Evaluation of Backcalculation Layer Moduli on Three-Layer Flexible Pavement System

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ABSTRACT: In 1943, Burmister introduced an analytical solution to overcome a practical problem in designing an economical pavement with sufficient thickness over a subgrade to provide adequate support for traffic load. Using this solution, a backcalculation algorithm can be developed to obtain the layer elastic moduli. Making use of hypothetical data, this paper evaluates the choice of the optimum configuration of deflection measurements for backcalculating the layer elastic moduli of a flexible pavement system consisted of three layers, i.e. surface layer, subbase layer and subgrade. Two computer programs (FPAVE3 based on closed-form backcalculation algorithm; and EVERCALC based on iterative trial and error backcalculation algorithm) were evaluated based on two types of deflections, exact and random deflections. The assessment of the optimum deflection selection was conducted by comparing the discrepancies between the computed elastic moduli against their true moduli and analyzing the dispersion of the computed moduli calculated based on random deflection. The results showed that the deflection sensors near the load could better estimate the layer moduli, especially for elastic moduli of surface and subbase layer. On the other hand, the estimation of elastic modulus of subgrade is not much dependent on the choice of deflection sensor configuration.

KEYWORDS: Flexible pavement system, backcalculation algorithm, deflection sensor configuration.

1 INTRODUCTION

The analytical solution of a three-layer flexible pavement system was derived by Burmister in 1945. The solution is an extension of the solution for two-layer flexible pavement system developed earlier by Burmister (1943, 1945a). The intention was to overcome the practical problem in designing an economical pavement with sufficient thickness over a weak subgrade to provide adequate support for heavy aircraft wheel loads. For this purpose, a granular layer is added between the surface layer and subgrade.

The use of granular materials in the pavement system usually has a purpose for economy, although they also may contribute to protect the subgrade by reducing the stress intensity through spreading the applied load over a larger area. In general, the use of granular material in the pavement system is to serve as a transition of two materials in the pavement system, i.e. surface layer and subgrade, which have a large difference in their structural capacity. In addition, the subbase also has a function as a filter to prevent the subgrade materials from infiltrating into the base course.

To make use of the Burmister's solution for three-layer flexible pavement in pavement maintenance programs using deflection measurements, a closed-form backcalculation algorithm, namely FPAVE3, was developed based on the solution. This paper intends to evaluate the selection of deflection sensor configuration in backcalculation analysis using the proposed algorithm and a backcalculation program based on iterative process, EVERCALC (WSDOT, 2005). For this purpose, two types of deflections were considered, that is, exact deflections and deflections with measurement errors.

2 BACKCALCULATION ALGORITHMS USED IN THIS STUDY

2.1 Closed-form Backcalculation Algorithm

Closed-form backcalculation algorithm, FPAVE3, was developed based on a Burmister's solution. In the backcalculation analysis of layer moduli of a three-layer flexible pavement system, there are two known parameters (thickness layer and Poisson ratio) and three unknown parameter which correlates with three elastic moduli of the pavement layers (E_1, E_2 and E_3). To solve simultaneously the unknowns, the algorithm requires at least three measured deflections from three different locations, as given by

$$w_{31} = \frac{\left(1-\mu_1^2\right)P}{\pi\, E_1} F_{31}(q,k) \tag{1a}$$

$$w_{32} = \frac{\left(1-\mu_1^2\right)P}{\pi\, E_1} F_{32}(q,k) \tag{1b}$$

$$w_{33} = \frac{\left(1-\mu_1^2\right)P}{\pi\, E_1} F_{33}(q,k) \tag{1c}$$

where w_{31}, w_{32} and w_{33} are the measured deflections of a three-layer pavement system at distance r_1, r_2, and r_3 respectively from the load P; k and q are the moduli ratios, and F_{31}, F_{32}, and F_{33} are deflection factors each is a function of k and q.

