

The Use of Deflection Bowl Parameters to Represent the Carrying Capacity of Pavement Structures

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The use of deflection bowl parameters to represent the carrying capacity of pavement structures

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1. Introduction

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In recent years, evaluation of road structural conditions has been directed at using the non-destructive testing (NDT) method and the use of backcalculation programs to determine the structural capacity of pavement structures. However, the use of the backcalculation program has two disadvantages, namely in terms of the availability of valid data, and the ability of personnel with in-depth knowledge about pavement materials and the process of backcalculation algorithm.

Deflection, which is the output of data collection in the field using the NDT method, is quite complex data because it contains the information about the amount of carrying capacity of each layer, the thickness of the layer, and the layer interface. Layer thickness is usually assumed to be similar throughout one segment even though it could be varied in practice. Detailed data about the layer thicknesses are very difficult to obtain, especially there are no tools that can be used to measure, such as ground penetrating radar (GPR). The difficulty in providing layer thicknesses in detail contributes to the inaccuracy of determining the elastic moduli using backcalculation programs. The pavement layers may be considered to be full friction between them, although there is a possibility that not all full friction is possible in practice.

Deflection bowl method, introduced firstly by Horak and Emery [1] is one solution to overcome problems encountered related to the use of backcalculation programs. The question is whether this

deflection bowl parameter can represent the carrying capacity of the pavement structure, as that produced by the backcalculation program? Therefore, this study proposed to evaluate the suitability of the deflection bowl parameters to represent the carrying capacity of different pavement structures.

2. Deflection bowl

Deflection bowl is a set deflection that is formed and measured simultaneously by FWD's geophones as a result of the impulse load is dropped on the surface of the pavement. In 1987, Horak and Emery [1] introduced the use of deflection bowl, in terms of deflection bowl parameters, to define the structural condition of pavement layers. Four parameters with direct correlations of the corresponding pavement structural conditions were proposed, that is, maximum deflection (D_0), base layer index (BLI), middle layer index (MLI) and lower layer index (LLI), to represent the carrying capacity of surface layer, base layer, subbase layer, and subgrade, respectively. Based on works by Stubstad et al. [2], Setiadji [3] proposed a revision of Horak and Emery's formulas to accommodate the use of sensors at a considerable and outermost distance from the load center to enable covering the response of base/subbase layer and subgrade, respectively (see figure 1). The formulas of the last three indices (BLI, MLI, and LLI) proposed by Setiadji [3] were shown below.

$$BLI = D_0 - D_{305} \quad (1)$$

$$MLI = D_{305} - D_{457} \quad (2)$$

$$LLI = D_{914} - D_{1524} \quad (3)$$

in which: $D_0, D_{305}, D_{457}, D_{914}, D_{1524}$ (in mm) are the deflection at sensor offset 0, 305, 457, 914, and 1524 mm (0, 12, 18, 36 and 60 inch), respectively from the load.

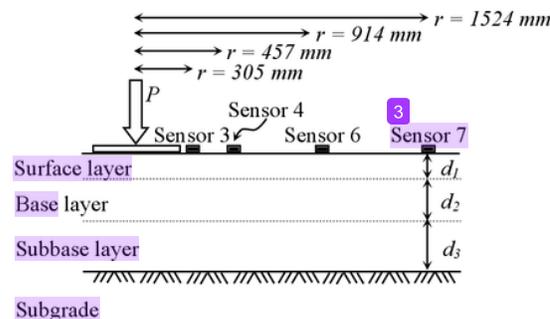


Figure 1. Typical pavement layers and sensor arrangement on the surface of road pavement.

Layer thicknesses ($d_1, d_2,$ and d_3 as seen in figure 1) are not required to determine deflection bowl parameters. Deflection bowl method is not intended to show the exact magnitude of the layers' carrying capacity but only used to evaluate the carrying capacity or condition of each layer against a specification or a certain criterion. Using this method, ones also can do a comparison between the carrying capacity of each layer on a historical time basis.

One method used to assess parameters is to classify these parameters in several structural condition rating criteria, i.e. sound, warning and severe (see table 1). The rating criteria may be adjusted to improve the sensitivity of evaluation.

