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Theoretical and practical methodology for recognizing the road surface structure

Stefan Firlej, Marcin Dębiński

Lublin University of Technology, Faculty of Civil Engineering and Architecture, Department of Roads and Bridges, Nadbystrzycka 40, 20-618 Lublin, e-mail: m.debinski@pollub.pl

Abstract: A recognition indicator of the possibility of further use of the road during transferring transport loads are changes in the condition of the road surface. If the surface condition indicates incorrect parameters of its equality, rutting, or cracks, the road durability is qualitatively assessed. In this case, the actual load capacity rating and possible reconstruction of the structure begins. Values of dynamic deflections can be used to recognize the modulus of elasticity and thus the possibility of assessing the durability of a structure. The mechanistic method is used to dimensioning the structure due to the movement planned. It allows a flexible approach to further construction, giving the opportunity to assess whether part or all of it should be left or apply an additional layer to meet future requirements. The elastic modulus needed for this pavement structure design method for existing layers has been recognized by identification as backcalculation methodology that have been used for many years.

Keywords: road surface, backcalculation, dynamic deflections, road durability.

1. Introduction

In recent years, the road network in Poland has been significantly expanded. Many kilometers of roads have been created. The development of the car transport and the increase in the number of vehicles on Polish roads will result in the need for maintenance and repair. Appropriate recognition of the surface condition enables an adequate assessment of the structure and a decision as to the type of a repair method. In order to compare the practical and theoretical methods of a structure recognition, research and analysis were performed using two methods. The practical method chosen for the study is the Falling Weight Deflectometer (FWD) dynamic deflectometer test and the theoretical method – by means of backcalculation methodology [1–2].

2. Results

2.1. Backcalculation method

The analysis of the implementation of the backcalculation methodology as the surface identification was carried out for 2-, 3- and 4-layer systems. Calculations of the elastic deflections were made with the strictly theoretical method according to the theory of the cylindrical layout of the structure. The center of the wheel load of the computational car was adopted as its center. The model with 5 or more layers was omitted due to the solution being too long even in a computerized approach. These models were loaded with a car wheel with a diameter of

30 cm and a road pressure of 0.707 MPa. The lowest layer in this case is of infinite thickness. The numbering of the layers has been taken from the bottom to the top, in which the lowest is 1, and the highest number is related to the number of layers.

2.1.1. Two-layer model

The construction of the model is shown in the figure below.

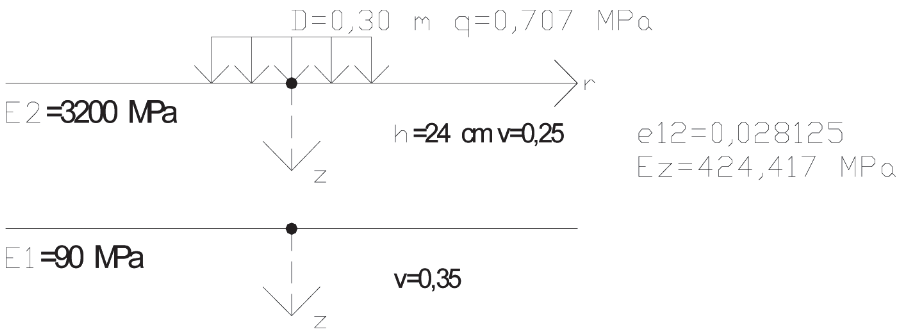

Fig. 1. 2-layer model

Fig. 1. 2-layer model

Computational vertical displacements of the road surface loaded from the center every 30 cm with an accuracy of 10^{-3} micrometers.

