EFFECT OF ERRORS IN LAYER THICKNESS ON BACKCALCULATED LAYER MODULI

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A study on how errors in layer thickness would affect backcalculated pavement layer moduli is presented. A number of theoretical dynamic and static backcalculation analyses were performed on a hypothetical pavement model, where pavement layer thicknesses were systematically varied. Results obtained showed a pattern in which backcalculated pavement layer moduli were affected by errors in the layer thickness. Variations were also observed in the results obtained using different backcalculation methods. Similar findings were obtained for the case of actual FWD data from Road Test Section 609. The dynamic loading case and static backcalculation method that led to better results were also identified.

Key Words: *FWD deflection, dynamic analysis, static analysis, backcalculation, pavement layer moduli, pavement layer thickness errors.*

1. INTRODUCTION

Nondestructive testing (NDT) of a pavement system using such devices as Falling Weight Deflectometer (FWD), which is a dynamic testing device, Benkelman Beam (static), Dynaflect and Road Rater (steady state vibratory), have been used in the evaluation process of pavement structural integrity. Among these devices, FWD appears to have gained quite a wide popularity among highway agencies and pavement researchers. FWD devices were developed in Europe and have since been widely used in the United States and Japan. FWD delivers an impulse load that is transferred to the pavement system through a loading plate (30cm diameter). The impulse load is created by means of a one/two mass system. Peak load can be varied by changing the magnitude of the dropping mass as well as the drop height[1)]. This impulse load can theoretically be closely approximated by a half-sinusoidal waveform. Advantages of using FWD stem from the simplicity and the ability of FWD to simulate pavement responses due to traffic loading. Other reasons are the fact that this deflection measurement technique is fast, relatively accurate, and can be used to evaluate structural condition of a pavement system with minimum disturbance and cost[2)].

Thickness of pavement layers, material properties of pavement and deflection measurements are commonly used in the evaluation process of the structural capacity of pavements. In this process, various pavement layer properties can be backcalculated and evaluated. The most commonly backcalculated property is the elastic modulus of each layer.

Because of the use of NDT devices like FWD, where pavement system is hardly disturbed, thickness of pavement layers are no more measured by coring, a method which is destructive to the pavement system, time consuming, expensive and interfere with traffic flow[3)]. Pavement layer thickness is obtained from the historical database of the road. A number of factors during the construction phase affect the final layer thickness, and hence most of the times, design and construction pavement layer thicknesses are different. In a real asphalt concrete pavement, studies have shown that there is a variability of layer thickness with distance[4)]. Therefore, the use of only one set of pavement model for a stretch of a road section is considered one source of errors on the backcalculated layer moduli. Other pavement layer properties, like Poisson ratio and density of pavement layer materials, are most of the times assumed.

E_{01} = 50000 kgf/cm², ν_1 = 0.35,
ρ_1 = 0.0023 gf/mm³, h_1 = 10 cm

E_{02} = 5000 kgf/cm², ν_2 = 0.35,
ρ_2 = 0.0019 gf/mm³, h_2 = 40 cm

E_{03} = 800 kgf/cm², ν_3 = 0.35,
ρ_3 = 0.0018 gf/mm³

(E_{0i}, ν_i, ρ_i, h_i = Young's modulus, Poisson ratio, density and height of layer i)

Fig.1 Hypothetical pavement model.

A few numbers of pavement researchers have tried to address the accuracy problem of layer moduli. One study looked at this as a result of a combined problem of deflection errors and layer thickness variability for a given road sections[5]. Furthermore, the study used only static backcalculation method to backcalculate layer moduli. Moreover, theoretical deflections used in this analysis were computed using randomly generated pavement layer thicknesses. In another study, layer thickness variability patterns were established using Ground-penetration Radar (GPR). However, this analysis was based on a composite pavement system[6].

The study to be presented in this paper, tried to look at the separate effects of errors in layer thicknesses on the backcalculated results of pavement layer moduli. Theoretical analyses were performed on a hypothetical pavement profile with known layer material properties, as shown in Fig.1. In order to evaluate the theoretical findings, actual FWD test result from Ministry of Construction, Road Test Section 609 was also analyzed. In both theoretical as well as real cases, several sets of systematically varied layer thicknesses were used. Backcalculation analyses were performed using Multilayer and FEM static backcalculation methods and FEM Dynamic backcalculation method.

