Research Article

Refinement of a Deflection Basin Area Index Method for Rigid Pavement

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Received 25 April 2021; Accepted 12 June 2021; Published 22 June 2021

Academic Editor: Zhigang Tao

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The accuracy of the prediction and reliability of the deflection basin area index method for rigid pavement heavily depend on the sensor layout scheme and the calculation theory. A total of 154 groups of deflection data were generated by the finite element software in different conditions, and the simulated results were in good agreement with the analytical solutions of thin plates on elastic foundation. The accuracy of several types of deflection basin area index methods was assessed with the database of pavement deflection results. It is found that, apart from densifying the distal sensor layouts locally, replacing the deflection value of a specific point with the average of all measured points in the deflection basin area index was also an effective measure to improve the back-calculation accuracy of pavement structural parameters up to 40%. Finally, a new deflection basin area index method was proposed based on the deflection database with the regression analysis. Comparisons between the theoretical calculations of several models and the practical deflection data of an airport in northern China revealed that the newly proposed method performs better on the back-calculation accuracy and efficiency, which can provide a valuable guideline for the practical engineering in the design.

1. Introduction

Sufficient load capacities are essential for the airport runway due to the considerable impact loads during the aircraft landing. The deflection, total deformations of the airport pavement under the load, is a critical parameter to reflect the overall load-bearing capacities of pavement structures. The heavy weight deflectometer (HWD) test, a vital technology for the strength design and performance evaluation of pavement structures, has been widely adopted to determine the deflection value [1–4]. In general, the primary methods for parameter back-calculation of the pavements' structural performance based on deflection values can be classified as follows.

The intelligent optimization method has been developed to find out the optimal solution of pavement structural parameters iteratively, such as neural network algorithm and genetic algorithm [5, 6]. However, the accuracy of these methods heavily depends on the reliability of the algorithm

and the calibration of some internal parameters [7, 8]. Darter et al. [9] have developed the back-calculation technique, like the point-by-point fitting method, to determine the optimal solution by comparing the objective function results of calibration error with the actual deflection basin through an iterative approach. Nevertheless, low efficiency was detected with this method in the iterative process. Besides, Sun et al. [10] have reported that the inherent information of the inert point on deflection curves remained constant regardless of the variations of resilient modulus of pavement slabs. Although the back-calculation of pavement structural parameters can be conducted once the specific inert point was obtained, the deterministic process of this point was relatively complicated [10, 11].

Compared with the back-calculation methods, the derived index method of the deflection basin [12] has been widely recognized by many researchers and engineers mainly due to the simplification of the back-calculation process. The method is also adopted by Chinese code MH/T

5024-2009 [13] and the U.S. Federal Aviation Administration [14] for the back-calculation of pavement structure parameters. This method simplifies the back-calculation process by constructing a deflection basin area index, which includes fitting formula method, back-calculation software method, and graphic method. However, related studies [15, 16] have revealed that the normalization of the basin area index during the aforementioned constructional process with only an assigned measurement point will cause the inferior accuracy and higher variability. To incorporate the effect of different measuring points, Lin et al. [15] have improved the back-calculation method by minimizing the calculated errors of the objective function, but the efficiency has been significantly influenced. However, either the calculation accuracy of these methods is not up to the standard, or the calculation process is too complex, which is not conducive to direct engineering application.

With this background, the finite element (FE) simulation was first applied to generate deflection information under different working conditions. Then, the error analysis was systematically conducted for the existing deflection basin area index methods based on the assembled database, and a new improved approach was developed in this study for practical engineering. By comparing with the measured data of an airport, the prediction accuracy of this method and other selection methods for back-calculation results were evaluated. The result shows that the improved deflection basin area index method has the advantages of simple calculation and high accuracy. In practical engineering application, it can not only save time but also achieve fast and accurate results, which is of great significance.

2. Finite Element Simulation

Considering that multiple variables cannot be considered simultaneously in a practical engineering, the effect of different conditions on the structures cannot be comprehensively estimated. Moreover, the test setup with high costs and measurement strategy may have a great impact on the accuracy of test results. Over the past decades, the FE technique has become increasingly popular in academic researches [17–20] because it can solve the problems that cannot be realized in engineering field. Thus, the finite element software was adopted to simulate the deflections of airport pavement structures under varied working conditions in this study. Studies on parameters were also conducted with the verified FE model for the following theoretical analysis.