Table 1. List of deflections of the 2-layer model

I	ri [cm]	w [µm]
0	0	438.525
1	30	342.773
2	60	254.289
3	90	187.33
4	120	140.68
5	150	109.237
6	180	88.117

The backcalculation methodology is the determination of the modulus of elasticity of the model layers based on deflections and other parameters such as the layer thickness, load, and Poisson's coefficients. The method of determination in the normal case would be a longer, 2-layer, equal to 2 unknowns. To shorten the calculations, the methodology was changed from the 2 to 1 of the unknown. Instead of the modules, their quotient E1/E2 was assumed in relation to the wi/wo deflection quotient. The successive changes of the E1/E2 value and the calculation of the quotient of appropriate deflections for the changing model lead to the determination of the correct quotient of the modules. Using the back-calculating method, models for the basis point and subsequent points were calculated. The assumed deflection value with an accuracy of 1 µm and 0.001 µm indicates how different the elasticity modules are. Leaving them gives the answer how exactly deflections should be measured using the FWD and Heavy Weight Deflectometer HWD [3–4].

Table 2. Identification results for an accuracy of 1 μm

i	wo [μm]	wi [μm]	E1 [MPa]	E2 [MPa]	Set of computational deflections for i, j [μm]						
0–1	439	343	90.01	3189.9	439	343	254.36	187.327	140.652	109.209	88.096
0–2	439	254	90.19	3178.24	439	342.746	254	289.966	140.337	108.952	87.89
0–3	439	187	90.17	3179.35	439	342.77	254.034	187	140.367	108.996	87.909
0–4	439	141	89.81	3202.78	439	343.279	254.756	187.726	141	109.493	883.23
0–5	439	109	90.16	3180.44	439	342.794	254.068	187.034	140.397	109	87.929
0–6	439	88	90.09	3184.48	439	342.882	254.192	187.159	140.506	109.089	88
1–4	343	141	89.82	3213.04	438.468	343	254.642	187.694	141	109.506	88.327

Table 3. Identification results for an accuracy of 0,001 μm

i–j	wi [μm]	wj [μm]	E1 [MP]	E2 [MPa]	Set of computational deflections for i, j [μm]						
0–1	438.525	342.773	90.0001	3200.0058	438.525	342.773	254.289	287.33	140.679	109.237	88.117
0–2	438.525	254.289	90.0001	3200.0049	438.525	342.773	254.289	287.33	140.679	109.237	88.117
0–3	438.525	187.33	90	3200.0085	438.525	342.773	254.289	287.33	140.68	109.237	88.117
0–4	438.525	140.68	89.9997	3200.0265	438.525	342.773	254.29	287.331	140.68	109.238	88.118
0–5	438.525	109.237	90.0002	3199.9949	438.525	342.773	254.289	287.33	140.679	109.237	88.117
0–6	438.525	88.117	90.0004	3199.9851	438.525	342.773	254.288	287.329	140.679	109.237	88.117
1–2	342.773	90.0001	90.0001	3200.0034	438.525	342.773	254.289	287.33	140.679	109.237	88.117

2.1.1. Three-layer model

The model data as in Fig. 2 was used for the analysis.

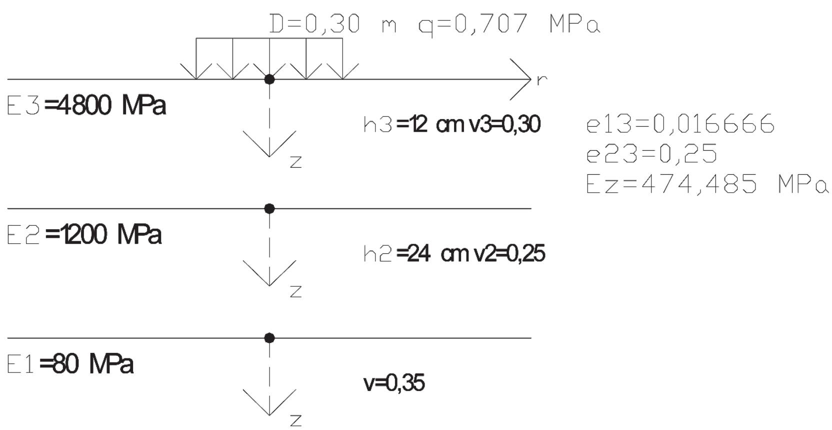

Fig. 2. 3-layer model

The method of the backcalculation of this model comes to establishing the ratio of w_i/w_o and w_j/w_o deflections quotients for the changing e_{13} and e_{23} quotients, so that the deflections of the searched and known model are consistent. The search function (1) and (2) is dependent respectively on (3) and (4). After determining the values of the e_{13} and e_{23} quotients, the values of the E_1, E_2, and E_3 modules are determined.