2. THEORETICAL BACKCALCULATION ANALYSIS

A three-layer hypothetical pavement system was used for the theoretical analysis (Fig.1). In order to obtain pavement deflections, a load of the magnitude of 5000 kgf was assumed. Loading plate was 30 cm in diameter. Static as well as dynamic loading cases were employed in this study. Loading durations, T_P, for theoretical dynamic cases were taken as 24 ms and 40 ms, thus representing loading durations for most popular FWD devices used in Japan; Komatsu and KUAB, respectively. Simulations of dynamic loading were done using two half-sinusoidal waveforms (see Eqns.1b and 1c) while static loading was considered a constant value. In general, loading, F, was computed as follows

$$\text{Static case;}\quad F = 5000\ \text{kgf} \qquad (1a)$$

This was named as MULTstc.

$$\text{Dynamic case;}\quad F = 5000\sin^2(\pi t/T_P)\ \text{kgf} \qquad (1b)$$

This was named as dynsq24 and dynsq40 for 24ms and 40ms loading durations, T_P, respectively.

$$\text{Dynamic case;}\quad F = 5000\sin(\pi t/T_P)\ \text{kgf} \qquad (1c)$$

This was named as dyn24 and dyn40 for 24ms and 40ms loading durations, T_P, respectively.
In all dynamic cases; $0 \leqq t \leqq T_P$.

In total, there were five (5) loading cases, see Fig.2.

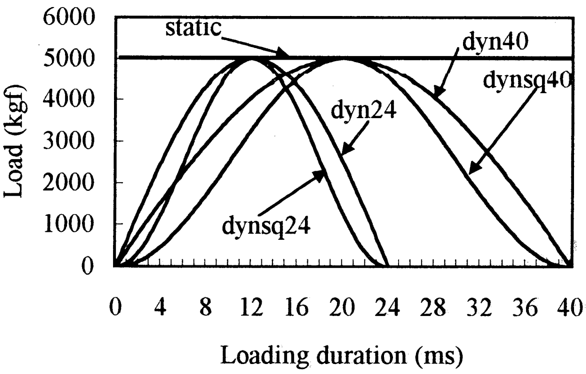


Fig.2 Theoretical static and dynamic loadings

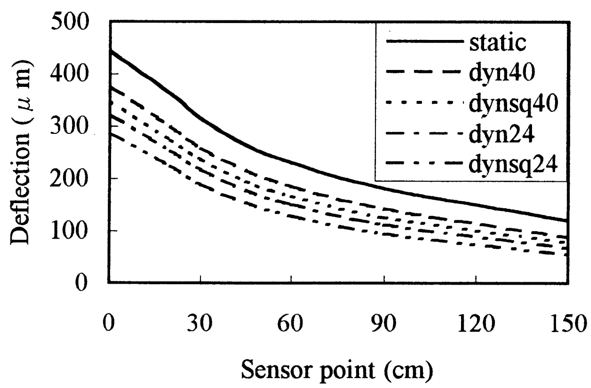


Fig.3 Theoretical static and dynamic peak deflections

In this study a static elastic multilayer program, BISAR[7] was used to compute pavement static deflections. Theoretical deflections were computed for the following seven sensor positions relative to the point of loading; 0 cm, 20 cm, 30 cm, 45 cm, 60 cm, 90 cm, and 150 cm. Peak deflection values were computed for these sensor points. Dynamic Finite Element Method (FEM) was used to compute time domain (dynamic) pavement response induced by the impulse load[8] at the same sensor points as for the static cases.

3. GENERATING DEFLECTION BASINS

In order to reduce error of deflection computations for the hypothetical pavement model, 100sets of normally distributed deflection data were randomly generated[9]. The following procedure was used to randomly generate the deflections; for the case of static deflections, theoretically computed sensor point deflections, as explained in chapter 2, were taken to be mean deflection values. Whereas, for the case of time domain (dynamic) deflections, which were computed using the dynamic loading simulations (chapter 2), peak deflections at each measured sensor point were found and taken as mean deflections, see Fig.3. A standard deviation of deflection values was assumed to be $2\,\mu$m. This is considered to be a level of accuracy for FWD device[5]. By using this standard deviation and mean deflection data, 100sets of normally distributed peak deflection data were generated by Monte Carlo simulation technique. The generated data were taken