All the equations above are composed of infinite integrals of product of Bessel functions; therefore it is difficult to solve them directly. To overcome this problem, this study simplified the equations by dividing the two of them by the third one to obtain two nonlinear equations with two unknowns k and q, as follows.

$$Y_{31} = w_{31}F_{32}(q,k) - w_{32}F_{31}(q,k) \tag{2a}$$

$$Y_{32} = w_{31}F_{33}(q,k) - w_{33}F_{31}(q,k) \tag{2b}$$

To obtain the roots (k, and q) from the nonlinear equations above, the Nelder-Mead optimization method (Nelder and Mead, 1965) was used. After the values of k and q are determined, the elastic modulus of the surface layer is calculated by using the deflection equations.

2.2 Iterative-based Backcalculation Algorithm

EVERCALC is an iterative-based backcalculation program using a nonlinear least-squares optimization technique with CHEVRONX (an enhanced version of the widely-used

CHEVRON program) as the forward calculation program. The error function at location *i* used by the program is represented by

$$r_i(E,h) = \frac{d_i^c(E,h) - d_i^m}{d_i^m} \tag{3}$$

where $d_i^c(E,h)$ is the calculated deflection at location *i* based on *E* and *h*, *E* is the layer moduli and layer thicknesses, and d_i^m is the measured deflection at location *i*. An efficient and general minimization method (Levenberg-Marquardt algorithm) has been implemented in EVERCALC, which makes it converge quickly with only a small number of calls to the mechanistic analysis program (Sivaneswaran et al., 1991).

The program produces a solution when the summation of the absolute values of the discrepancies between the measured and theoretical surface deflection falls within a predetermined allowable tolerance. EVERCALC backcalculation program requires a set of seed moduli to start the backcalculation analysis. The seed moduli may be determined by internal program or by user-input. However, EVERCALC only permits user to generate the seed moduli using the internal program if the number of pavement layer in the backcalculation process equals or less than three layers.

3 SELECTION OF THE OPTIMUM DEFLECTION

Evaluation procedure to select the optimum deflection basin adopted by this study is as follows.

a. Two types of deflection were considered in this study, that is, exact deflections and random deflections (deflection with measurement errors). For exact deflection, the deflections were calculated using Burmister's solution and CHEVRONX, based on the following four cases:

   - Case 1 (the original state): E_1 = 1,379.3 MPa (200 ksi), E_2 = 758.6 MPa (110 ksi), E_3 = 206.9 MPa (30 ksi), h_1 = 0.127 m (5 in.), h_2 = 0.254 m (10 in.), P = 71.1 kN (15,985 psi)
   - Case 2 (change the moduli of subbase and subgrade): E_2 = 206.9 MPa (30 ksi), and E_3 = 103.4 MPa (15 ksi), the rest of the data is same with case 1.
   - Case 3 (change the layer thicknesses): h_1 = 0.254 m (10 in.), h_2 = 0.635 m (25 in.), the rest of the data is same with case 1.
   - Case 4 (change the magnitude of the load): P = 44.5 kN (10 ksi), the rest of the data is same with case 1

   Six sensors with distance r_1, r_2, r_3, r_4, r_5, and r_6 equal to 0.203, 0.305, 0.457, 0.61, 0.914 and 1.524 m, respectively, from the load are adopted. The surface deflections calculated using Burmister's solution and CHEVRONX are depicted in Table 1. On the other hand, the random deflections in this study were generated using Pronk formula (1988) as follows.

$$d_m = d_t + 0.02 d_t \frac{(r_1 - 0.5) r_2}{|r_1 - 0.5|} + 2 \frac{(r_3 - 0.5) r_4}{|r_3 - 0.5|} \tag{4}$$

   in which d_m is the measured deflections (micrometers), d_t is the true deflections (micrometers); and $r_1 – r_4$ are random numbers between 0 and 1.

