test pits are filled back with suitable material and compacted so that they do not affect the structural condition of pavement and also do not create the traffic safety hazard. If test pits remain unfilled suitable barricading and proper safety devices are installed for ensuring night visibility at the area of excavation.

Samples of different layer materials from test pit can be collected which can be examined for signs of degradation and contamination of granular layers, stripping of bituminous mixes, and identification of rutted layers. Core samples can be tested in laboratory for determination of layer moduli and to find out cause of distresses mainly in bituminous mixes. These layer moduli then can be used for validation purpose by comparing these moduli with back-calculated layer moduli.

3.3.4 Analysis of Data

3.3.4.1 Processing of Load and Deflection Data

Load values obtained on different drops and the deflection values at different radial locations are collected at each test point. The deflection values which are unrealistic and incorrect should not be used. Three test data sets are collected at given location, average of that is taken for the selection of load and deflection value. Deflection values should not

be greater than the capacity of geophones. Figure 3.15 represents a pavement deflection bowl. Loading plate is attached at D_0 value and while moving away from loading plate the deflection values are also decreasing as presented in Figure 3.15.

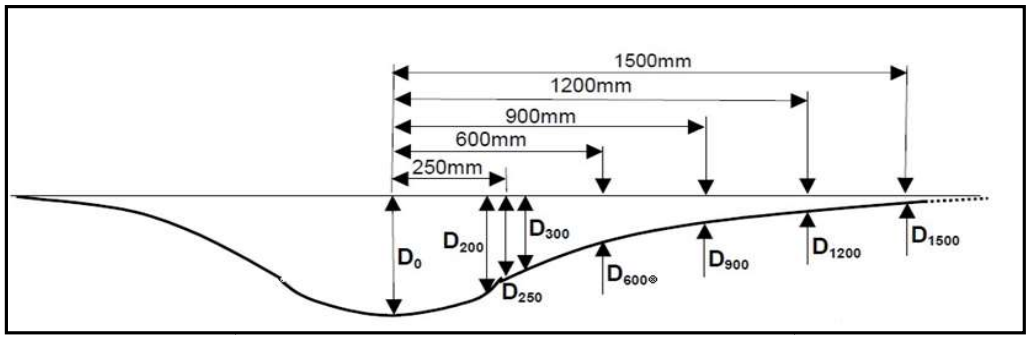


Figure 3.15 Typical View of Pavement Deflection Bowl

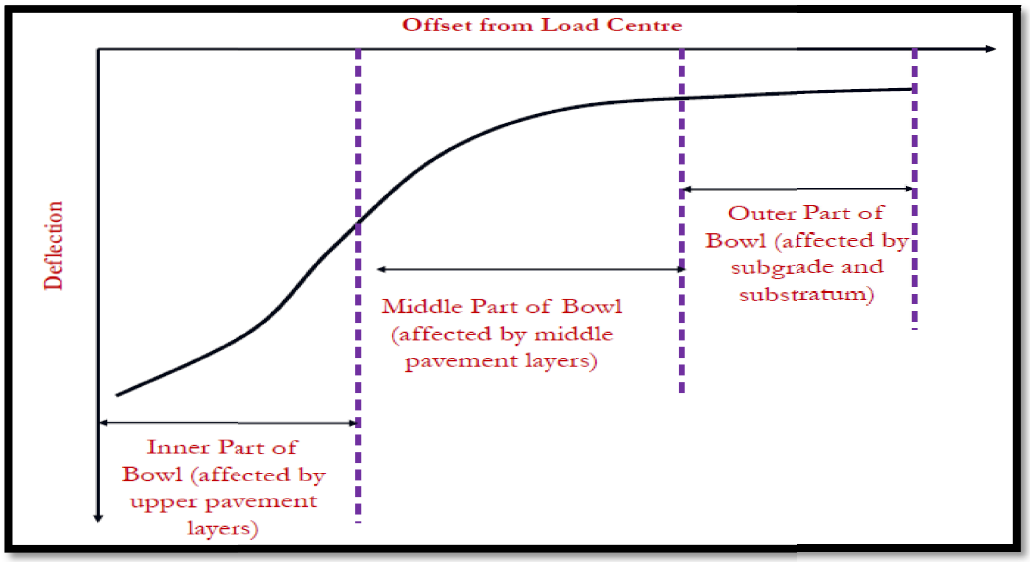


Figure 3.16 Characteristics of Deflection Bowl

Figure 3.16 is representing the characteristics of deflection bowl. It is showing that inner, middle and outer parts of deflection bowl are affected by upper, middle and subgrade layers respectively.

3.4 BACK-CALCULATION OF LAYER MODULI

It is very complex and time taking task to determine modulus values at field conditions by performing laboratory tests. Back calculation of FWD data can easily determine in-situ modulus values of different pavement layers. Back-calculation is a method of selection

and adjustment of layer moduli using different techniques as discussed in chapter 2. Figure 3.17 is representing the process of back-calculation. On the basis of assumed elastic moduli the deflection values are computed by the software. These computed deflections are compared with observed deflection values until they come close to each other.

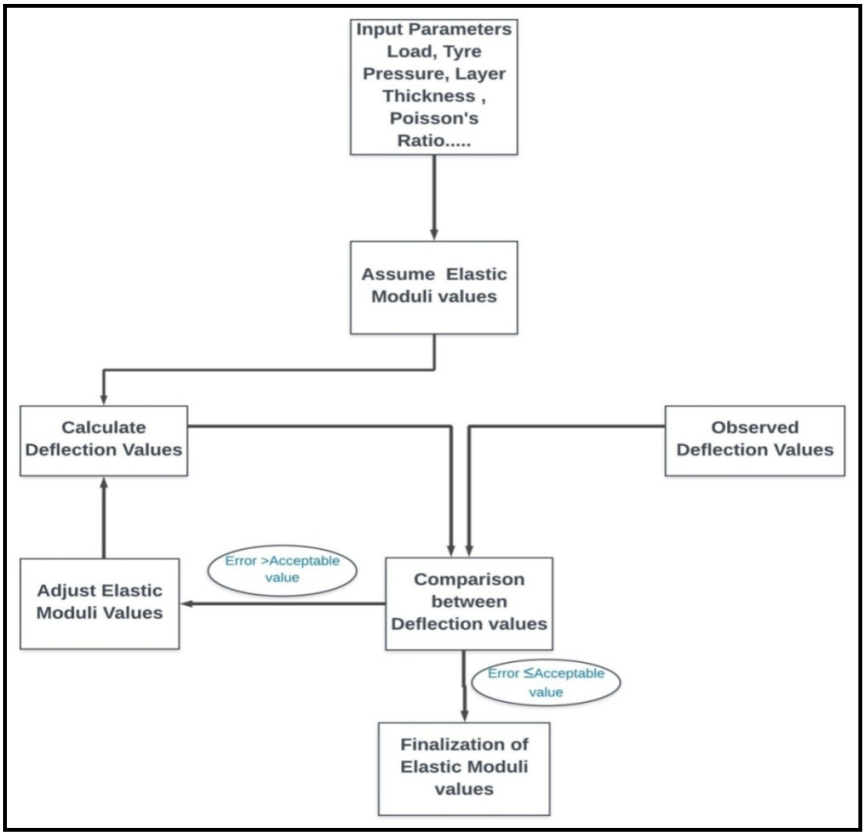


Figure 3.17 Schematic Diagram Representing the Process of Back-Calculation

There are various back-calculation software which are used for determination of layer moduli values. The KGPBACK software is recommended by IRC: 115-2014 for back-calculation of layer moduli values. Since, it is difficult to drop the exact 40 KN load so the measured deflection values have to be normalized corresponding to standard target load of 40 KN. The normalization of deflections is to be done linearly. Peak load and radius of the loading plate, Deflection values at different radial locations and their distances, pavement layer thicknesses and Poisson's ratio of different layers are inputs which are utilised by KGPBACK for back-calculation purpose.

There are two corrections applied on FWD readings:

- Correction of temperature
- Correction of Seasonal variation

3.4.1 Correction for Temperature

Pavement temperature affects the back-calculated moduli of the surface layer. Therefore, the correction should be applied on the moduli that are computed at other temperature than standard temperature. Standard Pavement Temperature is 35 degree Celsius. Equation (36) is used to calculate the temperature correction factor.

$$\lambda = \frac{1-0.238 \text{ In } (T_1)}{1-0.238 \text{ In } (T_2)} \quad (36)$$

Where,

λ= Temperature correction factor

To get the corrected surface layer moduli value, temperature correction factor calculated from equation (36) is multiplied with moduli value of surface layer for the given temperature as presented in equation (37).

$$E_{T1} = \lambda E_{T2} \quad (37)$$

Where,

E_{T1}=Back-calculated modulus (MPa) at Temperature T_1 (° C)

E_{T2} =Back-calculated modulus (MPa) at Temperature T_2 (° C)

3.4.2 Correction for Seasonal Variation

The strength of granular and subgrade layers is affected by the moisture content. Therefore it is suggested that deflection readings should be taken when subgrade is at its worst situation. In India this time period come about during monsoon season. If it is not possible to take readings during this season then correction should be applied. There are equations for seasonal correction given in code IRC: 115-2014 for subgrade and granular layers.

3.5 REMAINING SERVICE LIFE

The pavement layer moduli determined from the back-calculation process are utilised to calculate the required strain parameters for prediction of remaining life of pavement. The process which is followed for remaining life determination is shown in Figure 3.18.

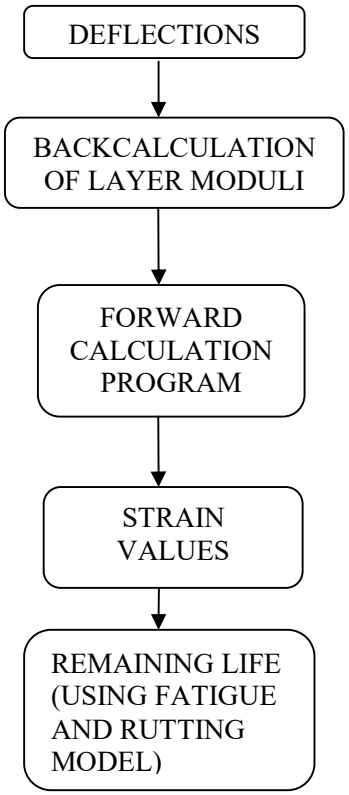


Figure 3.18 Remaining Life Estimation

3.6 SOME COMMERCIALLY AVAILABLE FWD MODELS

3.6.1 DYNATEST (USA)

Dynatest Company manufactures four FWD models 8000, 8081, 3031 and 8012 (Dynatest FWD, HWD, LWD and FastFWD). FWD and HWD used for evaluation of roads and airport pavements. LWD is suitable for testing those areas which are difficult to access e.g narrow channels, trenches etc. FastFWD is the upgraded version of FWD in which hydraulic system of FWD is replaced with new system. Figures 3.19, 3.20, 3.21 and 3.22 representing the different FWD models manufactured by Dynatest.

Table 3.2 is depicting the specifications of various FWD models made by Dynatest Company.

Table 3.2 Different FWD Models of Dynatest Company

FWD Models	FWD (8000)	HWD (8081)	LWD (3031)	FastFWD (8012)
Load Range	4-120 kN	30- 320 kN	Upto 15 kN	4-120 kN
Measurement speed	Upto 60 test points per hour	Upto 60 test points per hour	Upto 160 test points per hour	Slow



Figure 3.19 FWD (8000)
(Source: https://www.dynatest.com)



Figure 3.20 HWD (8081)
(Source: https://www.dynatest.com)



Figure 3.21 LWD (3031)

(Source: https://www.dynatest.com)

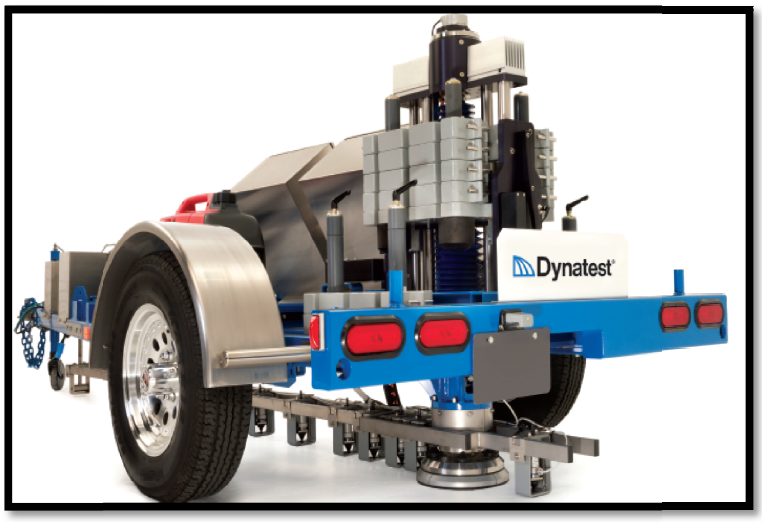


Figure 3.22 FastFWD (8012)

(Source: https://www.dynatest.com)

3.6.2 KUAB (Sweden)

Two types:

- Trailer-Mounted Version
- Vehicle- Mounted Version

Trailer-Mounted Version

This device is towed by the vehicle as shown in Figure 3.23. The device is ready for transport to the next test point at ordinary traffic speed immediately after the test. This is available with 7 or 9 sensors and in load capacities of 70 kN, 120 kN and 240 kN.

Vehicle- Mounted Version

This device is mounted on the commercial vehicle and it is highly user friendly and single man operation. This is a closed loop system and software only becomes functional once the operator pulls the hand brake of the vehicle, and after that test can be conducted. In this version special safety feature is there, that hand brake does not get released in case the Falling weights and sensors are deployed on the road. The hand brake only gets released once falling weight and sensors moved up, this feature avoids the damage.

Optional Accessories

GPR, GPS, Data Analysis Programs, other plate diameter, additional deflection sensors, other Deflection Sensor spacing, Calibration equipment, Camera system, Measurement in 700 mm deep test pits, 4 wheel trailer, trailer brakes, separate distance display, Automatic transport locks, 5 mm deflection sensor range, Deflection sensor with built-in reference calibration device, Warning Lights and signs. Specifications of KUAB FWD are presented in Table 3.3.



Figure 3.23 KUAB Falling Weight Deflectometer

Table 3.3 Specifications of KUAB FWD

Load Pulse	**Load Measurement**
Peak load range: 10-120 kN Rise time: 15 ms Number of drop heights: 4	Precision: ±1% ± 10 kgf Accuracy: ±2% ± 15 kgf
Loading Plate	**Deflection Measurement**
Size: 300 mm diameter	Range: 2 mm Number of Sensors: 7 or 9 Sensor Positions: 0,200,300,450,600,900,1200,1500 and 1800 mm from load centre

3.6.3 JILS (California United States)

JILS-20-FWD model is a trailer mounted FWD which is operated by driver in a tow vehicle. Data from the tests can be recorded in computer for future investigation. It takes thirteen seconds or less for collecting three drops of data. A four part mass buffer loading system is used by JILS FWD. It is shown in Figure 3.24.



Figure 3.24 Specifications of JILS FWD

(https://www.jilsfwd.com)

Specifications of JILS FWD are presented in Table 3.4.

Table 3.4 JILS FWD

Force Measurement	**Displacement Measurement**
Accuracy: 1% ± 0.07 kN Range: 0 to 300 kN Material: Stainless steel	Accuracy: 2% ± 1 micron Range: 0 to 2032 microns Sensors: 9
Temperature Measurement Pavement, Ambient Air Temperature	**Distance Measuring Instrument**
Global Positioning System	**Field Calibration Equipment**

3.7 VARIATIONS OF FWD

3.7.1 LOADMAN

(Livneh et al. 1997) Loadman is a portable FWD which is accessible in two type of models, light and heavy weight. Light weight Loadman is utilised for measuring the deflection caused by falling weight inside the device. This device can be easily used practically on all construction sites under any conditions and easy to handle. It is also utilised for measurement of bearing capacity of the pavement and compaction control of bound and unbound layers of pavement. Loadman FWD is as presented in Figure 3.25.

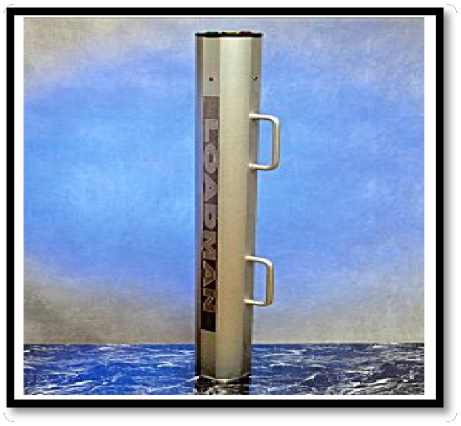


Figure 3.25 Portable FWD Loadman

(Source: https://www.al-engineering.fi/en/loadman.html)

Loadman-II is powered by rechargeable batteries and an improved version of original Loadman. It has USB connector for transferring data to a computer and has memory for saving that data.

3.7.2 Rolling weight Deflectometer

Rolling weight Deflectometer (RWD) measures continuous deflection profiles. It does not measure the deflections at separate points. **Bay et al. (1998)** had discussed the operating parameters for RWD testing on flexible and rigid pavements. RWD can move at highway speeds and can cover more distance as compared to standard FWD. While taking deflection measurements, workers are free from any kind of risk and no traffic interruption.

3.7.3 RAPTOR (Rapid Pavement Tester)

Dynatest developed this equipment for both structural and functional evaluation of the pavement at traffic speed, which offers continuous data collection. RAPTOR uses the Dynatest RWD for the collection of structural data and pavement deflections are measured by rolling wheel load using laser sensor. To ensure quality and reliability of structural data augmented from RAPTOR, Dynatest has conducted the comparative test between RAPTOR and FWD. Readings were taken on more than 100 km at 25 meters intervals. This comparative testing gives good correlation to FWD and hence proved that RAPTOR is give similar results to the FWD. RAPTOR is shown in Figure 3.26.

Speed: 2 – 100 kmph

9 line laser profilers recommended (expandable up to 24)



Figure 3.26 Dynatest Rapid Pavement Tester

(Source: https://www.dynatest.com)

3.7.4 Traffic Speed Deflectometer

It is a modern RWD measuring pavement response to applied load. Traffic speed deflectometer originally developed by Greenwood Engineering which is a Danish company and enhanced by ARRB Australia. Greenwood TSD is developed, designed and produced by Greenwood Engineering and this technology is mounted in a refrigerated trailer. TSD uses Doppler technology and standard configuration includes seven Doppler lasers. Outputs which we get from FWD and TSD are different from each other. Different

forms of load are applied in these devices so deflections necessarily differ from each other. The FWD measured the vertical deflections which are determined by geophones, whereas TSD device records the deflection slope measured from the Doppler lasers, and deflection bowl is calculated using integration. TSD is shown in Figure 3.27.

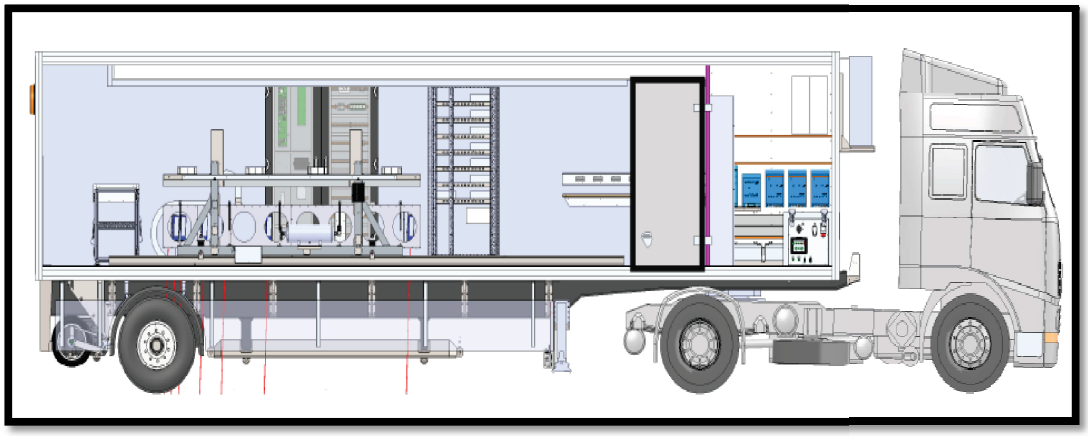


Figure 3.27 Traffic Speed Deflectometer

(Source: https://www.dynatest.com)

3.8 BACK-CALCULATION PROGRAMS

3.8.1 EVERCALC Program

EVERCALC is a computer program which is used for pavement analysis and to compute the elastic moduli of different pavement layers. For each pavement layer it determines the elastic modulus, estimates the stresses and strains at various depths. A back-calculation process followed by EVERCALC program is presented Figure 3.28.

WESLEA is used by EVERCALC program as layered elastic solution to determine the theoretical deflections and EVERCALC program also uses modified Augmented Gauss-Newton algorithm for optimization. The program uses iterative process for searching "final" modulus for each pavement layer from seed moduli (initial rough estimate of layer moduli).At each iteration deflections computed using WESLEA is compared with measured ones. The program ends when number of iterations achieved maximum number of iterations.

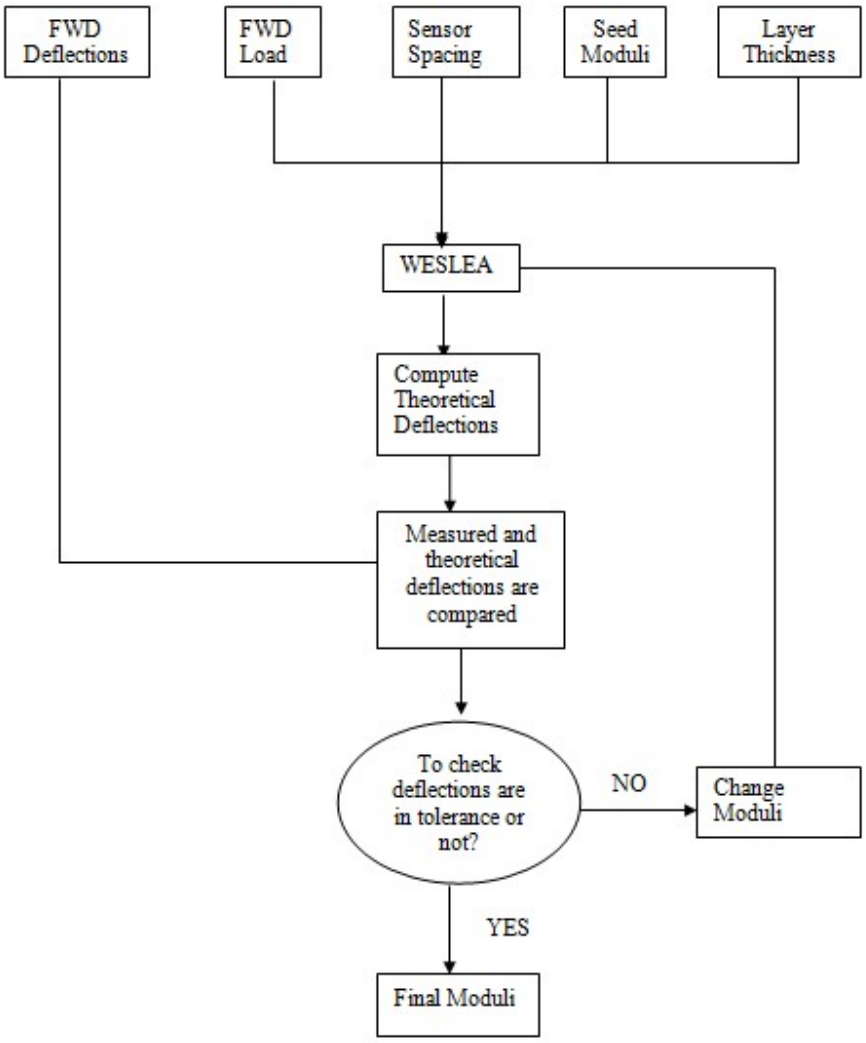


Figure 3.28 Back-calculation Process for EVERCALC Program

3.8.2 ELMOD-6 Program

In Elmod-6 program three methods are there for back-calculation. These methods are explained below:

3.8.2.1 Radius of Curvature Method

This method uses internal sensors to compute the upper pavement layer moduli and external sensors values to compute characteristics of subgrade. The modulus values of remaining layers are then computed based on overall pavement response to the applied load.

3.8.2.2 Deflection Basin Fit Method

It is also based on Odemark-Boussinesq approaches but in this method extra iteration process will use the convergence criteria based on degree of fit among overall calculated and measured deflection basins.

3.8.2.3 FEM/LET/MET

By selecting this alternative, back-calculation can be performed either with the FEM, LET or the MET. FEM utilises a modified version of axial symmetric finite element program. This program was firstly made by Duncan and Wilson at University of California **(Duncan et al., 1968)**. LET utilises WESLEA and MET is similar to Elmod's "Basin fit" method but with easy use of adjustment factors. Elmod directly applies adjustment factors on the computed responses where as MET directly applies traditional Odemark adjustment factors on layer thicknesses. Therefore moduli back-calculated by the two methods may be different.

3.8.3 KUAB Program

This program calculates the moduli of elasticity for the layers in a pavement, but values for each layer's thickness and Poisson's ratio should be given. It does so using an iteration procedure, where theoretical deflections in a mathematical model are compared with measured deflections. The program adjusts layer moduli until no further improvement is required. The program then calculates the strains in the layers and find out that which layer will fail according to the criteria for strain allowed and how many years this will take. Finally the program calculates the overlays required for the pavement to carry a certain number of standard axles. This program uses the equivalent thicknesses approach. To determine the compression of any layer, the other layers are converted to layers with the same modulus as the layer we are looking at, and with an equivalent thickness such that the thickness multiplied with the modulus raised to .33 is the same for equivalent layer as for the original layer. In equivalent pavement deflection at top and bottom of layer is calculated according to Boussinesq, and difference between these is the compression of the layer.

3.8.4 KGPBACK Program

KGPBACK is recommended in IRC: 115-2014 guidelines for back-calculation of layer moduli. It is based on Genetic Algorithm and a modified version of BACKGA program. The input parameters used in KGPBACK are Load, contact pressure, deflection values at different radial locations, layer thicknesses, Poisson's ratio and moduli ranges for three layers. A linear elastic layered theory is utilised by KGPBACK for analysis of pavement.

CHAPTER 4
STUDY AREA

4.1 GENERAL

In India, central and state governments are accountable for road construction and maintenance. Management of national highway is taken care by Ministry of State for Surface. State public works departments are responsible for maintenance of state roads. Various municipalities, districts and villages are responsible for the minor roads in the country. The Major challenges faced by Indian roads are poor class roads, rural areas having bad roads and congestion in metropolitan cities. During office hours cities like Delhi, Kolkata and Mumbai are very crowded. This is because of rapid increase in vehicle possession and industrialization. Overloading is other major cause for the deterioration of roads in India. Therefore, it becomes important to examine the existing conditions of pavements. The structural strength of pavements is computed using both destructive and non-destructive methods.

Benkelman beam and FWD both are non-destructive methods used for the evaluation of roads and to know the current condition and to suggest the improvement measures for these roads. Various non-destructive methods are discussed in chapter 3.

4.2 DESCRIPTION OF STUDY STRETCHES

Two study stretches of Gadaipur Bandh and Dera Bhatti road respectively were selected for our study. Both BBD and FWD testing were performed on these roads. Figures 4.1 and 4.2 are showing the maps of the roads which are selected for present study:

4.2.1 Gadaipur Bandh Road

Gadaipur Bandh road connects SSN Marg to Mandi Marg in South West Delhi. It is situated at a altitude of 218 meters above sea level. This road comes under Chhatarpur assembly constituency. There are various farmhouses are situated on the both sides of the road.

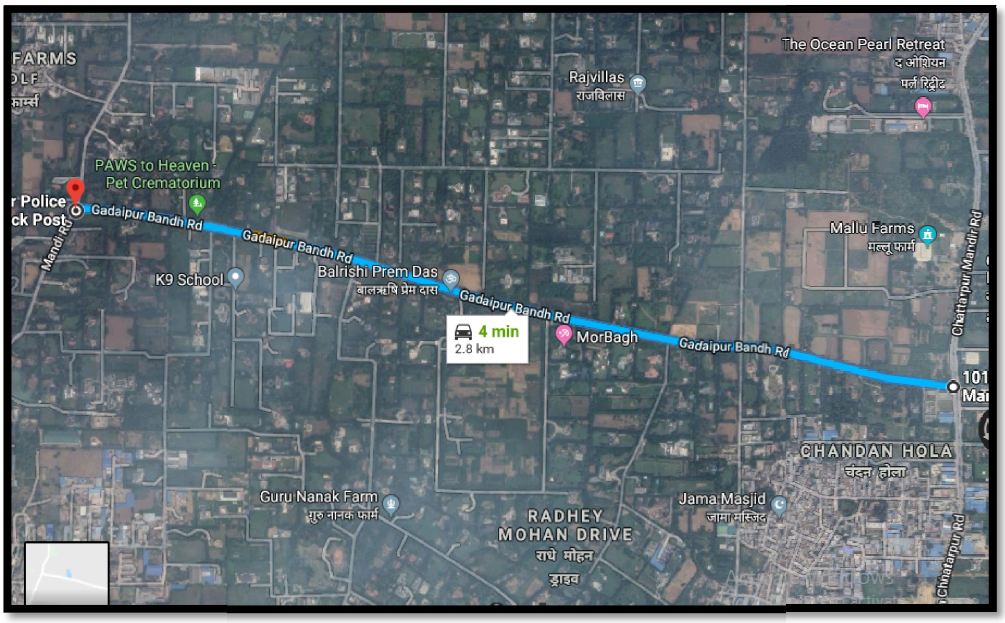


Figure 4.1 Map for Gadaipur Bandh Road (Source: Google Maps)

4.2.2 Derabhatti Road

Derabhatti road connects SSN Marg to Faridabad-Gurgaon Road. This road also comes under Chhatarpur assembly constituency.

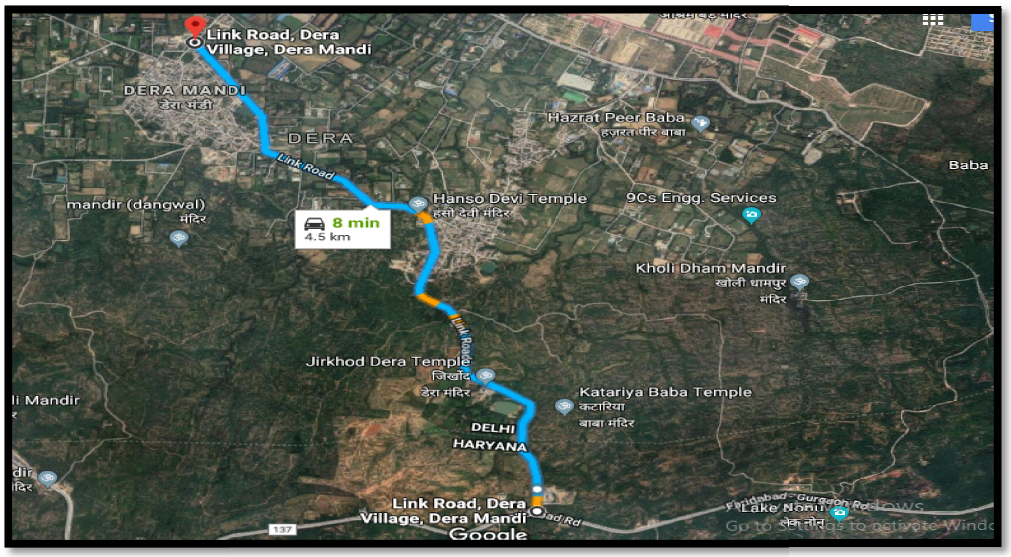


Figure 4.2 Map for Dera Bhatti Road (Source: Google Maps)

Details of study stretches of roads are presented in Table 4.1. For Gadaipur Bandh road, 0 to 3000 meters road length is Flexible pavement only. Dera Bhatti road 0 to 545 meters, 1300 to 2200 meters, and 3900 to 5760 meters are chainages for cement concrete road. Remaining road length is flexible pavement only.

Table 4.1 Details of Study Stretches of Roads

Road Name	Actual Location	Road Length (meters)	Type of pavement
Gadaipur Bandh Road	SSN Marg to Mandi Marg	0 to 3000	Flexible Pavement
Dera Bhatti Road	SSN Marg to Faridabad-Gurgaon Road	0 to 5760	Flexible Pavement and Cement Concrete Pavement

4.2.3 Climate

Delhi features an abnormal model of the humid subtropical climate. With the monsoon season in middle, summers are lengthy and very hot, from starting of the April to mid-October. At the end of February path of wind get reversed, from the north-western direction, to the south-western. Due to which hot waves from Rajasthan come towards Delhi and main reason for rise in temperature. The months of March to June are very hot. At the end of June month, monsoon arrives in Delhi and reduces some amount of temperature but humidity increases at the same time. Winter is from mid November to February.

Temperatures Range = −2.2 °C (35.96 °F) to 49 °C (120.2 °F).

Yearly Average Temperature = 29 °C (84.2 °F)

Monthly Average Temperatures Range = 14 °C to 33°C (57.2 °F to 91.4 °F)

Average Yearly Precipitation = 798 mm (a large portion of which is comes during the monsoons)

CHAPTER 5
METHODOLOGY AND FIELD WORK

5.1 GENERAL

This chapter presents the methodology and field work of present research. Pavement deflection data was collected using BBD and FWD along with temperature data, test pit details and traffic volume count data. Laboratory tests carried out for determining the modulus values of different layers are also explained in this chapter. Bituminous cores were obtained from the study stretches by using core cutter. Resilient modulus test was performed on these cores to determine the modulus value of bituminous layer. CBR of soil was determined to calculate the modulus of subgrade and granular layers respectively.