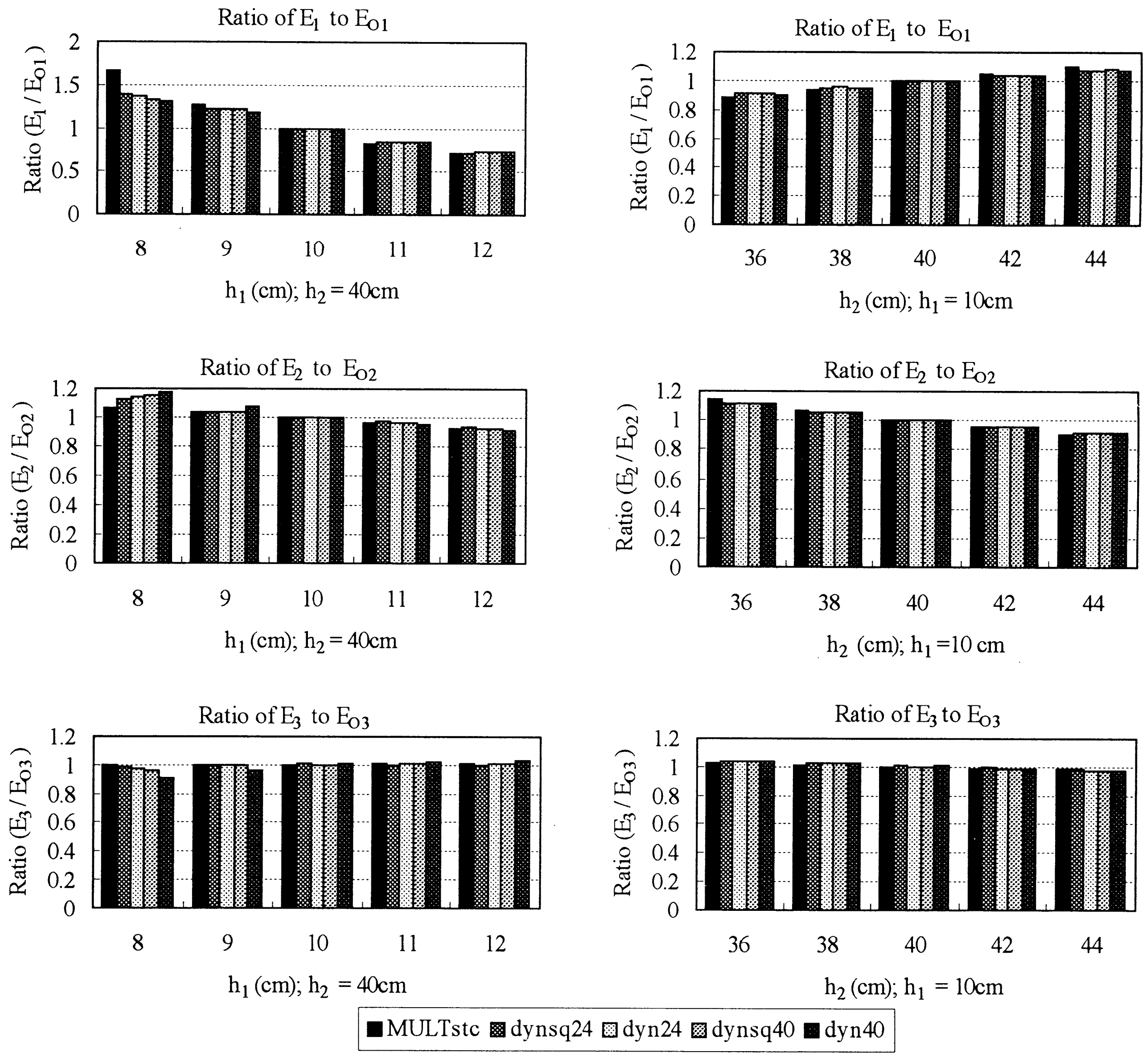


Fig.4 Effect of errors in h_1 and h_2 on backcalculated layer moduli for the hypothetical pavement model

as they were, for the case of static backcalculation. However, to obtain 100sets of time domain deflection data at any sensor point, computed dynamic deflection at any time, *t*, was multiplied by a ratio of generated deflection to computed peak deflection for that particular sensor point.

