DIFFERENCE OF RESULTS BETWEEN DYNAMIC AND STATIC ANALYSES OF FWD DATA

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Results of structural evaluation analysis of pavement using FWD data from route 219 at Saito in Miyazaki Prefecture, Japan are presented. FWD is a dynamic loading device. DSGT, a dynamic analysis method and AASHTO and NIPPO which are static analysis methods, are used for the analysis. Subgrade modulus and effective pavament full depth AC thickness are backcalculated. A potential problem of whether static analysis (mostly used method) or dynamic analysis should be performed on the data is discussed in this paper by looking at the difference of results these two methods give in the analysis of FWD data.

Key Words: *FWD Deflection, Dynamic analysis, Static analysis, Backcalculation, Subgrade Elastic Modulus, Full depth AC Thickness* .

1. INTRODUCTION

In recent years, as a consequence of decreasing number of new highway construction projects, maintenance and rehabilitation of existing highways have become increasingly important elements in the Pavement Management System (PMS). PMS is an essential decision making support system which in a systematic way integrates all activities related to a pavement system such as; collection, processing and analysis of various types of data, development, planning and scheduling of rehabilitation and maintenance programs and priority ranking of projects for optimum use of resources[1)].

Road pavements are complex physical structures responding in a complex way to the influence of numerous environmental and load related variables. It is always a demanding task for highway agencies to characterize material properties of existing in-service pavements. Material characterization is important because; it determines whether a pavement structure can adequately accommodate anticipated increase in traffic volume and subsequent increase in traffic loading, it provides input for overlay design when the pavement reaches unacceptable lower level of service and, it helps to develop proper recommendations for rehabilitation and maintenance strategies.

Most highway agencies, for the purpose of analyzing pavement structures, have been performing nondestructive testing (NDT) on pavements. There is a general agreement among highway agencies and researchers as well that, NDT measured surface deflections provide important information for the structural evaluation of the pavement[2)]. The use of deflection data is based on the fact that deflection measurements reflect the strength of the pavement structures as they were constructed without considering how they might have been designed. Further more, deflection measurements account for a number of pavement variables such as thickness, types of material and environment[3)].

Pavement surface deflection measurements by NDT device, Falling Weight Deflectometer (FWD), have gained wide acceptance because this technique is economical, quick to perform, relatively accurate and causes little disturbances to the pavement system[4)]. Moreover, FWD machine gives a very good simulation of the actual traffic loading effects on the pavement, especially, deflections[5)]. FWD, as a dynamic measuring machine, imparts impulsive load to the pavement and at the same time measures the surface deflections.

Although these tests are carried out quite rapidly in situ, most of the times, in-house data processing are quite tedious and often the final results by various methods are different. Another potential problem is that, although a dynamic load is applied in order to obtain pavement surface deflection in the field, static analysis methods are often used to analyze the data. This may not be acceptable because in many cases, generally, stress and strain distribution as well as pavement response due to dynamic loading can be different from those considered in the static analyses[6].

FWD data were analyzed using Dynamic Slab Ground Theory (DSGT), which is a dynamic analysis method developed by one of the authors[7]. AASHTO and Nihon Hodo Construction Company method, abbreviated in this paper as NIPPO, which are static analysis methods, were also used to analyze FWD data. Results obtained are presented, compared and discussed in this paper.

2. OBJECTIVE

The objective of this paper is to highlight difference of results obtained by using two different methods of analysis, namely; dynamic and static. The difference significantly show whether it is proper or not to continue applying static analysis methods for structural evaluation of pavement when using FWD data.

3. TEST FIELD AND FWD DATA

Data used in the analysis were obtained from route 219 at Saito in Miyazaki Prefecture, Japan. This route was selected most importantly, because it has recent data and has had less rehabilitation work throughout its life. Data received from Miyazaki Prefecture Office included inventory, age, traffic, Maintenance Control Index (MCI) and individual stresses.

Deflection measurement tests were conducted on September 27-29, 1994 using KUAB FWD machine with frequency of loading of 13.0Hz and a testing load of 5tf. Structural evaluation analysis results presented in this paper are from a 1700m stretch of the test road. Pavement surface temperature ranged between 25° C and 29° C for this section. FWD deflection measurements were taken on the left wheel track of the road.