5.2 METHODOLOGY ADOPTED

1. Selection of Road sections for the study (Two roads were selected for the present study)
2. Data Collection
    i. Structural Condition Data: For structural evaluation of the study sections BBD and FWD methods have been used. Further the deflection values collected from these methods is processed.
    ii. Traffic Volume Survey Data: Traffic volume count survey was performed to obtain the number of commercial vehicle. To compute the overlay for the design life 5% growth factor was considered.
    iii. Destructive testing: Core cutting was performed to obtain cores of surface layer. Test pits were excavated to determine the thickness values of different pavement layers.
3. Resilient modulus of the bituminous layer was determined in UTM (Universal Testing Machine). CBR test was performed for computation of CBR value of subgrade soil.
4. Various methods used for determination of modulus values of three layers were compared statistically and Pearson correlations were found between them.
5. Consistency and Reliability of these methods were also evaluated.

5.3 EVALUATION OF SELECTED PAVEMENTS USING BBD

As discussed in chapter 3 Benkelman beam was used for measuring the surface deflection of the pavement under standard axle truck loading on two study stretches of roads. Before starting the BBD test rear dual wheels of the truck was weighed and ensured to 40 kN on both sides of axle as shown in Figure 5.1. Deflection measurements were done using CGRA method.



Figure 5.1 Weighing Rear Dual Wheels and BBD Survey in Progress

5.3.1 Deflection Measurements

In every road section ten points were selected at identical distance in each lane of the traffic. Staggered points were marked on adjacent lane for roads. The test points were marked with paint for future investigation. Procedure given in section 3.1.1.3 was followed for deflection measurements.

Test pits were made using jackhammer in the shoulder and soil samples were collected for the determination of moisture content as presented in Figure 5.2.



Figure 5.2 Test Pit Excavation Using Jackhammer

5.4 EVALUATION OF SELECTED PAVEMENTS USING FWD

In this study deflections were calculated by using KUAB FWD and measured at seven different sensor locations (0, 200, 300, 600, 900, 1200 and 1500 mm). Figure 5.3 is showing FWD survey in progress. Crust thickness values were also determined during this study. By inputting these values in various programs the modulus values of component layers were computed. Modulus values back-calculated using different programs were compared with modulus values determined in the laboratory.

Procedure given in section 3.3.2 is followed for FWD testing. The test location which were marked with paint during BBD testing, FWD testing was performed on that locations only. To find out the consistency of the software FWD test was performed at the same positions with three magnitudes of loads; 40, 50 and 70 kN. Test pits were excavated to compute the thickness values of different pavement layers as presented in Figure 5.4.



Figure 5.3 Falling Weight Deflectometer Testing In Progress



Figure 5.4 Sample Collections and Measurement of Pavement Thickness

Thickness values measured for two different road sections are as given in Table 5.1.

Table 5.1 Crust details of Two Road Sections

Road Name	Type of Layer	Thickness (mm)	Total Thickness (mm)
Gadaipur Bandh Road	Surface Layer	90	535
	Granular Layer	445	
Dera Bhatti Road	Surface Layer	92	272
	Granular Layer	180	

Cross-sections of Gadaipur Bandh road and Dera Bhatti road with layer thickness values are presented in Figures 5.5 and 5.6 respectively.

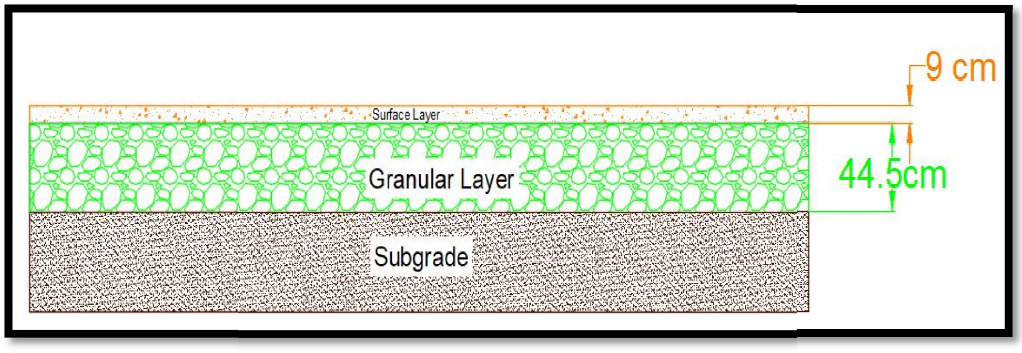


Figure 5.5 Cross-section of Gadaipur Bandh Road

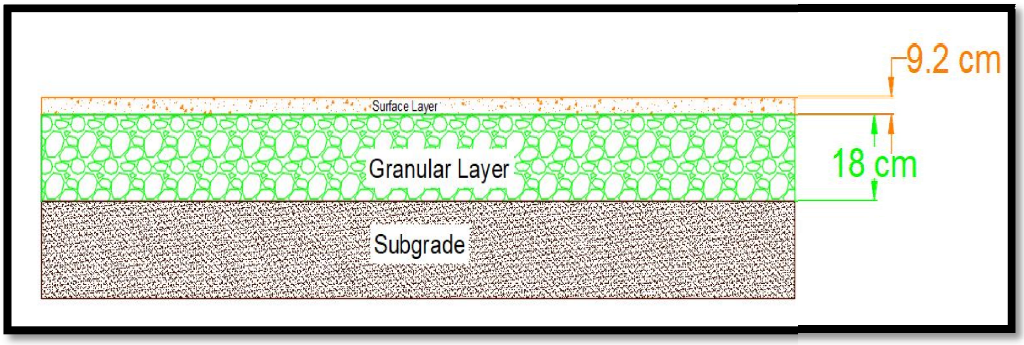


Figure 5.6 Cross-section of Dera Bhatti Road

Core cutting (as shown in Figure 5.7) was performed at different locations to get the surface layer samples for laboratory testing. In laboratory, modulus values for these samples were calculated.



Figure 5.7 Core Cutting in Progress

5.5 FUTURE DESIGN TRAFFIC

The present commercial vehicle counts on the two road stretches under study were obtained by performing traffic volume survey. The commercial vehicles per day for the next ten years were predicted according to IRC: SP: 84 guidelines. As per IRC: 115-2014 growth rate of 5 percent was adopted, as the annual growth rate was not available. The

equivalent standard axle count in millions (msa) was calculated using equation (35) given in chapter 3.

A vehicle count for two study stretches of roads are given in Appendix-D. Lane Distribution Factor = 50 % (for two lane single carriage way). Vehicle Damage Factor = 3.5 (For Plain terrain). The amount of cumulative standard axles was calculated according to equation (62) given by IRC: 37-2018. Design life of 10 years was considered. Standard axles calculated for selected road stretches are represented in Table 5.2.

Table 5.2 Standard Axles Computed for Two Road Stretches

Road Name	Present CVPD	Excepted CVPD	N (msa)
Gadaipur Bandh Road	971	1071	9
Dera Bhatti Road	1056	1165	10

5.6 RESILIENT MODULUS TEST

Resilient modulus is based upon the recoverable strain due to repetitive loadings. It is ratio of applied deviator stress to recoverable strain. Resilient Indirect Tension test is done to ensure the quality of materials present in the mix design. It is utilised as an input parameter for structural design of the pavement using multi-elastic theory and can also be used in the evaluation and analysis of the pavements. In this research work M_R test on core samples were performed in UTM machine as per ASTM D 4123-82. Figure 5.8 is depicting the strain under repeated loading. M_R can be determined using equation (38).

$$M_R = \frac{\sigma_d}{\epsilon_r} \quad (38)$$

In equation (2) σ_d = deviator stress

ϵ_r = recoverable strain

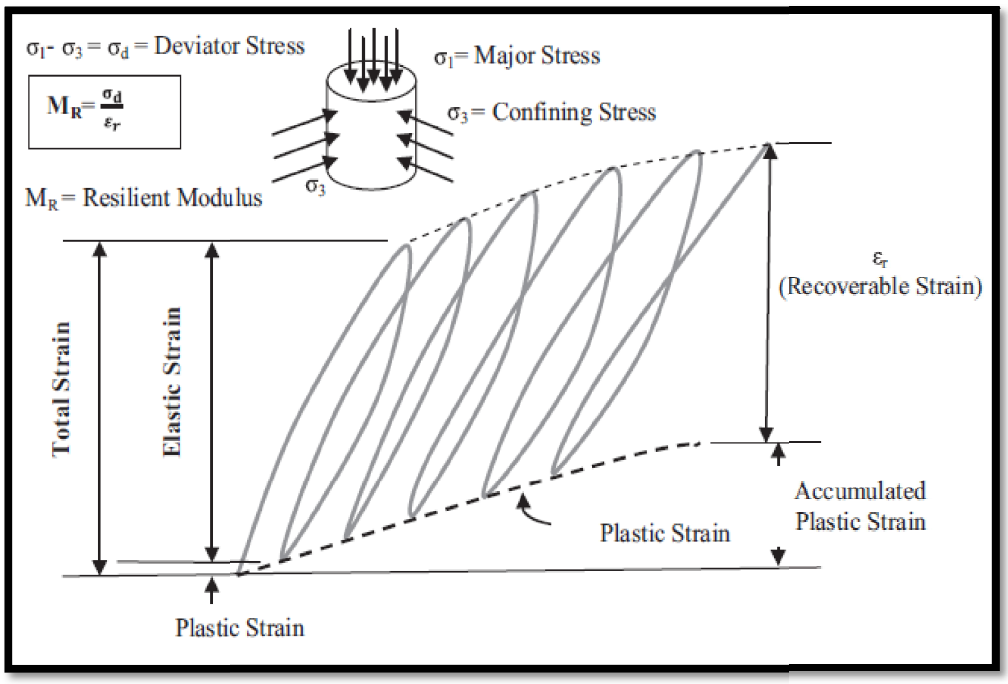


Figure 5.8 Strain under Repeated Loading (Huang, 2004)

The repeated load indirect tension test for computing modulus of bituminous core samples is performed by applying compressive load with a haversine or other appropriate waveform. The load is applied in the vertical diametric plane of the cylindrical core samples. The resilient modulus is determined using equation (39).

$$M_R = \frac{\mathbf{P\ (\nu + 0.27)}}{\mathbf{t * \delta}} \qquad (39)$$

P = peak load (lbf or N)

ν = assumed poisson's ratio

δ = horizontal deformation (inches or mm)

t = thickness of sample (inches or mm).

The assumed Poisson's ratio is generally taken as 0.35 for 25 ^{o}C temperature.

5.6.1 Procedure

1. The core specimens were extracted from the field, are presented in Figure 5.9.



Figure 5.9 Core Specimen Extracted From the Road

2. The cores excavated from the road were in irregular shape to convert them into specified size and shape, saw cutter was used. Saw cutter used for cutting the sample is shown in Figures 5.10 and 5.11.



Figure 5.10 Front View of the Saw Cutter



Figure 5.11 Sample Cutting in Progress

3. These core specimens were put in the controlled temperature cabinet for a minimum time of 4 h as presented in Figure 5.12.



Figure 5.12 Specimens kept in for conditioning in UTM

4. Diameter and length of the sample were measured. Diameter was drawn on one flat face of the sample with the help of chalk, and then the second diameter was drawn at the 90±10 ^{o} to the first. Test setup parameters are presented in Table 5.3.

Table 5.3 Setup Parameters

Loading pulse width (ms)	100
Pulse repetition period (ms)	1000
Conditioning pulse count	100
Target temperature (°C)	35
Peak loading force (N)	1000
Estimated Poisson's ratio	0.35

5. The specimen was then positioned into the loading apparatus as shown in Figure 5.13.



Figure 5.13 Arrangement of Specimen in UTM for Resilient Modulus Test

6. The sample was pre-conditioned by applying haversine loading for a minimum period to get the consistent deformation. The loading time was 0.1 s and rest time was set as 0.9 s which makes a total time period of 1s. The numbers of load repetitions applied to the specimen were 100 to make resilient deformation stable.

7. After making 100 load repetitions to make deformation stable, another five load cycles were applied to the sample and resilient modulus was measured as the mean of the last five pulses.



Figure 5.14 Resilient Modulus Test in progress

8. For each of the sample, resilient modulus was measured two times. As described above a sample was then rotated by 90^{o} and then test was repeated. For Gadaipur Bandh road resilient modulus values are presented in Table 5.4.

Table 5.4 Resilient Modulus Values for Gadaipur bandh Road

Location (m)	Resilient Modulus(MPa)
0	1253
1061	3291
1641	2689
2559	3373

For Dera Bhatti road resilient modulus values are presented in Table 5.5.

Table 5.5 Resilient Modulus Values for Dera Bhatti Road

Location (m)	Resilient Modulus (MPa)
0 m	707.50
1921 m	2534.00
2558 m	1048.50

5.7 DETERMINATION OF G_{mb} USING SSD METHOD

To compute the bulk specific gravity (G_{mb}) of core excavated specimens, this test was performed. The mass of specimen in the air, mass of specimen when submerged in water and mass of specimen in air after drying the surface (Saturated surface dry) was determined. First of all the mass of oven-dried specimen was determined. Then the specimen was put inside the bucket and mass in water was determined. In the last step mass of SSD specimen in air was calculated by blotting the sample. Mass of the sample divided by the mass of water it displaces is called bulk specific gravity. Figure 5.15 is showing the setup for measuring bulk specific gravity of samples.



Figure 5.15 Saturated surface dry in progress

$$G_{mb} = \frac{A}{(B-C)} \quad (40)$$

Where,

A = dry weight of specimen in air

B = SSD weight of specimen in air

C = weight of specimen in water at 25°

Using equation (40), bulk specific gravity values calculated for bituminous core samples are given in Table 5.6.

Table 5.6 Bulk Specific Gravity of Bituminous Cores

Core No.	Bulk Specific Gravity	
	Gadaipur Bandh Road	Dera Bhatti Road
1	2.07	2.15
2	2.22	2.08
3	2.27	2.23
4	2.22	2.16
5	2.2	2.23
6	2.17	2.2

5.8 CBR TESTING

The California Bearing Ratio (CBR) test is performed for assessing the strength of subgrade soil and other materials. In this study CBR test was done on the soil samples of two roads for the computation of subgrade modulus values. Figure 5.16 is showing the CBR apparatus, CBR mould and Automatic compactor.



Figure 5.16 CBR Apparatus, CBR Mould and Automatic Compactor

Modified Proctor Compaction Test was done to compute maximum dry density and optimum water content of soil. Water was added in soil at different proportions and compaction was done in five layers by the rammer of mass 4.89 kg with 25 equally distributed blows. Compaction curves were drawn, showing dry density at different water contents. Optimum moisture content at which soil can attain maximum dry density is determined from the compaction curve. Modified Proctor Compaction Test results are given in Appendix-E for both the roads. Remoulded specimen was prepared at Proctor's maximum dry density and CBR test was performed. CBR values for given study stretches of the roads are given in Table 5.8.

Table 5.7 CBR Value for Study Stretch Roads

Site Location	CBR (%)
Gadaipur Bandh Road	8.5
Dera Bhatti Road	5.5

CHAPTER 6
DATA ANALYSIS

6.1 GENERAL

Field data gathered through BBD and FWD on the project roads of the present study was analyzed. Correlation between deflection values measured from BBD and FWD was determined. KUAB, EVERCALC, KGPBACK and ELMOD programs were utilised to back-calculate pavement layer modulus values of stretches of roads under study. Some Analytical methods AASTHO (1993), Garg and Thompson (1999), Roque (1998) were also used for determination of subgrade modulus values. These back-calculated modulus values were compared with laboratory calculated modulus values. Pearson correlations between modulus values computed using different programs were found. Statistical analysis was performed to check significant difference between programs.

6.2 CORRELATION BETWEEN THE DEFLECTION VALUES (BBD & FWD)

The BBD deflection values after temperature and moisture correction and the peak deflection values of FWD at the middle of the loading plate were correlated for two study stretches of roads.

Gadaipur Bandh Road

The maximum deflections obtained from BBD (static load) method were found higher than those measured by FWD (Dynamic load). Figure 6.1 is showing the variation of maximum deflections on all locations.

Dera Bhatti Road

Similary, for Dera Bhatti road maximum deflections obtained from BBD (static load) method were found higher to those generated by FWD (Dynamic load). Figures 6.2 and 6.3 are showing the variation of deflections on locations for two different chainages.

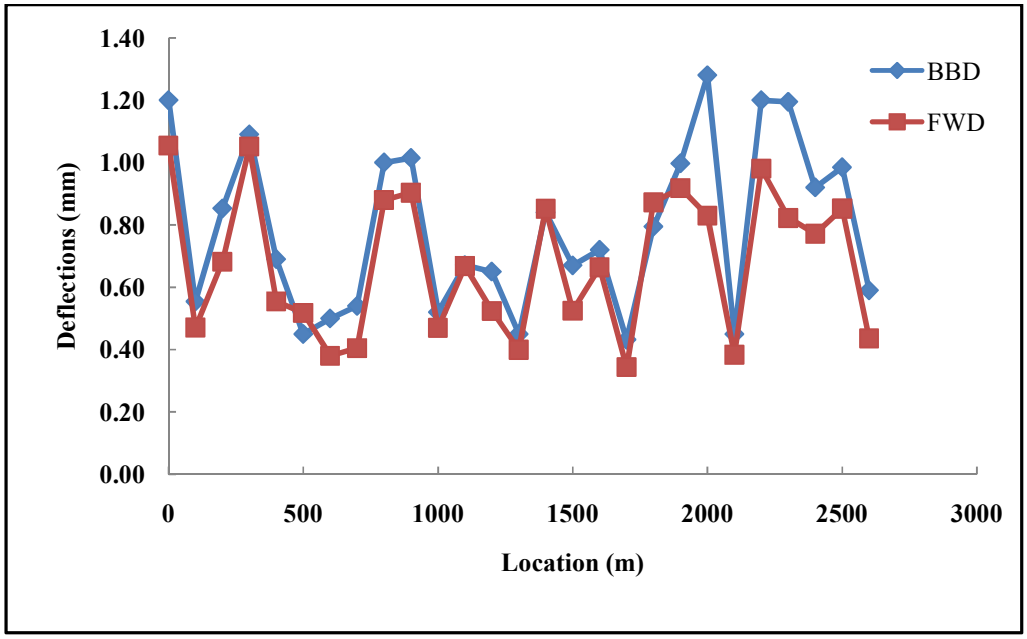


Figure 6.1 Deflections Obtained Using BBD and FWD Method

For chainage (0-661 m)

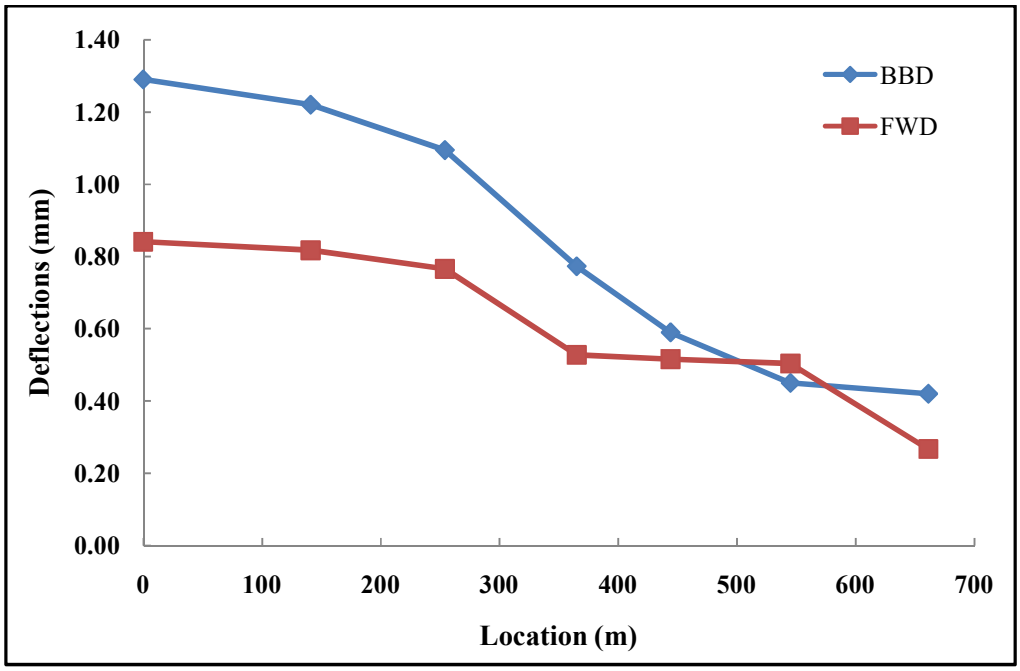


Figure 6.2 Deflections Obtained Using BBD and FWD Method

For chainage (1706-2573 m)

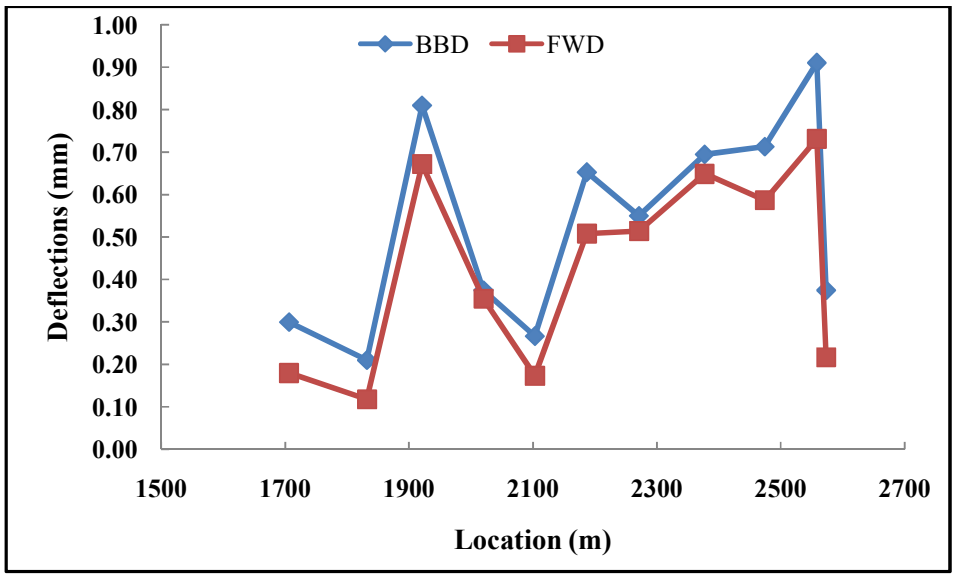


Figure 6.3 Deflections Obtained Using BBD and FWD Method

The correlation between the deflection data obtained from BBD and FWD was determined for Gadaipur Bandh road. It showed significant R^2 value (0.83-0.85) between deflections at same points using BBD and FWD, as shown in Figure 6.4.

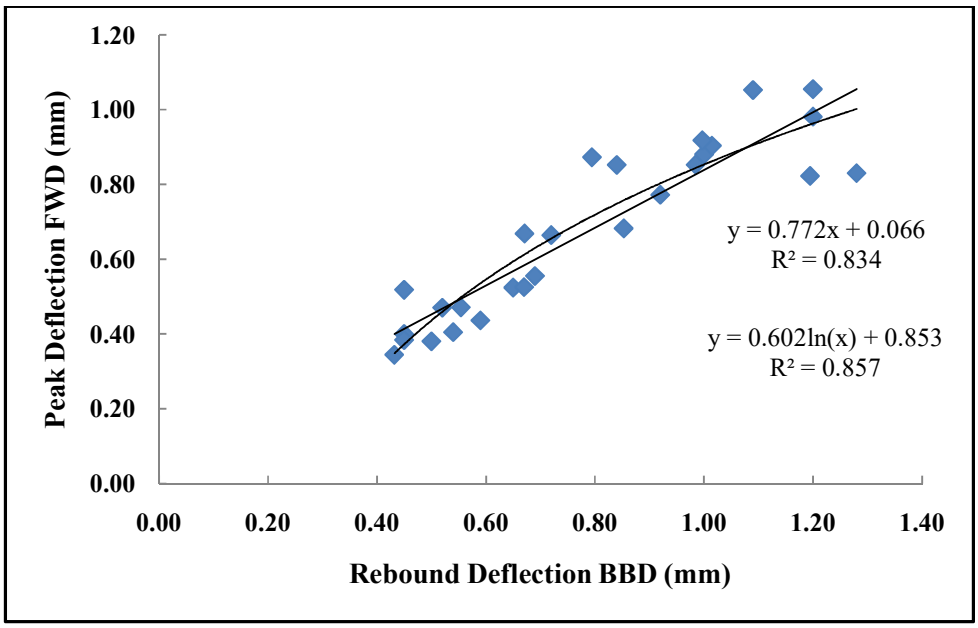


Figure 6.4 Deflection FWD v/s BBD of Gadaipur Bandh Road

Similarly, for Dera Bhatti road correlation between deflection values obtained from BBD and FWD was found. It showed significant R^2 value (0.88 to 0.93) between deflections at same points using BBD and FWD, as shown in Figure 6.5.

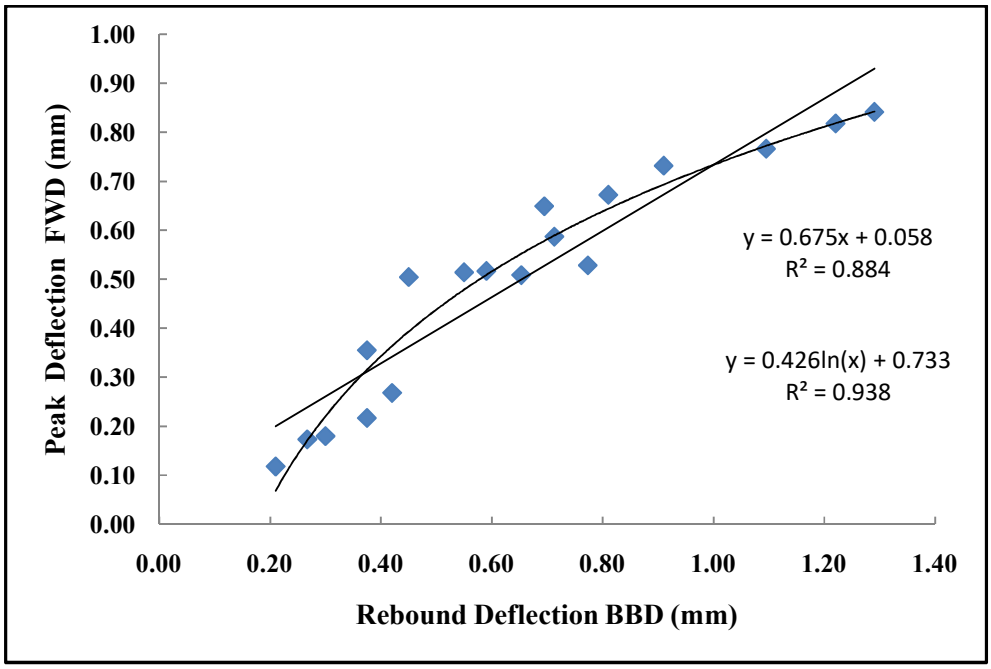


Figure 6.5 Deflection FWD v/s BBD of Dera Bhatti Road

Correlation equations between deflection values of FWD and BBD were developed using best fit curve and are presented in Table 6.1.

Table 6.1 Correlation Equations of Deflection Values

Gadaipur Bandh Road		Dera Bhatti Road	
Equation	**R^2 value**	**Equation**	**R^2 value**
y = 0.772x + 0.066	0.834	y = 0.675x + 0.058	0.884
y = 0.602ln(x) + 0.853	0.857	y = 0.426ln(x) + 0.733	0.938
x = Rebound Deflection BBD, y = Peak Deflection FWD			

6.3 BACK-CALCULATION OF LAYER MODULI

To compute modulus values of three layers for the in-service pavements EVERCALC, KUAB, Elmod and KGPBACK programs have been used. The screenshots while running various programs are presented below:

6.3.1 Layer Modulus determination using EVERCALC Program

The program was started by selecting EVERCALC icon. The screen as presented in Figure 6.6 was displayed.



Figure 6.6 About EVERCALC Screen

6.3.1.1 General Data File

General data file was selected from file option and the screen was displayed for entering the data as presented in Figure 6.7.

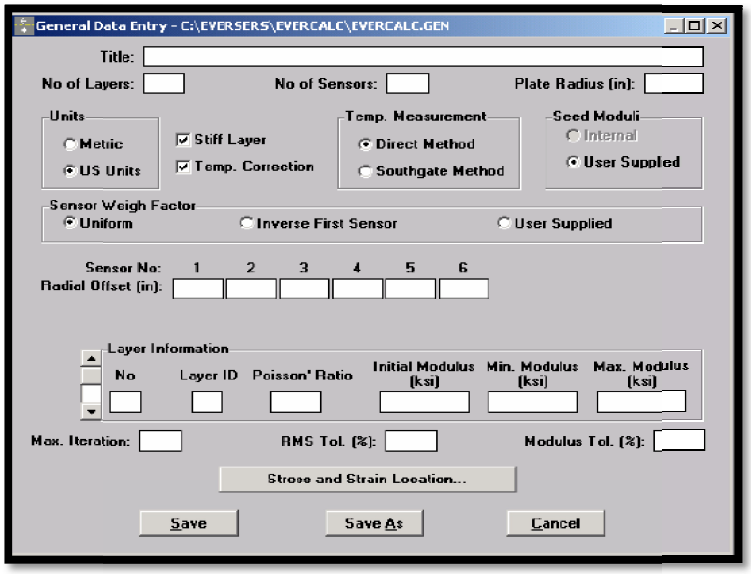


Figure 6.7 General Data Entry Screen

General data file components are explained in Table 6.2.

Table 6.2 Description of General Data File Components

Title	Any text that describes name of a file
No of Layers	Maximum number of layers = 5, Minimum number of layers = 2. If the number layers is more than three, seed moduli are needed. Three layers were selected in this study.
No of Sensors	Maximum ten numbers of FWD sensors can be used. Seven sensors were used in this study.
Units	Metric units were selected for our study.
Stiff Layer	No stiff layer was taken in the present study.
Temperature Correction	Temperature correction was done at a standard temperature of 35°C.
Temperature Measurement	It is required only when temperature correction is required. There are two options one is Direct method and another one is Southgate method. Direct Method option was used.
Plate Radius	FWD loading plate radius was 15 cm.
Seed Moduli	There are two options internal option and user supplied option. When the number of layers is more than three, internal option cannot be used.
Sensor Weigh factor	Uniform method as default method was used.
Radial Offsets	Radial distances of sensors from middle of loading Plate.
No	Layer number. Number one is designated to upper layer and move successively downwards.
Layer ID	Enter 0 if the layer modulus value is not known.
Poisson's Ratio	0.35 was taken for all three layers (Surface, Granular and Subgrade layer) as per IRC: 37-2018 guidelines.

Maximum Iteration	10 numbers of iterations were used.
RMS Tol. (%)	RMS Tolerance of 1% was used.
Modulus Tol. (%)	Modulus Tolerance of 1% was used.
Stress and Strain Location	Maximum of 10 locations can be entered. Three stress and strain locations were evaluated in this study.

6.3.1.2 Deflection Data File

Deflection data file was selected from the file option, deflection data entry screen was displayed as presented in Figure 6.8.

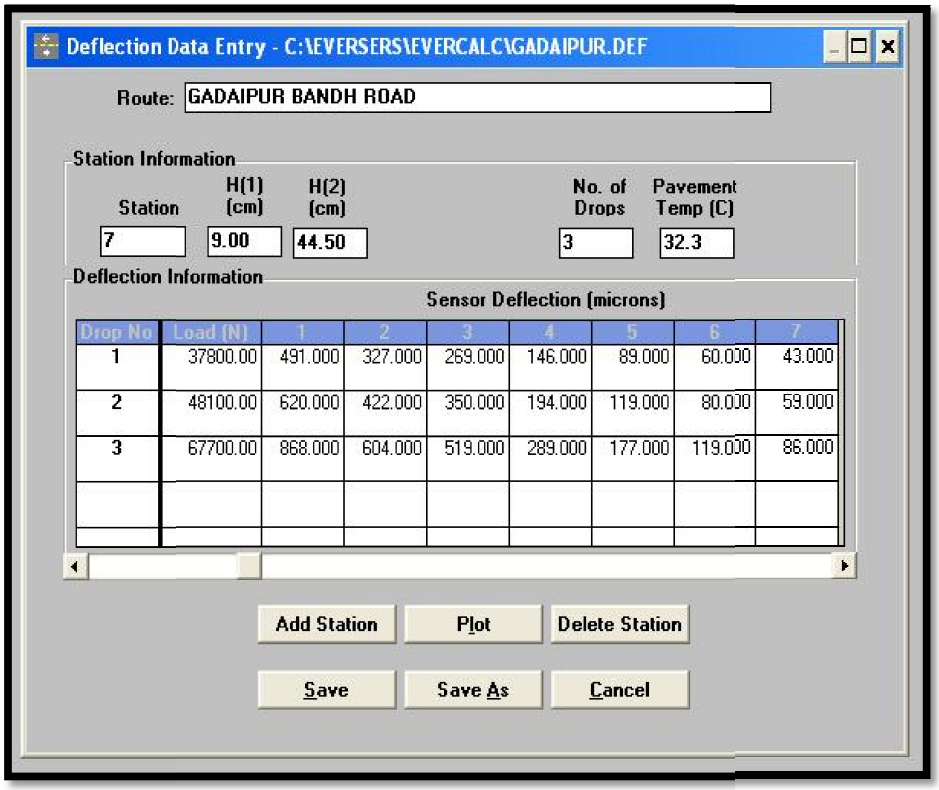


Figure 6.8 Deflection Data Entry Screen

Deflection data file components are explained in Table 6.3.

Table 6.3 Description of Deflection Data File Components

Station Information	
Station	It is taken as location number.
H(1) and H(2)	Thickness values of surface and granular layer respectively.
No. of Drops	In this study three drops were analysed.
Pavement Temperature	Temperature measured during deflection survey.
Deflection Information	
Load	Load value for each drop.
Sensor Deflection	Deflection values measured at different sensor locations given in Appendix-A.
Add Station	Adds station after current station
Plot	Deflection basin, thickness values of layers and normalized deflections (standard load of 9000 lb and 40 kN) plots can be viewed.