4. ERRORS IN LAYER THICKNESS

Having generated 100sets of normally distributed deflection data, backcalculation for corresponding 100sets of layer moduli followed. This was done first for the cases where asphalt concrete layer thickness, h_1, for the hypothetical pavement model (Fig.1) was varied by ± 1 cm and ± 2 cm while base course thickness, h_2, was kept constant. This was for the purpose of investigating how errors in h_1 would affect the backcalculated layer moduli. Backcalculation procedure for static analysis was done by using BALM, a computer program that uses BISAR computer program as a subroutine[10]. Backcalculation procedure for dynamic analysis was carried out using previously mentioned dynamic FEM computer program. In this program, the time required to compute the system of equations was quite substantially reduced by the introduction of matrix reduction approach based on Ritz vector[8]. In both static and dynamic backcalculations, Gauss-Newton method was used to minimize the objective function, and the truncated singular value decomposition was employed to prevent the propagation of errors contained in computed deflection data. In both static and dynamic methods, when backcalculated layer moduli were used in the computations of deflections, a good agreement between computed and generated deflection data was achieved.

Investigation on how changes in h_2 would affect

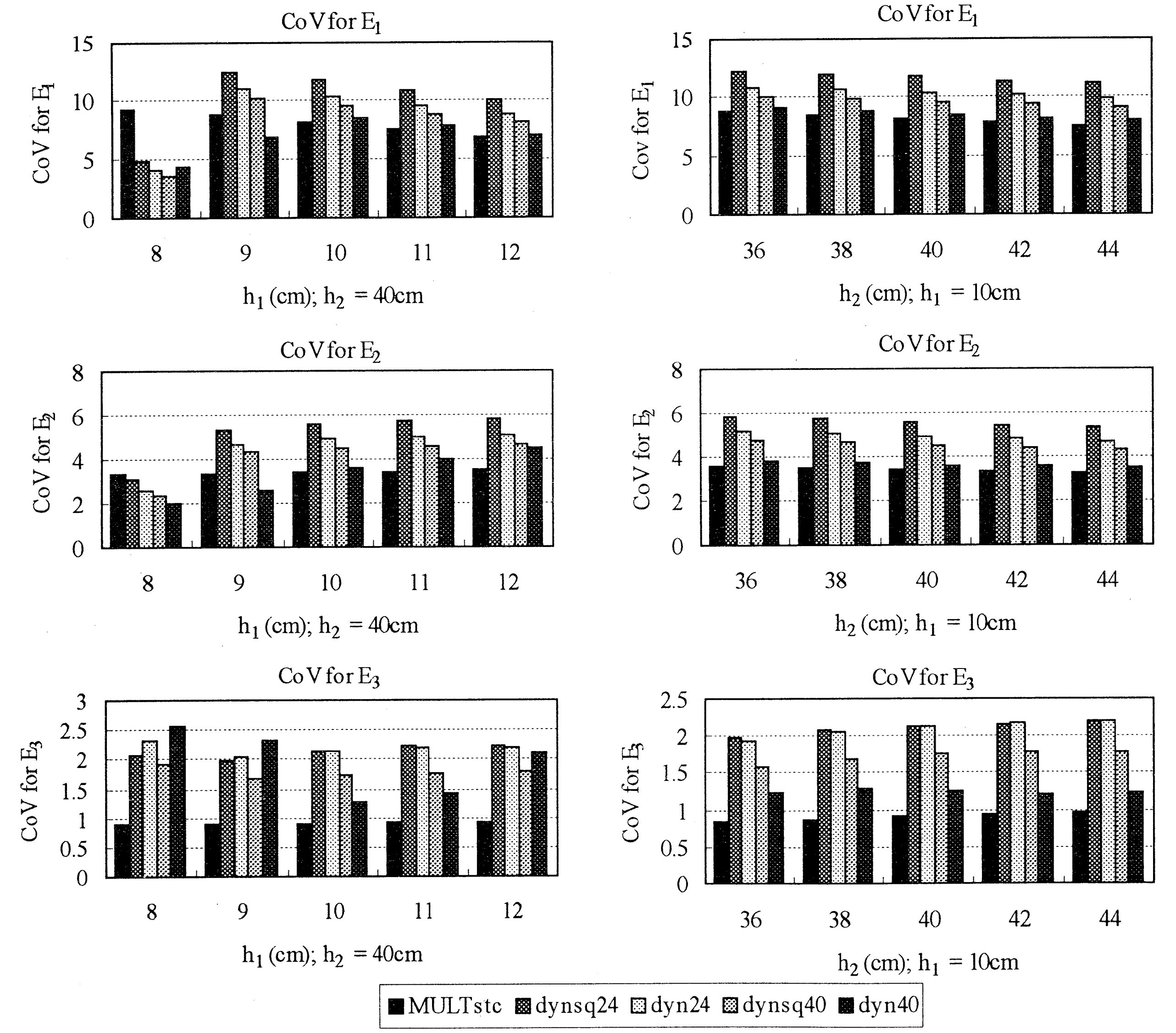


Fig. 5 Coefficient of Variation (CoV) for the backcalculated layer moduli

backcalculation results of layer moduli followed. In this case, the base course thickness, h_2, for the hypothetical pavement model was varied by ± 2 cm and ± 4 cm. Asphalt layer thickness, h_1, was kept constant throughout the backcalculation process. The results were expected to show how errors in h_2 would affect the backcalculated layer moduli. Backcalculation procedure for static analysis was also done by using BALM computer program. A good agreement between computed and generated deflection data was achieved. Backcalculation procedure for dynamic analysis was also carried out using the already mentioned dynamic FEM computer program. In this analysis of varying h_2, in both static and dynamic analyses employed also Gauss-Newton method to minimize the objective function, while the truncated singular value decomposition was employed to prevent propagation of errors in the computed deflection data. Fig.4 shows ratios of mean values, for each group of 100sets of backcalculated layer moduli, to original values. Coefficients of variation for layer moduli are shown in Fig.5.

(1) Discussion of results for hypothetical pavement with errors in h_1 & h_2 (Fig.4)

① Backcalculation results for deflections from the five different loadings are almost similar for a particular set of h_1 and h_2. In this case, the method of analysis is consistent with the method of loading, i.e. static analysis for static deflections, and dynamic analysis for dynamic deflections. Results show that computational errors in the methods used may be negligible.