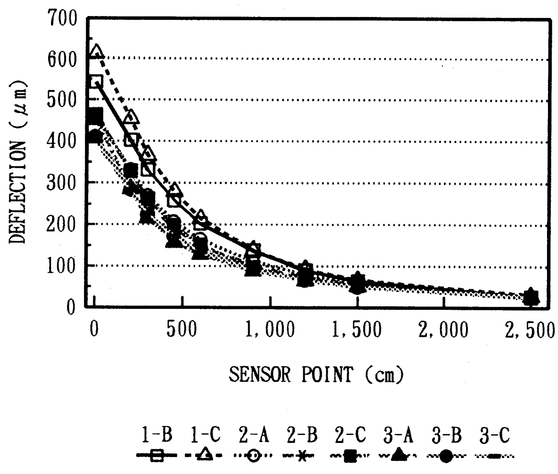

Fig. 1 Route 219 FWD deflections from 0-500m stretch "weak pavement section"

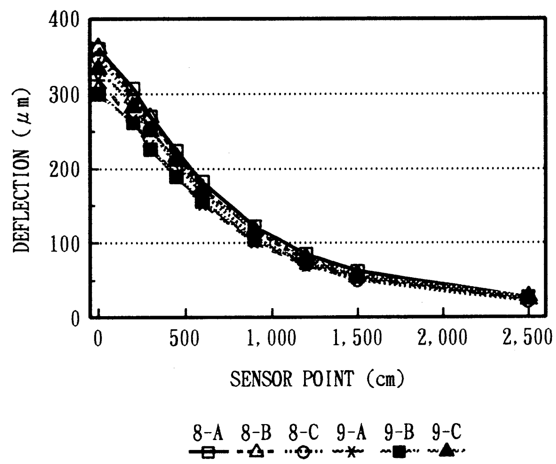

Fig. 2 Route 219 FWD deflections from 500-1700m stretch "strong pavement section"

Deflection data obtained were categorized into two main groups depending on the shape of the deflection basin and the extent the road surface had deflected. The first group showed characteristics which are typical of a weak pavement section with higher deflection values and surface deflected shapes suggesting a poor distribution of the applied load through the pavement structure. The second group showed characteristics which are typical of a relatively stronger pavement section with lower deflection values and surface deflected shapes suggesting a good distribution of the applied load. The first group of deflections, shown in Figure 1, were obtained from 0-500m stretch while deflections in the second group (see Figure 2) were from the remaining 500-1700m stretch.

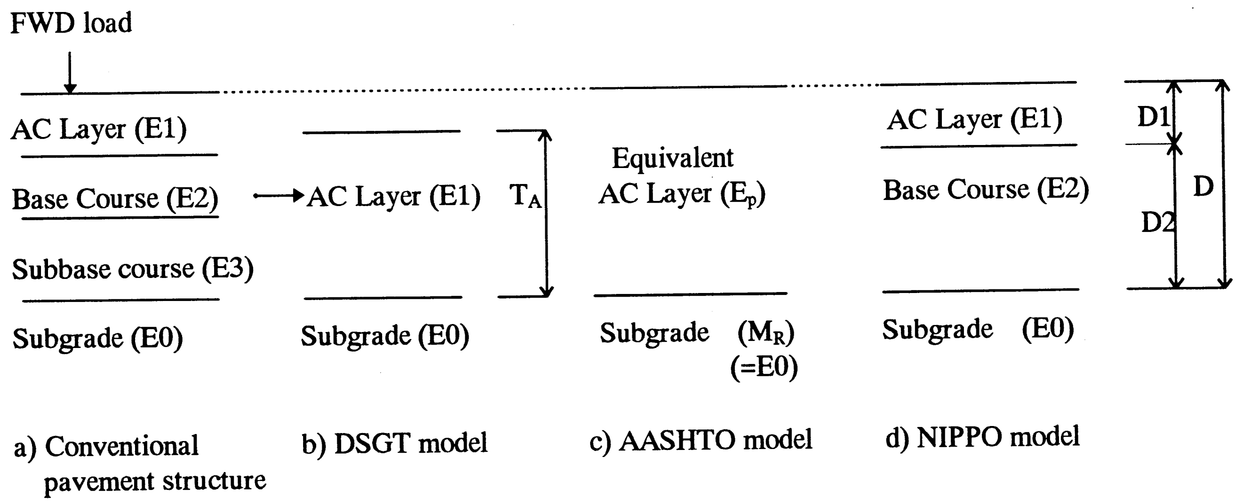

Fig. 3 : Conventional pavement structure as considered in the three methods' models.

