EVALUATION OF BACK-CALCULATED RESULTS OF RIGID PAVEMENT

Boming TANG [1],Teruhiko MARUYAMA[2], Osamu TAKAHASHI [3] and Etsuro NODA[4]

[1]Member of JSCE, Dr. Eng., Associate Professor, Dept. of Civil Eng., Nagaoka University of Technology (Nagaoka, Niigata, 940-21, JAPAN)
[2] Member of JSCE, Dr. Eng., Professor, Dept. of Civil Eng., Nagaoka University of Technology (ditto)
[3]Member of JSCE, M. Eng., Research Associate, Dept. of Civil Eng., Nagaoka University of Technology (ditto)
[4]Member of JSCE, Chief Engineer, Technical Lab., The Nippon Road Co., LDT. (11-20,Tamagawa 2 Chome, Ota-Ku, Tokyo, 146 JAPAN)

By comparatively analyzing the FWD measurements with plate-on-liquid model and plate-on-elastic solid assumption, some frequently concerned questions associated with back-calculation results of concrete pavement were described in this paper. The results of the analysis presented indicate that : (a) the concrete slab modulus values back-calculated on the basis of the liquid model are unreasonably higher than what would normally be expected. (b) temperature gradient has a significant effect on FWD deflections and back-calculation results. (c) ratios of foundation moduli derived from different load locations are considerably dependent on foundation models and temperature gradient.

Key Words : *concrete pavement, deflection testing, back-calculation, foundation models, temperature gradient, load locations*

1. INTRODUCTION

Nondestructive testing (NDT) is now widely recognized as an important tool for highway and airfield pavements structural evaluation. One of the most popularity applications of NDT measurements is to back-calculate(BC) the layer moduli of pavement, and the basic BC procedure is to adjust the set of moduli until an acceptable match between the theoretical and measured deflections is obtained. As computing power increasing, it is not difficult to improve the goodness-of-fit of computed deflection basin to measured deflection basin. However, since the theoretical models are not closely enough related to the realities of a pavement, improving the goodness-of-fit does not necessarily mean that the BC results are reasonableness. For example, in many cases, the backcalculated concrete elastic modulus is considerably higher than what would normally be expected[1),2)]. Furthermore, it is still not clear whether the BC moduli are dependent on the locations of load (center, edge and corner) and pavement structural models [2)-4)].

In this study the theoretical deflection basin characterizations of concrete pavement are comparatively analyzed using the finite element method for plate-on-liquid and plate-on-elastic solid foundation. And then, many field data and BC results, including Kurihashi test pavement, Florida test pavements and three SHRP jointed concrete monitor sites data, are evaluated to answer of above questions. Finally, implications of BC results on pavement evaluation and design are discussed.

2. DEFLECTION BASIN CHARACTERIZATIONS OF CONCRETE PAVEMENTS

(1) Effect of change of modulus on surface deflection basin

Backcalculation of pavement moduli is an inverse problem solution. The possibility of back-calculating layer moduli is depended to a very large extent on the information that is contained in the deflection basins. Portland cement concrete pavements are commonly characterized as slabs-on-grade, e.g., the Hertz-Westergaard model of a slab supported by a liquid foundation. For a reference pavement of slab thickness H=25cm, concrete elastic modulus Ec=35GPa, and foundation reaction modulus k=80MPa/m, the effect of change of modulus of each layer and slab thickness on surface deflections under slab center load were analyzed with the finite element program KENSLABS[5]. Fig.1 is quite clearly shown: (1)All deflection basins are heavily influenced by the foundation deformation. As the foundation stiffness (values-k) was decreased, the deflection basins would generally shift downward, while remaining in roughly the same shape. (2)Variations in concrete elastic modulus and slab thickness show significant influence on deflections occurring only at and near the applied load. At more than a certain distance (about 1.2m in this case) away from the load, the changes in Ec and H have few effects on surface deflection.