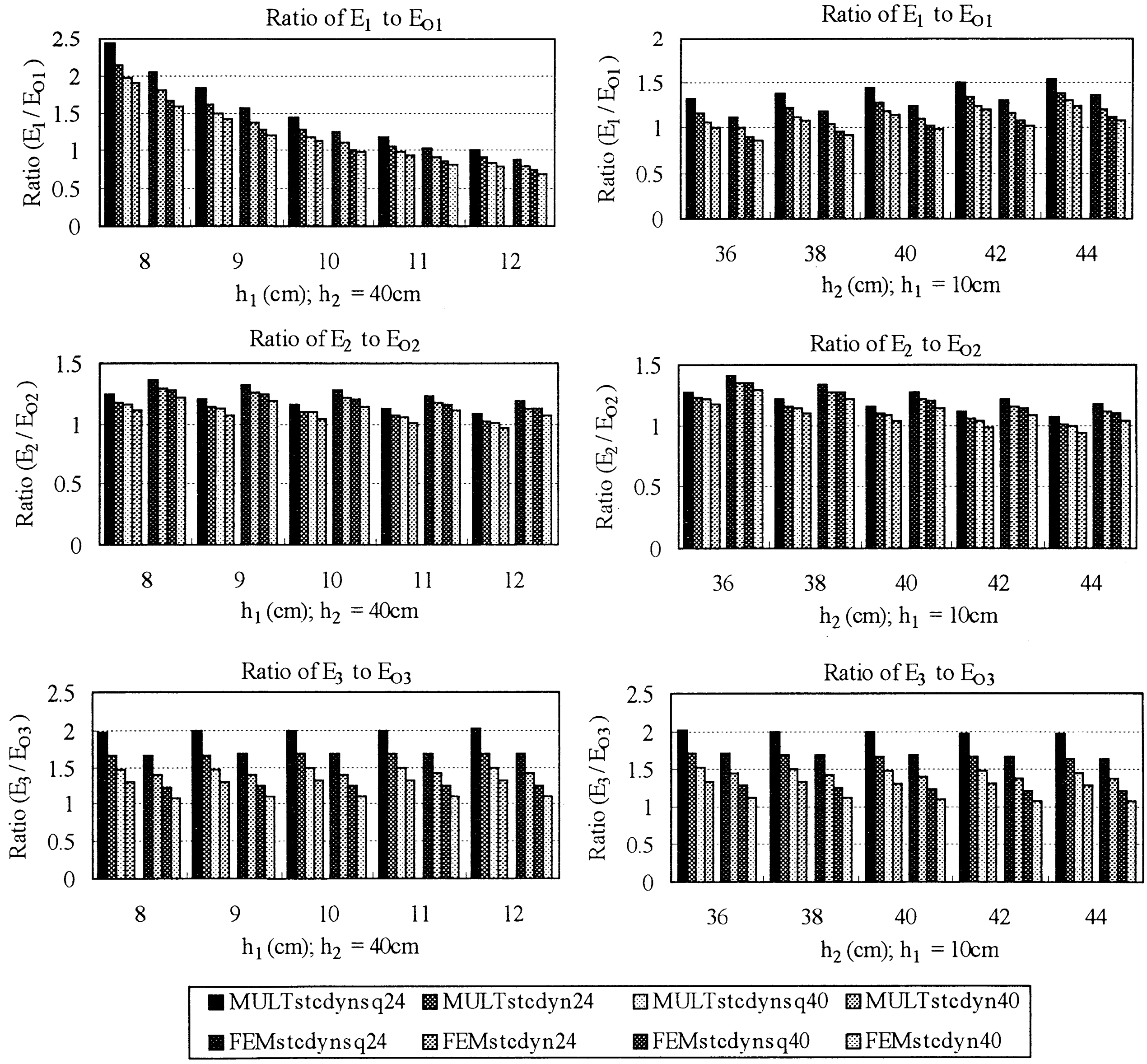


Fig.6 Backcalculated layer moduli using MULTstc and FEMstc on peak dynamic deflections

② Errors in h_1 showed larger effects on backcalculated E_1 moduli than errors in h_2.
③ Backcalculated E_1 values were larger when h_1 was smaller than the actual thickness and vice versa.
④ Errors in h_1 and h_2 showed very little effects on backcalculated E_2 and E_3.

(2) Discussion of CoV for the backcalculated layer moduli (Fig.5)
① Coefficient of Variation (CoV) was largest for E_1 and smallest for E_3.
② Backcalculation results for the deflections obtained using the five types of loading gave different CoV for each layer moduli.
③ For dynamic cases, CoV values decreased as loading durations increased with the exception of two cases in E_3 values.
④ Dynamic loading type with the longest (loading) duration (dyn40) gave overall smaller CoV among the dynamic results.

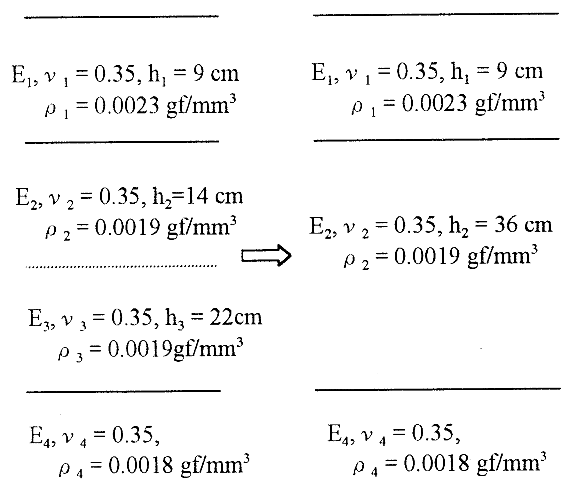
5. STATIC BACKCALCULATION USING PEAK DYNAMIC DEFLECTIONS

In practice, the most common and popular methods used to analyze FWD deflection data are static analysis methods. Bearing that in mind, peak dynamic FEM deflections due to dyn24, dynsq24, dyn40,and dynsq40 dynamic loading cases, were used in the backcalculation procedure employing static elastic multilayer program, BALM, as well as static FEM program. This was done purposely in order to find how backcalculation results would be affected by errors in layer thickness when dynamic deflections are analyzed by a static analysis method.

In this case, similar to the previous backcalculation procedures, 100sets of the normally distributed peak dynamic deflections generated by using Monte Carlo simulation were used. Mean values for each group of 100sets of backcalculated layer moduli were compared to the original layer moduli values and plotted as shown in Fig.6.

Results due to static elastic multilayer method were named as MULTstcdyn24, MULTstcdyn40 MULTstcdynsq24, and MULTstcdynsq40 and those due to static FEM methods were FEMstcdyn24, FEMstcdyn40, FEMstcdynsq24, and FEMstcdynsq40. The naming was decided considering the type of load and the method of analysis used.