2.1. Parameter Setting. The sectional size of the pavement slab was set as $30\text{ m} \times 30\text{ m}$ to reduce the influence of edge effect on the simulation because there are no relationships between the deflection value and the slab size for the position beyond 0.7 m away from the slab edge [21]. As per the Chinese code MH/T 5024-2009 [13], some basic parameters of the model were presented as follows: Poisson's ratio ($\nu = 0.15$); the elastic modulus of the thin concrete plate (32 GPa).

2.2. Boundary Conditions and Mesh. The spring foundation was added at the bottom surface of pavement slab, and the modulus of subgrade reaction was defined as k to simulate the equivalent reaction modulus of different soil layers under the pavement in actual engineering. Circular uniform load (0.15 m in radius) was applied on the upper surface of the model. No constraints were arranged on the other four sides. The static load of 1.5 MPa was used to simulate the maximum impact load produced by HWD test to obtain the corresponding deflection values according to the literature [19]. The free tetrahedral mesh was chosen, and the mesh element size was smaller than the thickness of the pavement slab h .

2.3. FE Model Results. One hundred and fifty-four groups of test data (see Table 1) were generated by uniformly extracting the deflection value at the position of 0 cm , 20 cm , 30 cm , 45 cm , 60 cm , 90 cm , 120 cm , 150 cm , and 180 cm away from the load center of the model. In this process, the value of the modulus of subgrade reaction k and the thickness of pavement slab h are continuously changed. Figure 1 shows the layout of the measuring points mentioned above. Figure 2 shows the simulation results of pavement slab with 28 mm in thickness and the modulus of subgrade reaction of 125 MN/m^3 . Furthermore, the value of h can be determined from the suggested slab thickness for the FE simulation provided by Cheng et al. [19]. The empirical value of subgrade reaction k can be referred to as the Chinese code GB 50307-2012 [22], and the selected ranges of h and k are presented in Table 2. To facilitate the following discussion, each working condition is given a name composed of letters and numbers. The first letter and the subsequent numbers represent the thickness of the slab (unit: mm). The second letter and the corresponding number stand for the modulus of subgrade reaction (unit: MN/m^3). For example, H28K125 represents the working condition with the pavement thickness of 28 mm and modulus of subgrade reaction of 125 MN/m^3 . N represents sensors in Figure 1.

2.4. FE Model Verification

2.4.1. Winkler Foundation Model. Chen et al. [20] have found that the Winkler foundation model performs better than the elastic half-space foundation model in calculating the structural responses of the pavement. It is assumed that the pressure p at one point on the foundation surface is proportional to the settlement w at the same point in the Winkler foundation model, and the pressure p is also independent of the pressure from surrounding points. The relationship between p and w can be presented as $p = k \cdot w$, which means that every single point of the foundation is supported by a spring, which works separately at different locations.

The analytical equation of the one thin slab deflection value predicted by the Winkler foundation model under uniformly distributed circular load is shown in equation (1) [23], which provides a reliable standard for the verification of deflection results obtained from the FE model.

TABLE 1: Comparison of simulated deflection and theoretical deflection under different working conditions.