3. Research methodology

The methodology of the study consisted of three main parts:

- (a) Determination of the elastic modulus of each layer of pavement structure using a backcalculation algorithm. For this purpose, a best-fit and trial backcalculation program, Evercalc from Washing-

ton State DOT, was used in this study. The data required in this study, either loading-response related or road segment characteristic data, were extracted from long-term pavement performance (LTPP) database.

Table 1. Structural condition rating criteria for pavement structure [4, 5].

Type of base	Deflection bowl parameters (mm)				Structural condition rating
	D_0	BLI	MLI	LLI	
Granular base	< 0.50	< 0.20	< 0.10	< 0.05	Sound
	0.50 – 0.75	0.20 – 0.40	0.10 – 0.20	0.05 – 0.10	Warning
Asphaltic treated base	< 0.40	< 0.20	< 0.10	< 0.05	Sound
	0.40 – 0.60	0.20 – 0.40	0.10 – 0.15	0.05 – 0.08	Warning
	> 0.60	> 0.40	> 0.15	> 0.08	Severe

From the preliminary analysis of the LTPP data, two road segments were selected as representatives for the purposes of this study. Two conditions of pavement structure were considered, i.e. original condition and condition after rehabilitation work, or stated as structure 1 and structure 2, respectively. The two road segments selected were as follows and the details of the road segments can be seen in table 2.

- Road segment with SHRP ID 4136 in the State of Florida (stated as road segment A for the rest of this paper). This road segment consists of 4 layers of original pavement structure (structure 1) and 6 layers of pavement structure after rehabilitation work (structure 2). Measurement of the structural condition of the road segment A was carried out for 4 times, that is, in 1989, and 1991 (structure 1), in 1994 and 1999 (structure 2).
- Road segment with SHRP ID 0159 in Kansas State (stated as road segment B). This road segment consists of 4 and 7 layers of structure 1 and structure 2, respectively. Unlike the road segment A, there was 83.83-mm road milling work in this segment before the first overlay was conducted. Measurement of the structural condition of the road segment B was carried out for 4 times, that is, in 1993, 1995 and 2001 (structure 1), and in 2004 (structure 2).

Table 2. Details of road segments evaluated.

Road segment (type of structure)	Layer details	Layer depth
A (1)	Asphalt concrete surface layer – 53.34 mm	53.34 mm (2.1 in.)
	Unbound base layer – 193.04 mm	246.38 mm (9.7 in.)
	Unbound subbase layer – 304.80 mm	551.18 mm (21.7 in.)
	Subgrade	
A (2)	Asphalt concrete overlay – 99.06 mm	99.06 mm (3.9 in.)
	Asphalt concrete binder course – 35.56 mm	134.62 mm (5.3 in.)
	Asphalt concrete surface layer – 53.34 mm	187.96 mm (7.4 in.)
	Unbound base layer – 193.04 mm	381.00 mm (15.0 in.)
	Unbound subbase layer – 304.80 mm	685.80 mm (27 in.)
B (1)	Subgrade	
	Asphalt concrete surface layer – 50.80 mm	50.80 mm (2 in.)
	Asphalt concrete binder course – 236.22 mm	287.02 mm (11.3 in.)
B (2)	Bound treated subbase layer – 152.40 mm	439.42 mm (17.3 in.)
	Subgrade	
	Asphalt concrete overlay – 30.48 mm	30.48 mm (1.2 in.)
	Asphalt concrete overlay – 33.02 mm	63.50 mm (2.5 in.)
	Asphalt concrete overlay – 71.12 mm	134.62 mm (5.3 in.)
	Asphalt concrete binder course – 152.40 mm	287.02 mm (11.3 in.)
Bound treated subbase layer – 152.40 mm	439.42 mm (17.3 in.)	
	Subgrade	

In this study, updated data is not a necessity, because the analysis carried out is general so that the results of the analysis can be transferable for other regions or time.

- (b) Evaluation of the carrying capacity of pavement structure in terms of four deflection bowl parameters. To do so, deflection data from the two road segments for both structures (original and after rehabilitation work) was used to determine the parameter values. To evaluate the values, structural condition criteria as presented in table 5 were used in this study.
- (c) Evaluation of the suitability of using deflection bowl parameters to assess different structural conditions of the road segments, by using elastic moduli for justifying the parameters.