$$w_i/w_o = w_{io} \tag{1}$$

$$w_j/w_o = w_{jo} \tag{2}$$

$$E_1/E_2 = e_{13} \tag{3}$$

$$E_2/E_3 = e_{23} \tag{4}$$

Table 4. List of deflections of the 3-layer model

I	ri [cm]	w [µm]
0	0	392.252
1	30	309.923
2	60	243.205
3	90	192.553
4	120	153.797
5	150	124.617
6	180	102.825

Table 5. Identification results for the model at the value of rounded deflections

I	j	k	E1 [MPa]	E2 [MPa]	E3 [MPa]	Set of computational deflections for i, j, k [µm]						
0	1	2	80.09	1177.38	4951.79	392	310	243	192	153	124	103
0	1	3	79.77	1212.96	4790.74	392	310	244	193	154	125	103
0	1	4	79.88	1200.52	4846.02	392	310	243	193	154	125	103
0	1	5	79.78	1211.41	4797.61	392	310	244	193	154	125	103
0	1	6	79.87	1200.83	4844.66	392	310	243	193	154	125	103
0	2	3	80.13	1388.77	3799.67	392	307	243	193	154	125	103
0	2	4	80.07	1280.82	4321.78	392	309	243	193	154	125	103
0	2	5	80.11	1359.61	3928.77	392	308	243	193	154	125	103
0	2	6	80.08	1304.66	4195.68	392	308	243	193	154	125	103
0	3	4	97.52	1050.26	6186.66	392	313	244	193	154	125	103
0	3	5	97.71	1182.53	5009.53	392	311	244	193	154	125	103
0	3	6	79.52	1049.32	6178.17	392	313	244	193	154	125	103
0	4	5	82.18	522.37	930.83	392	281	235	191	154	125	103
0	4	6	82.13	5602.52	883.87	392	279	234	190	154	125	103

Table 6. Identification results for 10^{-3} μm bottom layers

I	j	k	E1 [MPa]	E2 [MPa]	E3 [MPa]	Set of computational deflections for i, j, k [μm]						
0	1	2	80	1200.06	4799.61	392.252	309.923	243.205	192.553	153.797	124.617	102.825
0	1	3	80	1200.06	4799.62	392.252	309.922	243.205	192.553	153.797	124.617	102.825
0	1	4	80	1200.05	4799.63	392.252	309.922	243.205	192.553	153.797	124.617	102.825
0	1	5	80	1200.05	4799.62	392.252	309.922	243.205	192.523	153.797	124.617	102.825
0	1	6	80	1200.01	4799.91	252	923	205	523	797	617	825
0	2	3	80	1200.01	4799.62	252	922	205	553	797	617	825
0	2	4	80	1199.97	4800.19	252	924	205	553	797	617	825
0	2	5	80	1199.99	4800.07	252	923	205	553	797	617	825
0	2	6	80	1199.95	4801.31	252	924	205	553	797	617	825
0	3	4	79.99	1199.73	4801.91	252	925	206	553	797	617	825
0	3	5	80	1199.82	4801.23	252	926	206	553	797	617	825
0	3	6	80	1199.25	4805.29	252	936	208	553	797	617	825
0	4	5	80	1199.97	4800.18	252	924	205	553	797	617	825
0	4	6	80	1199.97	4800.19	252	924	205	553	797	617	825
0	5	6	80	1199.97	4800.19	252	924	205	553	797	617	825

2.1.2. Four-layer model

The analysis of the model was carried out for the data shown in Fig. 3.