Deflection basin and layer thickness plots are depicted in Figures 6.9 and 6.10 respectively.

Perform Back-calculation

After creating General and Deflection Data files respectively, next step is to perform back-calculation. Two options are there to run the back-calculation process interactive or batch mode. Interactive mode was selected in this study. By clicking print on the menu bar, all the output results can be printed.



Figure 6.9 Deflection Basin Plot

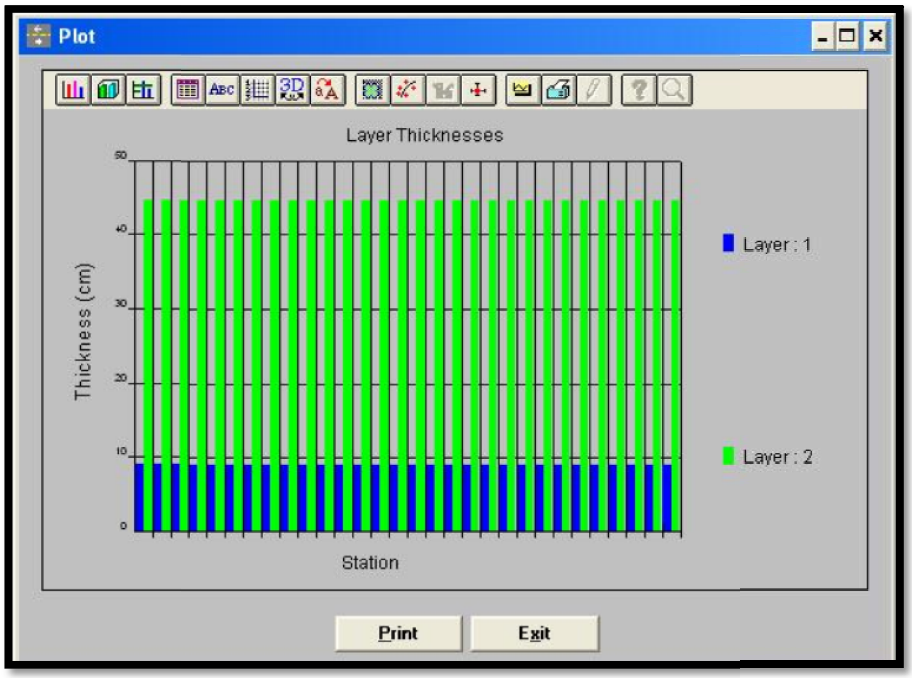


Figure 6.10 Layer Thickness Plot

6.3.2 Layer Modulus determination using KUAB program

The program was started by selecting KUAB icon and the screen presented in Figure 6.11 was displayed.

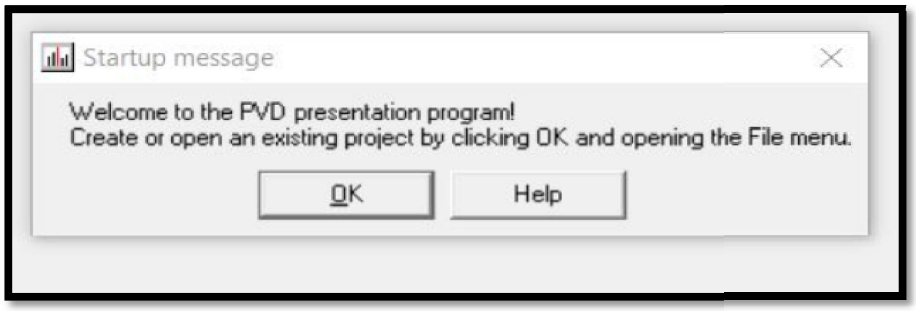


Figure 6.11 KUAB Main Screen

In this study back-calculation was performed for two impact loads 40000 N and 50000 N. In subdivision calculation screen there is option for selection of loads as presented in Figure 6.12.

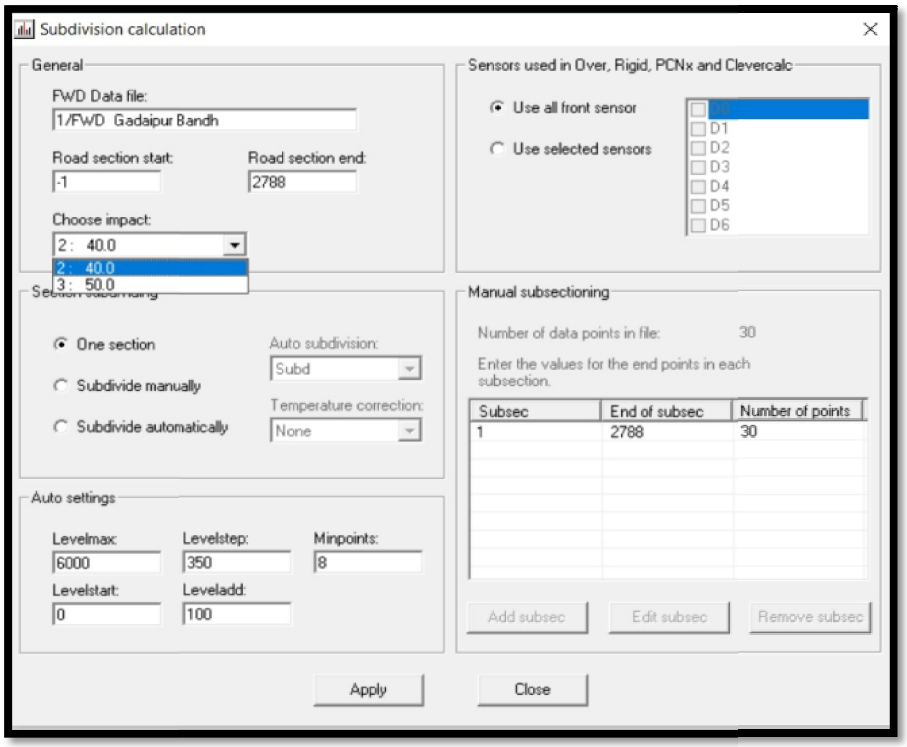


Figure 6.12 Subdivision Calculation Screen

To back-calculate pavement layer moduli value and to calculate overlay to carry certain number of standard axles, OVER Moduli and Overlay option was selected from Analysis dropdown menu. In this study **IRC 3 layers** was selected for analysing data. Traffic values and thickness values of different layers were also entered. After analysis, the output format was selected for generating the customised output data file. All the back-calculated layer moduli and overlay thickness values appear in output window as presented in Figure 6.13.

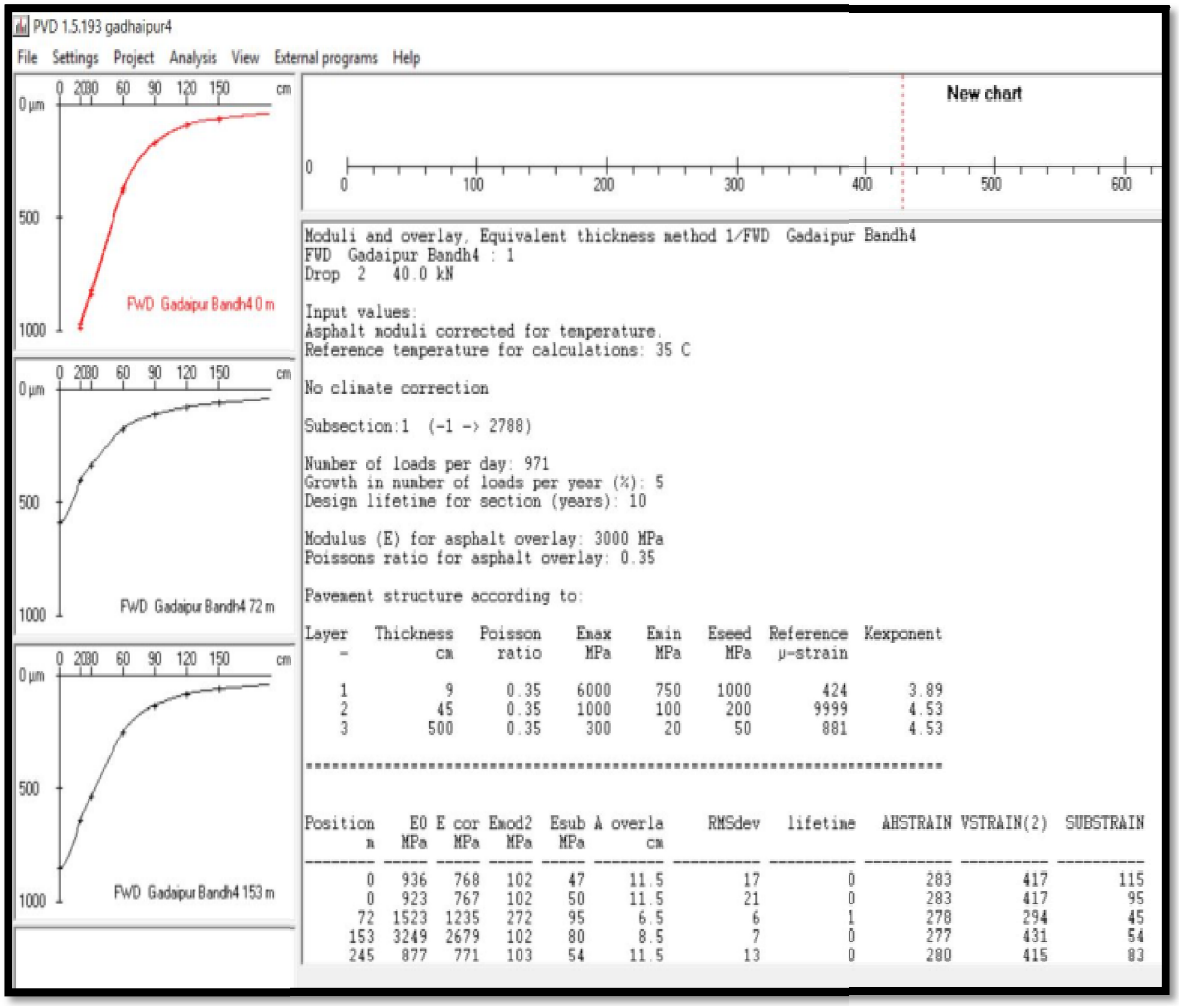


Figure 6.13 Output Values Screen

6.3.3 Layer Modulus calculation using Elmod-6 software

The program was commenced by selecting Elmod-6 icon and the screen presented in Figure 6.14 was displayed.

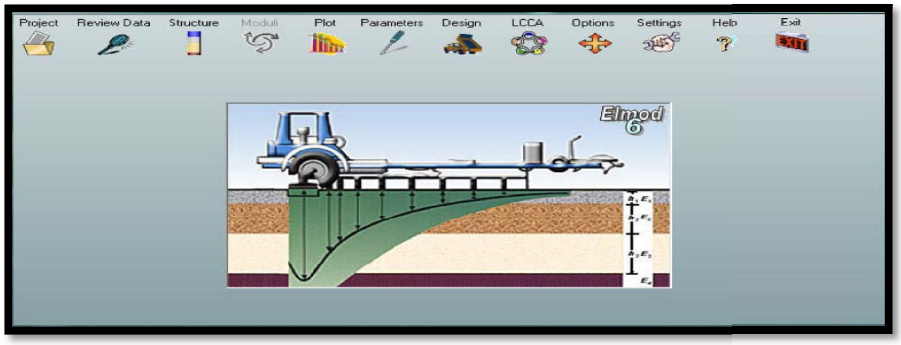


Figure 6.14 Elmod-6 Main Screen

In menu bar after selecting **Project** option new project was created by adding deflection data file.

Review Data – By clicking review data, information from an opened data file can be viewed and edited as presented in Figure 6.15.

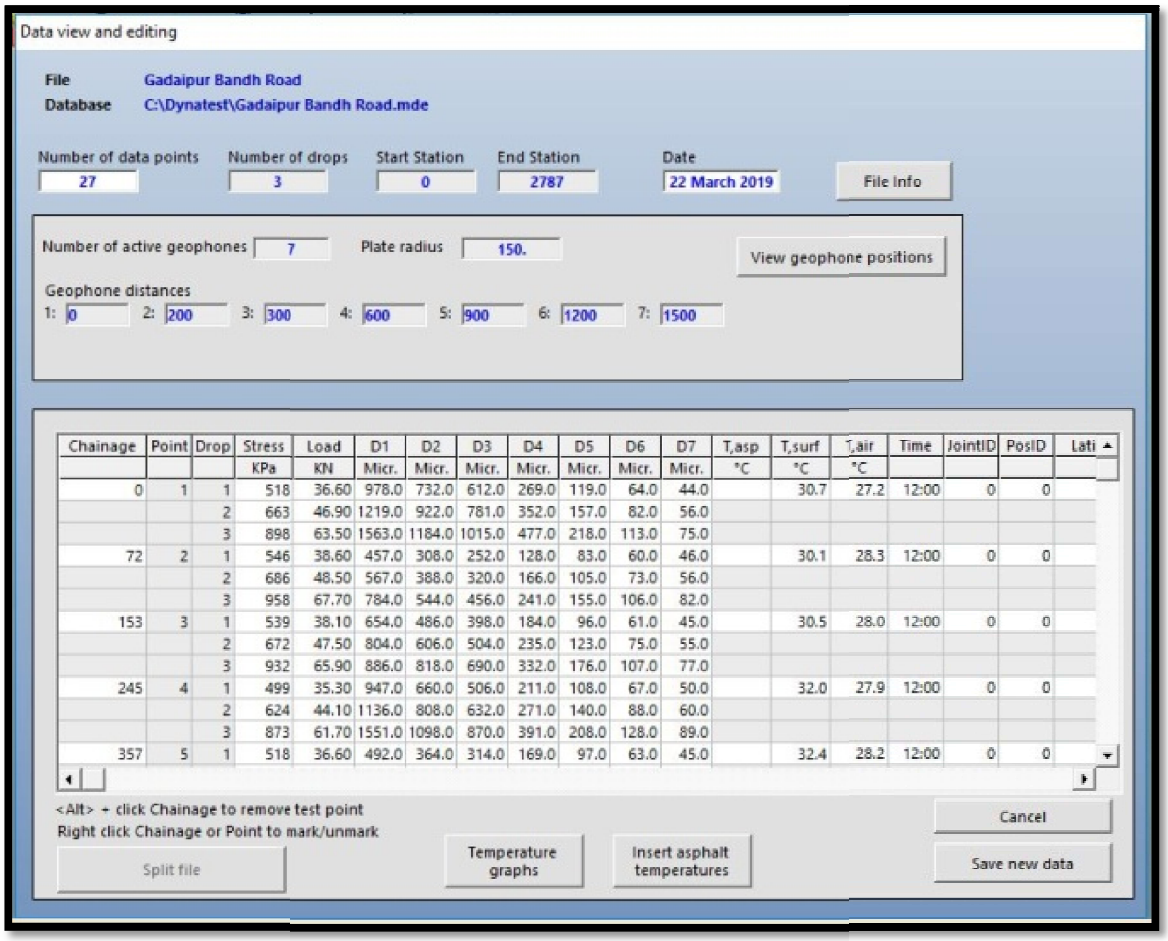


Figure 6.15 Review Data Screen

Structure – By clicking this option subsections were defined, pavement thicknesses and materials were entered.

Moduli – To initiate back-calculation of layer modulus values, there are three methods available for back-calculation which are Radius of curvature, Deflection Basin Fit and optional module FEM/LET/MET methods respectively**.** In this study Radius of Curvature and Deflection Basin fit methods were used.

Plot – This option was selected for presentation of deflection data and results. At the end, by selecting **Tools** results were exported to excel sheets. (Figure 6.16)

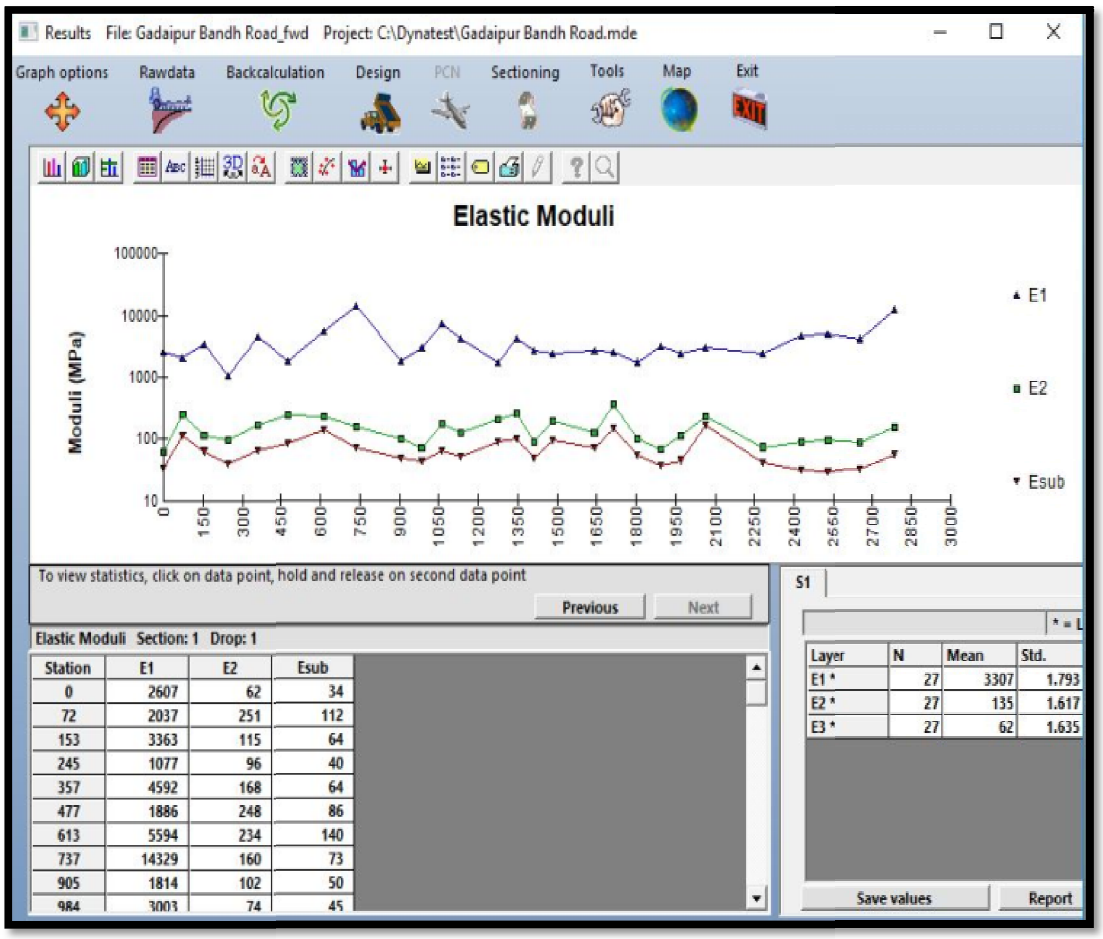


Figure 6.16 Screen Showing the Plot and Results

6.3.4 Layer Modulus calculation using KGPBACK software

The KGP-BACK software is recommended by IRC: 115-2014 for back-calculation of moduli. Peak load and radius of the loading plate, deflection values at different radial locations and their distances, pavement layer thicknesses and Poisson's ratio of different layers are inputs which are utilised by KGPBACK for back-calculation purpose. All these inputs were entered in program as presented in Figure 6.17 to back-calculate the layer moduli values.

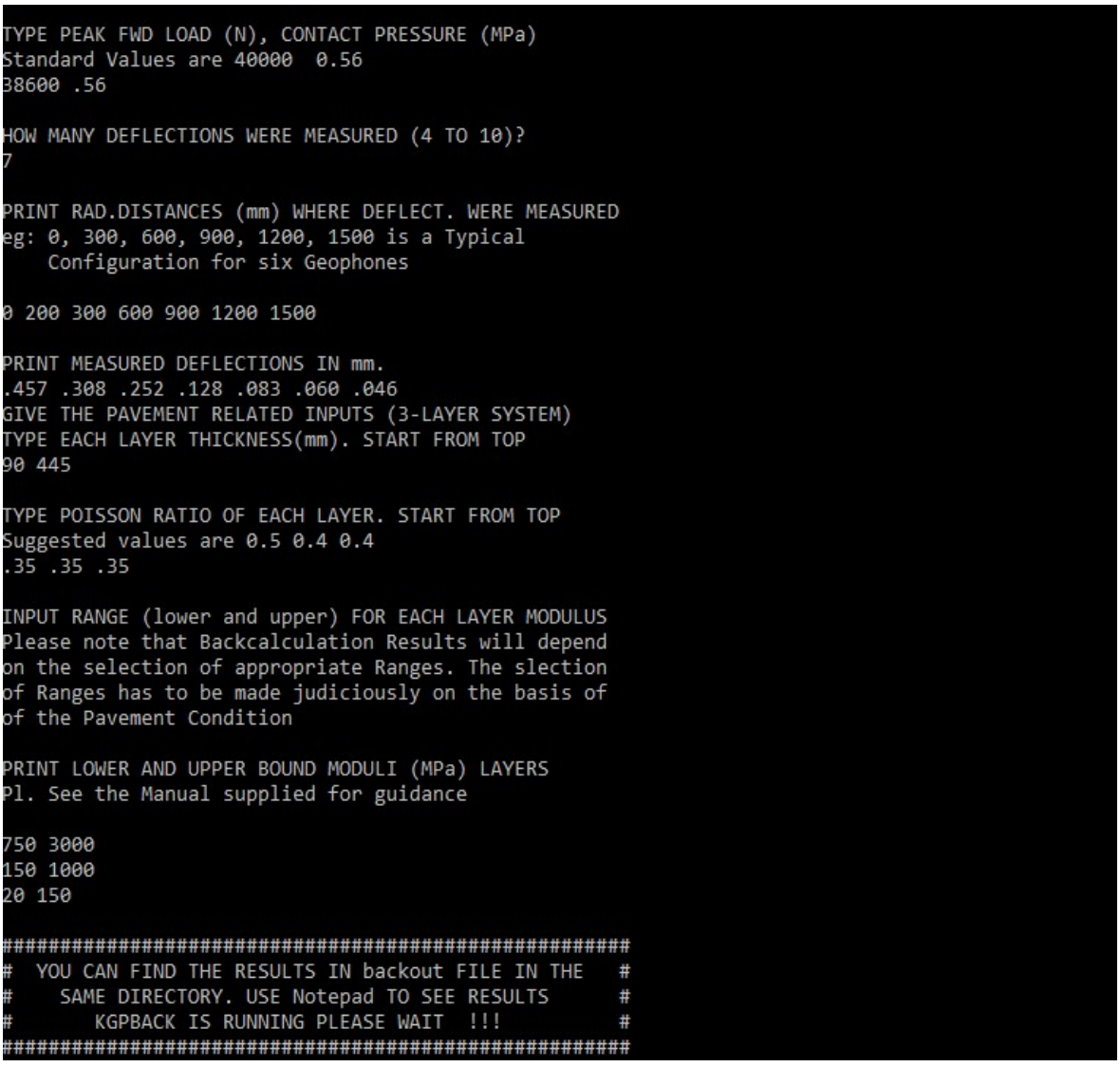


Figure 6.17 Inputting the Values in KGPBACK Software

The moduli of Surface, Base and Subgrade layers were obtained after inputting data in KGPBACK program are presented in Figure 6.18.

```
##################################################
#         !!!  THANKS FOR USING KGPBACK  !!!      #
#             THE RESULTS ARE GIVEN BELOW         #
##################################################

###############
#  INPUT DATA  #
###############
No.of Layers                          =  3
FWD Load (N)                          = 38600.00
Contact Pressure (MPa)                =  .56
No.of Deflection points               =  7
Deflections measured using FWD (mm)   =  .45700   .30800   .25200   .12800   .08300   .06000   .04600
Radial distances from centre of load(mm) =    .0  200.0  300.0  600.0   900.0  1200.0  1500.0
Layer thickness (mm)                  =  90.00 445.00
Poisson ratio values                  = .35 .35 .35
Layer Modulus (MPa) Ranges Selected :-
(a) Bituminous Surfacing              =  750.0   3000.0
(b) Granular Base                     =  150.0  1000.0
(c) Subgrade                          =   20.0   150.0


###############
# OUTPUT DATA  #
###############

Backcalculated Layer Moduli are:
Surface (MPa)  =    2892.2
Base (MPa)     =     182.4
Subgrade (MPa) =     146.3
```

Figure 6.18 KGPBACK Output Screen

6.4 VARIATION OF DEFLECTION VALUES

Figures 6.19, 6.20 and 6.21 shows the variation of deflections at 40 kN drop with locations, for Gadaipur Bandh and Dera Bhatti roads. D(0), D(1), D(2), D(3), D(4), D(5) and D(6) are deflections at 0 mm, 200 mm, 300 mm, 600 mm, 900 mm, 1200 mm and 1500 mm radial distances respectively. FWD deflections measured at Gadaipur Bandh and Dera Bhatti roads respectively are given in Appendix-A.

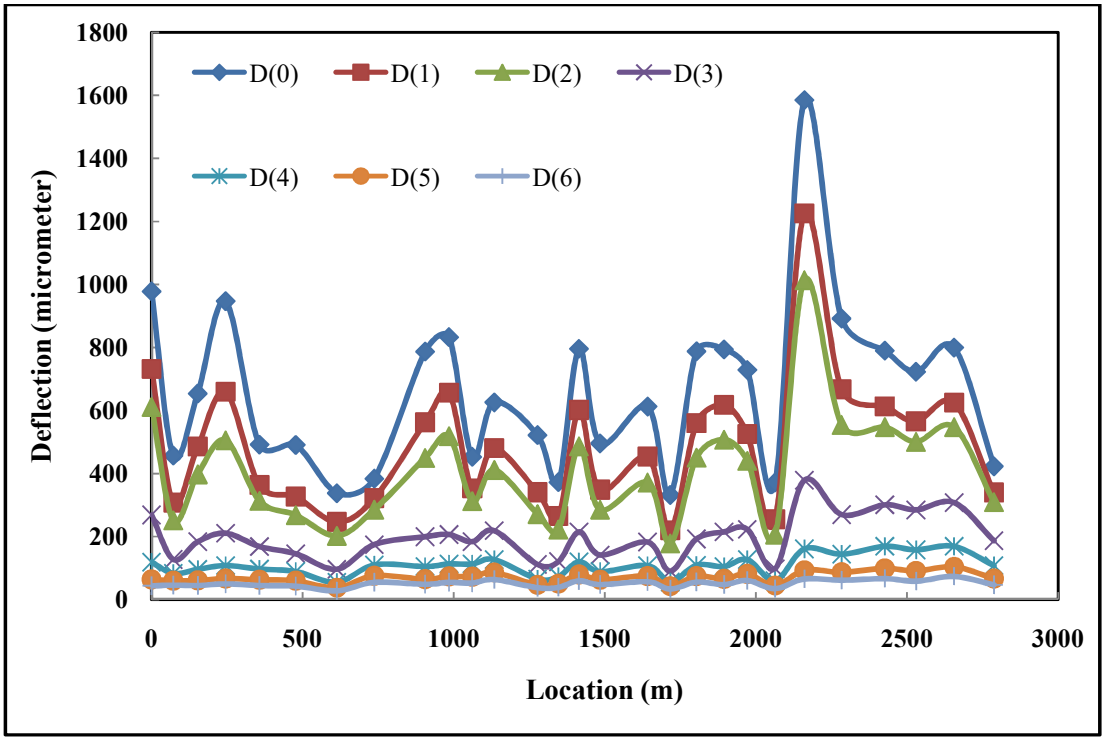


Figure 6.19 Variation of Deflection Measurements along Location for Gadaipur Bandh Road (40 kN)

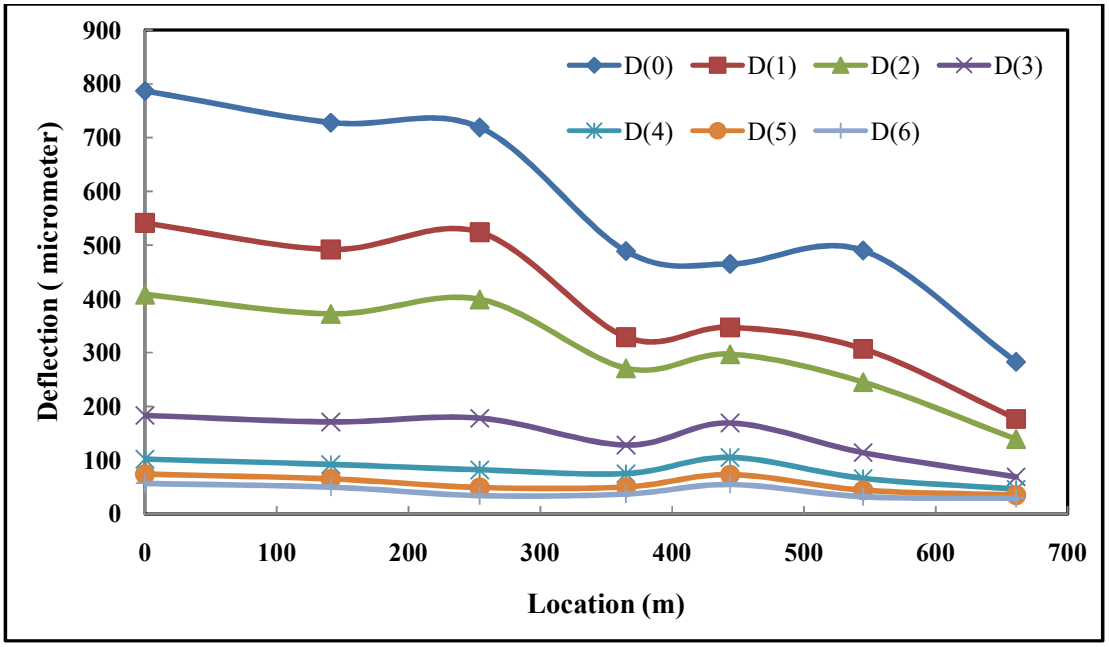


Figure 6.20 Variation of Deflection Measurements along Location for Dera Bhatti Road Section 0-661 m (40 kN)

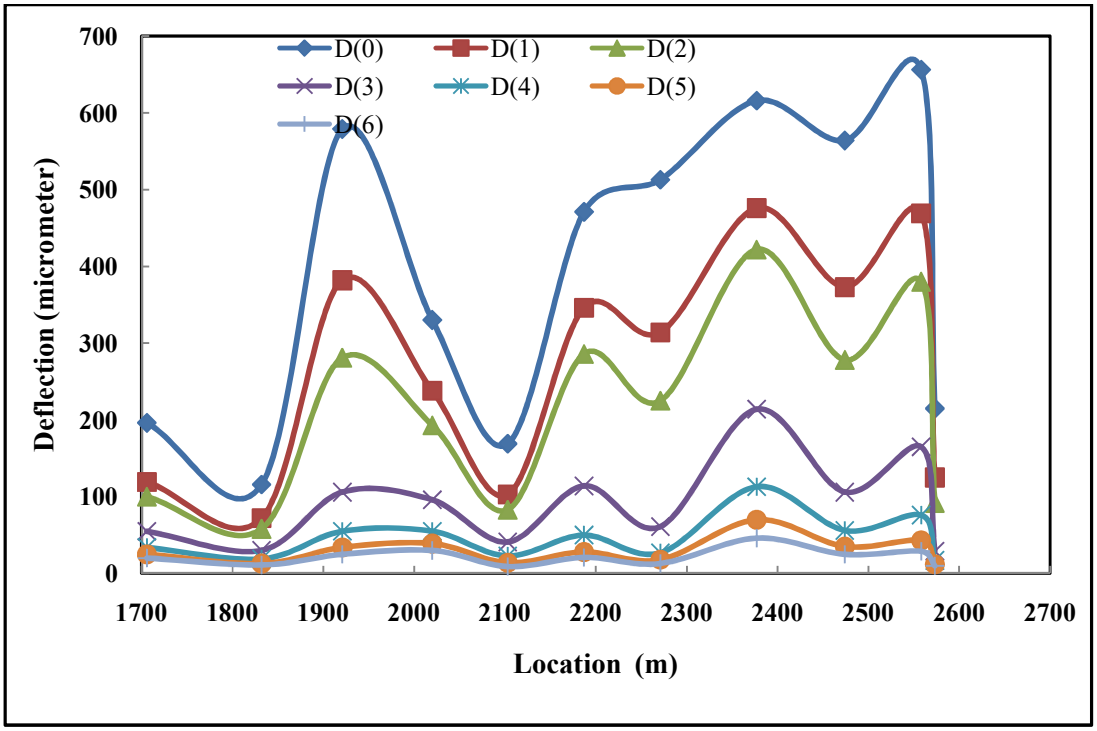


Figure 6.21 Variation of Deflection Measurements along Location for Dera Bhatti Road Section 1706-2573 m (40 kN)

6.5 ANALYSIS OF LAYER MODULI

Layer moduli determined from different methods for surface, granular and subgrade layer were compared for two study stretches of roads. Modulus values computed from different approaches are given in Appendix-B for Gadaipur Bandh and Dera Bhatti road respectively.

6.5.1 Subgrade Modulus

Subgrade modulus was back-calculated using KUAB, EVERCALC, KGPBACK, Elmod (Radius of curvature and Deflection Basin fit methods) programs. Analytical approaches given by AASTHO (1993), Garg and Thompson (1999), and Roque (1998) were also used for determination of subgrade modulus. The subgrade modulus was also computed using CBR value as per IRC: 37-2018 guidelines. The modulus values determined from aforementioned methods are given in Appendix-C for two study stretches of roads.