(1) Discussion of backcalculation results for dynamic peak deflections (Fig.6)
① For a particular set of h_1 and h_2, results from both static MULT and static FEM methods showed a decreasing trend of layer moduli values as dynamic loading duration becomes longer.
② For a particular type of loading, static FEM method gave smaller values of E_1 and E_3 than static MULT method. However, static MULT method gave smaller values of E_2 than static FEM method.
③ For a particular method, errors in h_1 showed larger effects on backcalculated E_1 values than errors in h_2.
④ Backcalculated E_1 values were larger than the actual value for the case where h_1 was smaller than the actual layer thickness.
⑤ Backcalculated E_1 values started to decrease and become smaller than the actual value as h_1 became larger than the actual layer thickness.
⑥ For the same backcalculation method, E_3 values were constant even as values of h_1 and h_2 changed. Almost similar trend was observed for the case of backcalculated E_2 values.
⑦ Variations in backcalculated results among the different methods, for a set of h_1 and h_2 values, were the largest in E_3.
⑧ For the case where actual pavement layer thicknesses were used (Fig.1 and Fig.6), overall results of FEMstcdyn40 were relatively closer to actual values than the results of the other methods.
⑨ Dynamic FEM deflection data. that were used in the analysis might have influenced the outcome of the backcalculation analyses when using static elastic multilayer and static FEM methods.



(E_i, ν_i, ρ_i, h_i = Young's modulus, Poisson ratio, density and height of layer i)