4. Results and discussion

Setiadji [3] proposed slightly different sensor distances from the load, compared to that recommended by Horak and Emery [1], to measure the deflections. This probably may not cause significant difference if the carrying capacity of each layer in pavement structure represented by deflection bowl parameters, however, this could be a serious problem if a backcalculation program is employed to determine the carrying capacity of the pavement layer in terms of elastic moduli.

The first step of this study was to perform backcalculation of deflection data from the two road segments, each of which consists of two different structures, and in parallel, using the same deflection data, the value of the four deflection bowl parameters were determined. Figure 2 presents the trend of the four deflection bowl parameters from deflection data measured at 4 different years. It should be informed that the four observations can be carried out in different seasons so that this can affect the amount of deflection measured. For example, measurement of deflection in road segment A, in 1989 measurements were made during winter, in 1991 measurements were made during spring, while the next two measurement times (2001 and 2004) were during summer.

In road segment A (figure 2), it is very clear to see that different seasons can affect the structural conditions of a pavement, as seen in the values of D_0 in the year 1989 and 1991 (original condition or structure 1) and values of D_0 in the year 1994 and 1999 (structural condition after rehabilitation work or structure 2). Rehabilitation work on road segment A is proven to increase the carrying capacity of the layer, especially the surface and base layer, where there was a change in structural condition criteria from warning to sound. On the other hand, there was a decrease in structural conditions of road segment B from the year 1993 to 2001, and then it increased after rehabilitation work in the year 2004. However, the increase in structural condition was not very significant due to the observations were conducted in the spring season of the year 2004 where the influence of freeze-thaw process still contributes closely to the condition of road pavement.

Figure 2 shows that deflection bowl parameters are very useful to evaluate the indication of the structural condition or the change of the structural condition of the pavement structure. The question that arises is: (i) related to the selection of deflection used in the deflection bowl parameters, are the deflections proposed by Setiadji [3] in accordance with the carrying capacity of each layer, as stated by elastic moduli?; and (ii) the deflection bowl parameter is designed to represent the structural condition of the four layers. If the pavement structure consists of more than 4 layers, are the deflection bowl parameters still relevant to be used?

To answer the first query, it is necessary to calculate the elastic moduli of the layers in the pavement structure using Evercalc backcalculation program. Similar to AREA method [6], the backcalculation process was performed by using 4 deflection data, instead of 7 deflection data, because the error produced by using fewer deflections in backcalculation process could be smaller [7]. In this study, the selection of deflections required was dependent on the depth of the pavement layers, therefore, the deflections selected may differ for road segments A and B. Refer to table 2, for road segment A, the deflections selected were those produced by sensors 1, 2, 4, and 7 which were 0, 203, 457 and 1524 mm (or 0, 8, 18 and 60 in.) from the load. While, for road segment B, the deflections used were those produced by sensors 1, 2, 3, and 7 that is offset 0, 203, 305 and 1524 mm (or 0, 8, 12, and 60 in.) from the load. The pattern of the moduli and deflection bowl parameter along one of the selected road segment evaluate, i.e. road segment A, is depicted in figure 3.