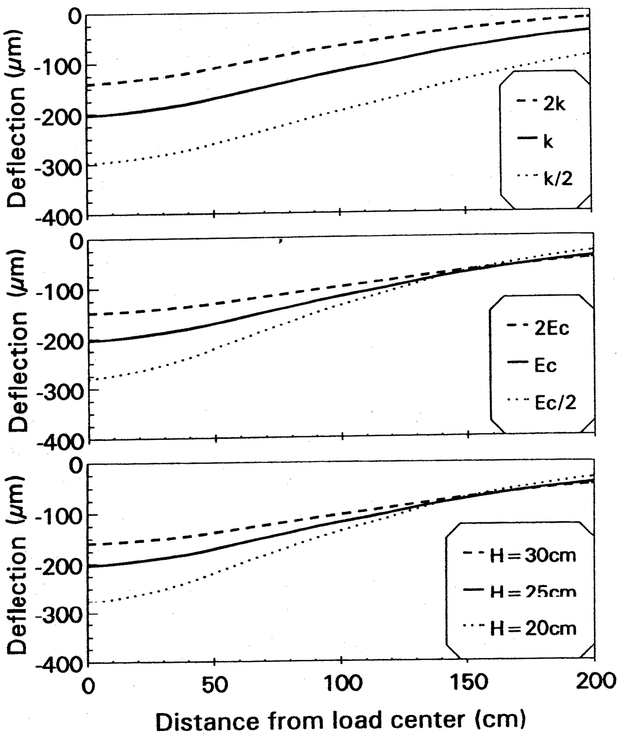

Fig. 1. Effect of change of moduli & slab thickness on theoretical deflection basins

According to above theoretical deflection basin features, it can be concluded that, for a measured pavement deflection basin, the backcalculation values-k is mainly dependent on the deflection at the farthest sensor from the test load, and the backcalculation values-Ec can be significant related to deflection basin shape. Therefore, the reasonable of BC moduli are heavily depended on the extent of theoretical deflection (especially the deflection basin shape) fitted in with practice pavements, if a theory model deviates some of an existing pavement structure, unreasonable moduli may be derived.

(2) Comparison between liquid and elastic solid foundation

In fact, all theory models are not closely enough related to the realities of a pavement, albeit of differing degrees, e.g., P.Ullidtz's recent investigations confirmed that "the agreement between measured and calculated response of asphalt pavement is far from satisfactory" [6].

In general, two types of structural models are widely used for evaluating the load deformation characteristics of concrete pavements. These are plate-on-liquid model (Winkler foundation) and plate-on-elastic solid assumption. In liquid model, the deflection at a node depends solely on the modulus subgrade reaction, k, and at the node but not elsewhere. In contrast to liquid foundation, elastic solid model takes into account the effect of shear interaction between adjacent foundation elements, the deflection at a node depends not only on the elastic modulus Es of the subgrade, but also on the deflections at other nodes. Because of the difference in the basic assumption of two types of supporting model, the shapes of the theoretical deflection basins of the concrete slab are different between the liquid foundation and the elastic foundation.

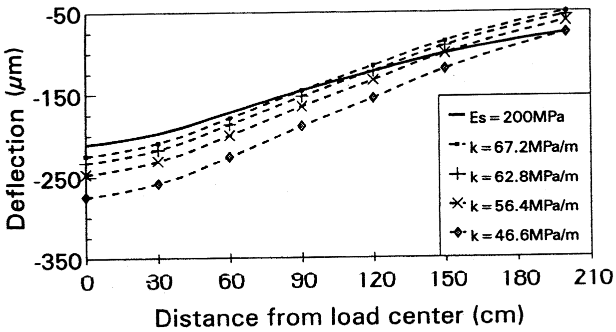

Fig. 2. Comparison of deflection basins shapes between liquid and solid foundation model

In Fig.2 the Es-value was assumed to be 200MPa for pavement on elastic assumption, the corresponding values of modulus of subgrade reaction k, used for pavements on liquid foundation were determined by matching deflections at 90cm, 120cm, 150cm, 200cm from load center in concrete pavement, respectively. It can be recognized that the deflection basin is much steeper in the liquid subgrade than in the elastic subgrade. When the deflection at the farther point is in agreement, the deflections closer to the load for the case of liquid sudgrade are consistently greater than those for a solid subgrade, and as the agreement point farther from load center, much greater difference exists in load center deflection between two models.

With regard to the BC moduli, it means that the Ec derived from liquid model should be always greater than that is from solid assumption, and as radial offset of the sensor increasing, the backcalculation Ec should be much greater. This observation can be verified by following BC examples. Fig.3 showed the FWD deflection basins and BC results of three typical test sections of SHRP-ETG[1]. It can be seen that: for goodness of fit of theory deflections to measured deflection basins, the concrete slab modulus value(Ec) backcalculated on the basis of the Winkler model is approximately 1.5 times as which is determined from plate-on-elastic solid model (in this case the radial of sensor is 150cm), and the former is usually higher than what would normally be expected, e.g., SHRP's range of reasonableness of Ec is between 21~49GPa. By the way, the BC Ec-values are also depended on base type, especially the cement treated base seems to result in apparently high slab moduli.