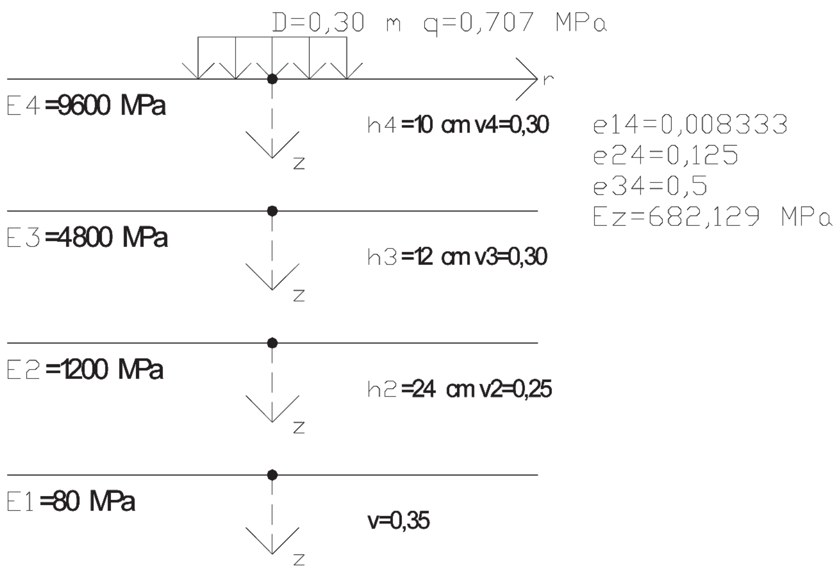

Fig. 3. 4-layer model

Table 7. Deflections in the 4-layer model

I	r_i [cm]	*w* [µm]
0	0	272.848
1	30	233.536
2	60	198.366
3	90	168.342
4	120	142.713
5	150	121.255
6	180	103.563

Identification of the 4-layer model on the basis of deflections calculated was carried out similarly to the previous one. The (5),(6),(7) modulus quotients were successively changed for the remaining data to obtain for these theoretical models the deflections quotients. If the deflections quotients matched with the quotients of the corresponding known values from Table 7 the (8),(9),(10) function and the modules quotients were obtained. The modules of the searched model were obtained on the basis of the quotients of the modules and the E_z replacement module. The list of identification (back-calculating) for deflections from below to 1µm is given in Tab. 8

$$e_{14}=E_1/E_4 \tag{5}$$

$$e_{24}=E_2/E_4 \tag{6}$$

$$e_{34}=E_3/E_4 \tag{7}$$

$$w_i/w_o = w_{io} \tag{8}$$

$$w_j/w_o = w_{jo} \tag{9}$$

$$w_k/w_o = w_{ko} \tag{10}$$

Table 8. Identification results for an accuracy of 1 µm

i	j	k	l	E1 [MPa]	E2 [MPa]	E3 [MPa]	E4 [MPa]	Set of computational deflections for i, j, k, l [µm]						
0	1	2	3	79.42	1117.92	3732.09	13350.38	273	234	198	168	142.572	121.321	103.794
0	1	2	4	78.83	1142.52	3386.73	14514.64	273	234	198	168.231	143	121.875	104.415
0	1	2	5	79.76	1106.19	3946.78	12692.9	273	234	198	167.868	142.326	121	103.437
0	1	2	6	79.22	1125.61	3612.64	13737.32	273	234	198	168.078	142.715	121.504	104
0	1	3	4	78.35	1156.66	2820.67	17148.8	273	234	197.605	168	143	122.069	104.742
0	1	3	5	79.89	1115.5	4203.94	11824.66	273	234	198.168	168	142.389	121	103.39
0	1	3	6	79.18	1122.6	3509.98	14169.13	273	234	197.913	168	142.665	121.483	104

i	j	k	l	E1 [MPa]	E2 [MPa]	E3 [MPa]	E4 [MPa]	Set of computational deflections for i, j, k, l [μm]						
0	1	4	5	80.98	1343.29	8860.74	5561.39	273	234	199.812	169.284	143	121	102.936
0	1	4	6	79.46	1155.25	4258.67	11398.27	273	234	198.502	168.524	143	121.631	104
0	1	5	6	78.41	1181.12	1804.14	24040.85	273	234	196.027	166.285	141.571	121	104
0	2	3	4	77.68	1108.69	1967.22	26224.36	273	235.706	198	168	143	122.175	104.966
0	2	4	6	79.81	1332.98	4706.59	8406.83	273	232.6	198	168.394	143	121.653	104
0	3	4	6	80.62	2088.05	7127.71	3595.28	273	227.999	196.471	168	143	121.722	104