For Gadaipur Bandh Road, average subgrade modulus determined using Roque (1998) approach was found maximum and it was found minimum, when Elmod's Deflection basin fit method was used. Average subgrade modulus computed using KUAB program (77.40 MPa) and Elmod's Radius of curvature method (77.05 MPa) were found to be closest to subgrade modulus calculated from CBR value as per IRC: 37-2018 guidelines (69.24 MPa). (Figure 6.22)

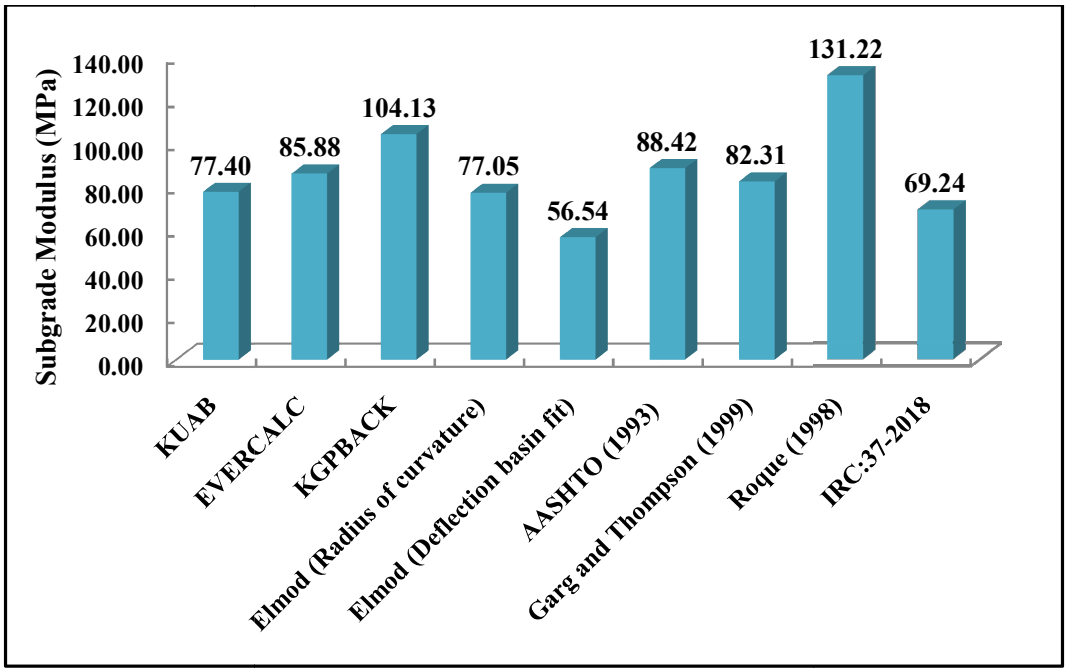


Figure 6.22 Comparison of Average Subgrade Modulus for Gadaipur Bandh Road by Different Methods

For Dera Bhatti Road, a very high value of average subgrade modulus was observed by using Roque (1998) approach (214.46 MPa) and modulus computed as per IRC: 37-2018 guidelines was lowest (52.40 MPa). A large variation of modulus was found between CBR method and other approaches as shown in Figure 6.23.

For Gadaipur Bandh Road (Chainage 0-984 m), except Roque (1998), Garg and Thompson (1999) methods; all other methods followed approximately similar trend for subgrade moduli values as presented in Figure 6.24.

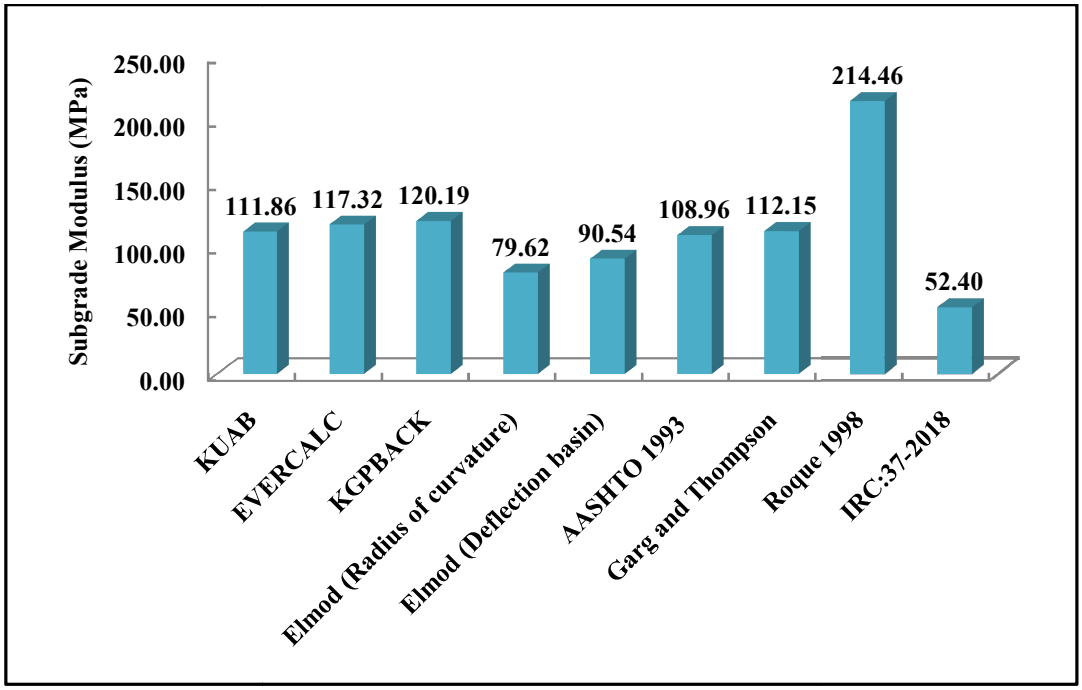


Figure 6.23 Comparison of Average Subgrade Modulus for Dera Bhatti Road by Different Methods

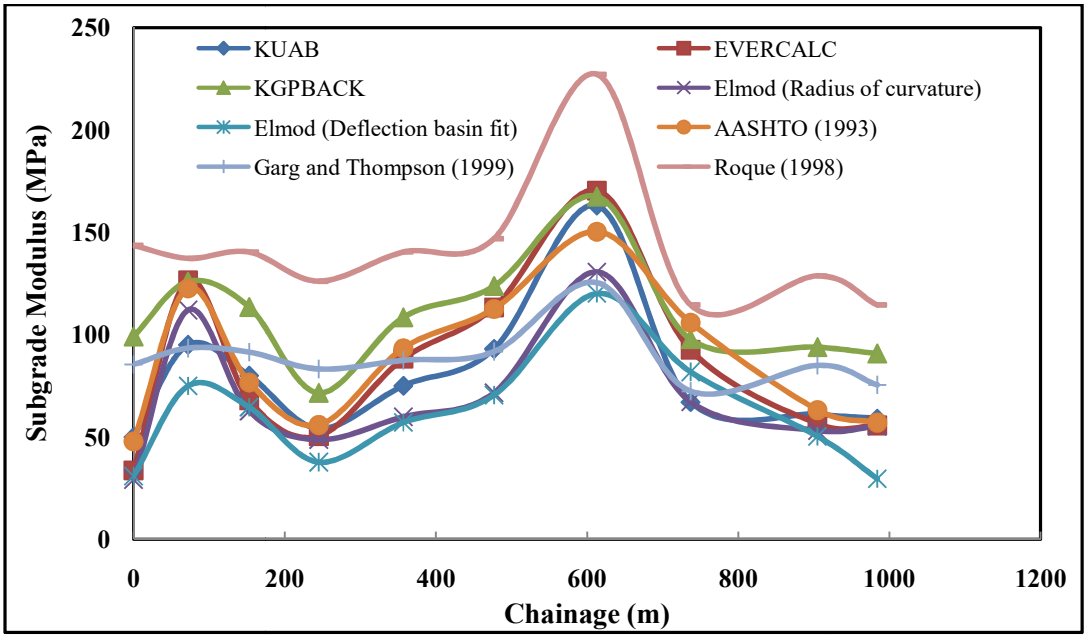


Figure 6.24 Variation of Subgrade Layer Moduli along Chainage (0-984 m) for Gadaipur Bandh Road

For Gadaipur Bandh Road (Chainage 1061-2655 m), subgrade moduli determined using different methods followed similar trend. The subgrade moduli values computed using Elmod deflection basin method was lowest as compared to other methods as shown in Figure 6.25.

For Dera Bhatti Road (Chainage 0-661 m), subgrade layer moduli determined using analytical methods Roque (1998), Garg and Thompson (1999), and KGPBACK software followed same trend. All other remaining approaches followed different trend but similar to each other. Higher subgrade moduli values were computed using Roque (1998) method as compared to other methods as shown in Figure 6.26.

For Dera-Bhatti Road (chainage 1921-2558 m), except Roque (1998), Garg and Thompson (1999), and Elmod deflection basin method all other approaches show similar trend for subgrade moduli values. Roque (1998) method had computed very high value of subgrade modulus as compared to other methods as presented in Figure 6.27.

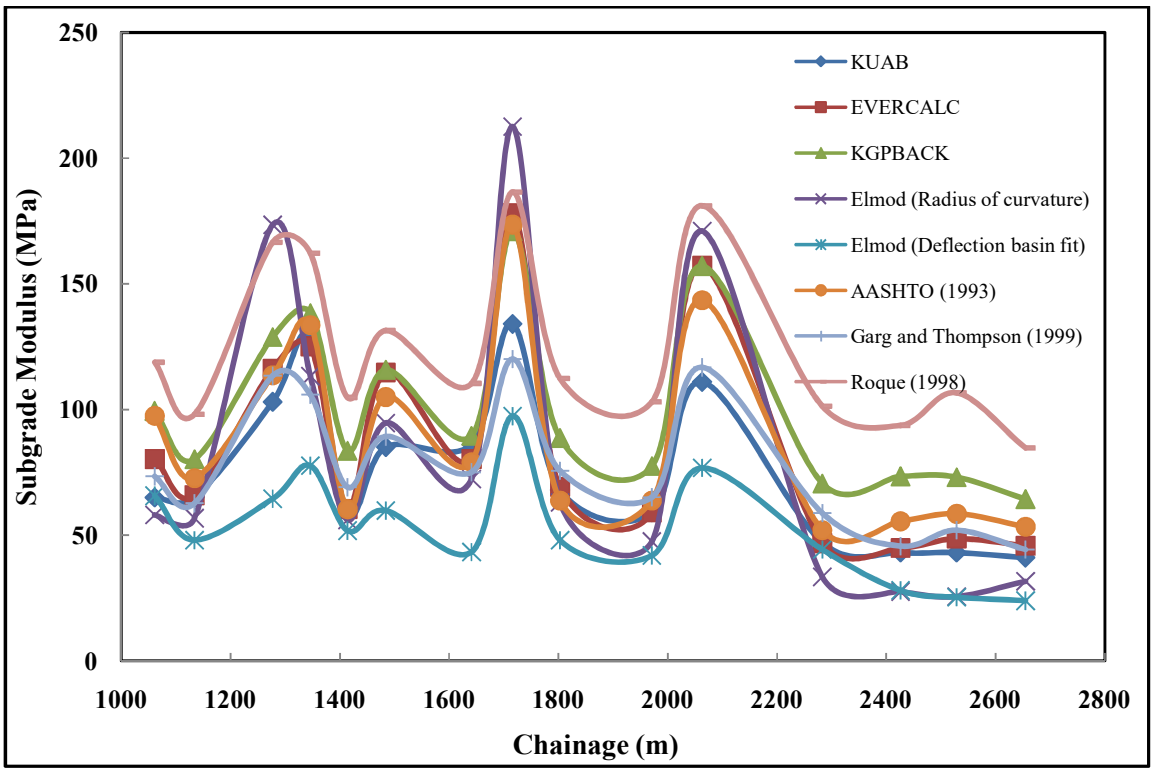


Figure 6.25 Variation of Subgrade Layer Moduli along Chainage (1061-2655 m) for Gadaipur Bandh Road

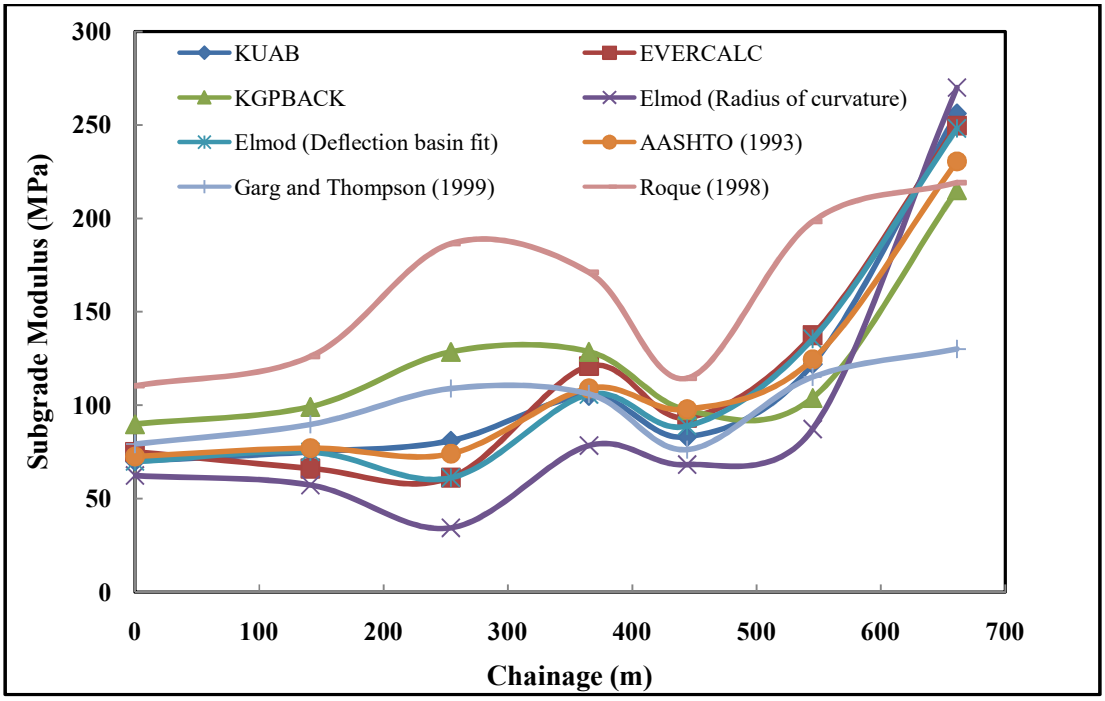


Figure 6.26 Variation of Subgrade Layer Moduli along Chainage (0-661 m) for Dera Bhatti Road

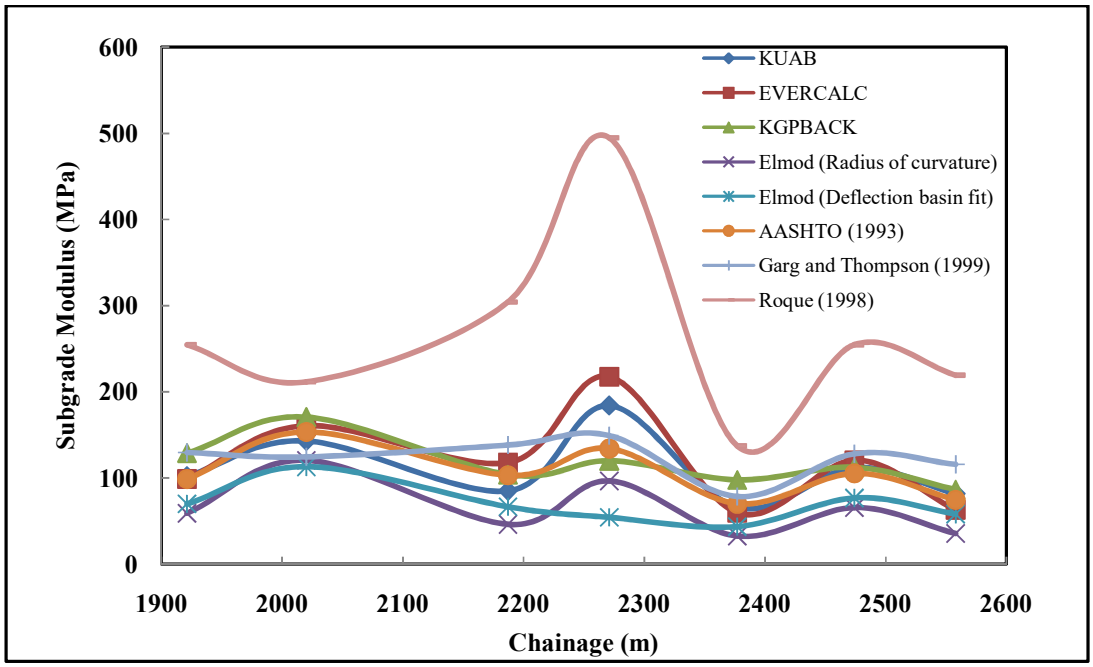


Figure 6.27 Variation of Subgrade Layer Moduli along Chainage (1921-2558 m) for Dera Bhatti Road

6.5.2 Granular Layer Modulus

Granular layer modulus was back-calculated using KUAB, EVERCALC, KGPBACK, Elmod (Radius of curvature and Deflection Basin fit methods) programs. Granular modulus was also computed using CBR value as per IRC: 37-2018 guidelines.

For Gadaipur Bandh Road, the average granular layer modulus calculated as per IRC: 37-2018 guidelines were the highest and computed by using EVERCALC program the lowest. The average modulus determined using KUAB (176.72 MPa) and Elmod (Deflection Basin method) (169.02 MPa) were nearly similar. Figure 6.28 is showing the comparison of average granular layer modulus for this road by different methods.

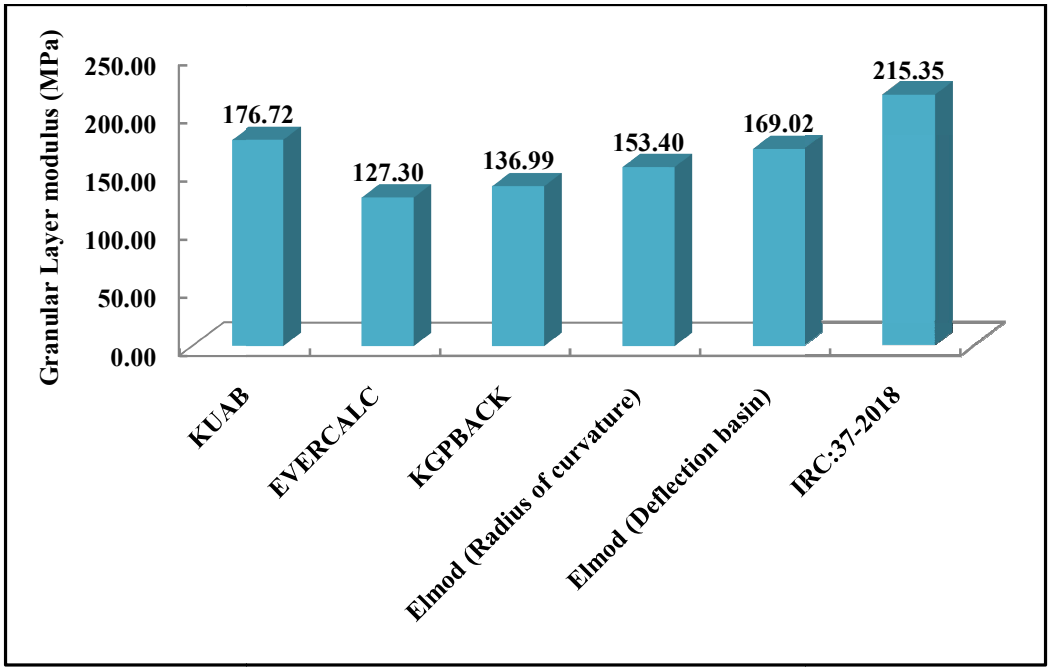


Figure 6.28 Comparison of Average Granular Layer Modulus for Gadaipur Bandh Road by Different Methods

For Dera Bhatti Road, two methods used by Elmod software have determined a very high value of average granular layer modulus (above than 400 MPa). The average modulus computed using IRC: 37-2018 guidelines (162.98 MPa) and KGPBACK program (163.17 MPa) were nearly similar. Figure 6.29 is depicting the comparison of average granular layer modulus for the given road by different methods.

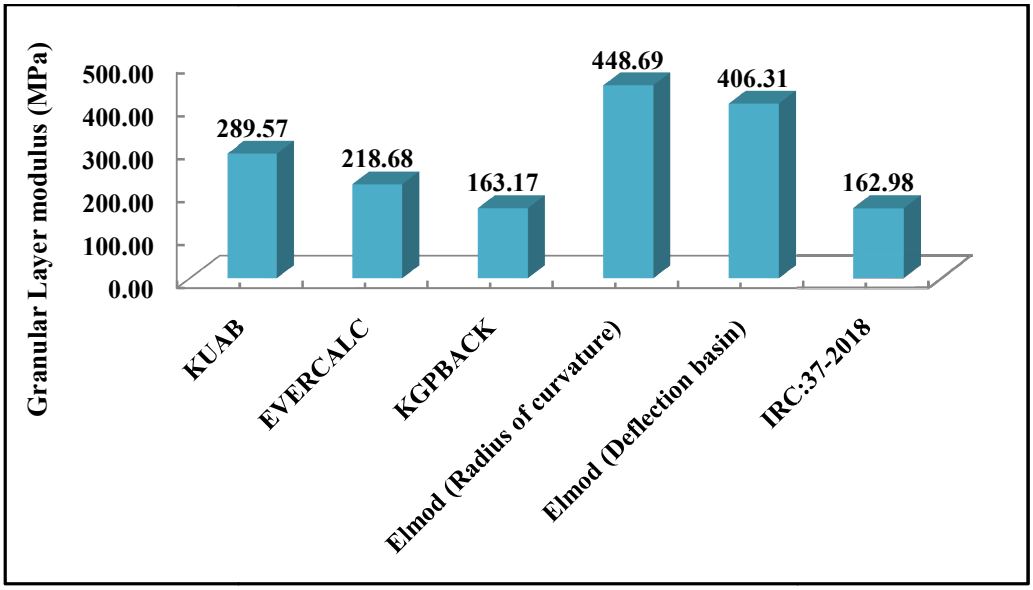


Figure 6.29 Comparison of Average Granular Layer Modulus for Dera Bhatti Road by Different Methods

For Gadaipur Bandh Road (chainage 0-984 m), from 0 to 300 m chainage, except KGPBACK the granular layer moduli determined using all other programs followed same trend. After that, significant variation was found in granular layer moduli values as shown in Figure 6.30. For **(**chainage 1061-2655 m), the granular layer moduli determined using different programs followed same trend as shown in Figure 6.31. The average granular layer modulus calculated using Elmod (Deflection Basin method) were the highest and computed by using KGPBACK program the lowest.

For Dera bhatti Road (Chainage 0-661 m), the granular layer moduli determined using KUAB and Elmod (Deflection basin fit method) programs followed similar trend. Similarly, EVERCALC and KGPBACK programs followed similar trend but computed lower values of moduli as compared to other programs. Elmod (Radius of curvature) program determined higher value of granular layer moduli. Figure 6.32 is showing the variation of granular layer moduli for the given road. For (Chainage 1921-2558 m), the granular layer moduli determined using KUAB, Elmod (Deflection basin fit method) and EVERCALC programs followed similar trend. Elmod (Deflection basin fit method) computed high moduli values and KGPBACK back-calculated low moduli values as shown in Figure 6.33.

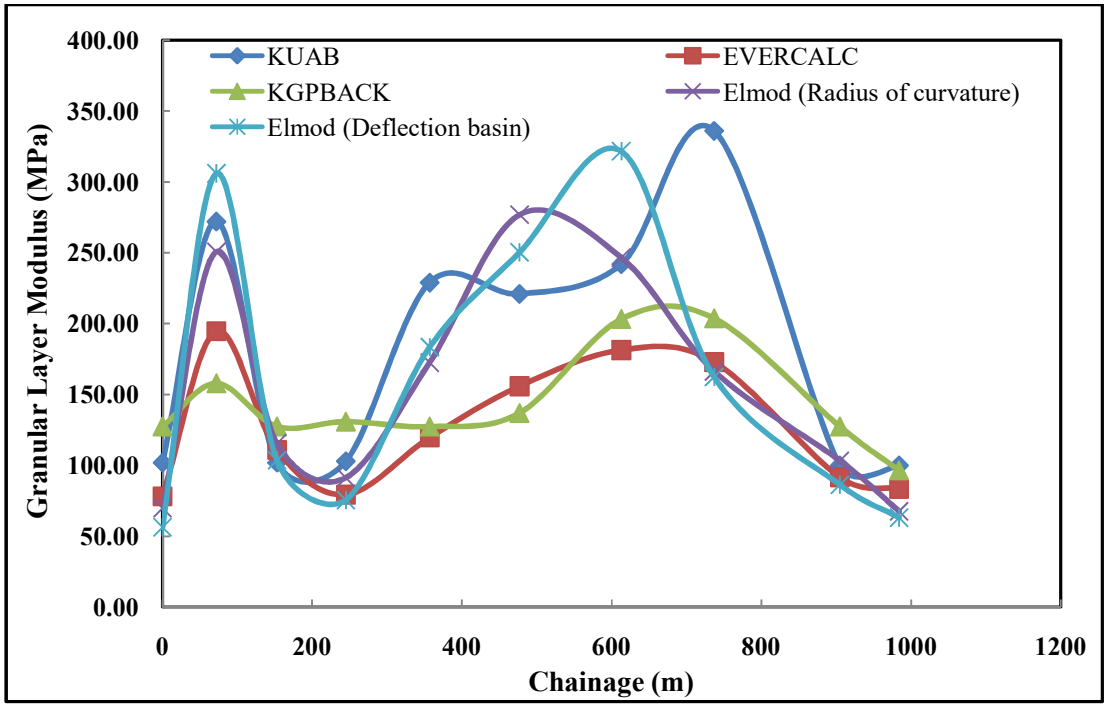


Figure 6.30 Variation of Granular Layer Moduli along Chainage (0-984 m) for Gadaipur Bandh Road

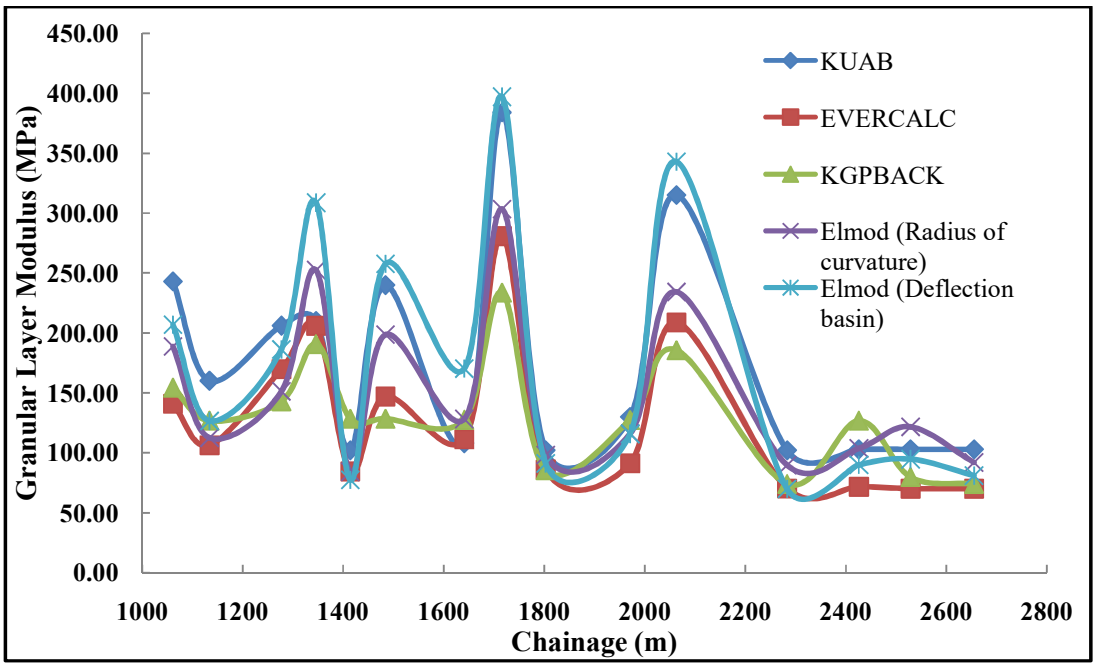


Figure 6.31 Variation of Granular Layer Moduli along Chainage (1061-2655 m) for Gadaipur Bandh Road

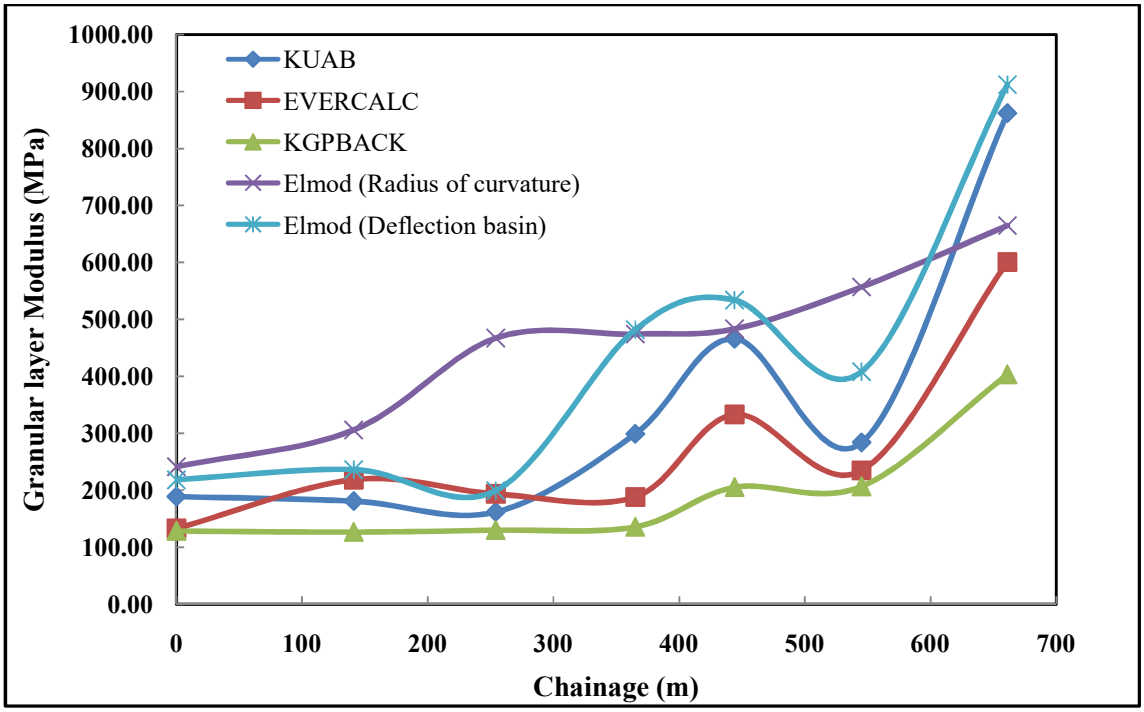


Figure 6.32 Variation of Granular Layer Moduli along Chainage (0-661 m) for Dera Bhatti Road

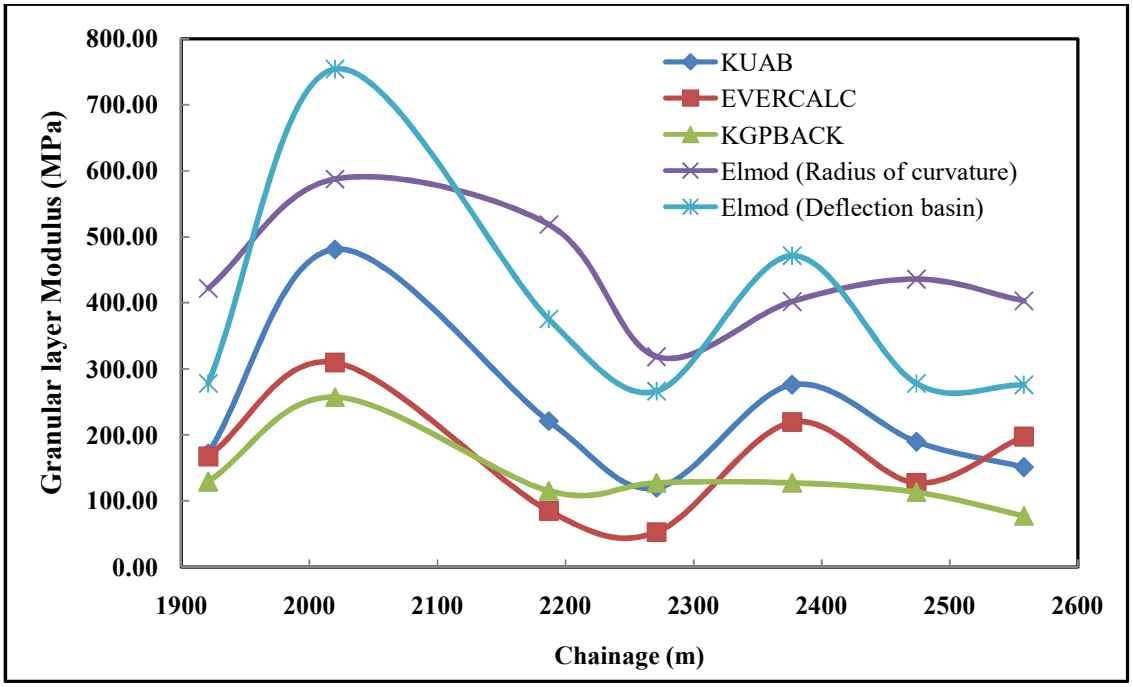


Figure 6.33 Variation of Granular Layer Moduli along Chainage (1921-2558 m) for Dera Bhatti Road

6.5.3 Surface Layer Modulus

Surface layer modulus was back-calculated using KUAB, EVERCALC, KGPBACK, Elmod (Radius of curvature and Deflection Basin fit methods) programs. Surface modulus was also determined in Laboratory by performing resilient modulus test on core samples.

For Gadaipur Bandh Road, Elmod (Radius of curvature) program gave high value of average surface layer modulus (3982.47 MPa) and KGPBACK program calculated low value (1950.22). Figure 6.34 is showing the comparison of average surface layer modulus for this road by different methods.