Table 1: Surface deflections by two different forward calculation programs

Methods	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_5 (mm)	d_6 (mm)
Case 1: original state (E_1 = 1,379.3 MPa, E_2 = 758.6 MPa, E_3 = 206.9 MPa, h_1 = 0.127 m, h_2 = 0.254 m, P = 71.1 kN)						
Burmister's solution	0.2844	0.2330	0.1824	0.1475	0.1014	0.0574
CHEVRONX	0.2896	0.2339	0.1826	0.1471	0.1011	0.0572
Case 2: change the subbase and subgrade moduli (E_2 = 206.9 MPa, E_3 = 103.4 MPa), the rest is same as case 1						
Burmister's solution	0.6720	0.5319	0.3899	0.2994	0.1963	0.1113
CHEVRONX	0.6680	0.5309	0.3912	0.2997	0.1963	0.1113
Case 3: change the thicknesses (h_1 = 0.254 m, h_2 = 0.635 m), the rest is same as case 1						
Burmister's solution	0.1796	0.1520	0.1259	0.1092	0.0868	0.0597
CHEVRONX	0.1862	0.1532	0.1260	0.1087	0.0861	0.0594
Case 4: change the load (P =44.5 kN), th rest is same as case 1						
Burmister's solution	0.1779	0.1458	0.1141	0.0923	0.0634	0.0359
CHEVRONX	0.1811	0.1463	0.1143	0.0919	0.0632	0.0358

Note: d_1, d_2, d_3, d_4, d_5 and d_6 are deflections at radial distance 0.203, 0.305, 0.457, 0.61, 0.914 and 1.524 m respectively from the load

Due to a small amount of deflection may cause a significant difference of the moduli resulted, different measured deflections were generated for each set of deflections produced by each forward-calculation program in this study. Ten sets of generated measured deflection for each backcalculation method are listed in Table 2.

Table 2: Random deflections for different backcalculation methods

Set	Random deflections for each backcalculation program (mm)											
	FPAVE3						EVERCALC					
	d_1	d_2	d_3	d_4	d_5	d_6	d_1	d_2	d_3	d_4	d_5	d_6
1	0.2882	0.2360	0.1845	0.1490	0.1021	0.0573	0.2935	0.2369	0.1848	0.1486	0.1018	0.0571
2	0.2847	0.2334	0.1829	0.1481	0.1021	0.0581	0.2899	0.2343	0.1831	0.1477	0.1018	0.0579
3	0.2833	0.2321	0.1818	0.1470	0.1011	0.0572	0.2884	0.2330	0.1820	0.1466	0.1008	0.0570
4	0.2818	0.2307	0.1803	0.1456	0.0996	0.0558	0.2870	0.2316	0.1805	0.1451	0.0993	0.0556
5	0.2901	0.2380	0.1867	0.1513	0.1045	0.0599	0.2954	0.2390	0.1869	0.1509	0.1042	0.0597
6	0.2820	0.2310	0.1807	0.1461	0.1002	0.0565	0.2871	0.2319	0.1809	0.1456	0.1000	0.0563
7	0.2865	0.2350	0.1843	0.1492	0.1030	0.0588	0.2917	0.2359	0.1845	0.1488	0.1027	0.0586
8	0.2818	0.2311	0.1811	0.1466	0.1010	0.0575	0.2869	0.2320	0.1813	0.1462	0.1007	0.0573
9	0.2846	0.2330	0.1821	0.1471	0.1007	0.0565	0.2898	0.2339	0.1823	0.1466	0.1004	0.0563
10	0.2809	0.2303	0.1805	0.1461	0.1007	0.0573	0.2860	0.2312	0.1807	0.1457	0.1004	0.0571

Note: The true deflections for d_1, d_2, d_3, d_4, and d_5 are 0.2844, 0.2330, 0.1824, 0.1475, 0.1014 and 0.0574 mm for FPAVE3; 0.2896, 0.2339, 0.1826, 0.1471, 0.1011 and 0.0572 mm for EVERCALC

b. Perform backcalculation analysis on assigned deflection readings. FPAVE3 requires minimum three deflection readings per each configuration for backcalculating three pavement properties (E_1, E_2 and E_3), while EVERCALC has no minimum requirement to start the backcalculation analysis. The use of only three deflection readings, instead of all readings, per configuration could minimize the error occurred in the backcalculation process since it is known that the measured deflection used in the calculation is almost not possible to have free errors.