Similarly, the backcalculation methodology was performed for some combinations of deflections, but with their accuracy up to 0.001 μm. The identification results obtained are presented in Table 9. The values of the modules were given with an accuracy of 0.01 MPa, and deflections with an accuracy of 0.001 μm.

Table 9. Identification results for an accuracy of 0,001 μm

i	j	k	l	E1 [MPa]	E2 [MPa]	E3 [MPa]	E4 [MPa]	Set of computational deflections for i, j, k, l [μm]						
0	1	2	3	80	1200	4801.63	9596.96	273	233.536	198.366	168.342	142.711	121.25	103.56
0	1	2	4	80	1200.02	4799.5	9601.11	273	233.536	198.366	168.343	142.713	121.252	103.562
0	1	2	5	80	1200.04	4797	9605.94	273	233.536	198.366	168.344	142.715	121.255	103.565
0	1	2	6	80	1200.02	4798.93	9602.21	273	233.536	198.356	168.343	142.713	121.253	103.563
0	1	3	4	80	1199.83	4795.64	9609.76	273	233.536	198.364	168.343	142.713	121.253	103.564
0	1	3	5	79.99	1199.73	4791.96	9617.61	273	233.536	198.363	168.343	142.714	121.253	103.566
0	1	3	6	80	1199.86	4796.65	9607.6	273	233.536	198.365	168.343	142.713	121.252	103.566
0	1	4	5	79.99	1199.38	4786.42	9630.54	273	233.536	198.36	168.34	142.713	121.252	103.567
0	1	4	6	80	1199.92	4797.52	9605.56	273	233.536	198.365	168.342	142.713	121.253	103.567
0	1	5	6	80	1201.03	4812.76	9569.53	273	233.536	198.375	168.351	142.718	121.253	103.567
0	2	3	4	79.99	1198.57	4787.36	9635.33	273	233.545	198.375	168.351	142.718	121.254	103.565
0	2	3	5	79.99	1198.02	4784.64	9650.16	273	233.548	198.375	168.351	142.714	121.254	103.567
0	2	3	6	80	1199.07	4793.65	9621.91	273	233.542	198.375	168.351	142.712	121.252	103.567
0	2	4	5	79.99	1197.05	4778.64	9671.73	273	233.554	198.375	168.341	142.712	121.252	103.568
0	2	4	6	80	1199.61	4796.62	9610.78	273	233.538	198.375	168.343	142.712	121.253	103.568
0	2	5	6	80.01	1203.5	4818.03	9531.37	273	233.516	198.366	168.348	142.718	121.253	103.568
0	3	4	5	79.98	1195.15	4772.3	9705.49	273	233.568	198.371	168.348	142.718	121.253	103.568
0	3	4	6	80	1200.59	4799.4	9594.48	273	233.531	198.363	168.348	142.718	121.253	103.568
0	3	5	6	80.02	1208.19	4828.01	9459.55	273	233.478	198.35	168.348	142.716	121.253	103.568
0	4	5	6	80.03	1218.89	4850.38	9299.92	273	233.391	198.313	168.329	142.716	121.253	103.568

Table 10. Identification results for a set of deflections for different accuracy

Accuracy	E1 [MPa]	E2 [MPa]	E3 [MPa]	E4 [MPa]	Deflections received [μm]						
10^{-3} μm	80	1200	4801.63	9596.96	272.85	233.536	198.37	168.34	142.71	121.25	103.56
10^{-2} μm	80.01	1199.77	4814.18	9574.79	272.85	233.54	198.37	168.34	142.7	121.24	103.55
10^{-1} μm	80.23	1206.5	5074.82	9065.12	272.8	233.5	198.4	168.3	142.57	121.07	103.35
1 μm	79.42	1117.92	3732.09	13350.4	273	234	198	168	142.57	121.32	103.79