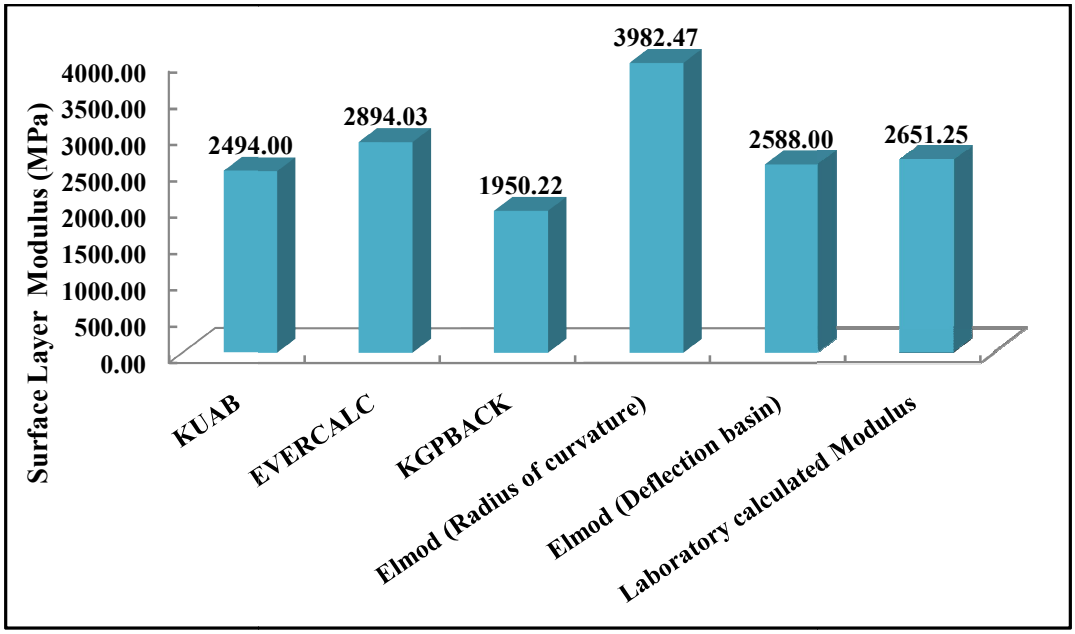


Figure 6.34 Comparison of Average Surface Layer Modulus for Gadaipur Bandh Road by Different Methods

For Dera Bhatti Road, EVERCALC program computed highest value (2286.51 MPa) of average surface layer modulus and Elmod (Deflection basin fit method) calculated lowest value (1158.49 MPa) as presented in Figure 6.35.

For Gadaipur Bandh Road (chainage 0-984 m), the surface layer moduli determined using KUAB, Elmod (Deflection basin fit method) and EVERCALC programs followed nearly similar trend. KGPBACK program was showing the large variation in moduli values. Elmod (Radius of curvature method) program had computed high moduli values as shown in Figure 6.36.

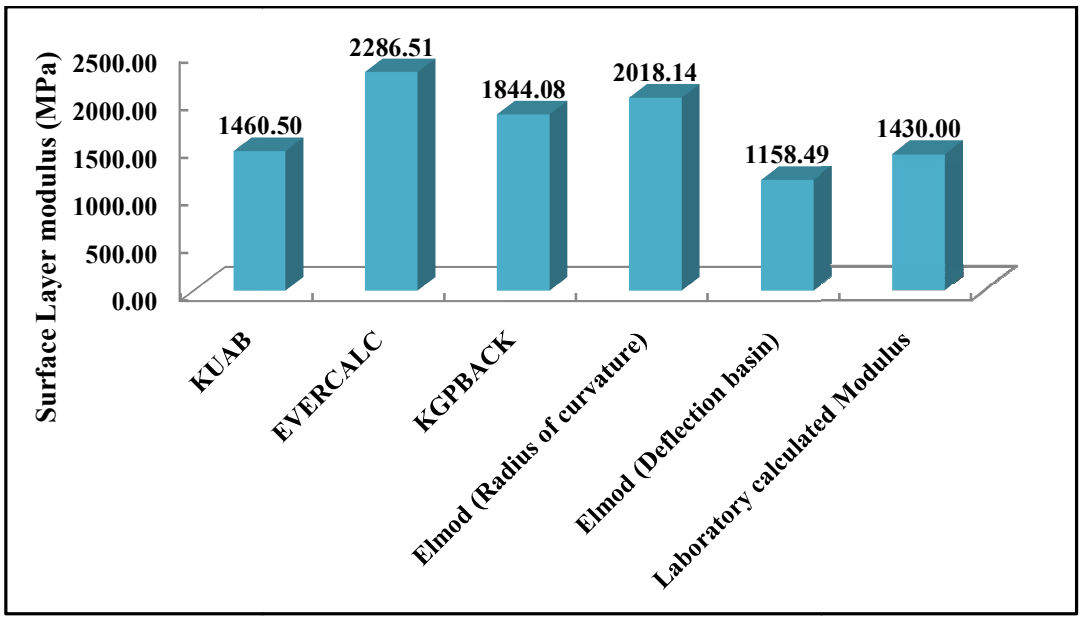


Figure 6.35 Comparison of Average Surface Layer Modulus for Dera Bhatti Road by Different Methods

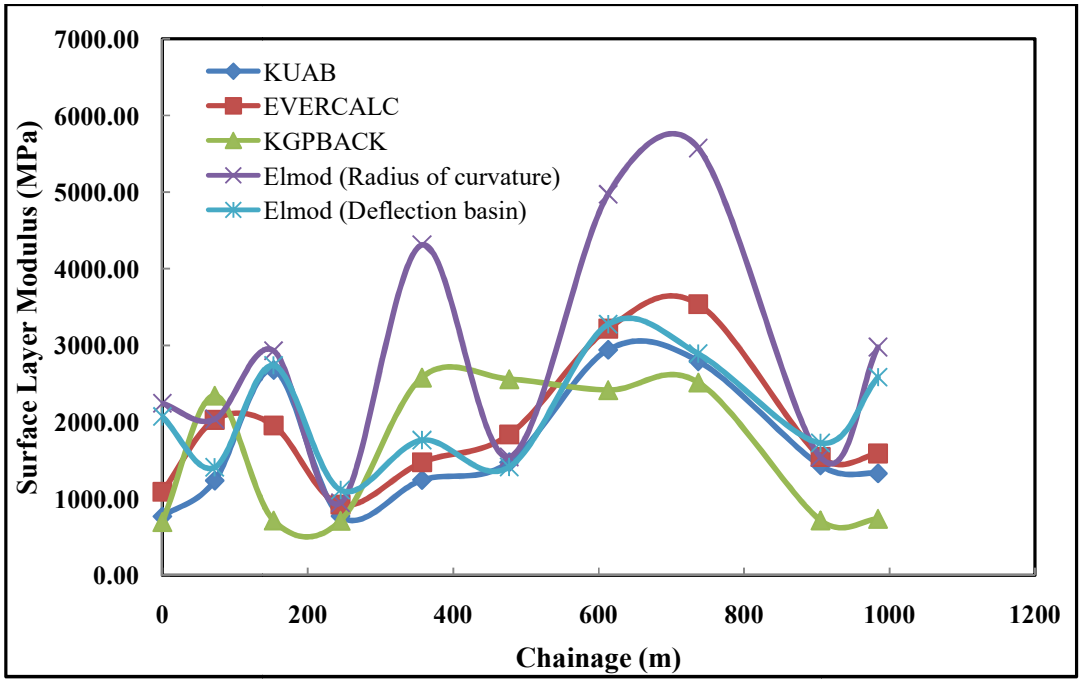


Figure 6.36 Variation of Surface Layer Moduli along Chainage (0-984 m) for Gadaipur Bandh Road

For Gadaipur Bandh Road (chainage 1061-2655 m), the surface layer moduli determined using KUAB and EVERCALC programs followed similar trend. The surface layer moduli which were computed from other programs showed large variations. Elmod (Radius of curvature method) program had back-calculated high moduli values. Figure 6.37 shows the variation of surface layer moduli for the given road.

For Dera Bhatti Road (chainage 0-661 m), the surface layer moduli determined using KUAB, and EVERCALC programs followed nearly similar trend. For chainage 0 to 200 m all programs were following same trend but after that large variation was found in layer moduli values. Elmod (Radius of curvature method) program had computed high moduli values. Figure 6.38 is showing the variation of surface layer moduli for the given road.

For Dera Bhatti Road (chainage 1921-2558 m), the surface layer moduli determined using KUAB and Elmod (Deflection basin fit method) programs followed similar trend. The surface layer moduli which were computed from other programs showed large variations. EVERCALC and Elmod (Radius of curvature method) programs were giving high moduli values as shown in Figure 6.39.

Figure 6.40 is showing the surface modulus values along different chainages for Gadaipur bandh road. The modulus values which were back-calculated by using KUAB, EVERCALC and Elmod (Deflection basin fit method) programs were found close to laboratory calculated modulus values. But it was found that modulus values determined from KUAB program were more close to laboratory calculated values.

From Figure 6.41 it was found that modulus values determined from KUAB program were more close to laboratory calculated values for Dera Bhatti road as compared to other programs.

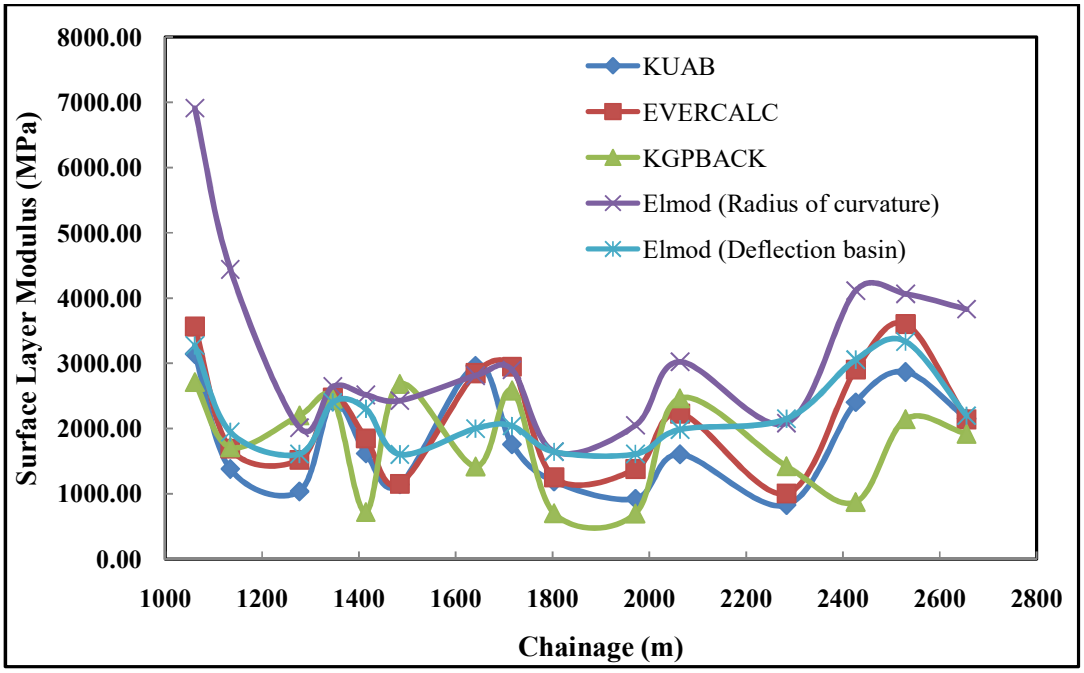


Figure 6.37 Variation of Surface Layer Moduli along Chainage (1061-2655 m) for Gadaipur Bandh Road

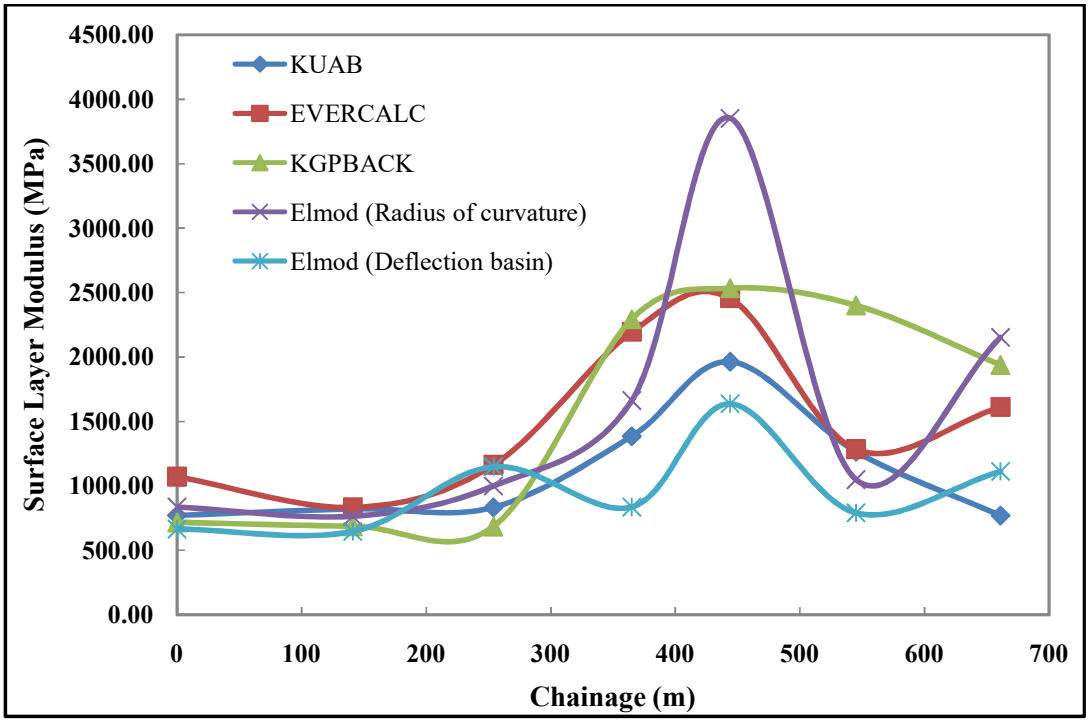


Figure 6.38 Variation of Surface Layer Moduli along Chainage (0-661 m) for Dera Bhatti Road

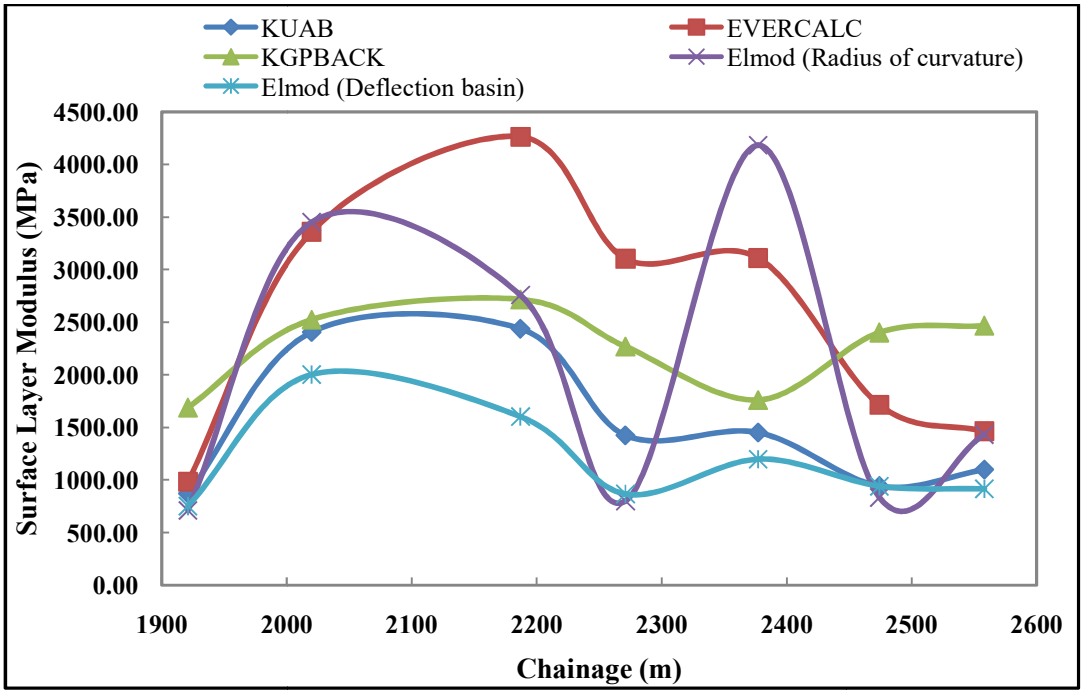
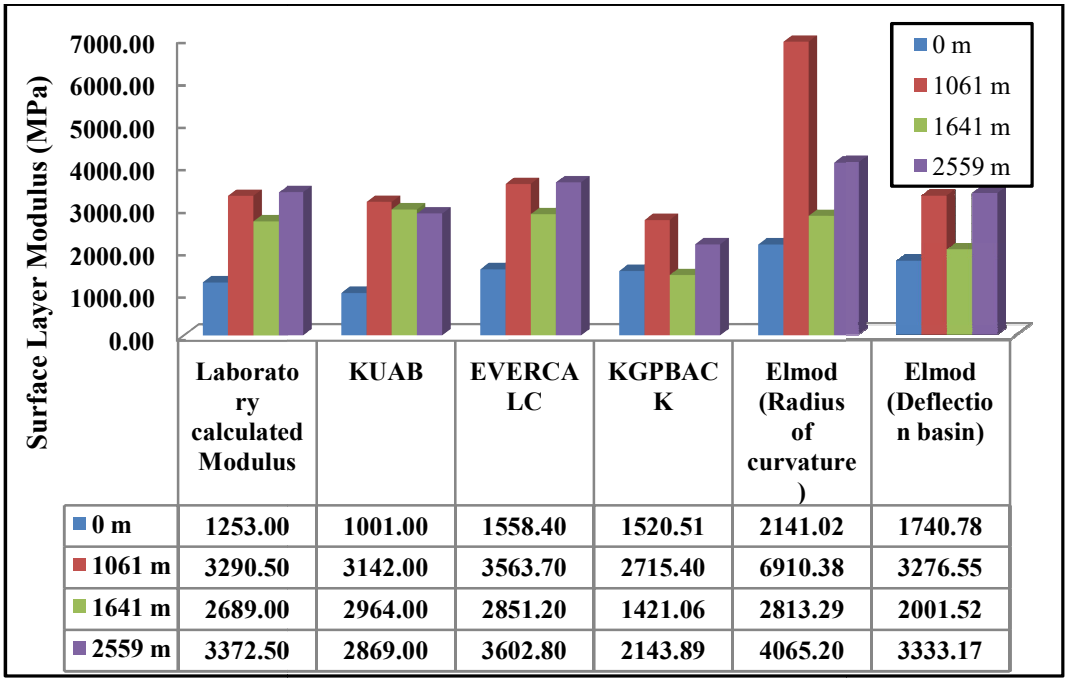
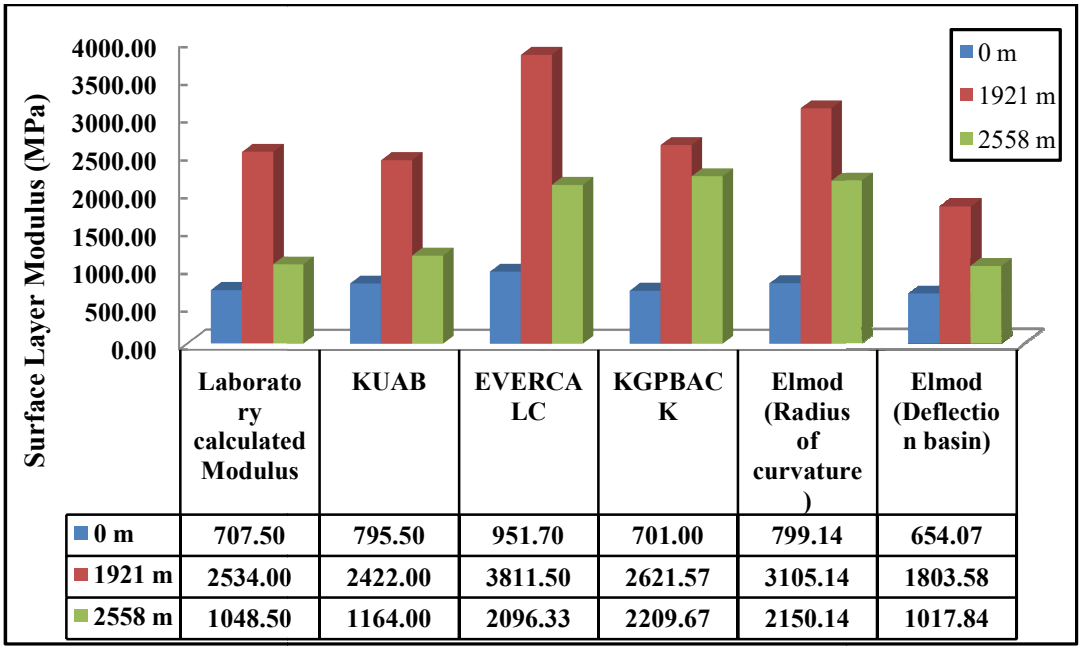


Figure 6.39 Variation of Surface Layer Moduli along Chainage (1921-2558 m) for Dera Bhatti Road



	Laboratory calculated Modulus	KUAB	EVERCALC	KGPBACK	Elmod (Radius of curvature)	Elmod (Deflection basin)
0 m	1253.00	1001.00	1558.40	1520.51	2141.02	1740.78
1061 m	3290.50	3142.00	3563.70	2715.40	6910.38	3276.55
1641 m	2689.00	2964.00	2851.20	1421.06	2813.29	2001.52
2559 m	3372.50	2869.00	3602.80	2143.89	4065.20	3333.17

Figure 6.40 Surface Modulus Values along Different Chainages for Gadaipur Bandh Road



	Laboratory calculated Modulus	KUAB	EVERCALC	KGPBACK	Elmod (Radius of curvature)	Elmod (Deflection basin)
0 m	707.50	795.50	951.70	701.00	799.14	654.07
1921 m	2534.00	2422.00	3811.50	2621.57	3105.14	1803.58
2558 m	1048.50	1164.00	2096.33	2209.67	2150.14	1017.84

Figure 6.41 Surface Modulus Values along Different Chainages for Dera Bhatti Road

6.6 CORRELATION BETWEEN DIFFERENT PROGRAMS

6.6.1 Gadaipur Bandh Road

The Pearson correlation between different programs for surface modulus values was computed as presented in Table 6.4. Surface modulus calculated from KUAB and EVERCALC programs indicated strong correlation between them.

Table 6.4 Correlation between Different Programs for Surface Modulus

PROGRAMS		KUAB	EVERCALC	KGPBACK	RADIUS OF CURVATURE	DEFLECTION BASIN FIT
KUAB	Pearson Correlation	1	0.901	.309	0.7	0.795
EVERCALC	Pearson Correlation	0.901	1	0.469	0.733	0.759
KGPBACK	Pearson Correlation	.309	0.469	1	0.449	.120
RADIUS OF CURVATURE	Pearson Correlation	0.7	0.733	0.449	1	0.766
DEFLECTION BASIN FIT	Pearson Correlation	0.795	0.759	.120	0.766	1

The Pearson correlations between different programs for granular modulus values were computed as presented in Table 6.5. Granular modulus computed from EVERCALC and

KUAB, EVERCALC and Radius of curvature methods indicated strong correlation respectively. The Pearson correlations between different methods used for determination of subgrade modulus values were computed. Subgrade modulus calculated from KUAB and EVERCALC programs indicated strong correlation as given in Table 6.6.

Table 6.5 Correlation between Different Programs for Granular Modulus

PROGRAMS		KUAB	EVERCALC	KGPBACK	RADIUS OF CURVATURE	DEFLECTION BASIN FIT
KUAB	Pearson Correlation	1	0.913	0.826	0.853	0.864
EVERCALC	Pearson Correlation	0.913	1	0.878	0.909	0.943
KGPBACK	Pearson Correlation	0.826	0.878	1	0.755	0.793
RADIUS OF CURVATURE	Pearson Correlation	0.853	0.909	0.755	1	0.964
DEFLECTION BASIN FIT	Pearson Correlation	0.864	0.943	0.793	0.964	1

Table 6.6 Correlation between Different Programs for Subgrade Modulus

PROGRAMS		KUAB	EVERCALC	KGPBACK	RADIUS OF CURVATURE	DEFLECTION BASIN FIT	AASHTO (1993)	Garg and Thompson (1999)	Roque (1998)
KUAB	Pearson Correlation	1.00	0.94	0.94	0.85	0.89	0.91	0.89	0.90
EVERCALC	Pearson Correlation	0.94	1.00	0.94	0.91	0.90	0.98	0.84	0.84
KGPBACK	Pearson Correlation	0.94	0.94	1.00	0.88	0.87	0.94	0.93	0.94
RADIUS OF CURVATURE	Pearson Correlation	0.85	0.91	0.88	1.00	0.75	0.89	0.85	0.79
DEFLECTION BASIN FIT	Pearson Correlation	0.89	0.90	0.87	0.75	1.00	0.90	0.80	0.82
AASHTO (1993)	Pearson Correlation	0.91	0.98	0.94	0.89	0.90	1.00	0.82	0.82
Garg and Thompson (1999)	Pearson Correlation	0.89	0.84	0.93	0.85	0.80	0.82	1.00	0.95
Roque (1998)	Pearson Correlation	0.90	0.84	0.94	0.79	0.82	0.82	0.95	1.00

6.6.2 Dera Bhatti Road

The Pearson correlations between different programs for surface modulus values were computed as presented in Table 6.7. KUAB and EVERCALC programs indicated strong correlation for surface modulus values.

Table 6.7 Correlation between Different Programs for Surface Modulus

PROGRAMS		KUAB	EVERCALC	KGPBACK	RADIUS OF CURVATURE	DEFLECTION BASIN FIT
KUAB	Pearson Correlation	1.00	0.88	0.66	0.71	0.84
EVERCALC	Pearson Correlation	0.88	1.00	0.62	0.68	0.72
KGPBACK	Pearson Correlation	0.66	0.62	1.00	0.41	0.48
RADIUS OF CURVATURE	Pearson Correlation	0.71	0.68	0.41	1.00	0.80
DEFLECTION BASIN FIT	Pearson Correlation	0.84	0.72	0.48	0.80	1.00

The Pearson correlations between different programs for granular modulus values were determined as presented in Table 6.8. It was found that granular moduli computed from KUAB and KGPBACK, KUAB and DEFLECTION BASIN FIT methods indicated strong correlation.

Table 6.8 Correlation between Different Programs for Granular Modulus

PROGRAMS		KUAB	EVERCALC	KGPBACK	RADIUS OF CURVATURE	DEFLECTION BASIN FIT
KUAB	Pearson Correlation	1.00	0.94	0.95	0.74	0.94
EVERCALC	Pearson Correlation	0.94	1.00	0.90	0.67	0.83
KGPBACK	Pearson Correlation	0.95	0.90	1.00	0.73	0.89
RADIUS OF CURVATURE	Pearson Correlation	0.74	0.67	0.73	1.00	0.79
DEFLECTION BASIN FIT	Pearson Correlation	0.94	0.83	0.89	0.79	1.00

The Pearson correlations between different programs for subgrade modulus values were determined as presented in Table 6.9. It was found that subgrade moduli computed from KUAB and EVERCALC, RADIUS OF CURVATURE and DEFLECTION BASIN FIT methods indicated strong correlation.

Table 6.9 Correlation between Different Programs for Subgrade Modulus

PROGRAMS		KUAB	EVERCALC	KGPBACK	RADIUS OF CURVATURE	DEFLECTION BASIN FIT	AASHTO (1993) (1993)	Garg and Thompson (1999)	Roque (1998)
KUAB	Pearson Correlation	1.00	0.96	0.83	0.92	0.78	0.95	0.60	0.49
EVERCALC	Pearson Correlation	0.96	1.00	0.74	0.85	0.69	0.93	0.66	0.59
KGPBACK	Pearson Correlation	0.83	0.74	1.00	0.87	0.80	0.88	0.44	0.16
RADIUS OF CURVATURE	Pearson Correlation	0.92	0.85	0.87	1.00	0.93	0.96	0.34	0.14
DEFLECTION BASIN FIT	Pearson Correlation	0.78	0.69	0.80	0.93	1.00	0.88	0.21	-0.10
AASHTO (1993)	Pearson Correlation	0.95	0.93	0.88	0.96	0.88	1.00	0.53	0.32
Garg and Thompson (1999)	Pearson Correlation	0.60	0.66	0.44	0.34	0.21	0.53	1.00	0.86
Roque (1998)	Pearson Correlation	0.49	0.59	0.16	0.14	-0.10	0.32	0.86	1.00

6.7 STATISTICAL ANALYSIS

To analyze the modulus values calculated from different programs statistical analysis was used. Mainly Parametric and Non Parametric tests are used for Statistical analysis. Parametric tests are those tests that make assumptions. Non-parametric tests make no assumptions.

Parametric tests are based on the following assumptions:

1. Data should be Normally Distributed (Histogram should be in bell-shaped).
2. Data from the different groups have the same variance which is called Homogeneity of variances.
3. Data should have linear relationship and independent.

Mainly, first two assumptions should be satisfied to use parametric tests. If these assumptions are not fulfilled than Non-parametric tests equivalent to that parametric tests are used.

Table 6.10 Parametric and Non Parametric Tests

Parametric Tests	Non-Parametric Tests
Independent samples t-test	Mann- Whitney test
Paired samples t-test	Wilcoxon Signed- Rank test
One- Way ANOVA	Kruskal-Wallis test
One-way Repeated Measures ANOVA	Friedman's ANOVA

Table 6.10 is presenting the parametric tests equivalent to non- parametric tests. To compare the mean of two mutually exclusive samples, Independent t-test is used and to compare the means of two dependent groups, Paired t-test is used. If samples are more than two, ANOVA is used.

In this study modulus values of different layers obtained from various methods were evaluated by using Hypothesis testing based on Non-Parametric test because assumptions of parametric tests were not fulfilled. As per Table 6.10, for comparing the two or more independent samples of equal or different sample sizes Kruskal-Wallis H test was used. Two road sections were considered for statistical analysis.

6.7.1 Gadaipur Bandh Road

Surface Layer Modulus

Testing of Normality

Kolmogorov – Smirnov test was used for determining the normality of data. For data to be normal, p-value should be greater than level of significance 0.05.

For surface modulus data as presented in Table 6.11, the distribution for

KGPBACK - df (25), p value = 0.008 < 0.05 non-normal data

RADIUS OF CURVATURE- df (25), p value = 0.020 < 0.05 non-normal data

Table 6.11 Test of Normality

Program		Kolmogorov-Smirnov		
		Statistic	df	Sig. (p- value)
SURFACE MODULI	KUAB	.173	25	.051
	EVERCALC	.123	25	.200
	KGPBACK	.205	25	.008
	RADIUS OF CURVATURE	.190	25	.020
	DEFLECTION BASIN	.120	25	.200

df = degrees of freedom and Sig. is representing the statistical significance of the test also called p-value.

Testing of Homogeneity

Levene test was performed to test Homogeneity of variances. For data to be homogenous, p-value should be more than level of significance 0.05.

Table 6.12 Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig. (p -value)
SURFACE MODULI	Based on Mean	4.474	4	120	.002
	Based on Median	2.997	4	120	.021
	Based on Median and with adjusted df	2.997	4	73.78	.024
	Based on trimmed mean	3.815	4	120	.006

As given in Table 6.12, the p-value (Based on Mean) =0.002 < 0 .05 which means data is not homogenous. Since, assumptions for parametric test are not fulfilled therefore; non-parametric test was used.

Kruskal-Wallis H test

This is a rank-based non-parametric test and utilised to compute statistically significant differences among two or more groups of an independent variable. Moduli back-calculated from five different programs were compared to find the significant difference between them. It is equivalent to parametric test ANOVA and extension to Mann-Whitney test.

Table 6.13 Descriptive Statistics

	N	Mean	Std. Deviation	Minimum	Maximum
Surface Moduli	125	2154.84	1043.72	696.03	6910.38
Program	125	3	1.42	1	5

Table 6.14 Ranks Calculated Using Kruskal-Wallis Test for Surface Moduli

	Program	N	Mean Rank
Surface Moduli	KUAB	25	49.68
	EVERCALC	25	61.24
	KGPBACK	25	48.48
	RADIUS OF CURVATURE	25	88.4
	DEFLECTION BASIN FIT	25	67.2
	Total	125	

Table 6.15 Test Statistics

	SurfaceModuli
Chi-Square	20.079
df	4
Asymp. Sig.	0.000482

From Table 6.15; Chi square (4) = 20.079, p = 0.000482 < 0.05. Mean rank surface moduli of 49.68 for KUAB, 61.24 for EVERCALC, 48.48 for KGPBACK, 88.40 for RADIUS OF CURVATURE and 67.20 for DEFLECTION BASIN FIT methods are presented in Table 6.14. Since, p value is less than level of significance as given in Table 6.16 null hypothesis is rejected. It implies that surface moduli determined from different programs show statistically significant difference.

Table 6.16 Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Surfacemoduli is the same across categories of Program.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Mann- Whitney test was performed on the groups of programs to check that which of the program groups showing the significant difference between the surface moduli values. Table 6.17 is showing the results obtained after the application of Mann-Whitney test.