Fig.7 Pavement structure of Road Test Section 609

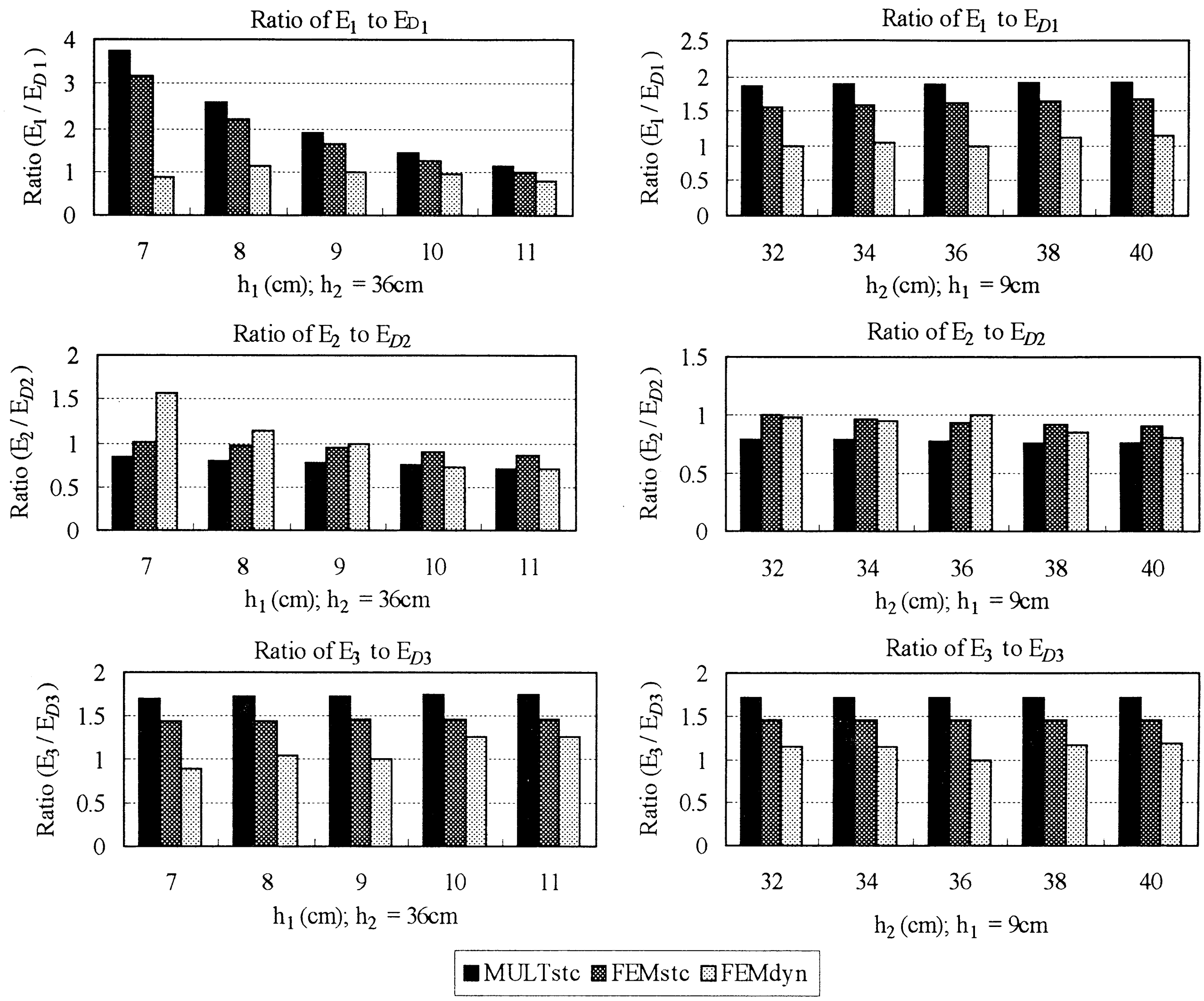


Fig. 8 Backcalculated layer moduli for Section 609

6. BACKCALCULATION OF FWD DATA FOR SECTION 609

It was necessary to observe the trend of results for the case of actual FWD results. In this case, only one FWD test result from Road Test Section 609 was considered enough to give a rough picture of how errors in layer thickness for actual pavement system would affect backcalculated layer moduli. Originally, pavement structure for Road Test Section 609 was a four-layer system. However, this research has been studying a three layer hypothetical pavement system and therefore, for the purpose of consistence it was found necessary to modify the pavement structure for Section 609 into a three layer pavement system. Base and subbase courses were combined to make one layer (see Fig.7).

Similar backcalculation methods as in the case of the hypothetical pavement were used to analyze actual FWD data from Road Test Section 609. Dynamic backcalculation results, E_{Di}, for a set of layer thickness considered to be actual pavement layer thickness were taken as standard values. All other backcalculated layer moduli were compared to these standard values. Results are shown in Fig.8.

(1) Discussion of backcalculation results for FWD deflections (Fig.8)

① Errors in h_1 showed larger effects on backcalculated E_1 moduli than errors in h_2.

② Backcalculated E_1 values increased, as h_1 became smaller than the actual thickness and vice versa.

③ Errors in h_1 and h_2 showed very little effects on backcalculated E_2, with the exception of h_1 =7 cm. All three methods gave approximately similar results for E_2.

④ The trend of backcalculated E_1 and E_3 were similar, but variations were larger for E_1 results than for E_3 results.

⑤ Static FEM method gave smaller value of E_1 and E_3 than static elastic multilayer method. The results were opposite for E_2 results.

⑥ For E_1 and E_3, dynamic FEM results were the smallest.

7. CONCLUSIONS