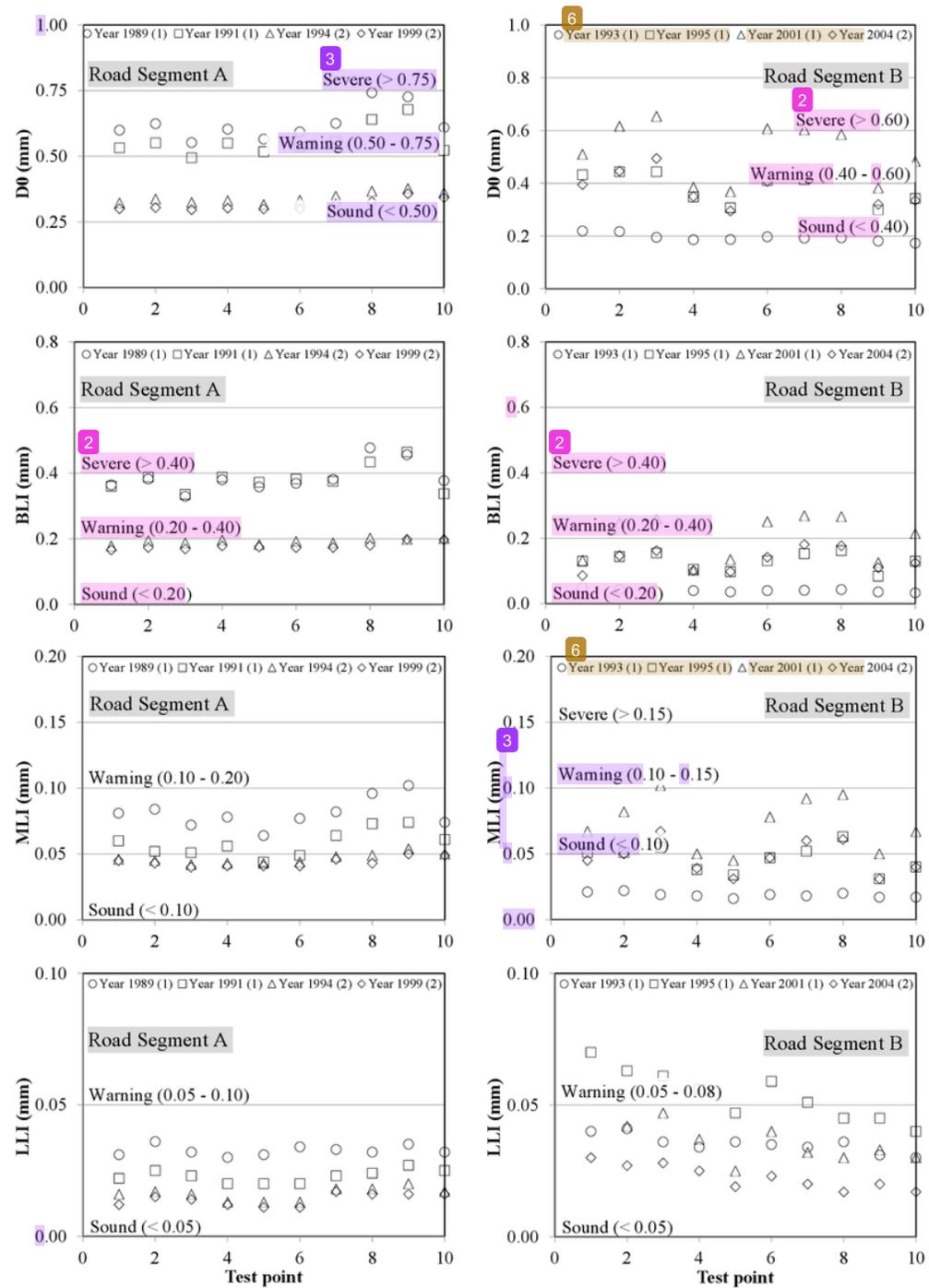


Figure 2. Deflection bowl parameters of the two road segments evaluated.