Table 1: Summary of the three methods of analysis

Model name	DSGT	AASHTO	NIPPO
Theory	Dynamic , slab on elastic half space	Static, elastic half space	Static, multielastic medium
Pavement layer system	Two layers	Two layers	Three layers
Input	E1(Temperature, frequency)	Total pavement depth, D	AC and Base course depths, D1 and D2
Deflection points used	Two points	Two points	All points
Backcalculated variables	E0, T_A	M_R(E0), SNEff(T_A)	E1, E2, E0, T_A

4. METHODS OF ANALYSIS

(1) GENERAL

General overview about the three methods of analysis is as summarized and shown on Figure 3 and Table 1.

(2) DSGT method

DSGT is a dynamic analytical solution of a slab (full depth asphalt concrete pavement) on the ground, on the surface of which a periodic uniformly distributed load acts. The slab is considered to be in smooth contact with the ground. Timoschenko type slab theory which takes shearing deformation and rotary inertia into consideration is applied to the slab and the ground is considered to be an elastic half space. Deflections of the slab are obtained by combining Mindlin's solution for Timoshenko type slab with the wave propagation solutions for the elastic half space.

Southgate[8], University of Kentucky in USA,

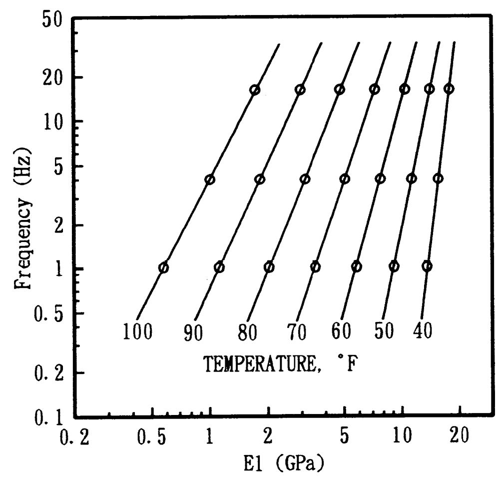

Fig. 4 Relationship of temperature, frequency of loading, and modulus of asphalt concrete.

presented results of tests shown in Figure 4, reported by Kallas and Rilley, which were used to develop University of Kentucky design procedure for asphalt concrete (AC) pavement, where elastic modulus of AC, E1 is calculated as a function of pavement mean temperature, T(° F) and frequency of cyclic load, f(Hz). The equation developed, which has been incorporated into DSGT[9], closely describe data in Figure 4 and is as follows;

$$\log E1 = a + bT + cT^2 + \left(d + eT + gT^2\right)\log f \qquad (1)$$

where $E1$: Elastic modulus of AC (psi)
T: Pavement mean temperature (° F)
f: FWD frequency of loading (Hz)
a=6.7638554, b=-0.0072846, c=-0.0001108
d=-0.1741191, e=0.0074997, g=-0.0000180

DSGT simultaneously backcalculate both subgrade elastic modulus, E0 and effective full depth AC pavement thickness, T_A using equations explained later in this paper.

(3) AASHTO method

This is a static analysis method and it is explained in the AASHTO Guide for Design of Pavement Structures. Basically, this method considers a pavement structure as a two layers system and uses FWD deflections in Boussinesq's solution to backcalculate resilient modulus, M_R of the subgrade. Thereafter, by using a series of computations, effective structural number, SN_{eff}, of the pavement structure above the subgrade can be calculated. Then, AASHTO specified asphalt concrete layer coefficient when applied on SN_{eff}, T_A value will be obtained.

(4) NIPPO method

This method was developed and is being used by Nihon Hodo Construction Company in Japan. It is a multilayer static analysis method, and uses Burmister solution to solve for the pavement layers moduli by making use of FWD deflections. Pavement layers coefficients, which are functions of layers moduli, when multiplied with as-built pavement layers thicknesses at a given point, the sum of the product will give T_A value for that given point.