The following general conclusions were drawn, and may be valid, with regards to the methods of analysis used. In this case, the conclusions were drawn from backcalculation results obtained using dynamic FEM method, static elastic multilayer method and static FEM method;

①Negative errors in h_1 (h_1 < actual h_1) have larger effects on the backcalculated E_1 than positive errors in h_1 (h_1 > actual h_1)

②Errors in h_2 have smaller effects on the backcalculated layers moduli than errors in h_1.

③E_2 is almost unaffected by errors in layers thickness.

④Dynamic analysis method gives smaller E_1 and E_3 values than the static analysis method.

⑤Different methods give similar E_2 values.

⑥Duration of dynamic loading influences dynamic as well as static backcalculated results.

⑦ A method used to obtain theoretical deflections may influence the backcalculation results obtained using other methods.

⑧ Dynamic loading case (dyn40) may provide better theoretical results since least CoV values were obtained among all the dynamic loading cases (Fig.5). This is especially true for the case where actual pavement layer thicknesses are used (see Fig.1). Therefore, if most layer moduli values are similar for all the dynamic methods (see Fig.4), CoV values may provide the basis for comparisons of the methods.

⑨ Fig.6 was used to identify the static method that may provide better results. This is the figure of results where dynamic deflections were used. For the case where actual pavement layer thicknesses were used (see Fig.1), overall results of FEMstcdyn40 are relatively closer to actual layer moduli values than the results of the other methods.

⑩ The general trend of static analysis results for theoretical and actual dynamic deflection data were similar (Fig.6 and Fig.8). This means, theoretical dynamic deflection data may be used to evaluate backcalculation results.

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層厚誤差が逆解析層弾性係数におよぼす影響評価

ジェイムス マイナ ・ 横田漠・松井邦人

本論文の目的は，舗装の層厚誤差が逆解析結果に与える影響を検討することである。あらかじめ舗装断面を仮定し，測定たわみに誤差が含まれていることも考慮して，層厚の値を一層づつ変化させ逆解析を行っている。また荷重には，静的荷重だけでなく動的荷重も考慮している．舗装誤差の影響は，静的及び動的な解析方法又はＦＷＤの種類に応じて種々みられたが，それは変動係数によって一義的に評価されることが分かった。これは，第１回共通試験の 609 工区におけるデータを用いた解析でも同様であった。解析手法とＦＷＤの組合せの中で最も精度のよいものも得られている。