For the sake of fairness, three deflection readings were selected for each configuration. Since six deflection readings were considered used in this study, it means that twenty sensor configuration (or ${}_6C_3$) were evaluated. For EVERCALC, the following seed moduli were set to start the backcalculation analysis: E_1 = 2,690 MPa (390 ksi), E_2 = 670 MPa (100 ksi) and E_3 = 207 MPa (30 ksi).

c. Assess the performance of all sensor configurations by means of:
   - deviation between the true and the computed moduli (for exact deflection)
   - statistic properties of the backcalculated moduli to analyze the dispersion of the computed moduli against the true ones (for random deflection).

4 ANALYSIS OF THE RESULTS

The analysis was conducted based on two types of deflections used, i.e. exact and random deflections. Table 3 conveys the deviation between the true and computed layer moduli produced by the two backcalculation algorithms using twenty sensor configurations. The errors values in this table represent the root mean square percent error (RMSPE) of four computed layer moduli (based on exact deflections in Table 1) in estimating the corresponding true moduli. As overall, it showed that FPAVE3 could better estimate the layer moduli than EVERCALC, as indicated by the values of the absolute error (see Table 3).

Table 3: Root mean square percentage errors (RMSPE) of computed layer moduli based on exact deflections

FPAVE3						EVERCALC					
E_1		E_2		E_3		E_1		E_2		E_3	
Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)
1-4-6	0.17	2-3-5	0.02	1-4-6	0.00	1-2-4	3.87	1-2-5	0.39	1-2-5	0.10
2-3-5	0.22	1-4-6	0.04	1-5-6	0.00	1-2-5	5.09	1-2-4	0.50	1-3-5	0.12
1-5-6	0.26	3-5-6	0.04	1-4-5	0.00	1-2-6	5.34	1-3-5	1.12	1-4-5	0.17
1-4-5	0.31	2-4-5	0.05	2-3-5	0.00	1-2-3	7.09	1-2-3	1.49	1-2-4	0.21
2-3-6	0.45	1-4-5	0.06	2-5-6	0.01	1-3-5	19.78	1-3-4	1.54	2-3-4	0.22
2-4-5	0.55	1-5-6	0.06	2-4-5	0.01	1-3-4	20.78	1-4-5	1.83	1-3-4	0.22
1-3-6	0.66	3-4-5	0.08	3-5-6	0.01	1-4-5	22.81	1-2-6	2.10	2-3-5	0.23
1-3-5	0.82	2-5-6	0.10	2-3-6	0.01	1-3-6	41.02	3-4-5	2.56	2-4-5	0.28
2-3-4	0.83	2-3-6	0.12	1-3-6	0.03	3-4-6	48.07	2-3-4	2.60	1-2-3	0.29
1-3-4	0.98	1-2-6	0.16	4-5-6	0.03	2-5-6	50.24	2-3-5	3.01	3-4-5	0.36
3-5-6	0.99	4-5-6	0.20	1-3-5	0.03	3-4-5	63.02	2-4-5	4.07	3-4-6	0.78
2-5-6	1.02	2-3-4	0.22	2-3-4	0.04	1-4-6	74.49	3-4-6	4.14	3-5-6	0.78
1-2-3	1.04	1-3-6	0.31	1-3-4	0.05	2-3-4	81.65	3-5-6	4.16	2-5-6	0.78
1-2-4	1.13	1-3-4	0.35	3-4-5	0.05	2-3-5	87.52	1-3-6	4.67	1-5-6	0.82
1-2-5	1.79	1-3-5	0.38	1-2-6	0.09	3-5-6	101.74	2-5-6	4.68	1-4-6	0.90
4-5-6	1.79	3-4-6	0.44	3-4-6	0.10	2-4-5	110.79	2-3-6	6.69	1-2-6	0.90
3-4-5	2.76	1-2-3	0.66	1-2-4	0.12	1-5-6	119.74	2-4-6	7.16	4-5-6	0.93
3-4-6	12.51	1-2-4	0.73	1-2-3	0.14	2-3-6	135.28	1-4-6	8.07	1-3-6	0.95
1-2-6	15.77	2-4-6	0.76	1-2-5	0.16	2-4-6	143.31	4-5-6	9.57	2-4-6	0.99
2-4-6	31.70	1-2-5	1.27	2-4-6	0.54	4-5-6	164.39	1-5-6	13.25	2-3-6	1.06

Although it is known that the selection of sensor configuration in backcalculation analysis will affect significantly the accuracy of the layer moduli obtained, the results in Table 3 conveys that, if exact deflections are used in the analysis, the use of almost all of the sensor configurations in FPAVE3 will produce small errors. It means that most of FPAVE3 sensor configurations have similar accuracy in backcalculating the layer moduli, except the last quarter of sensor configurations used to backcalculate E_1.