Table 6.17 Mann-Whitney Test on the Groups of Programs for Surface Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KUAB and EVERCALC	-1.446	0.148	Since, (0.148>0.05) Null Hypothesis Accepted	No
KUAB and KGPBACK	-0.669	0.503	Since, (0.503>0.05) Null Hypothesis Accepted	No
KUAB and RADIUS OF CURVATURE	-3.56	0.00037	Since, (0.00037<0.05) Null Hypothesis Rejected	Yes
KUAB and DEFLECTION BASIN FIT	-2.125	0.034	Since, (0.034<0.05) Null Hypothesis Rejected	Yes
EVERCALC and KGPBACK	-1.329	0.184	Since, (0.184>0.05) Null Hypothesis Accepted	No
EVERCALC and RADIUS OF CURVATURE	-2.784	0.005	Since, (0.005<0.05) Null Hypothesis Rejected	Yes
EVERCALC and DEFLECTION BASIN FIT	-0.844	0.399	Since, (0.399>0.05) Null Hypothesis Accepted	No

KGPBACK and RADIUS OF CURVATURE	-3.522	0.000429	Since, (0.000429<0.05) Null Hypothesis Rejected	Yes
KGPBACK and DEFLECTION BASIN FIT	-1.523	0.128	Since, (0.128>0.05) Null Hypothesis Accepted	No
RADIUS OF CURVATURE and DEFLECTION BASIN FIT	-2.454	0.014	Since, (0.014<0.05) Null Hypothesis Rejected	Yes

As presented in Table 6.17 the groups KUAB and EVERCALC, KUAB and KGPBACK, EVERCALC and KGPBACK, EVERCALC and DEFLECTION BASIN FIT, KGPBACK and DEFLECTION BASIN FIT have the p-value more than level of significance respectively. Therefore, there was no statistically significant difference between these program groups with respect to surface moduli.

Granular Layer Modulus

Testing of Normality

Similarly, for granular layer moduli Kolmogorov – Smirnov test was used for determining the normality of data. Since, data was found non-normal and non-homogenous therefore non-parametric test (Kruskal-Wallis H test) was used for statistical analysis.

Table 6.18 Ranks Calculated Using Kruskal-Wallis Test for Granular Moduli

Program		**N**	**Mean Rank**
Granular moduli	KUAB	25	73.30
	EVERCALC	25	50.78
	KGPBACK	25	63.04
	RADIUS OF CURVATURE	25	64.52
	DEFLECTION BASIN	25	63.36
	Total	125	

Table 6.19 Test Statistics

	Granular moduli
Chi-Square	4.912
df	4
Asymp. Sig.	.296

From Table 6.19; Chi square (4) = 4.912, p = 0.296 >0.05. Mean rank granular moduli of 73.30 for KUAB, 50.78 for EVERCALC, 63.04 for KGPBACK, 64.52 for RADIUS OF CURVATURE and 63.36 for DEFLECTION BASIN FIT methods are presented in Table 6.18. Since, p value is greater than level of significance as given in Table 6.20 null hypothesis is retained. It implies that granular moduli determined from different programs show no statistically significant difference.

Table 6.20 Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Granularmoduli is the same across categories of Program.	Independent-Samples Kruskal-Wallis Test	.296	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Subgrade Layer Modulus

Testing of Normality

Similarly, for subgrade layer moduli Kolmogorov – Smirnov test was used for determining the normality of data. Since, data was found non-normal and non-homogenous therefore non-parametric test (Kruskal-Wallis H test) was used for statistical analysis.

Table 6.21 Ranks Calculated Using Kruskal-Wallis Test for Subgrade Moduli

Program		N	Mean Rank
Subgrade Moduli	KUAB	25	85.38
	EVERCALC	25	95.22
	KGPBACK	25	131.60
	RADIUS OF CURVATURE	25	76.44
	DEFLECTION BASIN	25	51.30
	AASHTO (1993)	25	101.90
	Garg and Thompson (1999)	25	99.72
	Roque (1998)	25	162.44
	Total	200	

Table 6.22 Test Statistics

	Subgrade moduli
Chi-Square	60.168
df	7
Asymp. Sig.	.000

From Table 6.22; Chi square (7) = 60.168, p = .000<0.05. Mean rank subgrade moduli of 85.38 for KUAB, 95.22 for EVERCALC, 131.60 for KGPBACK, 76.44 for RADIUS OF CURVATURE, 51.30 for DEFLECTION BASIN FIT, 101.90 for AASHTO (1993), 99.72 for Garg and Thompson (1999), and 162.44 for Roque (1998) method are presented in Table 6.21. Since, p value is less than level of significance as given in Table 6.23 null hypothesis is rejected. It implies that subgrade moduli determined from different programs show statistically significant difference.

Table 6.23 Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Subgrademod is the same across categories of Program.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.

Mann- Whitney test was performed on the groups of programs to check that which of the program groups showing the significant difference between the subgrade moduli values.

Table 6.24 and Table 6.25 are showing the results obtained after the application of Mann-Whitney test.

Table 6.24 Mann-Whitney Test on the Groups of Programs for Subgrade Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KUAB and EVERCALC	-0.485	0.628	Since, (0.628>0.05) Null Hypothesis Accepted	No
KUAB and KGPBACK	-3.153	0.002	Since, (0.002<0.05) Null Hypothesis Rejected	Yes
KUAB and RADIUS OF CURVATURE	-0.864	0.388	Since, (0.388>0.05) Null Hypothesis Accepted	No
KUAB and DEFLECTION BASIN	-2.416	0.016	Since, (0.016<0.05) Null Hypothesis Rejected	Yes
KUAB and AASHTO (1993)	-0.999	0.318	Since, (0.318>0.05) Null Hypothesis Accepted	No
KUAB and Garg and Thompson (1999)	-1.213	0.225	Since, (0.225>0.05) Null Hypothesis Accepted	No
KUAB and Roque (1998)	-4.764	0.000002	Since, (0.000002<0.05) Null Hypothesis Rejected	Yes
EVERCALC and KGPBACK	-2.222	0.026	Since, (0.026<0.05) Null Hypothesis Rejected	Yes
EVERCALC and RADIUS OF CURVATURE	-1.077	0.282	Since, (0.282>0.05) Null Hypothesis Accepted	No
EVERCALC and DEFLECTION BASIN	-2.687	0.007	Since, (0.007<0.05) Null Hypothesis Rejected	Yes
EVERCALC and AASHTO (1993)	-0.456	0.648	Since, (0.648>0.05) Null Hypothesis Accepted	No
EVERCALC and Garg and Thompson (1999)	-0.437	0.662	Since, (0.662>0.05) Null Hypothesis Accepted	No
EVERCALC and Roque (1998)	-3.697	0.000219	Since, (0.000219<0.05) Null Hypothesis Rejected	Yes
KGPBACK and RADIUS OF CURVATURE	-3.211	0.00132	Since, (0.00132<0.05) Null Hypothesis Rejected	Yes

As presented in Table 6.24 and Table 6.25 the groups KUAB and EVERCALC, KUAB and RADIUS OF CURVATURE, KUAB and AASHTO (1993), KUAB and Garg and Thompson (1999), EVERCALC and RADIUS OF CURVATURE, EVERCALC and AASHTO (1993), EVERCALC and Garg and Thompson (1999), RADIUS OF CURVATURE and DEFLECTION BASIN, RADIUS OF CURVATURE and AASHTO (1993), RADIUS OF CURVATURE and Garg and Thompson (1999), AASHTO (1993) and Garg and Thompson (1999) have the p-value greater than level of significance

respectively. Therefore, it was found that subgrade moduli computed using these groups of programs do not show statistically significant difference.

Table 6.25 Mann-Whitney Test on the Groups of Programs for Subgrade Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KGPBACK and DEFLECTION BASIN	-4.957	0.000001	Since, (0.000001<0.05) Null Hypothesis Rejected	Yes
KGPBACK and AASHTO (1993)	-2.028	0.043	Since, (0.043<0.05) Null Hypothesis Rejected	Yes
KGPBACK and Garg and Thompson (1999)	-2.513	0.012	Since, (0.012<0.05) Null Hypothesis Rejected	Yes
KGPBACK and Roque (1998)	-2.998	0.003	Since, (0.003<0.05) Null Hypothesis Rejected	Yes
RADIUS OF CURVATURE and DEFLECTION BASIN	-1.213	0.225	Since, (0.225>0.05) Null Hypothesis Accepted	No
RADIUS OF CURVATURE and AASHTO (1993)	-1.717	0.086	Since, (0.086>0.05) Null Hypothesis Accepted	No
RADIUS OF CURVATURE and Garg and Thompson (1999)	-1.911	0.056	Since, (0.056>0.05) Null Hypothesis Accepted	No
RADIUS OF CURVATURE and Roque (1998)	-4.104	0.000041	Since, (0.000041<0.05) Null Hypothesis Rejected	Yes
DEFLECTION BASIN and AASHTO (1993)	-3.202	0.00136	Since, (0.00136<0.05) Null Hypothesis Rejected	Yes
DEFLECTION BASIN and Garg and Thompson (1999)	-3.559	0.000319	Since, (0.000319<0.05) Null Hypothesis Rejected	Yes
DEFLECTION BASIN and Roque (1998)	-5.792	0.000001	Since, (0.000001<0.05) Null Hypothesis Rejected	Yes
AASHTO (1993) and Garg and Thompson (1999)	-0.068	0.946	Since, (0.946>0.05) Null Hypothesis Accepted	No
AASHTO (1993) and Roque (1998)	-3.735	0.000188	Since, (0.000188<0.05) Null Hypothesis Rejected	Yes
Garg and Thompson (1999) and Roque (1998)	-4.958	0.000001	Since, (0.000001<0.05) Null Hypothesis Rejected	Yes

6.7.2 Dera Bhatti Road

Surface Layer Modulus

Testing of Normality

Similarly, for subgrade layer moduli Kolmogorov – Smirnov test was used for determining the normality of data. Since, data was found non-normal and non-homogenous therefore non-parametric test (Kruskal-Wallis H test) was used for statistical analysis.

Table 6.26 Ranks Calculated Using Kruskal-Wallis Test for Surface Moduli

Program		N	Mean Rank
Surface Moduli	KUAB	14	30.07
	EVERCALC	14	44.93
	KGPBACK	14	43.29
	RADIUS OF CURVATURE	14	36.21
	DEFLECTION BASIN	14	23.00
	Total	70	

Table 6.27 Test Statistics

	Surface Moduli
Chi-Square	11.349
df	4
Asymp. Sig.	.023

From Table 6.27; Chi square (4) = 11.349, p = .023 < 0.05. Mean rank surface moduli of 30.07 for KUAB, 44.93 for EVERCALC, 43.39 for KGPBACK, 36.21 for RADIUS OF CURVATURE, 23.00 for DEFLECTION BASIN FIT methods are presented in Table 6.26. Since, p value is less than level of significance as given in Table 6.28 null hypothesis is rejected. It implies that surface moduli determined from different programs show statistically significant difference.

Table 6.28 Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of SurfaceModuli is the same across categories of Program.	Independent-Samples Kruskal-Wallis Test	.023	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Mann- Whitney test was performed on the groups of programs to check that which of the program groups show the significant difference between the surface moduli values. Table 6.29 is showing the results obtained after the application of Mann-Whitney test.

Table 6.29 Mann-Whitney Test on the Groups of Programs for Surface Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KUAB and EVERCALC	-2.16	0.031	Since, (0.031<0.05) Null Hypothesis Rejected	Yes
KUAB and KGPBACK	-1.792	0.073	Since, (0.073>0.05) Null Hypothesis Accepted	No
KUAB and RADIUS OF CURVATURE	-0.597	0.55	Since, (0.55>0.05) Null Hypothesis Accepted	No
KUAB and DEFLECTION BASIN FIT	-1.057	0.291	Since, (0.291>0.05) Null Hypothesis Accepted	No
EVERCALC and KGPBACK	-0.046	0.963	Since, (0.963>0.05) Null Hypothesis Accepted	No
EVERCALC and RADIUS OF CURVATURE	-1.057	0.291	Since, (0.291>0.05) Null Hypothesis Accepted	No
EVERCALC and DEFLECTION BASIN FIT	-2.895	0.004	Since, 0.004<0.05) Null Hypothesis Rejected	Yes
KGPBACK and RADIUS OF CURVATURE	-0.459	0.646	Since, (0.646>0.05) Null Hypothesis Accepted	No
KGPBACK and DEFLECTION BASIN FIT	-2.711	0.007	Since, (0.007<0.05) Null Hypothesis Rejected	Yes
RADIUS OF CURVATURE and DEFLECTION BASIN FIT	-1.378	0.168	Since, (0.168>0.05) Null Hypothesis Accepted	No

As presented in Table 6.29 the groups KUAB and EVERCALC, EVERCALC and DEFLECTION BASIN FIT, KGPBACK and DEFLECTION BASIN FIT have the p-value less than level of significance respectively. Therefore, it was found that Surface moduli calculated using these groups of programs show statistically significant difference.

Granular Layer Modulus

Testing of Normality

Similarly for granular layer moduli Kolmogorov – Smirnov test was used for determining the normality of data. Since, data was found non-normal and non-homogenous therefore non-parametric test (Kruskal-Wallis H test) was used for statistical analysis.

Table 6.30 Ranks Calculated Using Kruskal-Wallis Test for Granular Moduli

Program		N	Mean Rank
Granular Moduli	KUAB	14	32.93
	EVERCALC	14	26.14
	KGPBACK	14	16.43
	RADIUS OF CURVATURE	14	54.57
	DEFLECTION BASIN	14	47.43
	Total	70	

Table 6.31 Test Statistics

	Granular Moduli
Chi-Square	32.583
df	4
Asymp. Sig.	.000001

From Table 6.31; Chi square (4) = 32.583, p = .000001<0.05. Mean rank granular moduli of 32.93 for KUAB, 26.14 for EVERCALC, 16.43 for KGPBACK, 54.57 for RADIUS OF CURVATURE, 47.43 for DEFLECTION BASIN FIT methods are presented in Table 6.30. Since, p value is less than level of significance as given in Table 6.32 the null hypothesis is rejected. It implies that granular moduli determined from different programs show statistically significant difference.

Table 6.32 Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Granularmoduli is the same across categories of Program.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Mann- Whitney test was performed on the groups of programs to check that which of the program groups showing the significant difference between the granular moduli values. Table 6.33 is showing the results obtained after the application of Mann-Whitney test.

Table 6.33 Mann-Whitney Test on the Groups of Programs for Granular Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KUAB and EVERCALC	-0.781	0.435	Since, (0.435>0.05) Null Hypothesis Accepted	No
KUAB and KGPBACK	-2.665	0.008	Since, (0.008<0.05) Null Hypothesis Rejected	Yes
KUAB and RADIUS OF CURVATURE	-2.987	0.003	Since, (0.003<0.05) Null Hypothesis Rejected	Yes
KUAB and DEFLECTION BASIN FIT	-2.114	0.035	Since, (0.035<0.05) Null Hypothesis Rejected	Yes
EVERCALC and KGPBACK	-1.47	0.141	Since, (0.141>0.05) Null Hypothesis Accepted	No
EVERCALC and RADIUS OF CURVATURE	-3.676	0.000237	Since, (0.000237<0.05) Null Hypothesis Rejected	Yes
EVERCALC and DEFLECTION BASIN FIT	-3.033	0.002	Since, (0.002<0.05) Null Hypothesis Rejected	Yes
KGPBACK and RADIUS OF CURVATURE	-4.227	0.000024	Since, (0.000024<0.05) Null Hypothesis Rejected	Yes
KGPBACK and DEFLECTION BASIN FIT	-3.906	0.000094	Since, (0.000094<0.05) Null Hypothesis Rejected	Yes
RADIUS OF CURVATURE and DEFLECTION BASIN FIT	-1.379	0.168	Since, (0.168>0.05) Null Hypothesis Accepted	No

As presented in Table 6.33 the groups KUAB and EVERCALC, EVERCALC and KGPBACK, RADIUS OF CURVATURE and DEFLECTION BASIN FIT have the p-value greater than level of significance respectively. Therefore, it was found that granular moduli computed using these groups of programs do not show statistically significant difference.

Subgrade Layer Modulus

Testing of Normality

Similarly, for subgrade layer moduli Kolmogorov – Smirnov test was used for determining the normality of data. Since, data was found non-normal and non-homogenous therefore non-parametric test (Kruskal-Wallis H test) was used for statistical analysis.

Table 6.34 Ranks Calculated Using Kruskal-Wallis Test for Subgrade Moduli

Program		N	Mean Rank
Subgrade Moduli	KUAB	14	54.21
	EVERCALC	14	55.93
	KGPBACK	14	65.43
	RADIUS OF CURVATURE	14	26.86
	DEFLECTION BASIN	14	36.07
	AASHTO (1993)	14	54.25
	Garg and Thompson (1999)	14	64.46
	Roque (1998)	14	94.79
	Total	112	

Table 6.35 Test Statistics

	Subgrade Moduli
Chi-Square	38.703
df	7
Asymp. Sig.	.000002

From Table 6.35; Chi square (7) = 38.703, p = .000002<0.05. Mean rank subgrade moduli of 54.21 for KUAB, 55.93 for EVERCALC, 65.43 for KGPBACK, 26.86 for RADIUS OF CURVATURE, 36.07 for DEFLECTION BASIN FIT, 54.25 for AASHTO (1993), 64.46 for Garg and Thompson (1999), and 94.79 for Roque (1998) methods are presented in Table 6.34. Since, p value is less than level of significance as given in Table 6.36 null hypothesis is rejected. It implies that subgrade moduli determined from different programs show statistically significant difference.

Table 6.36 Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of SubgradeModuli is the same across categories of Program.	Independent-Samples Kruskal-Wallis Test	.000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Mann- Whitney test was performed on the groups of programs to check that which of the program groups showing the significant difference between the subgrade moduli values. Tables 6.37 and 6.38 are showing the results obtained after application of Mann-Whitney test.

Table 6.37 Mann-Whitney Test on the Groups of Programs for Subgrade Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KUAB and EVERCALC	-0.046	0.963	Since, (0.963>0.05) Null Hypothesis Accepted	No
KUAB and KGPBACK	-1.424	0.154	Since, (0.154>0.05) Null Hypothesis Accepted	No
KUAB and RADIUS OF CURVATURE	-2.573	0.01	Since, (0.01<0.05) Null Hypothesis Rejected	Yes
KUAB and DEFLECTION BASIN	-1.792	0.073	Since, (0.073>0.05) Null Hypothesis Accepted	No
KUAB and AASHTO (1993)	0	1	Since, (1>0.05) Null Hypothesis Accepted	No
KUAB and Garg and Thompson (1999)	-1.057	0.291	Since, (0.291>0.05) Null Hypothesis Accepted	No

KUAB and Roque (1998)	-3.401	0.001	Since, (0.001<0.05) Null Hypothesis Rejected	Yes
EVERCALC and KGPBACK	-0.643	0.52	Since, (0.52>0.05) Null Hypothesis Accepted	No
EVERCALC and RADIUS OF CURVATURE	-2.343	0.019	Since, (0.019<0.05) Null Hypothesis Rejected	Yes
EVERCALC and DEFLECTION BASIN	-1.562	0.118	Since, (0.118>0.05) Null Hypothesis Accepted	No
EVERCALC and AASHTO (1993)	0	1	Since, (1>0.05) Null Hypothesis Accepted	No
EVERCALC and Garg and Thompson (1999)	-0.551	0.581	Since, (0.581>0.05) Null Hypothesis Accepted	No
EVERCALC and Roque (1998)	-3.033	0.002	Since, (0.002<0.05) Null Hypothesis Rejected	Yes
KGPBACK and RADIUS OF CURVATURE	-3.308	0.001	Since, (0.001<0.05) Null Hypothesis Rejected	Yes

Table 6.38 Mann-Whitney Test on the Groups of Programs for Subgrade Modulus

Back-calculation Programs	Z value	Asymp. Sig. (2-tailed)	Remarks	Statistically Significant Difference
KGPBACK and DEFLECTION BASIN	-2.573	0.01	Since, (0.01<0.05) Null Hypothesis Rejected	Yes
KGPBACK and AASHTO (1993)	-1.149	0.251	Since, (0.251>0.05) Null Hypothesis Accepted	No
KGPBACK and Garg and Thompson (1999)	-0.046	0.963	Since, (0.963>0.05) Null Hypothesis Accepted	No
KGPBACK and Roque (1998)	-3.401	0.001	Since, (0.001<0.05) Null Hypothesis Rejected	Yes
RADIUS OF CURVATURE and DEFLECTION BASIN	-1.149	0.251	Since, (0.251>0.05) Null Hypothesis Accepted	No
RADIUS OF CURVATURE and AASHTO (1993)	-2.711	0.007	Since, (0.007<0.05) Null Hypothesis Rejected	Yes
RADIUS OF CURVATURE and Garg and Thompson (1999)	-3.124	0.002	Since, (0.002<0.05) Null Hypothesis Rejected	Yes
RADIUS OF CURVATURE and Roque (1998)	-3.861	0.00011	Since, (0.00011<0.05) Null Hypothesis Rejected	Yes
DEFLECTION BASIN and AASHTO (1993)	-1.838	0.066	Since, (0.066>0.05) Null Hypothesis Accepted	No

DEFLECTION BASIN and Garg and Thompson (1999)	-2.665	0.008	Since, (0.008<0.05) Null Hypothesis Rejected	Yes
DEFLECTION BASIN and Roque (1998)	-3.861	0.00011	Since, (0.00011<0.05) Null Hypothesis Rejected	Yes
AASHTO (1993) and Garg and Thompson (1999)	-1.218	0.223	Since, (0.223>0.05) Null Hypothesis Accepted	No
AASHTO (1993) and Roque (1998)	-3.631	0.000282	Since, (0.00028<0.05) Null Hypothesis Rejected	Yes
Garg and Thompson (1999) and Roque (1998)	-3.447	0.001	Since, (0.001<0.05) Null Hypothesis Rejected	Yes

As presented in Table 6.37 and Table 6.38 the groups KUAB and EVERCALC, KUAB and KGPBACK, KUAB and DEFLECTION BASIN, KUAB and AASHTO (1993), KUAB and Garg and Thompson (1999), EVERCALC and KGPBACK, EVERCALC and DEFLECTION BASIN, EVERCALC and AASHTO (1993), EVERCALC and Garg and Thompson (1999), KGPBACK and AASHTO (1993), KGPBACK and Garg and Thompson (1999), RADIUS OF CURVATURE and DEFLECTION BASIN, DEFLECTION BASIN and AASHTO (1993), AASHTO (1993) and Garg and Thompson (1999) have the p-value greater than level of significance respectively. Therefore, it was found that subgrade moduli computed using these groups of programs do not show statistically significant difference.

6.8 CONSISTENCY ANALYSIS BASED ON FREQUENCY PLOT

Consistency of software was determined by evaluating the results of software from three sets of data varied for three load levels at a single location in the field. In this study three back-calculation methods were analyzed for consistency. They were EVERCALC, Elmod (Radius of Curvature method) and Elmod (Deflection Basin Fit method). Frequency plots of these back-calculated moduli from different locations of Gadaipur Bandh road were plotted at 40, 50 and 70 kN load levels respectively. A back-calculation method is said to be consistent if the frequency plot for these load levels overlap on each other and show little or no variation.

Gadaipur Bandh Road

Surface Layer Moduli

Figures 6.42, 6.43 and 6.44 were plotted to check the consistency of back-calculation methods for surface layer. From Figure 6.42 it was observed that the frequency distributions of surface modulus from Elmod (Deflection Basin Fit method) at specified loads did not overlap on each other. At a surface modulus value of 3000 MPa, the frequencies of 40, 50, and 70 kN load lines were 8, 12 and 11 respectively. The frequency distribution plot of EVERCALC did not overlap for three specified loads as shown Figure 6.43. The frequency distribution of Elmod (Radius of Curvature method) is shown in Figure 6.44 did not overlap over the modulus variation but load levels of 40 and 50 kN follows similar trend. From these plots it can be said that for the back-calculation of surface modulus some amount of consistency was shown by Elmod (Radius of Curvature method) as compared to other methods.

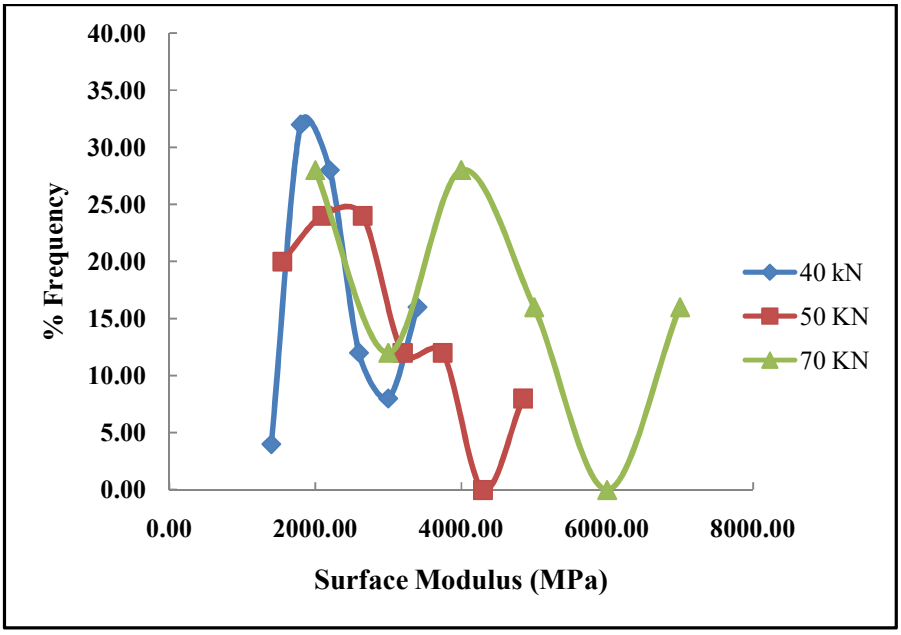


Figure 6.42 Frequency Distribution of Surface Modulus for Elmod (Deflection Basin Fit Method)

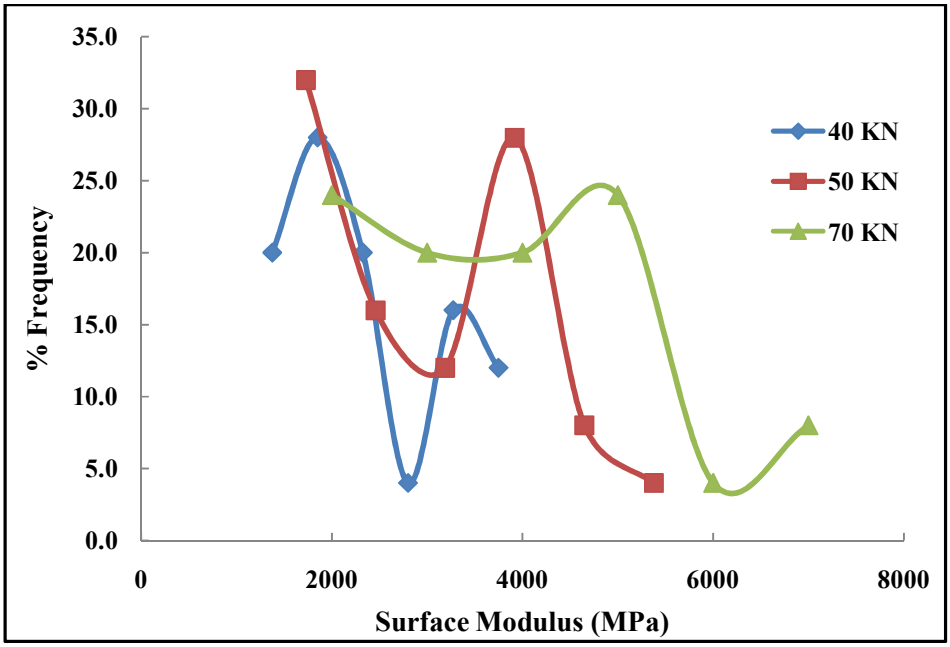


Figure 6.43 Frequency Distribution of Surface Modulus for EVERCALC

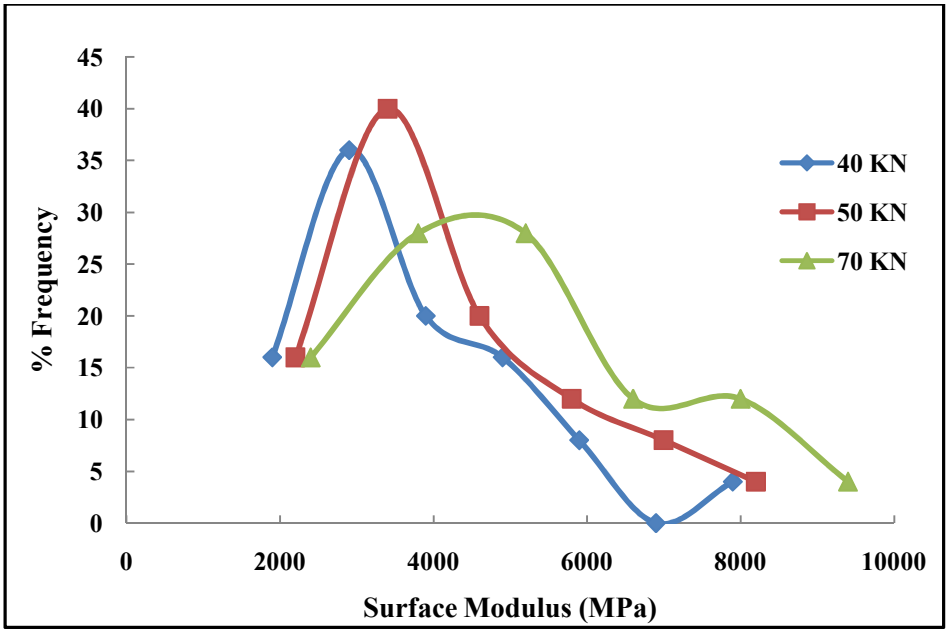


Figure 6.44 Frequency Distribution of Surface Modulus for Elmod (Radius of Curvature Method)

Granular Layer Moduli

The frequency distribution plots of different back-calculation methods for granular layer are shown in Figures 6.45, 6.46 and 6.47. From Figure 6.45 it was observed that at a base modulus value of 170 MPa, the frequencies 40 kN, 50 kN and 70 kN load levels are 12, 16 and 15 respectively. The frequency distribution of the granular modulus from Elmod (Deflection Basin Fit method) at 40 and 50 kN loads starts deviating from each other after 170 MPa. These lines do not overlap at any range of modulus variation except 290 MPa.

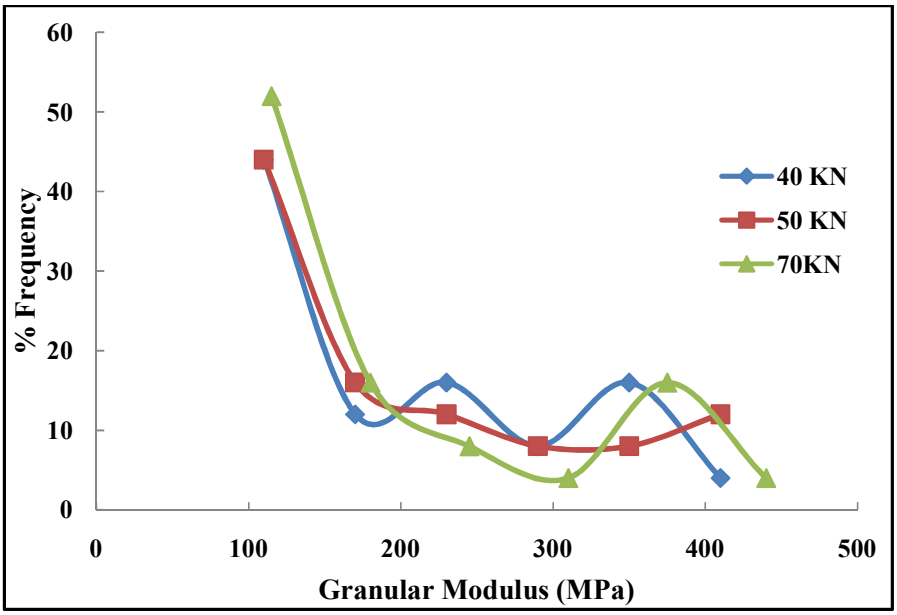


Figure 6.45 Frequency Distribution of Granular Modulus for Elmod (Deflection Basin Method)

From the Figure 6.46 it can be visible that the frequency distribution plots for EVERCALC overlap at 50 and 70 kN loads for almost all modulus variations except at modulus value of 160 MPa. The frequency distribution plot of 40 kN was showing higher deviation from those of 50 and 70 kN at modulus value of 150 MPa.

From Figure 6.47 it was clearly visible that variations in frequency distributions of granular modulus from Elmod (Radius of curvature method) were significant. The frequency distributions were not overlap on each other.

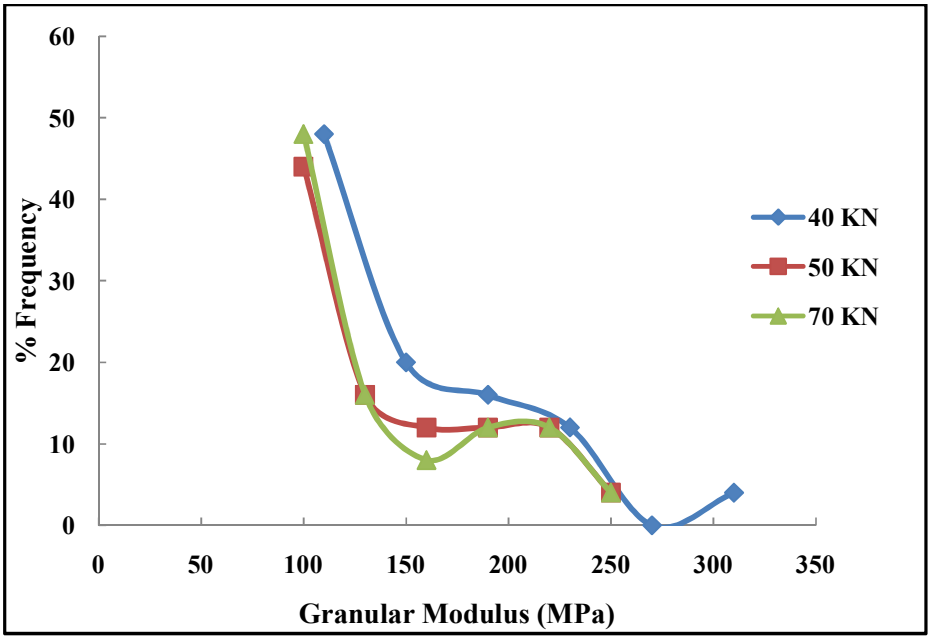


Figure 6.46 Frequency Distribution of Granular Modulus for EVERCALC

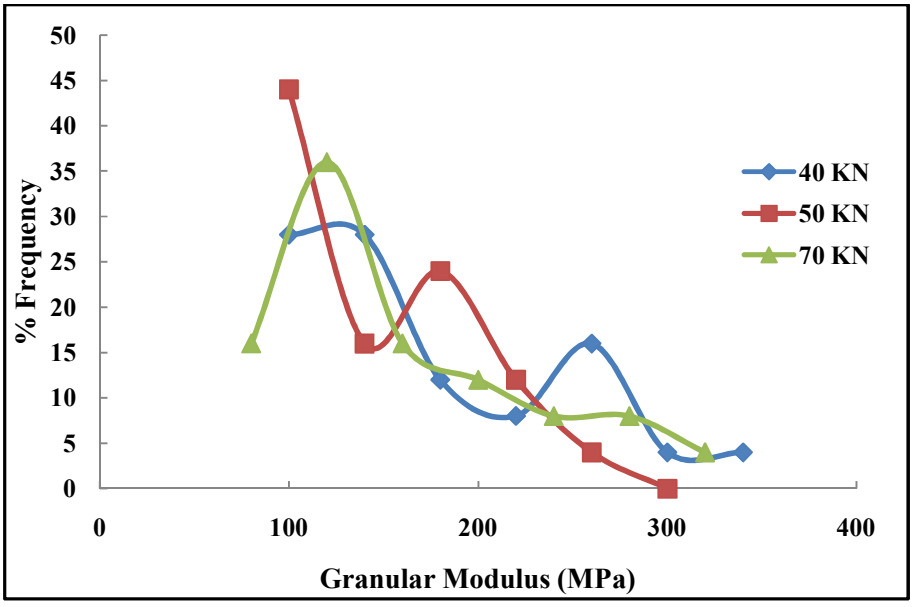


Figure 6.47 Frequency Distribution of Granular Modulus Elmod (Radius of Curvature Method)

Therefore, EVERCALC was found most consistent among three programs, for the determination of granular modulus.