2.2. Examples of identification on rebuilt roads

When assessing the bearing capacity of a road undergoing reconstruction, measurements with the use of the FWD are often carried out to determine the suitability of existing layers for the new structure. In this case, the identification analysis was carried out based on the recognition of the existing surface – what are the materials in the layers, and what are the thicknesses of the layers. Materials can be determined from archival data or from the small-sized boreholes. The layer thickness can also be determined by a georadar or other possible method. In the measurement itself, the unit pressure value under the plate, the diameter of the plate, and the temperature of the test are known [5–8].

2.2.1. Kraśnik – Janów Lubelski road DK-19 km 376+000,00 -377+200,00

The following deflections were converted to a pressure of 0.707 MPa, so that the average values for individual geophones can be determined from the measurement set in the section.

Table 11. List of average deflections from geophones on section 1–3

Section	Roadway	The average deflection under the geophone [μm]						
		w0	w1	w2	w3	w4	w5	w6
from 376+000,00 to 376+325,00	Left	386.5	239.12	153.26	98.26	76.31	56.62	45.45
	Right	475.45	288.41	184.49	124.18	88.1	62.66	49.16
from 376+350,00 to 376+825,00	Left	408.28	245.26	160.06	110.7	79.72	58.3	45.7
	Right	444.61	279.67	185.38	123.1	89.28	62.82	48.25
from 376+850,00 to 377+200,00	Left	637.69	398.06	242.63	156.3	110.49	76.02	59.98
	Right	574.3	367.22	221.99	147.11	104.13	79.08	64.88

After converting the measurement temperature of 20 °C to 10 °C, the modules shown in Tab. 12 were received.

Table 12. Elastic modules of the surface

Section	Layer thickness [m]		Poisson's ratio			Layers' modules [MPa]		
	h3	h2	v3	v2	v1	E3	E2	E1
from 376+000,00 to 376+325,00	0.185	0.18	0.3	0.3	0.3	1525	116	60
from 376+350,00 to 376+825,00	0.07	0.17	0.3	0.3	0.3	6150	290	88
from 376+850,00 to 377+200,00	0.13	0.17	0.3	0.3	0.3	1730	390	50

Layers in this construction are:
- upper layer of the MMA surface with different composition
- middle layer – a road grit
- ground substrate made of the clay sand or clay

2.2.2. DK 82 Lublin Włodawa road in the Łęczna km 23+670,00-24+820,00

Table 13. The construction of the existing surface

Section	Layer thickness [m]			Poisson's ratio			
	h4	h3	h2	v4	v3	v2	v1
23+670,00	0.15		0.07	0.4	0.3	0.3	0.35
24+100,00	0.1	0.17	0.1	0.4	0.3	0.3	0.35
24+600,00	0.09	0.13	0.09	0.4	0.3	0.3	0.35
24+700,00	0.16	0.13	0.07	0.4	0.3	0.3	0.35
24+820,00	–	0.2	0.2	–	0.4	0.3	0.35

Table 14. Reliable deflections obtained from the FWD and the identification modules

Section	The average deflection under the geophone [µm]							Layers' modules [MPa]			
	w0	w1	w2	w3	w4	w5	w6	E4	E3	E2	E1
23+670,00	626	390	230	142	96	69	54	1983	206	22	99
24+100,00	677	409	241	154	109	79	63	1593	465	33	139
24+600,00	654	383	226	146	103	76	61	841	804	78	142
24+700,00	571	360	227	148	104	74	61	720	884	32	106
24+820,00	346	281	198	144	101	76	57	–	2508	426	101