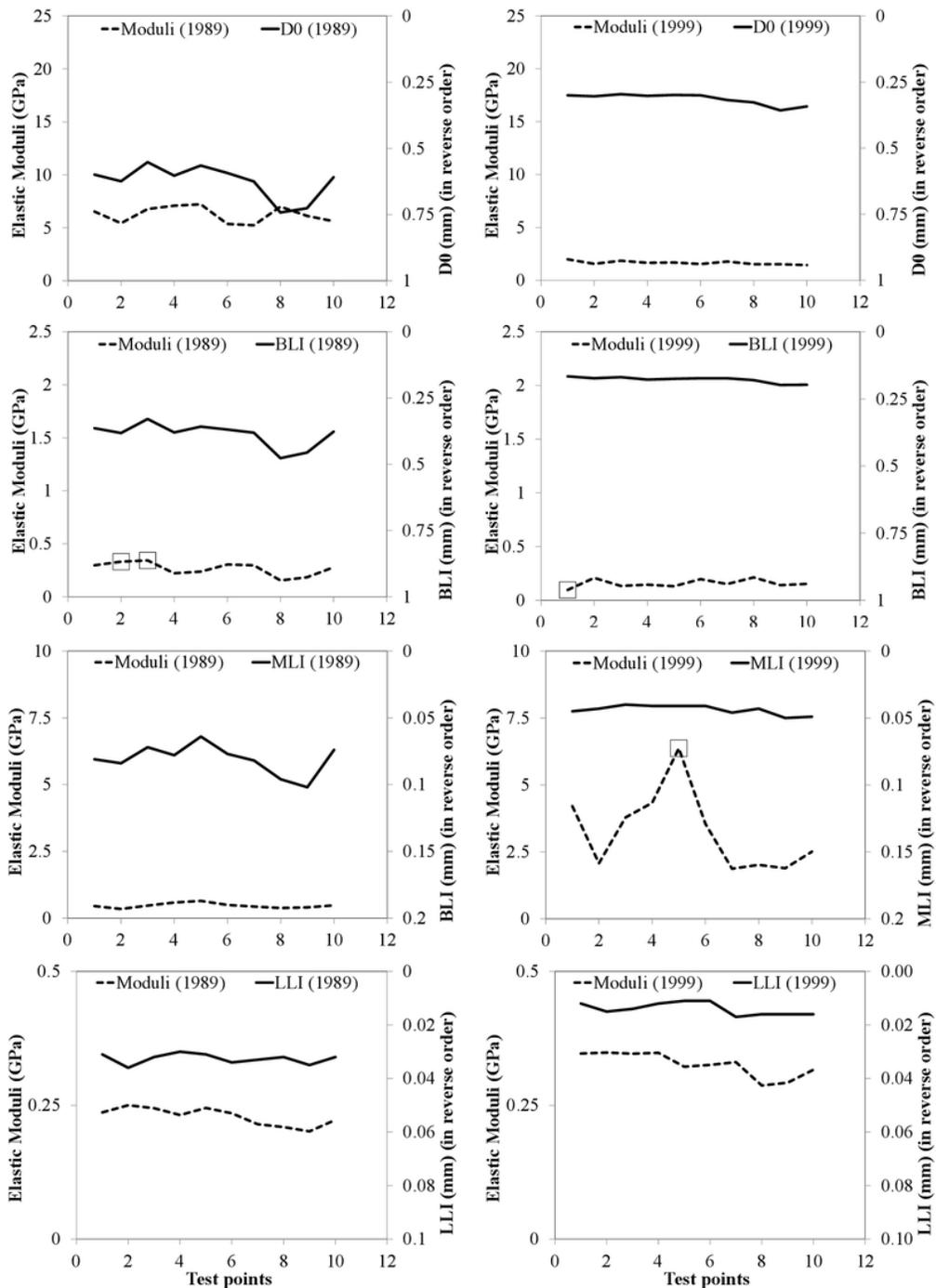


Figure 3. The pattern of layer moduli and deflection bowl parameter along road segment A.

Figure 3 shows the relationship between the deflection bowl parameter and the elastic modulus of each layer. The scale of the deflection bowl parameter was reversed to better understand the causal relationship of the two variables. It can be seen in figure 3 that there are similarities between the patterns shown by the deflection bowl parameter and the elastic moduli along road segment A, especially between LLI and the subgrade elastic modulus. This is because most of the best-fit trial and error backcalculation program initially determines the pavement layer moduli from the subgrade; therefore, the subgrade elastic modulus generally has the highest accuracy [8]. To test the hypothesis of the similarity between the mean of elastic moduli and deflection bowl parameters, a two-tailed t-test was carried out in this study. The results of the test are presented in table 3.

Table 3. Hypothesis test results of the similarity between the mean of elastic moduli and deflection bowl parameter on road segment A.

Type of structure (year)	Paired of layered elastic moduli and deflection bowl parameter	t Stat	Remarks ^a
Structure 1 (1989)	Original surface layer elastic modulus and D0	1.027	Accept
	Unbound granular base elastic modulus and BLI	3.247	Reject
	Unbound granular subbase elastic modulus and MLI	1.898	Accept
	Subgrade elastic modulus and LLI	1.509	Accept
Structure 2 (1999)	Original surface, AC binder & overlay elastic modulus and D0	1.605	Accept
	Unbound granular base elastic modulus and BLI	4.488	Reject
	Unbound granular subbase elastic modulus and MLI	2.431	Reject
	Subgrade elastic modulus and LLI	-1.691	Accept

^a t critical two-tail = 2.262

The results indicated that most of the deflection bowl parameters along road segment A have a similar pattern with the elastic moduli. Some rejections shown in table 3 are generally only due to one or two points of the elastic moduli produced by the backcalculation program (as indicated by rectangular markers in figure 3) that is out of as expected. These outliers are evidence that the determination of the elastic moduli using backcalculation program sometimes is quite difficult due to unpredictable measured deflection curve and unclear data input, such as layer thickness. It can be summarized that the deflection bowl parameters proposed by Setiadji [3] has a strong relationship to the layer elastic moduli and be able to represent a good indication of carrying capacity for the pavement structure.