On the other hand, the results produced by EVERCALC showed that the modulus of subgrade was better estimated than the modulus of subbase, and the modulus of subbase was better estimated than the modulus of asphalt layer. This is because most of the iterative-based backcalculation algorithm calculates the elastic modulus of the subgrade first using the outer sensor deflections. Once the elastic modulus of the subgrade is calculated, it is used as an input for the backcalculation of the moduli of the overlying layers (Huang, 2003). In estimating the modulus of asphalt layer, the use of the configuration with sensor offset near the load was preferable, since the deflections closer to the load are dominated by the effect of surface layer properties.

This study also evaluated the influence of random deflection in selecting the sensor configuration used to obtain optimum deflection basins in backcalculation analysis. The results of the evaluations are presented in Tables 4 and 5, and Figure 1. Table 4 analyzes the sensitivity of each sensor configuration against the measurement errors by means of coefficient of variation (CV). Table 5 presents the deviation between the computed layer moduli based on random deflection and the corresponding true layer moduli. The dispersion of the computed layer moduli of all sensor configurations is depicted in Figure 1.

Table 4: Measure of dispersion of layer properties

FPAVE3						EVERCALC					
E_1		E_2		E_3		E_1		E_2		E_3	
Sensor	CV (%)	Sensor	CV (%)	Sensor	CV (%)	Sensor	CV (%)	Sensor	CV (%)	Sensor	CV (%)
1-2-3	2.46	1-2-3	1.05	1-2-4	1.11	1-2-4	2.56	3-5-6	0.92	3-4-5	1.18
1-2-4	5.81	1-3-4	1.10	1-2-3	1.17	2-3-4	5.68	1-2-3	1.16	4-5-6	1.19
1-3-4	13.88	1-2-5	1.32	2-3-4	1.19	1-3-4	6.40	1-2-4	1.32	1-2-3	1.20
1-2-5	15.33	1-2-4	1.41	1-3-4	1.20	1-2-5	6.50	1-3-4	1.63	1-2-4	1.22
1-2-6	16.41	2-3-4	1.43	1-2-6	1.21	1-2-3	7.36	2-3-4	1.66	1-3-4	1.23
3-4-5	18.44	2-3-5	2.50	2-3-5	1.28	2-3-5	15.64	1-2-5	1.89	2-3-4	1.28
2-3-4	23.02	1-3-5	2.53	3-4-5	1.30	1-4-5	21.52	2-5-6	2.76	2-5-6	1.29
2-5-6	23.19	3-4-5	2.59	1-3-5	1.33	1-2-6	23.19	3-4-5	2.86	3-5-6	1.29
3-4-6	24.85	1-5-6	3.18	1-4-5	1.34	1-3-5	23.35	2-3-5	2.99	1-4-5	1.31
1-3-5	29.83	1-2-6	3.65	2-4-5	1.34	1-3-6	25.84	3-4-6	3.31	1-3-5	1.32
3-5-6	31.53	1-4-5	3.68	1-2-5	1.39	2-4-5	27.13	1-3-5	3.39	1-2-5	1.35
4-5-6	32.01	2-4-5	4.98	3-5-6	1.46	2-3-6	30.19	1-4-5	3.88	2-3-5	1.39
1-5-6	34.79	2-5-6	5.38	4-5-6	1.52	1-4-6	33.58	2-4-5	4.15	3-4-6	1.42
2-3-5	37.71	2-4-6	5.80	3-4-6	1.53	1-5-6	40.20	1-2-6	4.57	2-4-5	1.43
1-4-5	38.24	3-5-6	6.02	1-4-6	1.56	2-4-6	42.73	4-5-6	4.94	1-5-6	1.53
1-3-6	42.37	3-4-6	6.48	1-5-6	1.63	3-4-5	50.42	1-3-6	6.19	1-4-6	1.67
1-4-6	49.37	2-3-6	6.54	2-4-6	1.65	3-4-6	58.21	2-3-6	6.89	2-4-6	1.76
2-3-6	56.73	1-4-6	6.96	2-3-6	1.75	3-5-6	66.16	1-4-6	8.79	1-3-6	1.78
2-4-6	62.02	1-3-6	7.41	1-3-6	1.89	2-5-6	66.89	2-4-6	8.98	2-3-6	1.83
2-4-5	66.24	4-5-6	7.41	2-5-6	4.71	4-5-6	89.64	1-5-6	12.56	1-2-6	2.04