5. DSGT THEORETICAL ANALYSIS

A computer program written based on DSGT and parts of Kentucky University design procedure for AC pavement was used to generate theoretical pavement deflections as a function of elastic modulus of AC, E1, elastic modulus of subgrade, E0 and full depth AC pavement thickness, T_A. Frequencies of loading were taken as 0Hz, for static loading condition and 13.0Hz, which was obtained from

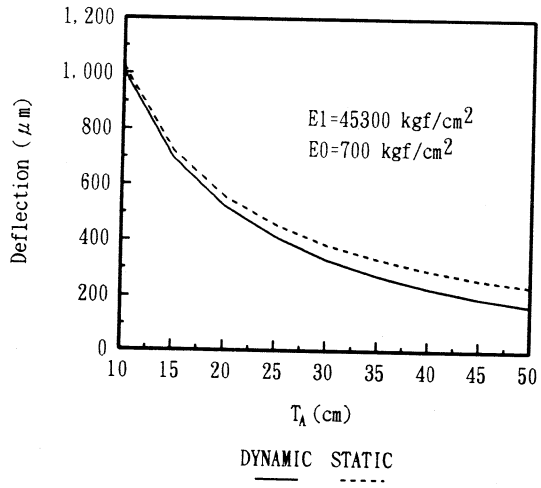

Fig. 4 A sample of theoretical Dynamic and Static deflections against T_A for constant E1 and E0 values

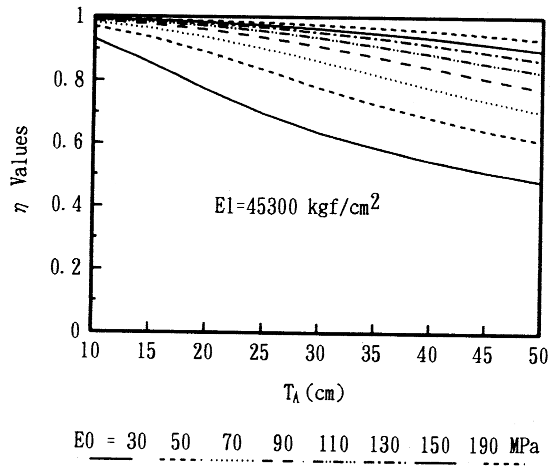

Fig. 5 Relation between η (Ratio of Dynamic to Static deflections) and T_A

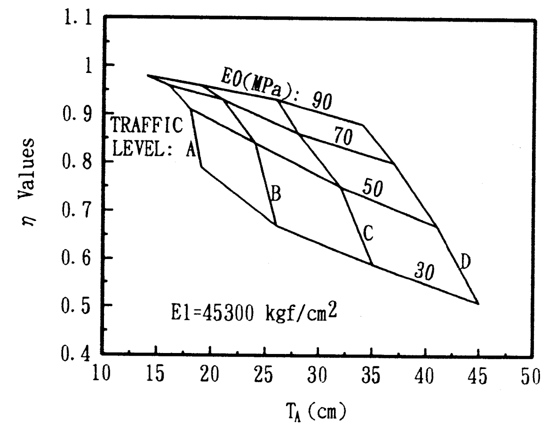

Fig. 6 Relation between η and T_A for various E0 and Traffic levels

FWD test records on route 219, for dynamic loading condition. Frequency of loading has two kinds of effect on the final deflection value; a) it affects elastic modulus of asphalt concrete and b) it generally affects how the pavement system responds to the acting load, i.e. dynamic and static responses. Since AASHTO and NIPPO calculate E1 values using FWD deflections, which implies that these E1 values are pseudo-dynamic values, therefore, for consistency purposes, in DSGT computer program a value of 13.0Hz as the frequency of loading was used for the calculation of E1 values in equation (1) for both dynamic and static cases.

Using the calculated E1 values and a range of assumed E0 and T_A values, DSGT computer program generated theoretical dynamic and static deflections. A sample of the theoretical dynamic and static deflections for constant E1 and E0 values is shown in Figure 4. This figure shows the response of a pavement system due to dynamic and static loads. Looking at this figure, it is clear that dynamic and static analysis methods even when used under strict constant conditions are bound to give different final results because their theoretical deflections, which were used in the analysis, can be defined by different types of equation. Figure 5 shows the ratio of theoretical dynamic to static deflections for the range of assumed E0 and T_A values at constant E1. This figure indicates that, as T_A increases or E0 decreases the deflection ratio decreases. This means that difference between dynamic and static backcalculated values increases as T_A increases or E0 decreases. And using Japanese standards for pavement thickness for various ranges of traffic levels and E0 values[10], corresponding ratios of dynamic to static deflections were computed and are shown in Figure 6.

6. ANALYSIS OF FWD DATA

Multiple regression analysis was performed on the generated theoretical dynamic deflections, by DSGT, from the point of loading, W_0, and the fourth point away from the point of loading, W_4, in order to get equations which express deflection as a function of three variables; pavement mean temperature, T, full depth AC pavement thickness, T_A, and subgrade elastic modulus, E0. These deflection points were selected after several trials and checks.