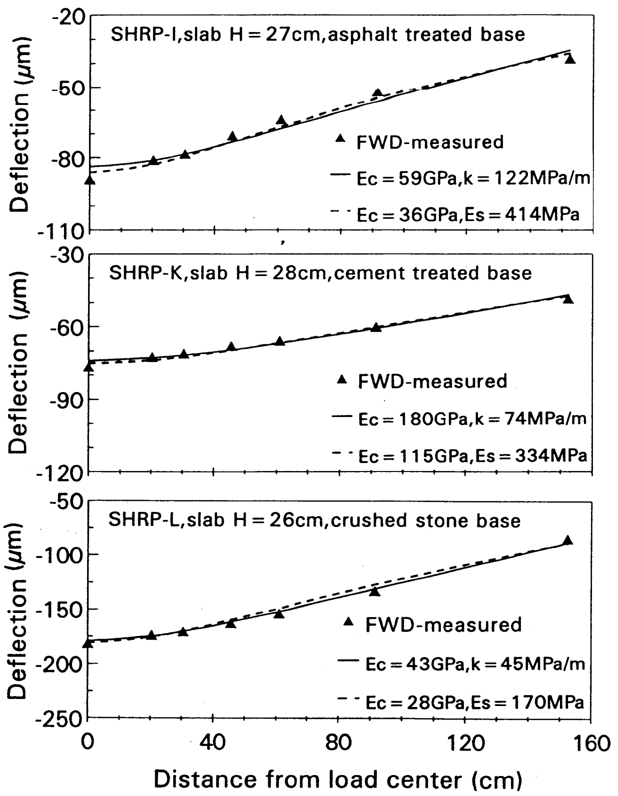

Fig. 3. Comparison of measured and computed deflection basins for three sections of SHRP

Furthermore, based on some BC results from ILLI-BACK3.0[1], one of six backcalculation software selected by SHRP's Expert Task Group, it can be observed(see Fig.4) that the Ec derived from large sensor case(0~150cm) is about 1.5 times as which is from 0-90cm of sensor arrangement.

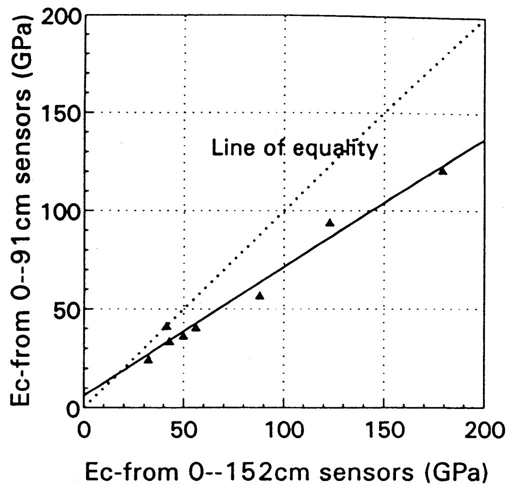

Fig. 4. Comparison values-Ec derived from different sensor arrangement

In United States, especially in University of Illinois, to avoid unrealistically high Ec-values, the sensor at large r values was usually ignored, e.g., in the research subject of "Performance of jointed concrete pavements" [7], a lot of deflection data were measured by FWD which sensors located between 0~150cm from load center, but the BC analysis was done only according to 0~90cm sensors. The reason for ignoring sensors at large distance is that "concrete pavement deflection are so small that measurements from large r sensors may be unreliable" [1),7)]. This is not a satisfactory explanation, however. It is the author's opinion that the unreasonable higher BC Ec-values are mainly due to the deviation between theory model and actual pavement structure, especially, the deflection basin shapes.

3. EFFECT OF LOAD LOCATIONS ON BACKCALCULATION RESULTS

Current concrete pavement backcalculation procedures are usually for slab center FWD load case. However, for concrete pavement design and evaluation, the critical load positions are slab edge (for stresses) and slab corner (for deflections).