Although FPAVE3 program enable the use of almost all of the sensor configurations to estimate the layer moduli with similar accuracy, however, not all of the sensor configuration could give good answer in terms of dispersion, if random deflections were considered in the backcalculation analysis. For estimation of E_1 and E_2, only sensor configurations consisted of sensor no. 1 and 2 or sensors no. 1 and 3 (with exception of sensor no. 6 as the third sensor in the configuration) commonly gave less variation (see Table 4). This contributed by the fact that sensor further from the load generally are more sensitive to measurement errors than sensor closer to the load. Therefore, the inclusion of sensor no. 6 in the configuration was not recommended.

While the high CV was occurred on estimating E_1, it is noted that the estimation of E_2 and E_3 does not suffer from this problem. And as a whole, the layer moduli produced by FPAVE3 were less sensitive to measurement errors than those of EVERCALC.

Table 5 gives an indirect support to the findings in Table 4 that sensor configurations having sensors no. 1 and 2 or sensors no. 1 and 3 (with exception of sensor no. 6 as the third sensor in the configuration) should produce less error. It is interesting to know that several sensor configurations with less variation could have a high error, such as sensor configurations 2-3-4 and 2-3-5 (in Table 4 under EVERCALC – E_1, they are in the 2nd and 6th position, but in Table 5, they shows high errors and drop to the 10th and 12th position). More obvious description about the dispersion of the computed layer moduli and the deviation between the true and computed layer moduli was presented in Figure 1.

Table 5: Root mean square percentage errors (RMSPE) of computed layer moduli based on random deflections