The developed regression equations were as follows;

$$w_i = (a_i + b_i T) E0^{(c_i + d_i T)} * \left(\exp\left((e_i + g_i T) + (h_i + k_i T)\ln E0\right) T_A\right) \tag{2}$$

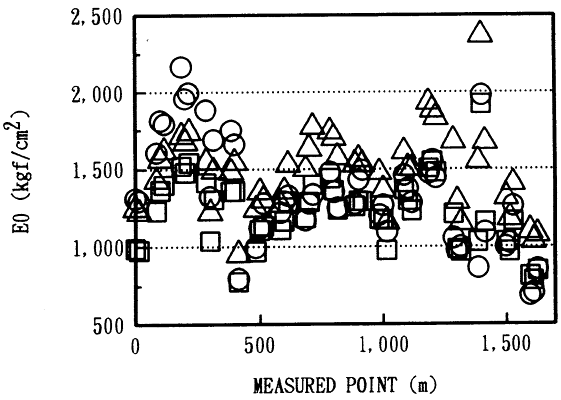

Fig. 7 Backcalculated E0 values by the three methods

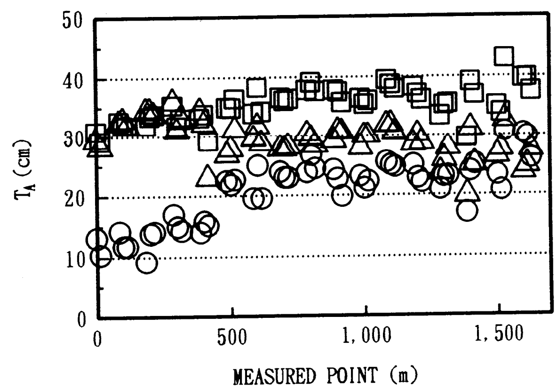

Fig. 8 Backcalculated T_A values by the three methods

where; $E0$, T, and T_A are as earlier defined
a, b, c, d, e, g, h, k are coefficients of regression, and
i=0 or 4

Using a computer subroutine provided to us by a member of University of Kentucky design team, it was possible to calculate pavement mean temperature, T as a function of pavement surface temperature, 5days mean air temperature prior to the day of testing, pavement AC layer thickness and total FWD test time. Having obtained the values of T, only two unknowns remained in the developed regression equations.

When these equations were converted into linear functions and solved simultaneously using another computer program and substituting actual FWD deflections for W_0 and W_4, then E0 and T_A values

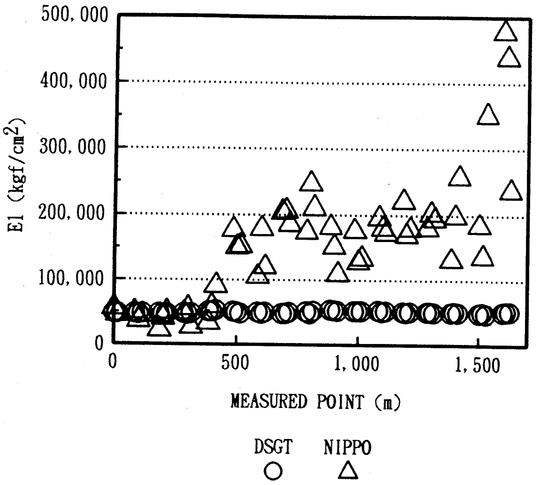

Fig. 9 Modulus of asphalt concrete, E1

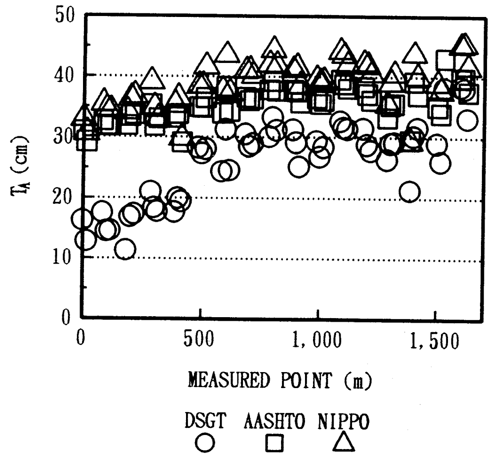

Fig. 10 Modified backcalculated T_A values

were obtained. Steps explained in the AASHTO Guide for Design of Pavement Structures were followed in the backcalculation analysis using AASHTO method.