Ones may expect that there will be a clearer relationship between elastic moduli and deflection bowl parameters. However, it is known that one deflection does not reflect the elastic modulus of a certain layer, except the outermost sensor which can really reflect carrying capacity of the subgrade. The deflection bowl parameters, except D_0 , are actually a pair of deflections whose deviation between them is used to indicate the carrying capacity of a layer. In practice, the deflection bowl parameters can be used as an indication of the carrying capacity of pavement structure to enable comparing them on the selected time frame basis. The acceptance of the deflection bowl parameters will depend on the structural condition rating criteria used, therefore, the development and standardization of the criteria is very important and will be one of the critical parts of the future research.

To answer the second question, a simulation using Evercalc was conducted to examine whether the use of 4 deflection bowl parameters (which represent 4 layers of pavement structure) was suitable for a structure consisting of more than 4 layers. For this purpose, 6-layer road segment A was simulated as a 4-layer and 5-layer pavement structure. Due to the limitations of the Evercalc program which can only accommodate a maximum of 5 layers, three asphalt concrete layers in road segment A (as seen in Table 2) were combined into 1 and 2 layers for the case of 4- and 5-layer structures, respectively.

Figure 4 shows a comparison of the two structures. It was seen that there were similarities in the pattern of elastic moduli for both asphalt and base layers (which represent D_0 and BLI in the deflection bowl parameter) for the two measurement periods. The 1st layer in the 4-layer structure has an elastic modulus value in between the elastic modulus of the 1st and 2nd layers in the 5-layer structure. This

indicated that the use of D_0 in the deflection bowl parameter can represent elastic modulus of more than 1 layer of the surface (with total thickness up to 203 mm or 8 in.).

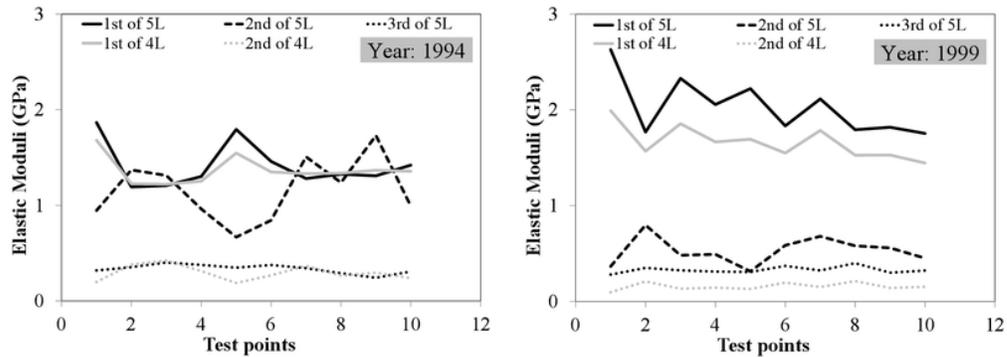


Figure 4. Comparison of moduli of a 6-layer road segment A that was simulated as a four-layer (4L) and five-layer (5L) pavement structure.

5. Conclusions

This paper evaluated the suitability of the use of the proposed deflection bowl parameters to represent carrying capacity, in terms of elastic moduli, of different pavement structures in practice. To determine the layered elastic moduli, a backcalculation program, Evercalc, was used in this study. It resulted in: (i) there is a similarity in pattern between calculated elastic moduli and deflection bowl parameters along the road segments examined. This indicated that the deflection bowl parameter has a strong relationship with the layered moduli. It is suggested that the standardization of the structural condition rating criteria is very important in order to these parameters can be widely accepted; (ii) the maximum deflection or D_0 can represent overlay because of rehabilitation work up to 205 mm or 8 in. thickness, even though the number of the overlay is more than one layer.

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