FPAVE3						EVERCALC					
E_1		E_2		E_3		E_1		E_2		E_3	
Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)	Sensor	RMSPE (%)
1-2-3	4.49	1-2-3	1.02	1-2-4	1.05	1-2-4	4.19	1-2-3	1.13	3-4-5	1.12
1-2-4	11.89	1-3-4	1.10	1-2-3	1.11	1-2-3	7.61	1-2-4	1.27	4-5-6	1.13
1-3-4	19.96	1-2-5	1.26	1-3-4	1.15	1-2-5	8.17	1-3-4	1.88	1-2-3	1.13
1-2-5	26.90	1-2-4	1.34	2-3-4	1.16	1-3-4	14.30	1-2-5	1.89	1-2-4	1.16
3-4-5	35.22	2-3-4	1.70	2-3-5	1.22	1-2-6	21.63	3-5-6	2.64	1-3-4	1.16
2-5-6	36.55	2-3-5	2.41	3-4-5	1.24	1-3-5	28.27	2-3-4	2.78	2-3-4	1.21
3-5-6	45.75	1-3-5	2.45	1-2-6	1.26	1-4-5	45.23	3-4-5	3.04	2-5-6	1.22
4-5-6	50.43	3-4-5	2.47	1-3-5	1.27	1-3-6	52.41	1-3-5	3.22	3-5-6	1.23
3-4-6	54.27	1-5-6	3.52	1-4-5	1.27	3-4-5	94.33	2-3-5	4.34	1-4-5	1.24
2-3-4	59.73	1-4-5	3.56	2-4-5	1.28	2-3-4	94.38	1-2-6	4.43	1-3-5	1.25
1-3-5	60.01	1-2-6	4.57	1-2-5	1.32	1-4-6	105.83	1-4-5	4.44	1-2-5	1.28
1-2-6	60.76	2-4-5	4.74	3-5-6	1.39	2-3-5	115.50	4-5-6	4.80	2-3-5	1.32
2-3-5	64.52	2-4-6	5.64	4-5-6	1.45	2-5-6	127.24	3-4-6	4.81	3-4-6	1.36
1-4-5	71.72	3-5-6	5.70	3-4-6	1.45	3-5-6	129.08	2-5-6	4.96	2-4-5	1.37
1-5-6	83.02	3-4-6	6.19	1-4-6	1.48	3-4-6	137.23	2-4-5	5.66	1-5-6	1.46
2-4-5	108.60	2-5-6	6.21	1-5-6	1.55	2-3-6	143.90	1-3-6	6.60	1-4-6	1.60
1-4-6	116.17	2-3-6	6.58	2-4-6	1.56	2-4-5	147.22	2-3-6	7.92	1-3-6	1.70
1-3-6	117.96	4-5-6	7.01	2-3-6	1.67	4-5-6	151.79	2-4-6	9.93	2-4-6	1.72
2-4-6	121.89	1-4-6	7.05	1-3-6	1.81	1-5-6	176.23	1-4-6	10.99	2-3-6	1.79
2-3-6	141.83	1-3-6	7.83	2-5-6	4.72	2-4-6	186.45	1-5-6	16.70	1-2-6	1.94