2.2.3. DW 815 Wisznice – Parczew – Lubartów provincial road km 27+525,00-37+225,00

Table 15. List of authoritative deflections on sections

Section	Roadway	The average deflection under the geophone [μm]							Layers' modules [MPa]		
		w0	w1	w2	w3	w4	w5	w6	E3	E2	E1
from 27+525,00 to 30+450,00	Left	589.3	492	382.6	308	267	218	176	1987.12	302.83	63.19
	Right	610.2	489.8	375.3	308.9	246.7	170.7	131	1932.65	177.49	70.47
from 31+275,00 to 35+500,00	Left	730	594	515.7	397	310	224	180	1952.07	159.7	54.18
	Right	766.5	605.3	463	382	294	190	140.1	1757.84	105.35	59.98
from 35+850,00 to 36+450,00	Left	784	646	523.9	410	303	249	190	1255.36	107.52	50.16
	Right	759.3	623.4	493.2	402	329	248	202.6	1171.97	554.28	50.58
from 36+625,00 to 37+225,00	Left	524.9	459	366.1	298	255	218	169	3407.14	184.25	68.49
	Right	560	444.1	347.9	302	225	165	134.9	2188.6	151.06	79.55

Table 16. Technical data of the existing structure on sections

Section	Roadway	Layer thickness [m]		Poisson's ratio		
		h3	h2	v3	v2	v1
from 27+525,00 to 30+450,00	Left	0.194	0.212	0.35	0.3	0.3
	Right	0.194	0.212	0.35	0.2	0.3
from 31+275,00 to 35+500,00	Left	0.184	0.239	0.35	0.3	0.3
	Right	0.184	0.239	0.35	0.3	0.3
from 35+850,00 to 36+450,00	Left	0.22	0.11	0.35	0.3	0.3
	Right	0.22	0.11	0.35	0.3	0.3
from 36+625,00 to 37+225,00	Left	0.204	0.15	0.35	0.3	0.3
	Right	0.204	0.15	0.35	0.3	0.3

Note: the ground substrate is the clay sand or clay; geophones were spaced from the center of the load plate – 26.5, 45, 60, 82.5, 120, and 144 cm.

3. Conclusion

Analysis of the results obtained from the theoretical method and practical tests was performed. When comparing both methods and the results, the following conclusions were noted:

1. The most accurate results are always for the lowest layer for the 2, 3 and 4-layer models.
2. The closest to the correct set of modules is in the case of known deflections with an accuracy of 10^{-3}μm and those with the smallest roundness.

3. The largest deviations in relation to the correct module are when a set of deflections with the extreme points from the set is used.
4. It is possible to recognize the structure model by omitting the zero point and taking further into account.
5. A set of more results for a homogeneous section gives better possibilities of identifying modules due to the equalization of discrepancies and possible incorrect readings.
6. To determine the modules with the method, it is best to take the average reliable values after rejecting the extreme values based on the Chauvenet criterion.
7. The modulus of elasticity will be most likely for readings from geophones the closest to the FWD loading board.

References

[1] Nagórski R. *Mechanika nawierzchni drogowych w zarysie.* PWN, Warszawa 2014.
[2] Firlej S. *Wyznaczanie parametrów modelu nawierzchni drogowej z dynamicznych badań FWD.* Politechnika Lubelska 2015.
[3] Bajak M., Firlej S. *Wykorzystanie metody ugięć do projektowania wzmocnień nawierzchni drogowych* Drogownicwo 1 (2018) 22.
[4] Woszuk A., Firlej S. *Metoda uwzględniania wartości ugięć poza zakresem nomogramu przy projektowaniu nawierzchni*, Drogownictwo 10 (2013) 314–318.
[5] Bajak M., Firlej S. *Wpływ rzeczywistego obciążenia na trwałość nawierzchni*. Magazyn Autostrady 7 (2010) 56–59.
[6] Katalog Przebudów I Remontów Nawierzchni Podatnych i Półsztywnych GDDKiA Warszawa 2013.
[7] Chai G., Manoharan S., Golding A., Kelly G., Chowdhury S. *Evaluation of the Traffic Speed Deflectometer data using simplified deflection model*. 6th Transport Research Arena, April 18–21 2016.
[8] Zofka A., Graczyk M., Rafa J., *Qualitative evaluation of stochastic factors affecting the traffic speed deflectometer results*. Transportation Research Board 94th Annual Meeting Washington DC 2015.