The validity of using center slab backcalculation k-values and slab Ec values at the slab edge was studied by Foxworthy[8], and results from several pavement sections showed that it was entirely appropriate to BC k & Ec from the center deflection and to use these values at the edge for stress calculations. However, J.Uzan's recent study [3),4)] concluded that the k-values at the center of slab appear very low, and k at the edge is two to four times higher than that obtained from the center slab.

Why they have above contradictory results? How to explain these results?

(1) For slab corner load case

For concrete pavements, the curling of slab due to temperature gradient(TG) causes a large variation in measured deflection, and then has a significant influence on BC results. Therefore, the temperature conditions must be carefully considered when comparing the BC moduli from different load locations.

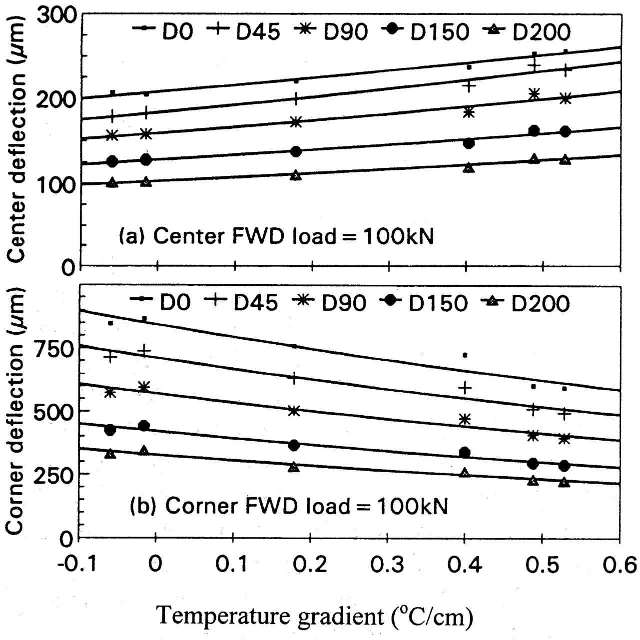

Fig. 5. Temperature gradient versus deflections (measured at Kurihashi test slab in 1995/9/25)

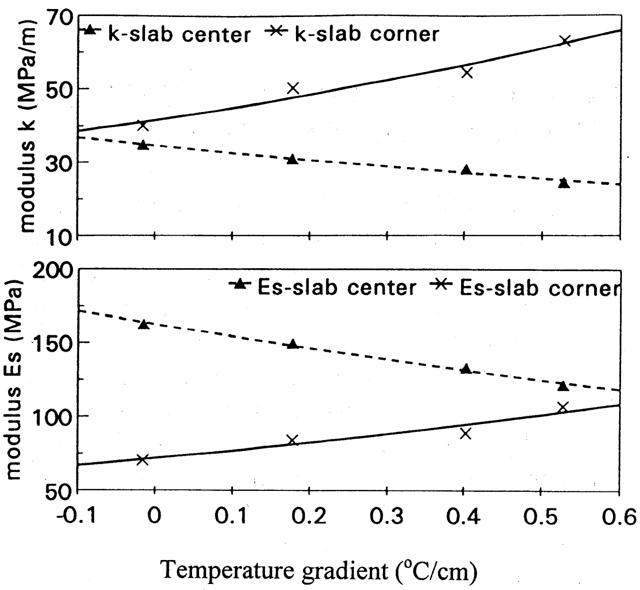

Fig. 6. Backcalculation foundation moduli versus temperature gradient

Fig.5 showed typical results from Kurihashi test slab[9], it was noted that the deflection basins varied significantly as the TG varied, when the TG increases, the slab center FWD load deflection increase, and, conversely, the corner load deflection basin decrease.

The backcalculated results of above deflection basins data indicate that as the TG varying, slab concrete elastic modulus Ec-values shows little change only, but foundation moduli k & Es vary significantly(see Fig.6). It is interesting to note from Fig.7 that as TG increasing, the ratio between corner modulus and center modulus increase, for Winkler model, the ratios is about 1 to 2.5, whereas for solid foundation assumption, the ratios is consistently less than 1. When TG=0, the ratios for k and Es foundation are 1.2 and 0.5, respectively.