Subgrade Layer Moduli

The frequency distribution plots of different back-calculation methods for subgrade modulus are shown in Figure 6.48, 6.49 and 6.50. From Figure 6.48 it was clearly visible that there are large deviations in the frequency distribution of subgrade modulus values for Elmod (Deflection Basin Fit method.) Load levels 40 kN and 50 kN were only overlaps at 49 MPa and 97 Mpa.

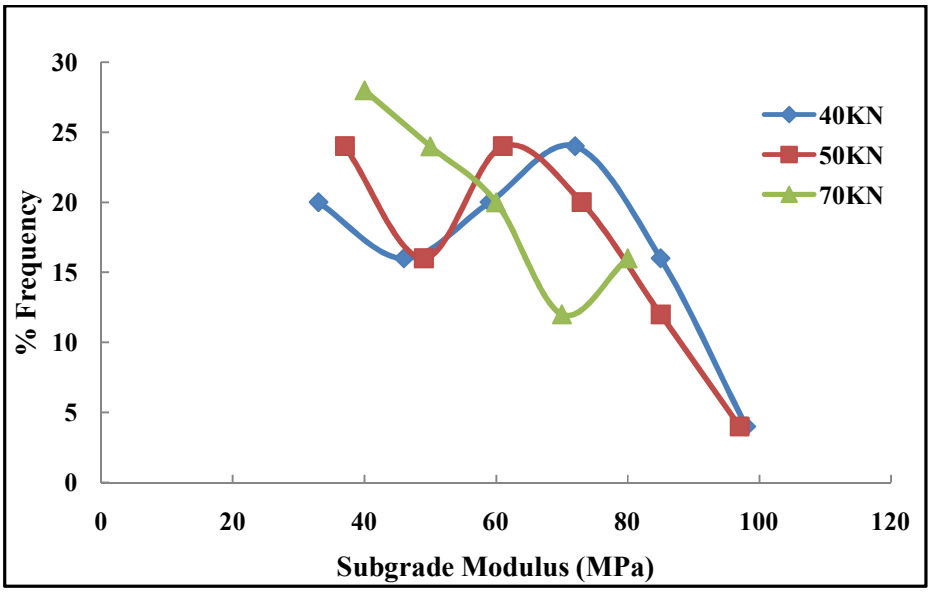


Figure 6.48 Frequency Distribution of Subgrade Modulus for Elmod (Deflection Basin Fit Method)

The frequency distributions for EVERCALC are shown in Figure 6.49 mostly overlap on each other. At a subgrade modulus value of 80 MPa, the frequencies of 40, 50 and 70 kN load levels were 28, 32 and 28 respectively. For 130 MPa, the frequencies were 20, 20 and 16 and for 155 MPa, frequencies were 0, 4 and 4 respectively.

From Figure 6.50 it was observed that frequency distributions of subgrade modulus from Elmod (Radius of Curvature method) at specified loads overlap on each other over the range 55-105 MPa. After that lines deviate slightly at 130 MPa. At the subgrade modulus value of 180 MPa, the frequencies for three different load levels were 8, 4 and 4 respectively.

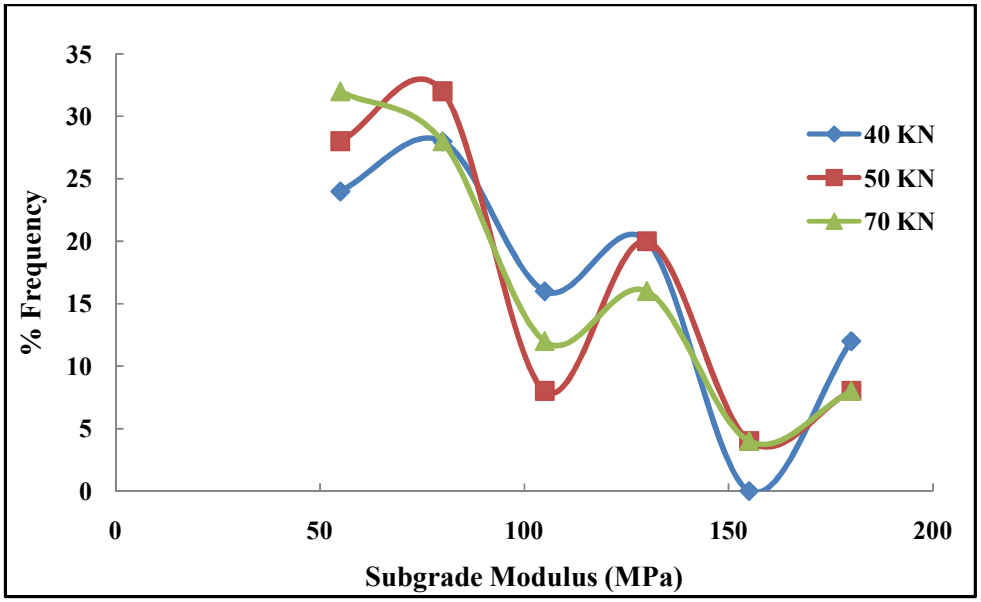


Figure 6.49 Frequency Distribution of Subgrade Modulus for EVERCALC

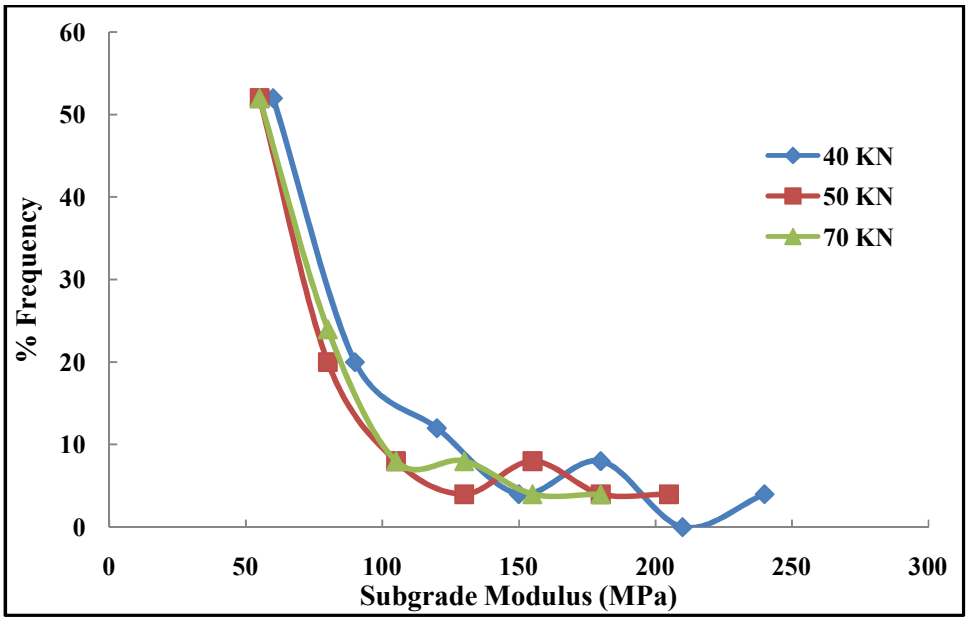


Figure 6.50 Frequency Distribution of Subgrade Modulus for Elmod (Radius of Curvature Method)

Therefore, Elmod (Radius of Curvature method) was found most consistent among the three of the methods for determination of subgrade modulus.

6.9 RELIABILTY ANALYSIS

Gadaipur Bandh Road

Figure 6.51 was plotted to determine the reliability of program based on surface modulus for Gadaipur Bandh road. In this figure Laboratory measured surface modulus was plotted on the horizontal axis and back-calculated modulus was plotted on the vertical axis. The line of equality was drawn through the points where laboratory and back-calculated modulus are the same. That program is considered to be reliable whose most of the output points are on or nearer the line of equality.

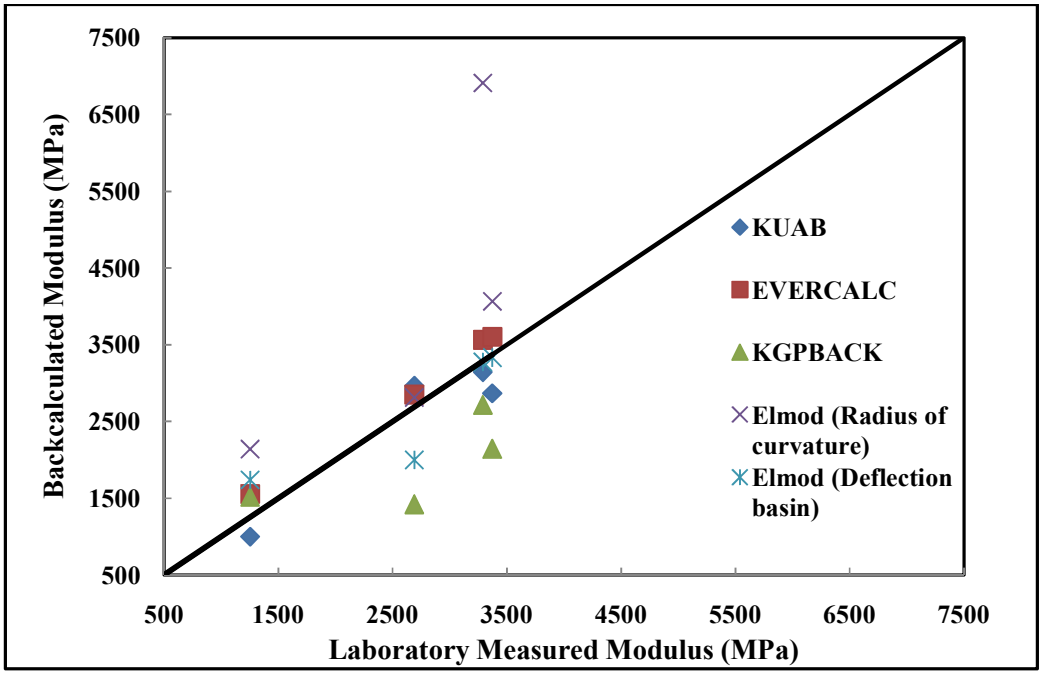


Figure 6.51 Laboratory Measured Surface Modulus versus Back-calculated Modulus

From Figure 6.51 it was found that data from KUAB and EVERCALC was near to line of equality. But data from KUAB was on or more close to line of equality. Therefore, KUAB was found more reliable than other programs.

Dera Bhatti Road

Figure 6.52 was plotted to determine reliability of programs based on surface modulus for Dera Bhatti road. Similarly, the line of equality was drawn through the points where laboratory and back-calculated modulus are the same. The program is considered to be

reliable when its output points are on or nearer to the line of equality. For Dera Bhatti road again the moduli calculated from KUAB were close to line of equality. Therefore, KUAB was found reliable for Dera Bhatti road also.

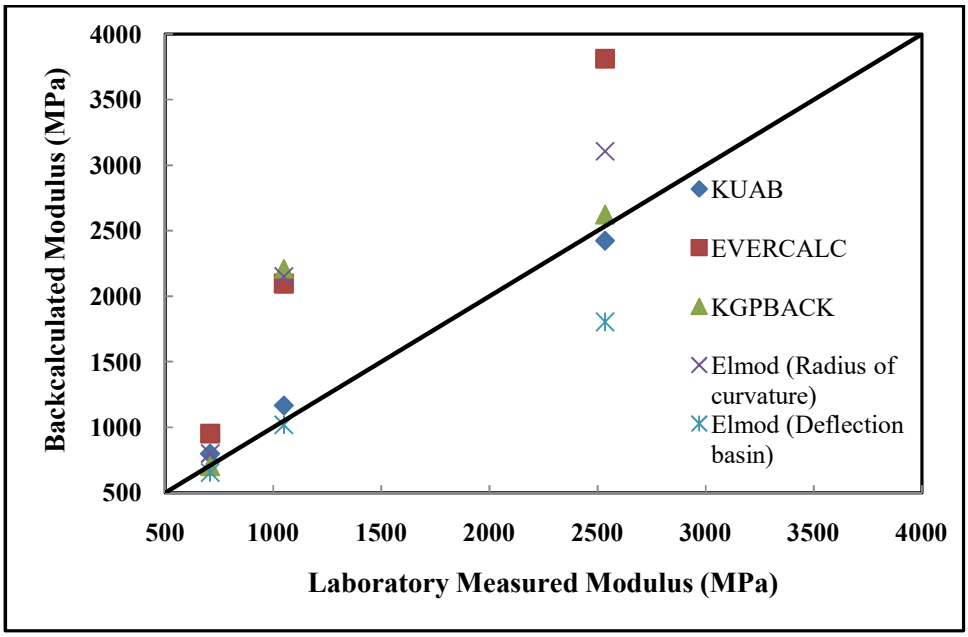


Figure 6.52 Laboratory Measured Surface Modulus versus Back-calculated Modulus

CHAPTER 7
CONCLUSIONS AND SCOPE OF FURTHER RESEARCH

7.1 CONCLUSIONS

The major conclusions that can be drawn from this study are as follows:

- Correlation analysis between deflection values obtained from BBD and FWD survey depict good correlation. For Gadaipur Bandh road and Dera Bhatti road coefficient of determination (R^2 value) was found to be 0.857 and 0.938 respectively.
- For Gadaipur Bandh Road average subgrade modulus values computed using KUAB (77.40 MPa) and Elmod's Radius of curvature method (77.05 MPa) programs were found to be closest. Average subgrade modulus determined using Roque (1998) approach was found maximum and it was found minimum, when Elmod's Deflection basin fit method was used.
- In case of Dera Bhatti Road average subgrade modulus values determined using KUAB (111.86 MPa), Garg and Thompson (1999) method (112.15 MPa), EVERCALC (117.32 MPa) and KGPBACK (120.19 MPa) were found close to each other respectively. A very high value of average subgrade modulus was observed by using Roque (1998) approach (214.46 MPa) and modulus computed as per IRC: 37-2018 guidelines was the lowest (52.40 MPa).
- For Gadaipur Bandh road, average granular layer modulus values computed from KUAB (176.7 MPa) and Elmod's Deflection Basin Method (169.02 MPa) were nearly similar. The average granular layer modulus calculated as per IRC: 37-2018 guidelines was the highest and computed by using EVERCALC program the lowest.
- In case of Dera Bhatti road two methods used by Elmod program have determined a very high value of average granular layer modulus (above 400 MPa). The average modulus values computed using IRC: 37-2018 guidelines (162.98 MPa) and KGPBACK program (163.17 MPa) were nearly similar.

- For Gadaipur Bandh road, Elmod's Radius of curvature program gave high value of average surface layer modulus and KGPBACK program calculated low value. The average modulus values computed using KUAB (2494 MPa) and Elmod's Deflection Basin Method (2588 MPa) were found close to Laboratory calculated modulus (2651.25 MPa).
- In case of Dera Bhatti road, EVERCALC program computed the highest value of average surface layer modulus and Elmod (Deflection basin fit method) calculated lowest value. The average modulus computed using KUAB program (1460.25 MPa) was found close to Laboratory calculated modulus (1430 MPa).
- For Gadaipur Bandh road, Pearson correlation between different programs for modulus values was computed. Surface modulus calculated from KUAB and EVERCALC programs indicated strong correlation (R=0.901) between them. Granular modulus computed from EVERCALC and KUAB, EVERCALC and RADIUS OF CURVATURE methods indicated strong correlations (R=0.913 and 0.909 respectively). Subgrade modulus obtained from KUAB and EVERCALC programs also indicated strong correlation (R= 0.94).
- For Dera Bhatti road, KUAB and EVERCALC programs indicated strong correlation (R= 0.88) for surface modulus values. Granular layer moduli computed from KUAB and KGPBACK, KUAB and DEFLECTION BASIN FIT methods indicated strong correlations (R=0.95 and 0.94 respectively). Subgrade modulus obtained from KUAB and EVERCALC, RADIUS OF CURVATURE and DEFLECTION BASIN FIT methods indicated strong correlation (R=0.96 and 0.93 respectively).
- Statistical analysis was performed by using Kruskal-Wallis H test on layer modulus values computed from different methods. To compare the mean of modulus values of two program groups Mann-Whitney test was used. For Gadaipur Bandh road, there was no statistically significant difference between KUAB and EVERCALC, KUAB and KGPBACK, EVERCALC and KGPBACK, EVERCALC and DEFLECTION BASIN FIT, KGPBACK and DEFLECTION BASIN FIT program groups with respect to surface moduli. For granular layer moduli there was no statistically significant difference between the different

program groups. Subgrade moduli obtained from the KUAB and EVERCALC, KUAB and RADIUS OF CURVATURE, KUAB and AASHTO, KUAB and Garg and Thompson (1999), EVERCALC and RADIUS OF CURVATURE, EVERCALC and AASHTO, EVERCALC and Garg and Thompson (1999), RADIUS OF CURVATURE and DEFLECTION BASIN, RADIUS OF CURVATURE and AASHTO, RADIUS OF CURVATURE and Garg and Thompson (1999), AASHTO and Garg and Thompson (1999) program groups did not show statistically significant difference.

- For Dera Bhatti road, the surface moduli determined from KUAB and EVERCALC, EVERCALC and DEFLECTION BASIN FIT, KGPBACK and DEFLECTION BASIN FIT program groups were showing statistically significant difference. Except these groups of programs there was no statistically significant difference between all other groups with respect to surface moduli value. For granular moduli there was no statistically significant difference between KUAB and EVERCALC, EVERCALC and KGPBACK, RADIUS OF CURVATURE and DEFLECTION BASIN FIT program groups respectively. With respect to subgrade moduli, there was no statistically significant difference between KUAB and EVERCALC, KUAB and KGPBACK, KUAB and DEFLECTION BASIN, KUAB and AASHTO, KUAB and Garg and Thompson (1999), EVERCALC and KGPBACK, EVERCALC and DEFLECTION BASIN, EVERCALC and AASHTO, EVERCALC and Garg and Thompson (1999), KGPBACK and AASHTO, KGPBACK and Garg and Thompson (1999), RADIUS OF CURVATURE and DEFLECTION BASIN, DEFLECTION BASIN and AASHTO, AASHTO and Garg and Thompson (1999) program groups respectively.
- The consistency of FWD back-calculation programs was evaluated using frequency distributions of back-calculated moduli at three levels of FWD loads. For surface modulus, Elmod (Radius of Curvature method) was found more consistent than EVERCALC and Elmod (Deflection Basin Fit method). The granular modulus variation was least in EVERCALC; therefore it was more consistent as compared to other programs. For subgrade modulus, Elmod (Radius

of Curvature method) was more consistent than EVERCALC and Elmod (Deflection Basin Fit method). Overall, the large variation was found in Elmod (Deflection Basin Fit method) and EVERCALC ranked second.

- The reliability of back-calculated surface modulus for two roads was examined by comparing back-calculated modulus to the laboratory resilient modulus. It was found that KUAB produces modulus values close to laboratory resilient modulus compared to the EVERCALC, KGPBACK, Elmod (Radius of Curvature method) and Elmod (Deflection Basin Fit method) programs respectively.

7.2 SCOPE OF FURTHER RESEARCH

- The programs used in this study are based on layered elastic theory and they consider a static loading which do not simulate the dynamic loads applied by FWD. A new back-calculation program which use dynamic analysis can be used for modulus determination and should be developed for our Indian conditions.

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APPENDIX - A

Table 1 Measured Deflections at Gadaipur Bandh Road (0-1134 m)

Chainage (m)	Load (kN)	Temperature (°C)		Surface Deflections (micron) at radial distance 0, 200, 300, 600, 900, 1200 and 1500 mm from the centre of the loading plate						
		Air	Pavement	D(0)	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)
0	36.6	27.2	30.7	978	732	612	269	119	64	44
0	46.9	27.2	30.7	1219	922	781	352	157	82	56
0	63.5	27.2	30.7	1563	1184	1015	477	218	113	75
72	38.6	28.3	30.1	457	308	252	128	83	60	46
72	48.5	28.3	30.1	567	388	320	166	105	73	56
72	67.7	28.3	30.1	784	544	456	241	155	106	82
153	38.1	28.0	30.5	654	486	398	184	96	61	45
153	47.5	28.0	30.5	804	606	504	235	123	75	55
153	65.9	28.0	30.5	886	818	690	332	176	107	77
245	35.3	27.9	32.0	947	660	506	211	108	67	50
245	44.1	27.9	32.0	1136	808	632	271	140	88	60
245	61.7	27.9	32.0	1551	1098	870	391	208	128	89
357	36.6	28.2	32.4	492	364	314	169	97	63	45
357	47.2	28.2	32.4	674	485	422	230	132	84	60
357	66.2	28.2	32.4	1012	683	599	333	191	120	84
477	37.8	28.1	32.3	491	327	269	146	89	60	43
477	48.1	28.1	32.3	620	422	350	194	119	80	59
477	67.7	28.1	32.3	868	604	519	289	177	119	86
613	38.1	27.6	30.0	338	247	203	97	55	38	28
613	49.7	27.6	30.0	503	322	270	130	74	50	38
613	69.1	27.6	30.0	568	446	375	186	106	69	52
737	37.8	27.2	31.2	384	322	286	175	110	76	55
737	47.6	27.2	31.2	479	398	359	221	140	96	69
737	67.6	27.2	31.2	661	558	503	318	204	140	100
905	35.5	28.1	32.6	787	563	450	200	105	65	49
905	45.3	28.1	32.6	988	713	574	260	136	84	63
905	62.8	28.1	32.6	1300	958	784	365	194	119	88
984	37.0	28.5	33.1	833	657	519	207	113	74	55
984	46.7	28.5	33.1	1057	843	670	277	150	99	73
984	63.3	28.5	33.1	1393	1148	931	394	211	135	97
1061	38.1	29.2	33.0	453	353	313	184	113	73	53
1061	48.3	29.2	33.0	560	442	398	240	150	95	68
1061	67.0	29.2	33.0	678	602	541	340	216	137	99
1134	37.4	28.9	31.6	626	481	412	219	127	86	64
1134	47.6	28.9	31.6	793	620	530	289	167	111	82
1134	66.1	28.9	31.6	964	865	752	412	239	154	112

Table 2 Measured Deflections at Gadaipur Bandh Road (1277-2655 m)

Chainage (m)	Load (kN)	Temperature (°C)		Surface Deflections (micron) at radial distance 0, 200, 300, 600, 900, 1200 and 1500 mm from the centre of the loading plate						
		Air	Pavement	D(0)	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)
1277	38.6	28.5	31.7	522	341	272	112	65	47	38
1277	49.0	28.5	31.7	620	438	352	148	86	61	48
1277	65.7	28.5	31.7	825	595	484	206	118	82	64
1346	37.2	29.0	31.2	373	265	223	121	73	51	39
1346	47.4	29.0	31.2	471	334	285	155	91	63	48
1346	67.3	29.0	31.2	845	478	416	227	134	92	69
1414	36.7	28.9	32.5	796	602	487	215	120	80	60
1414	46.4	28.9	32.5	969	748	615	284	159	106	79
1414	63.6	28.9	32.5	1238	969	810	392	221	144	105
1484	37.5	29.3	33.0	496	349	286	142	89	63	48
1484	47.8	29.3	33.0	622	447	370	189	118	84	62
1484	66.5	29.3	33.0	766	613	517	267	167	115	84
1641	36.7	28.4	32.8	613	454	372	183	108	75	57
1641	46.7	28.4	32.8	770	579	484	244	145	100	75
1641	64.9	28.4	32.8	1086	789	663	346	205	141	103
1716	38.8	28.3	31.8	332	220	179	91	56	43	34
1716	49.1	28.3	31.8	424	286	237	120	73	53	42
1716	69.4	28.3	31.8	519	414	350	177	107	76	60
1803	35.9	28.7	30.4	788	560	451	193	109	75	56
1803	45.3	28.7	30.4	981	701	571	250	143	97	74
1803	62.5	28.7	30.4	1240	927	764	347	201	136	102
1971	35.1	27.3	32.5	729	525	441	223	127	82	61
1971	45.3	27.3	32.5	938	673	575	295	167	108	79
1971	63.8	27.3	32.5	1251	939	810	429	246	157	114
2063	37.1	27.6	32.3	372	255	207	99	60	45	35
2063	48.7	27.6	32.3	445	334	277	136	82	60	47
2063	68.5	27.6	32.3	582	470	399	198	121	87	68
2283	36.0	28.6	32.0	892	667	555	270	144	87	62
2283	45.3	28.6	32.0	1098	826	696	351	191	114	79
2283	62.8	28.6	32.0	1375	1102	946	488	269	159	107
2426	38.0	28.8	33.5	790	613	548	301	169	99	67
2426	47.7	28.8	33.5	969	756	680	381	216	126	84
2426	65.5	28.8	33.5	1266	992	901	515	298	173	119
2529	36.6	29.4	33.6	723	566	501	285	158	91	59
2529	46.5	29.4	33.6	875	691	621	360	204	120	79
2529	65.7	29.4	33.6	1143	904	818	485	280	165	106
2655	36.5	29.0	32.6	800	625	548	308	169	104	74
2655	45.9	29.0	32.6	949	760	673	388	219	138	99
2655	64.6	29.0	32.6	1184	971	871	513	296	187	134

Table 3 Measured Deflections at Dera Bhatti Road (0-2558m)

Chainage (m)	Load (kN)	Temperature (°C)		Surface Deflections (micron) at radial distance 0, 200, 300, 600, 900, 1200 and 1500 mm from the centre of the loading plate						
		Air	Pavement	D(0)	D(1)	D(2)	D(3)	D(4)	D(5)	D(6)
0	37.0	29.3	32.7	787	541	408	183	102	74	57
0	47.0	29.3	32.7	977	666	509	235	135	96	73
0	65.0	29.3	32.7	1447	872	686	328	191	133	101
141	35.8	28.7	32.8	728	492	372	171	92	65	50
141	45.6	28.7	32.8	937	638	491	223	117	80	62
141	63.5	28.7	32.8	1283	899	708	318	164	112	88
254	36.9	29.4	32.6	719	524	399	178	82	49	34
254	47.3	29.4	32.6	890	653	510	236	110	65	45
254	65.1	29.4	32.6	1201	866	691	333	159	91	62
365	36.9	28.8	31.8	489	329	271	128	75	50	37
365	47.2	28.8	31.8	621	427	353	175	103	69	51
365	65.9	28.8	31.8	853	597	505	258	152	99	72
444	36.3	28.8	31.4	465	347	297	169	105	73	55
444	47.7	28.8	31.4	621	468	407	234	144	99	72
444	66.7	28.8	31.4	820	657	572	335	206	138	99
545	38.1	28.7	31.6	490	307	245	114	66	44	32
545	48.6	28.7	31.6	600	392	321	155	89	58	42
545	68.3	28.7	31.6	798	535	454	228	133	84	60
661	40.0	28.7	32.4	283	177	139	69	46	35	29
661	50.9	28.7	32.4	322	220	177	92	60	45	35
661	71.8	28.7	32.4	325	299	242	133	88	64	51
1921	34.7	28.3	32.3	579	382	281	106	55	34	25
1921	47.0	28.3	32.3	795	529	404	156	80	48	34
1921	65.7	28.3	32.3	1128	759	600	244	124	72	50
2020	37.0	28.7	31.4	330	238	193	96	55	39	30
2020	48.6	28.7	31.4	429	317	262	136	78	55	40
2020	67.1	28.7	31.4	763	440	371	197	116	76	56
2187	36.9	28.9	32.9	471	346	286	114	50	28	21
2187	47.0	28.9	32.9	595	445	369	154	69	39	29
2187	66.2	28.9	32.9	1195	619	523	229	103	56	40
2271	37.7	28.9	33.2	513	314	225	61	27	18	13
2271	47.8	28.9	33.2	578	392	287	83	37	25	18
2271	67.4	28.9	33.2	577	541	406	123	53	33	24
2377	37.0	29.2	33.7	616	476	422	214	113	70	46
2377	46.3	29.2	33.7	731	610	543	282	148	89	60
2377	64.9	29.2	33.7	981	856	775	416	222	129	87
2474	36.6	29.8	33.4	564	373	278	106	56	35	25
2474	46.3	29.8	33.4	645	475	364	147	79	48	34
2474	65.9	29.8	33.4	916	668	529	224	118	71	49
2558	35.4	29.3	33.3	656	469	380	165	76	43	29
2558	45.9	29.3	33.3	828	600	498	223	101	56	38
2558	64.7	29.3	33.3	1543	818	684	316	144	79	54

APPENDIX - B

Table 4 Back-calculated Layer Moduli for Gadaipur Bandh Road

Different Software	KUAB			EVERCALC			KGPBACK			ELMOD					
										Radius of Curvature Method			Deflection Basin Method		
Chainage (m)	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$
0	767.00	102.00	50.00	1089.60	78.20	33.60	696.03	127.51	99.07	2244.80	69.83	29.09	2072.32	56.49	30.89
72	1235.00	272.00	95.00	2027.20	194.70	126.40	2344.99	157.93	125.92	2037.24	250.73	111.91	1409.23	306.00	74.93
153	2679.00	102.00	80.00	1954.30	110.90	67.80	715.62	127.51	113.48	2931.21	115.45	62.57	2737.47	103.63	64.57
245	771.00	103.00	54.00	922.10	79.40	50.40	712.78	130.89	71.51	945.97	91.27	48.66	1114.44	75.55	37.68
357	1242.00	229.00	75.00	1475.80	119.70	88.20	2581.68	127.41	108.44	4311.78	172.55	59.84	1764.30	183.53	57.08
477	1475.00	221.00	93.00	1837.20	155.90	113.20	2560.91	136.98	123.71	1544.53	276.86	71.56	1413.89	250.36	70.49
613	2942.00	242.00	163.00	3218.70	181.40	170.30	2416.95	203.30	167.45	4972.18	246.55	130.54	3273.96	321.65	120.10
737	2793.00	336.00	67.00	3537.10	173.00	92.50	2515.33	203.81	97.69	5573.08	166.34	67.06	2891.14	162.32	81.81
905	1432.00	100.00	61.00	1543.40	91.60	56.40	717.36	127.41	93.87	1540.55	103.23	53.18	1727.11	86.33	50.31
984	1328.00	100.00	59.00	1588.50	83.50	55.60	737.60	96.41	90.72	2977.17	67.67	55.30	2583.45	63.11	29.54
1061	3142.00	243.00	65.00	3563.70	140.80	80.30	2715.40	154.29	99.41	6910.38	188.66	58.06	3276.55	206.97	65.66
1134	1380.00	160.00	65.00	1692.20	106.30	65.90	1714.95	126.71	80.20	4440.42	112.54	56.74	1948.60	126.66	48.03
1277	1040.00	206.00	103.00	1519.80	169.70	116.20	2203.48	142.99	128.84	2015.38	151.21	173.46	1612.49	186.22	64.46
1346	2421.00	210.00	129.00	2475.90	206.00	125.20	2457.42	190.78	138.38	2645.13	252.35	113.30	2402.72	308.65	77.65
1414	1620.00	102.00	59.00	1851.00	84.40	60.40	724.17	128.40	83.62	2517.30	84.25	56.05	2303.07	77.48	51.78
1484	1144.00	240.00	85.00	1152.50	147.00	114.70	2683.13	128.40	115.81	2428.29	198.61	94.59	1605.37	257.66	59.79
1641	2964.00	108.00	86.00	2851.20	111.30	80.30	1421.06	127.51	89.57	2813.29	128.25	72.30	2001.52	170.29	43.31
1716	1760.00	384.00	134.00	2948.10	280.70	178.20	2583.71	233.69	170.93	2901.08	303.29	212.57	2041.44	397.10	97.37
1803	1189.00	102.00	68.00	1253.40	86.00	69.20	706.07	85.39	88.69	1649.80	98.30	62.96	1646.91	91.13	48.02
1971	926.00	130.00	59.00	1382.90	91.30	59.00	698.51	127.41	77.48	2051.06	116.00	47.51	1611.66	115.79	41.89
2063	1605.00	315.00	111.00	2230.50	208.80	157.20	2467.07	185.63	157.07	3025.80	234.27	170.94	1986.15	342.95	76.78
2283	830.00	102.00	47.00	1004.60	70.20	46.80	1424.85	73.98	70.58	2083.95	89.70	33.40	2149.90	69.93	44.26
2426	2406.00	103.00	43.00	2904.60	71.60	44.90	875.47	126.71	73.36	4113.20	103.65	27.49	3056.54	89.97	28.01
2529	2869.00	103.00	43.00	3602.80	70.00	48.60	2143.89	79.73	73.08	4065.20	121.58	25.56	3333.17	94.70	25.27
2655	2156.00	103.00	41.00	2141.10	70.00	45.80	1919.53	73.98	64.29	3831.75	91.87	31.62	2198.12	80.97	23.88