NIPPO results presented in Figures 7 and 8 are as submitted to us by the company. According to the method, T_A values were calculated using AC layer coefficients with the assumption that, for E1 value greater than 25500 kgf/cm^2, AC layer coefficient was assigned a value equals to 1.0, if the above condition is not true then actual AC layer coefficient was used. Figure 9 shows values of modulus of AC layer, E1 backcalculated using DSGT and NIPPO methods.

Figure 10 shows backcalculated T_A values with NIPPO and DSGT values modified by a factor, α obtained by using a relation between modulus of AC, E1=25500 kgf/cm^2, backcalculated E1 and T_A values. E1=25500 kgf/cm^2 at 20°C is a value specified in AASHTO guide as a standard condition and was used in this research in analyzing FWD data from Route 219 for the purpose of achieving a common base among the three methods.

The equation used to calculate α , has been used in among others, AASHTO document as an approximate solution of two layers system using one layer theory. The equation used is as follows;

$$\alpha = T_A\left(\frac{E1(\text{GPa})}{2.55(\text{GPa})}\right)^{\frac{1}{3}} \tag{3}$$

7. DISCUSSION OF THE RESULTS

The results obtained, especially on the elastic modulus of the subgrade, E0 (see Figure 7) are reasonably well compared for all the three methods.

For the case of backcalculated T_A values, in Figure 8, DSGT values are a bit smaller than those obtained using the other two methods, especially, on the 0-500m stretch. This stretch was the one whose FWD deflections data depicted characteristics of a weak pavement structure. Figure 9, shows well compared results only on 0-500m stretch of the test road section. NIPPO values on 500-1700m stretch are very large as compared to DSGT values. These values, even though they support the theory that the pavement section is relatively stronger, they appear not to be realistic. They are too large. Looking at Figure 10, T_A differences between DSGT and the other two methods are much more clearer throughout the test section, but still, with bigger differences on 0-500m stretch. The findings when grouped together suggest that, even under constant conditions, dynamic and static analyses give different backcalculated T_A values for the analysis of FWD data. Moreover, the difference will be bigger if the pavement is weak. This means that the influence of dynamic loading on the backcalculated values between the two methods tends to be larger in a weak pavement section than in a relatively stronger one.

It can generally be said that static analysis tend to overestimate effective full depth AC pavement structure thickness when the results are compared to dynamic analysis results. This overestimation becomes even bigger, when the analysis is on the FWD data from a relatively weaker pavement. The main reason behind the difference is the mere fact that in static analysis inertial effect (radiation damping and resonance) of the pavement structure is not considered. This means, in simple terms, that the effect of the time dependent FWD loading in the pavement system is completely neglected. Simply replacing Young's modulus in the static analysis by the resilient pseudo-dynamic modulus obtained by using FWD deflection is not enough to explain dynamic response of a pavement system[4].

8. CONCLUSION

Results obtained for elastic modulus of the subgrade, E0 are reasonably well compared for all the three methods throughout the test road section. But, T_A values by DSGT are clearly smaller than those obtained by using AASHTO and NIPPO methods. Figures 8 and 10 have clearly shown that differences will be bigger if the pavement is weak. This means that the influence of dynamic loading on the backcalculated values using dynamic and static analyses tends to be larger in a weak pavement section than in a relatively stronger one.

Backcalculation result depends on, among other things, layer thickness, material stiffness and NDT device operating frequency of loading. In which case for example, if NDT device operating frequency of loading is close to the pavement system natural frequency, a much different pattern of deflections will result and hence bigger difference of results between the two methods of analysis may happen.

It is therefore recommended herein that dynamic analysis should be used to analyze pavement structural capacity in case FWD data are used.

It has not been possible to derive any simple or otherwise relation between dynamic and static analyses.

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ＦＷＤによる動的逆解析と静的逆解析結果の相違

James W.MAINA・横田　漠・牧　君明

本論文は、宮崎県西都市の国道２１９号で行われたＦＷＤ舗装構造の逆解析結果について述べるものである。ＦＷＤは動的載荷システムであるが、その逆解析は通常、静的理論が用いられている。ここでは、動的理論解析であるＤＳＧＴを逆解析に適用し、同結果をＡＡＳＨＴＯと日本鋪道の手法による解析結果と比較検討を行い、動的解析の必要性について吟味している。その結果、路床の弾性係数については３手法の結果に差異は認められなかったが、残存T_Aについては動的解析では小さめに評価され、特に弱い舗装の場合にそれが顕著に現れることが分かった。