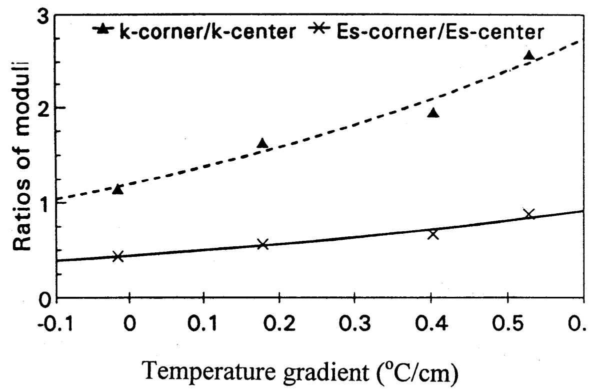

Fig. 7. Ratios of foundation moduli versus TG

(2) For slab edge load case

Kurihashi test pavement only has slab center & corner measurements, to investigate edge load case, the FWD data from concrete pavement sections on highway I-10 in Florida will be analyzed in this section[10),11)]. In I-10 pavement, the concrete slab is 3.6m wide, 6m long and 23cm thick. For slab center case, the FWD test was run at midnight when the recorded TG was negative, and the slab had full contact with the subgrade at the center. For edge of a slab, tests were conducted at midday when the recorded TG was positive, the slab was curled downward at the edges and had fill contact with the subgrade at the edges.

The measurements and BC results of these test slab are presented in Table 1 and Table 2. For slab center & edge case, the Ec-values are nearly same, and the k-values obtained from free-edge loading case is about 1.7 times as the values obtained from the interior loading case, whereas for solid foundation assumption, the Es from edge case is consistently less than the values derived from the interior loading case.

Table 1. Comparison of measured & computed FWD deflection basins for center load case

(measured at midnight on Florida highway--section I-10, FWD load P=40kN)

Slab Number	Deflection, μm	D0	D30	D60	D90	D120	D150	Ec, GPa	Es, MPa	k, MPa/m
115#	measured	109.0	103.0	79.0	75.0	60.0	49.0			
	calculated-1	109.1	102.7	89.4	73.9	58.5	43.9	45		55
	calculated-2	109.0	101.4	86.7	71.5	58.7	47.9	28	170	
215#	measured	59.0	49.0	38.0	32.0	25.0	21.0			
	calculated-1	53.2	49.4	41.8	33.4	25.4	18.9	70		137
	calculated-2	56.0	50.5	41.0	32.2	25.1	19.7	35	400	
413#	measured	77.4	64.2	53.0	37.7	28.5	21.4			
	calculated-1	74.4	67.6	54.5	40.9	28.9	19.1	35		128
	calculated-2	74.0	65.3	51.1	38.5	29.1	22.5	20	340	
416#	measured	61.2	51.9	43.6	32.2	25.9	20.8			
	calculated-1	57.2	52.8	44.2	34.8	25.9	18.3	59		136
	calculated-2	58.0	52.5	42.8	33.8	26.4	20.8	35	381	

Table 2. Comparison of measured & computed FWD deflection basins for edge load case

(measured at midday on Florida highway--section I-10, FWD load P=40kN)

Slab Number	Deflection, μm	D0	D30	D60	D90	D120	D150	Ec, GPa	Es, MPa	k, MPa/m
115#	measured	211.2	186.9	164.6	136.7	102.9	81.5			
	calculated-1	199.5	187.7	162.1	132.6	104.0	78.6	45		95
	calculated-2	209.0	194.0	163.7	132.0	104.2	81.7	28	126	
215#	measured	102.3	89.7	71.4	54.0	39.6	29.9			
	calculated-1	97.3	89.9	74.5	57.6	42.2	29.5	65		245
	calculated-2	99.7	89.8	71.3	53.6	39.6	29.5	35	310	
413#	measured	125.3	111.0	92.7	69.3	53.0	35.6			
	calculated-1	122.0	112.6	92.8	71.4	51.8	35.8	50		200
	calculated-2	125.9	113.5	90.2	67.9	50.3	37.5	28	245	
416#	measured	119.3	95.5	78.9	56.0	42.5	31.1			
	calculated-1	103.7	95.6	79.0	60.7	44.0	30.5	59		235
	calculated-2	107.7	96.5	75.8	56.4	41.3	30.6	30	294	

* 1) calculated-1 is BC from plate-on-liquid model, calculated-2 is BC from elastic solid model.

2) D0, D30, D60, D90, D120, and D150 represent the deflections at the center, 30, 60, 90, 120 and 150cm away from FWD load center.