Notes: $E_{Surface}$ = Back-calculated Surface Layer Modulus (MPa), $E_{Granular}$ = Back-calculated Granular Layer Modulus (MPa), $E_{Subgrade}$ = Back-calculated Subgrade Layer Modulus (MPa)

Table 5 Back-calculated Layer Moduli for Dera Bhatti Road

Different Software	KUAB			EVERCALC			KGPBACK			ELMOD					
										Radius of Curvature Method			Deflection Basin Method		
Chainage (m)	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$	$E_{Surface}$	$E_{Granular}$	$E_{Subgrade}$
0	770	189	70	1070.50	133.00	75.10	715.82	128.40	89.84	835.01	241.23	62.34	663.62	218.41	69.88
141	821	181	75	832.90	218.60	66.20	686.18	126.71	99.16	763.27	305.83	57.29	644.51	235.95	75.04
254	833	162	81	1162.80	193.70	61.30	685.01	129.99	128.51	998.35	467.16	34.41	1146.96	199.22	61.26
365	1385	299	105	2194.00	188.20	120.90	2292.60	135.71	128.59	1661.35	474.20	78.41	834.31	481.58	105.82
444	1963	466	83	2455.10	332.90	93.30	2532.85	205.41	97.34	3851.59	483.42	68.22	1635.98	533.72	88.93
545	1265	284	122	1283.30	234.70	137.50	2400.55	206.85	103.95	1047.41	557.07	87.29	788.92	407.93	135.52
661	769	862	256	1611.70	600.40	249.50	1937.24	403.29	215.04	2150.58	664.75	269.93	1111.70	911.71	248.12
1921	870	172	102	982.80	167.40	99.00	1688.39	129.20	128.84	711.77	422.03	59.12	750.79	278.18	69.88
2020	2406	481	143	3359.40	309.70	160.60	2525.32	257.27	170.63	3451.45	587.64	120.68	2003.65	753.99	113.19
2187	2438	221	85	4263.60	85.00	117.90	2717.82	115.44	103.87	2758.83	518.78	46.26	1603.51	375.72	66.77
2271	1425	120	184	3103.50	53.10	217.60	2269.14	127.70	120.00	800.99	318.50	96.57	866.27	266.20	54.45
2377	1451	276	66	3110.10	219.60	59.80	1760.50	127.51	97.86	4184.19	402.00	32.76	1197.65	471.59	43.66
2474	941	190	112	1714.90	127.50	120.70	2401.63	113.48	112.39	833.68	435.87	65.74	940.78	278.18	76.87
2558	1100	151	82	1464.00	197.70	63.10	2466.86	77.44	86.65	1432.54	403.16	35.67	915.08	276.02	58.19

Notes: $E_{Surface}$ = Back-calculated Surface Layer Modulus (MPa), $E_{Granular}$ = Back-calculated Granular Layer Modulus (MPa), $E_{Subgrade}$ = Back-calculated Subgrade Layer Modulus (MPa)

APPENDIX – C

Table 6 Subgrade Modulus for Gadaipur Bandh Road

SUBGRADE MODULUS (MPa)								
Chainage (m)	KUAB	EVERCALC	KGPBACK	ELMOD		AASHTO (1993)	Garg and Thompson (1998)	Roque (1998)
				Radius of curvature	Deflection basin			
0	50	33.60	99.07	29.09	30.89	47.88	85.39	143.54
72	95	126.40	125.92	111.91	74.93	122.63	93.42	137.21
153	80	67.80	113.48	62.57	64.57	76.64	91.45	140.30
245	54	50.40	71.51	48.66	37.68	55.85	83.21	126.07
357	75	88.20	108.44	59.84	57.08	93.32	87.47	140.30
477	93	113.20	123.71	71.56	70.49	112.50	91.74	146.93
613	163	170.30	167.45	130.54	120.10	150.26	125.38	227.09
737	67	92.50	97.69	67.06	81.81	105.81	72.39	114.45
905	61	56.40	93.87	53.18	50.31	63.16	84.98	128.68
984	59	55.60	90.72	55.30	29.54	57.08	75.47	114.45
1061	65	80.30	99.41	58.06	65.66	97.45	73.35	118.83
1134	65	65.90	80.20	56.74	48.03	72.68	62.68	98.13
1277	103	116.20	128.84	173.46	64.46	113.61	113.42	166.57
1346	129	125.20	138.38	113.30	77.65	133.55	105.85	162.23
1414	59	60.40	83.62	56.05	51.78	60.33	69.05	104.77
1484	85	114.70	115.81	94.59	59.79	104.97	89.24	131.40
1641	86	80.30	89.57	72.30	43.31	78.98	75.05	110.37
1716	134	178.20	170.93	212.57	97.37	173.54	120.05	186.47
1803	68	69.20	88.69	62.96	48.02	63.73	75.63	112.37
1971	59	59.00	77.48	47.51	41.89	63.72	65.08	103.03
2063	111	157.20	157.07	170.94	76.78	143.49	116.74	181.07
2283	47	46.80	70.58	33.40	44.26	51.93	58.77	101.34
2426	43	44.90	73.36	27.49	28.01	55.52	45.60	93.67
2529	43	48.60	73.08	25.56	25.27	58.49	51.95	106.57
2655	41	45.80	64.29	31.62	23.88	53.32	44.30	84.68

Table 7 Subgrade Modulus for Dera Bhatti Road

SUBGRADE MODULUS (MPa)								
Chainage (m)	KUAB	EVERCALC	KGPBACK	ELMOD		AASHTO (1993)	Garg and Thompson (1998)	Roque (1998)
				Radius of curvature	Deflection basin			
0	70.00	75.10	89.84	62.34	69.88	72.60	79.27	110.37
141	75.00	66.20	99.16	57.29	75.04	77.05	89.81	126.07
254	81.00	61.30	128.51	34.41	61.26	74.04	109.00	186.47
365	105.00	120.90	128.59	78.41	105.82	109.01	106.11	171.14
444	83.00	93.30	97.34	68.22	88.93	97.85	76.33	114.45
545	122.00	137.50	103.95	87.29	135.52	124.50	115.15	198.31
661	256.00	249.50	215.04	269.93	248.12	230.39	130.12	219.15
1921	102.00	99.00	128.84	59.12	69.88	98.86	129.59	254.78
2020	143.00	160.60	170.63	120.68	113.19	153.48	124.50	211.73
2187	85.00	117.90	103.87	46.26	66.77	103.29	138.35	304.10
2271	184.00	217.60	120.00	96.57	54.45	134.14	149.12	494.79
2377	66.00	59.80	97.86	32.76	43.66	70.19	78.63	137.21
2474	112.00	120.70	112.39	65.74	76.87	105.40	128.13	254.78
2558	82.00	63.10	86.65	35.67	58.19	74.58	115.97	219.15

APPENDIX - D

Table 8 Traffic Volume Count Survey for Gadaipur Bandh Road

TRAFFIC VOLUME COUNT SURVEY							
Direction of the traffic :Band Road to Gadaipur				**Name of the Road : Gadaipur Bandh Road**			
Time	**Heavy commercial Vehicles**						
	LCVs	**2 Axle**	**Multi Axle**	**Bus**	**LPVs**	**Other**	**Total Motorized Vehicles**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
9 PM TO 10 PM	8	17	6	0	0	0	**31**
10 PM TO 11 PM	12	11	0	0	0	0	**23**
11PM TO 12 AM	6	8	0	0	0	0	**14**
12 AM TO 1AM	11	7	2	0	0	0	**20**
1 AM TO 2 AM	8	3	0	0	0	0	**11**
2 AM TO 3 AM	6	4	2	0	0	0	**12**
3 AM TO 4 AM	3	6	0	0	0	0	**9**
4 AM TO5 AM	7	5	3	0	0	0	**15**
5 AM TO 6 AM	9	2	2	1	0	0	**14**
6 AM TO 7 AM	16	1	0	3	0	0	**20**
7 AM TO 8 AM	11	0	1	4	0	0	**16**
8 AM TO 9 AM	12	1	0	1	0	0	**14**
9 AM TO 10 AM	4	11	0	1	1	0	**17**
10AM TO 11 AM	7	13	0	0	0	0	**20**
11AM TO 12 PM	7	21	1	2	0	0	**31**
12 PM TO 1 PM	9	19	0	0	0	0	**28**
1 PM TO 2 PM	3	20	1	1	1	0	**26**
2 PM TO 3 PM	10	23	2	0	2	0	**37**
3 PM TO 4 PM	13	17	3	3	1	0	**37**
4 PM TO 5 PM	7	14	5	1	0	0	**27**
5 PM TO 6 PM	9	20	0	4	3	0	**36**
6 PM TO 7 PM	5	13	0	4	0	0	**22**
7 PM TO 8 PM	4	11	0	3	0	0	**18**
8 PM TO 9 PM	3	7	0	3	0	0	**13**
Total	**190**	**254**	**28**	**31**	**8**	**0**	**511**

Table 9 Traffic Volume Count Survey for Gadaipur Bandh Road

TRAFFIC VOLUME COUNT SURVEY							
Direction of the traffic : Gadaipur to Band Road				**Name of the Road : Gadaipur Bandh Road**			
Time	**Heavy commericial Vehicles**						
	LCVs	**2 Axle**	**Multi Axle**	**Bus**	**LPVs**	**Other**	**Total Motorized Vehicles**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
9 PM TO 10 PM	12	3	0	0	0	0	**15**
10 PM TO 11 PM	5	5	0	0	0	0	**10**
11 PM TO 12 AM	0	5	2	0	0	0	**7**
12 AM TO 1AM	3	2	1	0	0	0	**6**
1 AM TO 2 AM	2	1	0	0	0	0	**3**
2 AM TO 3 AM	3	2	1	0	0	0	**6**
3 AM TO 4 AM	1	2	0	0	0	0	**3**
4 AM TO5 AM	2	3	1	0	0	0	**6**
5 AM TO 6 AM	3	5	1	0	0	0	**9**
6 AM TO 7 AM	5	8	0	4	0	0	**17**
7 AM TO 8 AM	3	1	1	5	0	0	**10**
8 AM TO 9 AM	9	13	1	3	0	0	**26**
9 AM TO 10 AM	12	21	0	3	0	0	**36**
10 AM TO 11 AM	11	18	2	0	0	0	**31**
11 AM TO 12 PM	7	24	1	0	0	0	**32**
12 PM TO 1 PM	8	25	0	1	3	0	**37**
1 PM TO 2 PM	12	26	1	2	0	0	**41**
2 PM TO 3 PM	9	18	2	2	0	0	**31**
3 PM TO 4 PM	11	16	0	1	0	0	**28**
4 PM TO 5 PM	11	21	5	1	1	0	**39**
5 PM TO 6 PM	6	11	0	1	0	0	**18**
6 PM TO 7PM	8	16	2	0	0	0	**26**
7 PM TO 8 PM	4	8	0	0	0	0	**12**
8 PM TO 9 PM	5	6	0	0	0	0	**11**
Total	**152**	**260**	**21**	**23**	**4**	**0**	**460**

Table 10 Traffic Volume Count Survey for Dera Bhatti Road

TRAFFIC VOLUME COUNT SURVEY							
Direction of the traffic : SSN Road to Gurugram road				**Name of the Road : Dera Bhatti Road**			
Time	**Heavy commericial Vehicles**						
	LCVs	**2 Axle**	**Multi Axle**	**Bus**	**LPVs**	**Other**	**Total Motorized Vehicles**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
9 PM TO 10 PM	1	0	2	1	0	0	**4**
10 PM TO 11 PM	5	1	0	1	0	0	**7**
11 PM TO 12AM	4	3	2	1	0	0	**10**
12 AM TO 1AM	4	5	2	0	0	0	**11**
1 AM TO 2 AM	3	5	4	0	0	0	**12**
2 AM TO 3 AM	5	10	7	0	0	0	**22**
3 AM TO 4 AM	1	3	4	0	0	0	**8**
4 AM TO5 AM	2	3	2	0	0	0	**7**
5 AM TO 6 AM	2	3	6	0	0	0	**11**
6 AM TO 7 AM	8	1	7	1	1	0	**18**
7 AM TO 8 AM	12	2	1	0	0	0	**15**
8 AM TO 9 AM	6	2	6	0	0	0	**14**
9 AM TO 10 AM	3	3	2	0	0	0	**8**
10 AM TO 11AM	3	2	5	0	0	0	**10**
11 AM TO 12PM	7	11	3	0	0	0	**21**
12 PM TO 1 PM	13	18	4	2	0	0	**37**
1 PM TO 2 PM	11	2	6	1	0	0	**20**
2 PM TO 3 PM	12	3	5	0	0	0	**20**
3 PM TO 4 PM	16	5	0	2	0	0	**23**
4 PM TO 5 PM	6	6	1	1	0	0	**14**
5 PM TO 6 PM	8	6	0	0	0	0	**14**
6 PM TO 7PM	3	5	2	1	0	0	**11**
7 PM TO 8 PM	4	6	4	0	0	0	**14**
8 PM TO 9 PM	4	3	2	0	0	0	**9**
Total	**143**	**108**	**77**	**11**	**1**	**0**	**340**

Table 11 Traffic Volume Count Survey for Dera Bhatti Road

TRAFFIC VOLUME COUNT SURVEY							
Direction of the traffic : Gurugram road to SSN Road				**Name of the Road : Dera Bhatti Road**			
Time	**Heavy commericial Vehicles**						
	LCVs	**2 Axle**	**Multi Axle**	**Bus**	**LPVs**	**Other**	**Total Motorized Vehicles**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
9 PM TO 10 PM	8	11	4	1	0	0	**24**
10 PM TO 11 PM	10	20	4	0	0	0	**34**
11 PM TO 12 AM	3	12	2	0	0	0	**17**
12 AM TO 1AM	12	18	12	0	0	0	**42**
1 AM TO 2 AM	8	27	17	0	0	0	**52**
2 AM TO 3 AM	11	27	28	0	0	0	**66**
3 AM TO 4 AM	18	12	3	0	0	0	**33**
4 AM TO5 AM	17	11	3	0	0	0	**31**
5 AM TO 6 AM	12	8	3	0	0	0	**23**
6 AM TO 7 AM	10	4	13	0	0	0	**27**
7 AM TO 8 AM	5	8	8	1	0	0	**22**
8 AM TO 9 AM	14	6	5	1	0	0	**26**
9 AM TO 10 AM	27	7	7	2	2	0	**45**
10 AM TO 11 AM	11	6	4	2	1	0	**24**
11 AM TO 12 PM	8	22	6	3	0	0	**39**
12 PM TO 1 PM	28	11	5	2	2	0	**48**
1 PM TO 2 PM	32	12	11	2	0	0	**57**
2 PM TO 3 PM	17	3	7	0	0	0	**27**
3 PM TO 4 PM	11	6	2	2	1	0	**22**
4 PM TO 5 PM	12	3	8	0	0	0	**23**
5 PM TO 6 PM	7	2	3	0	0	0	**12**
6 PM TO 7PM	2	3	1	0	0	0	**6**
7 PM TO 8 PM	3	2	2	0	0	0	**7**
8 PM TO 9 PM	3	2	4	0	0	0	**9**
Total	**289**	**243**	**162**	**16**	**6**	**0**	**716**

APPENDIX - E

HEAVY COMPACTION TEST

GADAIPUR BANDH ROAD

Mass of empty Mould = 2132 gm

Table 12 Heavy Compaction Test Results

Sr. No.	Determination Number	1	2	3	4	5
(1)	Mass of mould + compacted soil (gm)	3996	4083	4202	4281	4244
(2)	Mass of compacted soil W_t(gm)	1864	1951	2070	2149	2112
(3)	Wet density $\gamma_t = \frac{W_t}{V}$ (g/cc)	1.864	1.951	2.070	2.149	2.112
(4)	Crucible No.	25	A1	A	P3	1
(5)	Mass of crucible + wet soil (gm)	157.1	150.1	155.5	147.2	171.8
(6)	Mass of crucible + dry soil (gm)	149.7	140.2	144.7	134.1	153.5
(7)	Mass of water (5)-(6)	7.4	9.9	10.8	13.1	18.3
(8)	Mass of crucible,(gm)	37.2	24.8	40.7	24.8	23
(9)	Mass of dry soil, (6) – (8)	112.5	115.4	104	109.3	130.5
(10)	Water content w = $\frac{(7)}{(9)} \times 100$ (%)	6.57	8.58	10.38	11.98	14.02
(11)	Dry Density, $\gamma_d = \frac{\gamma_t}{1+w}$ (g/cc)	1.749	1.797	1.875	1.92	1.852

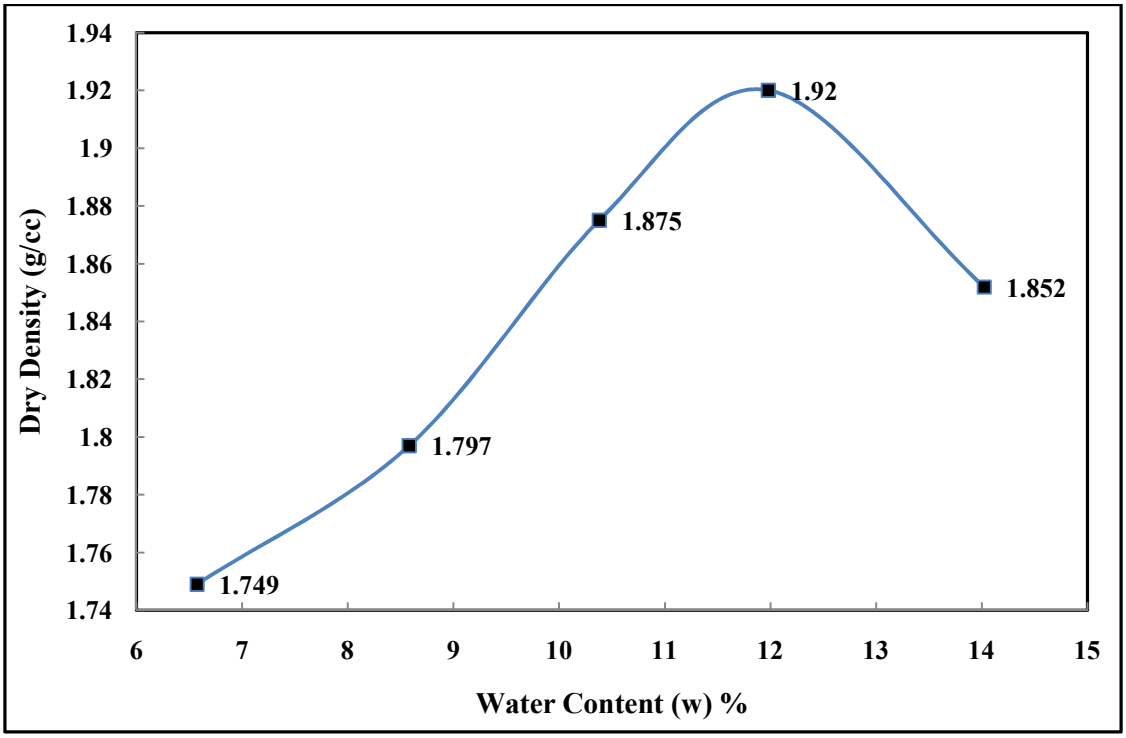


Figure 1 Compaction Curve

Water Content = 11.9 %
Maximum Dry Density = 1.91 g/cc

HEAVY COMPACTION TEST

DERA BHATTI ROAD

Mass of empty Mould = 2132 gm

Table 13 Heavy Compaction Test Results

Sr. No.	Determination Number	1	2	3	4
(1)	Mass of mould + compacted soil (gm)	4210	4314	4376	4320
(2)	Mass of compacted soil W_t(gm)	2078	2182	2244	2188
(3)	Wet density $\gamma_t = \frac{W_t}{V}$ (g/cc)	2.078	2.182	2.244	2.188
(4)	Crucible No.	25	22	A	P3
(5)	Mass of crucible + wet soil (gm)	145	134.1	173.7	122.8
(6)	Mass of crucible + dry soil (gm)	138.3	125.7	161.8	113
(7)	Mass of water (5)-(6)	6.7	8.4	11.9	9.8
(8)	Mass of crucible,(gm)	37.1	26.4	41.1	24.9
(9)	Mass of dry soil, (6) – (8)	101.2	99.3	120.7	88.1
(10)	Water content w = $\frac{(7)}{(9)} \times 100$ (%)	6.62	8.46	9.86	11.12
(11)	Dry Density, $\gamma_d = \frac{\gamma_t}{1+w}$ (g/cc)	1.949	2.012	2.04	1.969

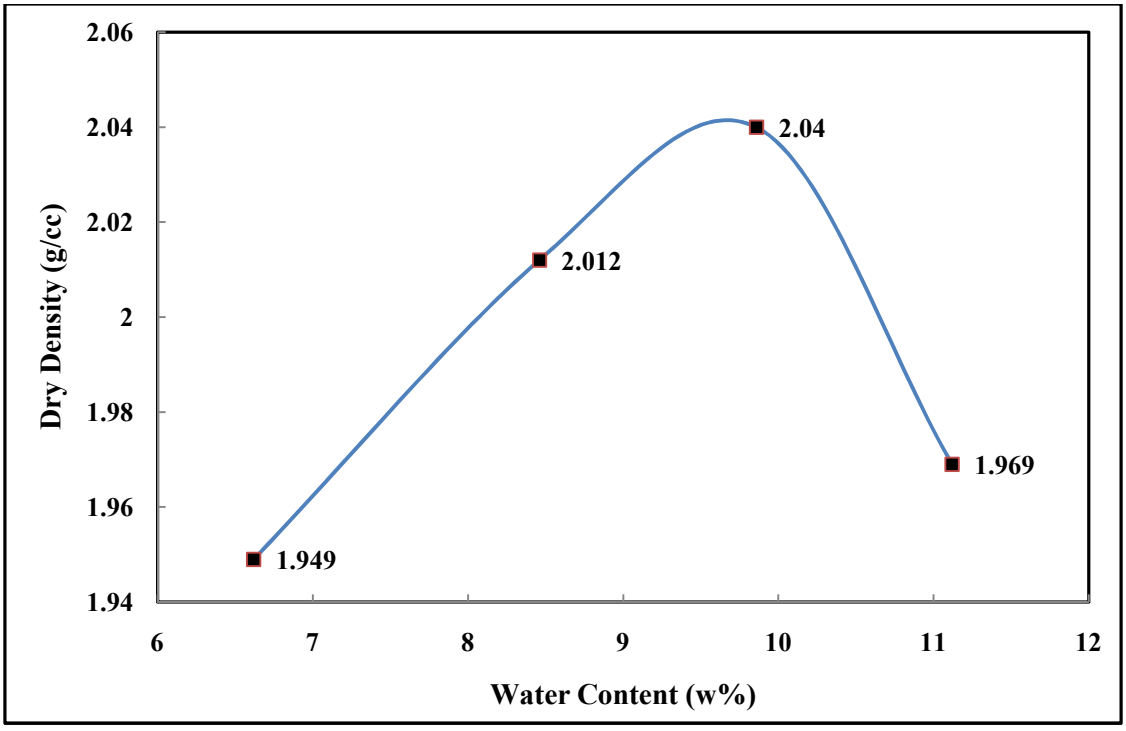


Figure 2 Compaction Curve

Water Content = 9.8 %

Maximum Dry Density = 2.03 g/cc

APPENDIX -F

Pit No. 1 at Gadaipur Bandh Road

Pit No. 2 at Dera Bhatti Road

For Subgrade Soil

Pit No.	Percent Passing through IS Sieve						Gravel content %	Sand content %	LL %	PL %	PI %	MDD gm/cc	OMC %	CBR %	Type of soil
	20 mm	10 mm	4.75 mm	2.36 mm	0.425 mm	0.075 mm									
1	100	83	76	71	57	34	24	42	—	—	NP	1.910	11.90	8.5	SM
2	100	93	91	90	88	67	7	24	—	—	NP	2.030	9.80	5.5	ML

For Granular sub-base

Pit no.	Percent Passing through IS Sieve								PI %	MDD gm/cc%	OMC %	Physical Properties of coarse Aggregate		CBR %
	75 mm	53 mm	26.5 mm	9.5 mm	4.75 mm	2.36 mm	0.425 mm	0.075 mm				10%FV(KN)	W.Ab. %	
1	100	97	62	43	35	31	19	6	NP	2.17	6.50	120	0.55	32
2	100	96	64	44	38	27	18	5	NP	2.19	5.80	110	0.58	25

FV = % Fine value, WA (%) = Water Absorption, MDD = Maximum Dry Density, OMC = Optimum Moisture Content

For WMM

Pit no.	Percent Passing through IS Sieve								PI %	MDD gm/cc %	OMC %	Physical Properties Of coarse Aggregate		
	53 mm	45 mm	22.4 mm	11.2 mm	4.75 mm	2.36 mm	0.600 mm	0.075 mm				AIV %	W.Ab.%	FI+EI %
1	100	98	84	55	30	19	12	4	NP	2.19	6.00	16.5	0.53	29.5
2	100	100	84	57	40	27	15	3	NP	2.18	6.50	16.5	0.53	29.5

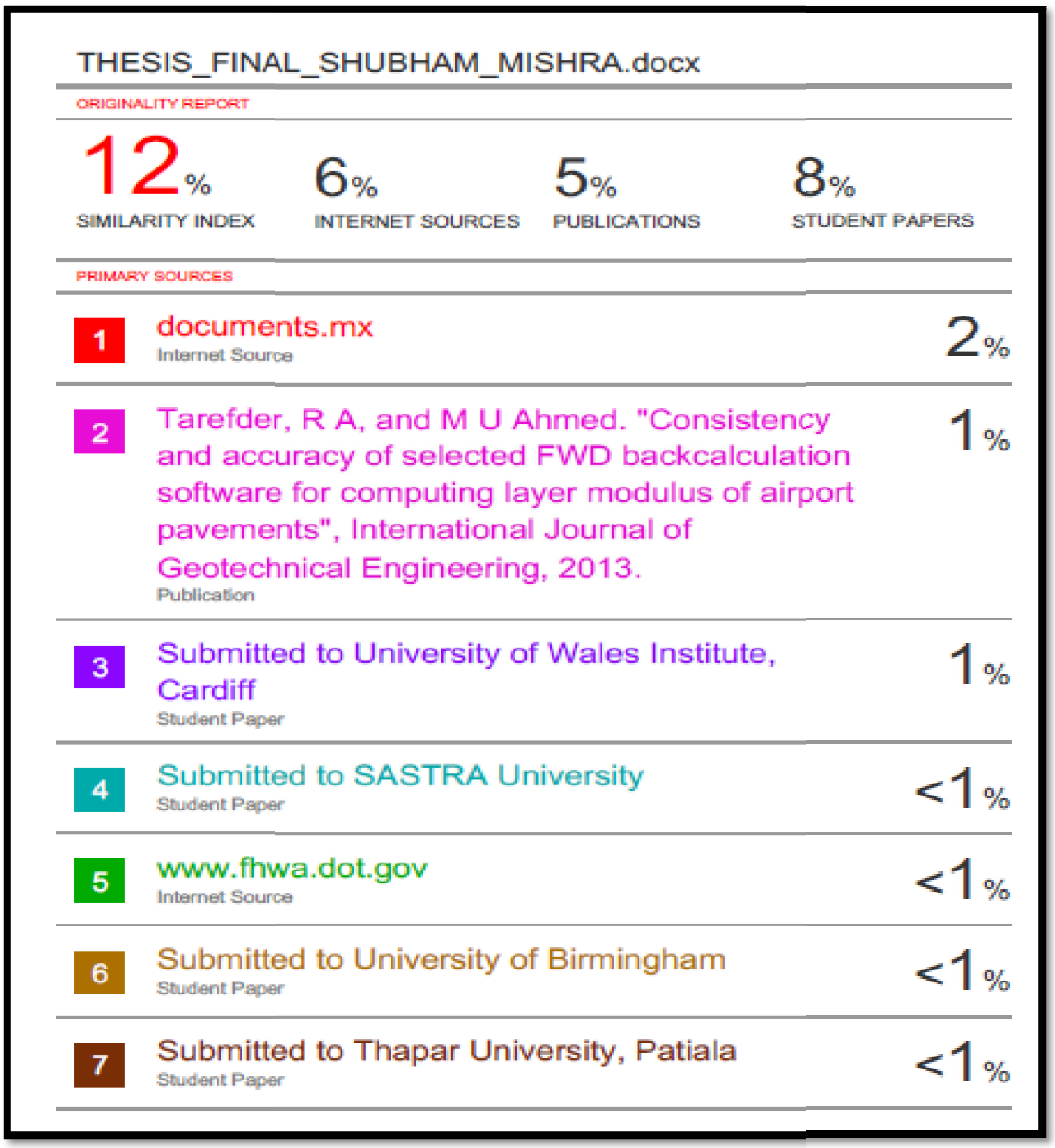
FI =Flakiness Index, EI =Elongation Index, AIV = Aggregate Impact Value

For BC

Pit no.	Binder content (%)	Percent Passing through IS Sieve										Physical Properties of coarse Aggregate		
		19.0 mm	13.2 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	.600 mm	0.300 mm	.150 mm	0.075 mm	AIV %	W.Ab. %	FI+EI %
1	4.35	100	97	73	49	36	29	20	14	10	3	18	0.68	32.3
2	4.26	100	99	70	51	38	28	21	13	9	4	18.2	0.7	33.3

For DBM

Pit no.	Binder content (%)	Percent Passing through IS Sieve								AIV %	W.Ab. %	FI+EI %
		37.5 mm	26.5 mm	19.0 mm	13.2 mm	4.75 mm	2.36 mm	0.300 mm	0.075 mm			
1	3.85	100	100	97	60	33	21	10	3	17.7	0.65	29.8
2	3.75	100	100	96	62	34	20	8	2	17.5	0.65	29.5



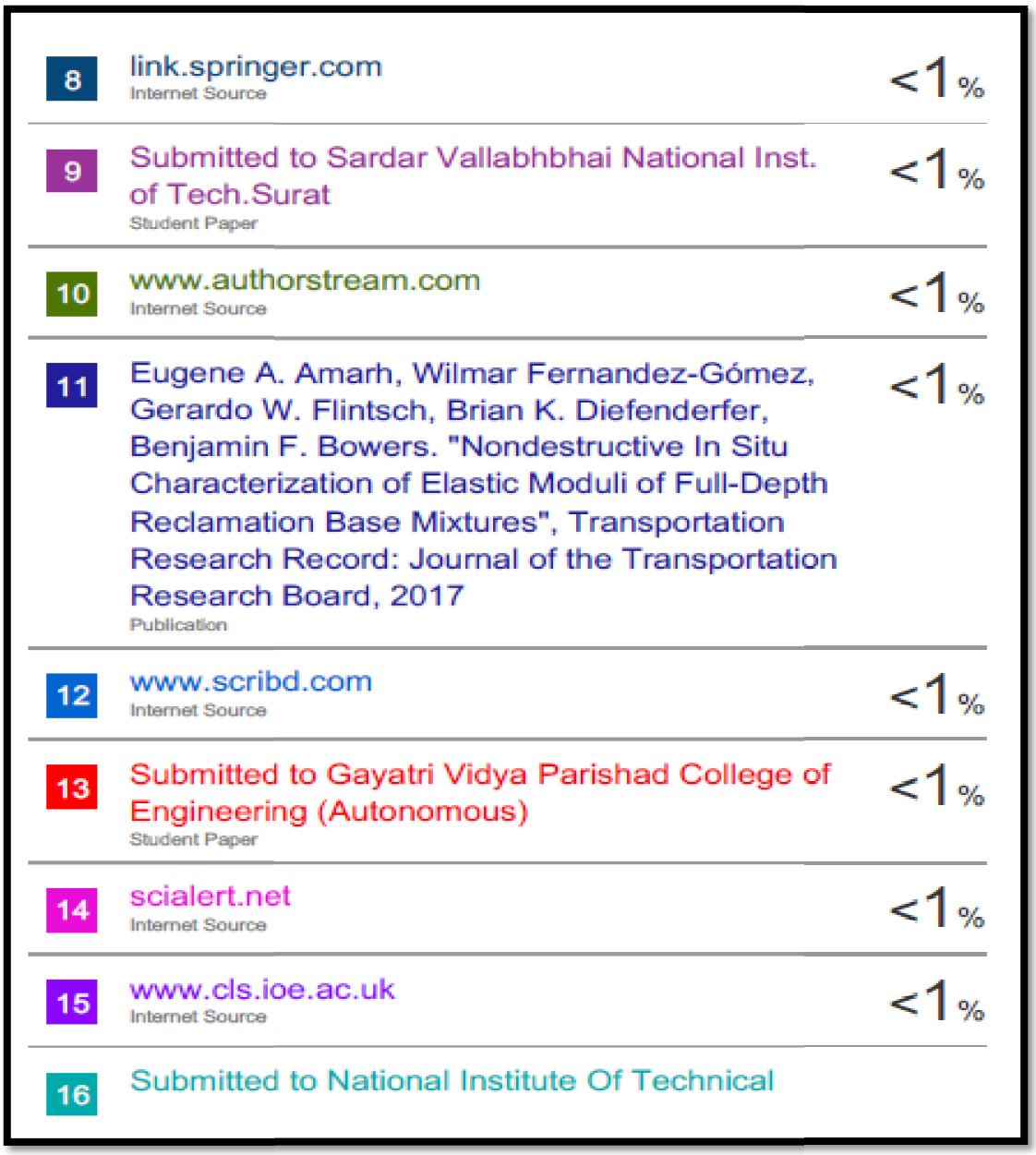
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