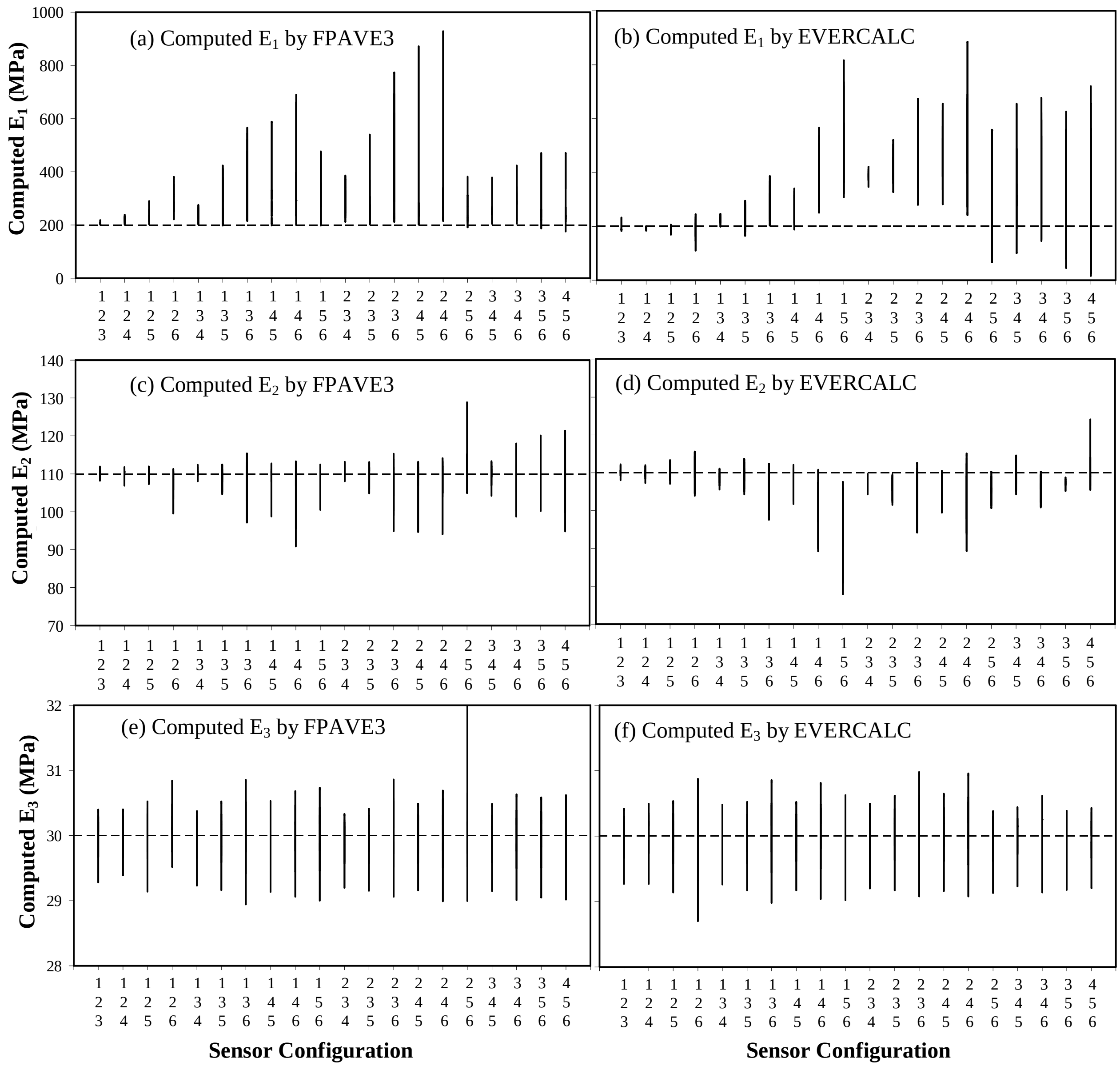

Figure 1: Comparison of the dispersion of the computed layer moduli based on random deflection

In Figure 1, it is very clear that in estimating E_1 and E_2, only sensor configurations consisted of sensors no. 1 and 2 or sensors no. 1 and 3 generally could produce less deviation between true and computed layer moduli. In addition, there was no significant difference of the computed E_3 produced by all sensor configurations. It means that any sensor deflections could be used to estimate E_3.

5 CONCLUSIONS

It is known that, besides the type of backcalculation algorithm used, the selection of deflection sensor configuration in the backcalculation analysis could also affect significantly the accuracy of the layer moduli obtained. In this paper, an evaluation is conducted to select the appropriate sensor configuration in backcalculation analysis that can produce the best estimation of layer moduli. The analysis indicates that in estimating the elastic modulus of surface and subbase layer, the sensor configuration consisted of sensors no. 1 and 2 or sensors no. 1 and 3 (with the exception of sensor no. 6 as the third sensor in the configuration) tend to produce less error and less sensitive to error. The use of sensor no. 6 in the configuration is not recommended because this sensor is relatively sensitive against measurement error. In addition, the estimation of the elastic modulus of subgrade could be performed using any sensor configuration because the magnitude of error does not vary significantly with the choice of sensor configuration.

REFERENCES.

Burmister, D.M., 1943. *The Theory of Stresses and Displacements in Layered Systems and Applicationsto Design of Airport Runways.* Proceedings of Highway Research Board, Vol. 23, pp. 126-148.

Burmister, D.M, 1945. *The General Theory of Stresses and Displacements in Layered Soil Systems III.* Journal of Applied Physics, Vol. 16, pp. 296-302.

Huang, Y.H., 2003. *Pavement Analysis Design* 2nd Edition, Prentice-Hall, New Jersey, USA.

Nelder, J.A. and Mead, R., 1965. *A Simplex Method for Function Minimization*. The Computer Journal, Vol. 7, pp. 308-313.

Pronk, A.C., 1988. *Interpretation Problems and Reliability of Falling Weight Deflectometer (FWD) Measurements on Three Layer Systems*. Proceeding of Association of Asphalt Paving Technologist, Williamsburg, VA., Vol. 57, pp. 502-518.

Sivaneswaran, N., S.L. Kramer, and J.P. Mahoney, 1991. *Advanced Backcalculation using a Nonlinear Least Square Optimization Technique*. Presented at the 70th Annual Meeting of the Transportation Research Board, Washington, D.C.

Washington Department of Transportation (WSDOT), 2005. *EVERSERIES User's Guide Pavement Analysis Computer Software and Case Studies*.