(3) Discussion of the results

Based on above, it appears that the BC moduli is obviously depended on the location of load. However, it is still not clear what the cause is of the discrepancy of the moduli ratio and considerably different between k & Es models. To explain above observation, the theory relationship between k & Es will be analyzed in this section.

The Es model is usually regarded as a more realistic representation of actual foundation behavior. However, due to simplicity in application, k values have been used most frequently for the design and evaluation of concrete pavement. Vesic and Saxean[3),12)] presented an extensive theoretical analysis of slab on liquid and elastic foundations and concluded that no one-to-one correlation can exist between k and Es. Ioannides's recent study also shows that the relationship between k & Es depends on the structural properties of the slab[13)] (namely: placed layers; supporting medium; and geometry of applied loads). In this study, deflections are the author's main concern. Using the finite element method, numerous theoretical deflection basins were generated for Es model pavement, and the corresponding values of modulus of subgrade reaction k, were then determined by matching the maximum deflection between Es and k models. Based on above analysis procedure, following equations were obtained:

For center loading $k=0.4(Es/Ec)^{1/3}Es/(1-\mu_s^2)/h$ (1)

For edge loading $k=(Es/Ec)^{1/3}\ Es/(1-\mu_s^2)/h$ (2)

For corner loading $k=1.9(Es/Ec)^{1/3}\ Es/(1-\mu_s^2)/h$ (3)

where μ_s is the Poisson ratio of foundation; h is the slab thickness.

It is interesting to note that the relationship between k & Es depends on the loading positions, if using same Es-values for different loading positions, the corresponding k-values should be $k_{edge}=2.5\ k_{center}$, and $k_{corner}=4.75\ k_{center}$. On the other hand, if using same k-values for different load positions, the corresponding Es-values should be $Es_{edge}=0.5Es_{center}$, and $Es_{corner}=0.3Es_{center}$. In fact, the dense liquid and elastic solid models may be viewed as two ends of a spectrum of possible foundation idealizations. In situ subgrade behavior probably lies between these two extremes, sometimes closer to one than the other. In China, Es model has been used for concrete pavement design for many years, and results from a large number of test pavements indicated that the Es-values for the edge loading condition is nearly 75 percent of that for the interior loading case[14]. Accordingly, $k_{edge}=1.7k_{center}$ can be derived from equation(1)&(2). Ioannides's theory study also indicated that a gradual increase in the k-values as the load moves from the center to the edge and then to the corner would be acceptable[15].

4. SUMMARY AND CONCLUSIONS

Backcalculation methods for determining elastic moduli from deflection basins obtained by NDT devices have provided engineers with a tool to improve pavement design and management. Nevertheless, it is important to verify the reliability of BC results. However, since we do not know exactly the in situ layer moduli, and the verification of pavement response models is unfortunately rather difficult, so that, it is hard to find an adequate criteria for evaluating the reasonableness of the moduli derived from backcalculation methods. Based on comparison analysis method, which is between liquid and elastic solid models, some frequently concerned questions associated with BC moduli of concrete pavement were described in this paper. The main conclusions from this study can be summarized as follows:

(1). In general, the concrete slab modulus value(Ec) backcalculated on the basis of the plate-on-winkler model is approximately two times as which is determined using the plate-on-elastic solid model, and the former is usually higher than what would normally be expected. Of course, unreasonably high Ec-values can not be used for stress calculation, since this would lead to greatly overestimated load stresses and temperature stresses.

(2). Temperature gradient has a significant effect on FWD deflections and BC results. As TG increase, the interior deflection increase, and, conversely, the edge/corner deflection decrease. With regard to the BC moduli, for slab center case, the foundation moduli derived from midday testing is only about half of that from midnight testing (during the summer season), but for edge & corner locations, the results are opposite to above case.

(3). Theoretical studies and BC practices indicate that the foundation moduli seems to depend on the load locations, and the ratios of BC moduli derived from different load locations are considerably dependent on the foundation models and temperature gradient. For winkler model, backcalculated edge/corner k-values are higher than interior values, whereas for solid foundation assumption(Es), backcalculated edge/corner Es-values are consistently less than interior values. The appropriate choice of foundation support model is perhaps the most controversial of decisions, but it is shown from above studies that the Es model may be more suitable than k model. Briefly, it is the author's opinion that we should carefully consider which value of k & Es will be used in the overlay design.

Currently, multi-layer theory and dynamic finite-element analysis seems to be the most promising method for concrete pavements back-calculation. However, the method chosen should be compatible with that is used to make design calculations. In a word, the gap between analysis of deflection data and application in practice is the most important research needed.

ACKNOWLEDGMENT : The writers would to thank Japan FWD Research Association for the availability of the valuable data of Kurihashi test slab. The technical advice provided by Dr.Tatsu Nishizawa are appreciated.

REFERENCES

1) A.M.Ioannides(1994), Concrete pavement back-calculation using ILLI-BACK3.0, Nondestructive Testing of Pavement and Backcalculation of Moduli (Second Volume), ASTM STP 1198.

2) M.I.Darter, K.D.Smith, K.T.Hall(1992), Concrete pavement backcalculation results from field studies, Transportation Research Record 1377.

3) J.Uzan, R.Briggs, T.Scullion(1992), Backcalculation of design parameters for rigid pavements, Transportation Research Record 1377, TRB.

4) J.Uzan(1992), Rigid pavement evaluation using NDT--case study, Journal of Transportation Engineering, ASCE, Vol.118, No.4.
5) Y.H.Huang(1993), Pavement analysis and design, Prentice-Hall, Inc.
6) P.Ullidtz N.F.Coetzee(1995), Analytical procedures in Nondestructive Testing pavement evaluation, Transportation Research Record 1482, TRB.
7) K.D.Smith, D.G.Peshkin et al.(1990), Performance of jointed concrete pavements, Volume 2--Evaluation and Modification of concrete pavement design and analysis models. FHWA-RD-89-137, FHWA, U.S.Department of Transportation.
8) P.T.Foxworthy(1985), Concepts for the development of a Nondestructive Testing and evaluation system for rigid airfield pavements. Ph.D.thesis, University of Illinois at Urbana-champaign.
9) Japan FWD Society(1995), FWD research report--Second Volume (in Japanese).
10) M.Tia, K.S.Eom, et al.(1989), Development of the DBCONPAS computer program for estimation of concrete pavement parameters from FWD data, Nondestructive Testing of Pavement and Backcalculation of Moduli, ASTM STP 1026.
11) C.L.Wu, M.Tia(1994), Field testing and structural evaluation of selected concrete pavement sections in Florida, Nondestructive Testing of Pavement and Backcalculation of Moduli(Second Volume), ASTM STP 1198.
12) Y.T.Chou(1983), Subgrade contact pressures under rigid pavements, Journal of Transportation Engineering, ASCE, Vol.109, No.3.
13) A.M.Ioannides(1991), Subgrade characterization for Portland cement concrete pavements, Proceedings, International Conference on Geotechnical Engineering for Coastal Development--Theory and Practice, PHRI, MOT, Japan.
14) Y.Zukang(1985), Structural design of concrete pavements in China, Proceedings, Third International Conference on Concrete Pavement Design and Rehabilitation. Purdue University.
15) A.M.Ioannides et al.(1985), Westergaard solutions reconsidered, Transportation Research Record 1043, TRB.
16) J.A.Crovetti(1994), Evaluation of support conditions under jointer concrete pavement slabs, Nondestructive Testing of Pavement and Backcalculation of Moduli(Second Volume), ASTM STP 1198.
17) A.A.A.Molenaar, State of the art of pavement evaluation, Proceedings, the 4th International Conference on the Bearing Capacity of Roads and Airfields, Minnesota, U.S.A.
18) M.I.Dater, K.T.Hall, C.M.Kuo(1995), Support under Portland cement concrete pavements, NCHRP Project 1-30, TRB

コンクリート舗装の弾性係数の逆解析に関する一検討

唐伯明・丸山暉彦・高橋 修・野田悦郎

本研究は，コンクリート舗装の弾性係数をFWDの測定たわみから逆解析によって求める場合，解析結果に影響を及ぼす主要因子について検討した．特に，路盤モデルにWinkler路盤と弾性路盤を用いた場合の解析結果を比較し，その違いについて言及した．その結果，以下のことが確認された．(a)Winkler路盤で逆解析したコンクリート版の弾性係数は通常の値よりも大きく計算される．(b)FWD測定たわみはコンクリート版内に生じる温度勾配に影響され，解析結果もその影響を受けることになる．(c)路盤の逆解析弾性係数はコンクリート版の載荷位置の違いによって異なるが，路盤モデルの違いおよび温度勾配によっても多大な影響を受ける．