Number	w0 (mm)			w20 (mm)			w30 (mm)			w45 (mm)			w60 (mm)			w90 (mm)			w120 (mm)			w150 (mm)			w180 (mm)		
	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%
H20K15	712	725	-1.8	689	707	-2.5	671	687	-2.3	639	651	-2.0	599	610	-1.9	512	521	-1.7	425	431	-1.4	343	347	-1.2	269	272	-1.0
H20K25	550	560	-1.9	528	543	-2.7	511	525	-2.5	481	491	-2.1	445	454	-2.0	368	375	-1.7	293	298	-1.4	226	228	-1.1	168	169	-0.8
H20K35	464	473	-1.9	442	456	-2.9	427	438	-2.7	398	407	-2.1	364	372	-2.0	294	299	-1.7	227	230	-1.3	168	170	-0.9	120	120	-0.5
H20K45	408	416	-1.9	388	400	-3.1	372	383	-2.8	345	353	-2.2	313	319	-2.1	247	251	-1.7	186	188	-1.2	134	135	-0.7	91	92	-0.1
H20K55	369	376	-1.9	348	360	-3.2	334	344	-2.9	307	314	-2.2	277	282	-2.1	214	218	-1.7	158	160	-1.1	110	111	-0.6	73	73	0.2
H20K65	339	345	-1.9	319	330	-3.3	304	314	-3.0	279	285	-2.3	249	255	-2.1	190	193	-1.6	137	138	-1.0	93	94	-0.4	60	59	0.6
H20K75	315	321	-1.9	295	306	-3.4	281	290	-3.1	257	263	-2.3	228	233	-2.1	171	174	-1.6	121	122	-0.9	81	81	-0.2	50	49	1.0
H20K85	296	301	-1.9	276	286	-3.5	262	271	-3.1	238	244	-2.3	210	215	-2.1	156	158	-1.6	108	109	-0.8	71	71	0.0	42	42	1.4
H20K95	279	285	-1.9	260	270	-3.6	247	255	-3.2	223	228	-2.3	196	200	-2.1	143	145	-1.6	98	99	-0.7	62	62	0.2	37	36	1.9
H20K105	265	271	-1.9	246	256	-3.7	233	241	-3.0	210	215	-2.3	184	188	-2.1	133	135	-1.5	89	90	-0.6	56	56	0.4	32	31	2.3
H20K115	253	258	-1.9	235	244	-3.7	222	229	-3.3	199	204	-2.3	173	177	-2.1	124	125	-1.5	82	83	-0.5	50	50	0.6	28	27	2.9
H20K125	243	248	-1.9	224	233	-3.8	211	219	-3.4	189	194	-2.3	164	167	-2.1	116	117	-1.5	76	76	-0.4	46	45	0.8	25	24	3.4
H20K135	234	238	-1.9	215	224	-3.9	202	210	-3.4	181	185	-2.3	156	159	-2.1	109	110	-1.4	70	71	-0.3	42	41	1.0	22	21	4.0
H20K145	225	230	-1.9	207	215	-3.9	194	201	-3.4	173	177	-2.4	148	152	-2.1	103	104	-1.4	66	66	-0.2	38	38	1.2	20	19	4.6
H20K155	218	222	-1.9	200	208	-4.0	187	194	-3.5	166	170	-2.4	142	145	-2.1	97	99	-1.3	61	61	0.0	35	35	1.4	18	17	5.3
H20K165	211	215	-1.8	193	201	-4.0	181	187	-3.5	160	164	-2.4	136	139	-2.1	92	94	-1.3	58	58	0.1	32	32	1.7	16	15	6.0
H20K175	205	208	-1.8	187	195	-4.1	175	181	-3.6	154	158	-2.4	131	134	-2.1	88	89	-1.3	54	54	0.2	30	29	1.9	14	13	6.8
H20K185	199	203	-1.8	181	189	-4.1	169	175	-3.6	149	152	-2.4	126	129	-2.1	84	85	-1.2	51	51	0.3	28	27	2.1	13	12	7.7
H20K195	194	197	-1.8	176	184	-4.2	164	170	-3.6	144	148	-2.4	122	124	-2.1	80	81	-1.2	49	48	0.4	26	25	2.4	12	11	8.6
H20K205	189	192	-1.8	171	179	-4.2	159	166	-3.7	140	143	-2.4	117	120	-2.1	77	78	-1.1	46	46	0.6	24	24	2.6	11	10	9.6
H20K215	184	188	-1.8	167	174	-4.3	155	161	-3.7	136	139	-2.4	114	116	-2.0	74	75	-1.1	44	43	0.8	21	22	2.9	10	9	10.6
H20K225	180	183	-1.7	163	170	-4.3	151	157	-3.7	132	135	-2.3	111	112	-2.0	71	72	-1.1	42	41	0.7	21	21	3.2	9	8	11.8
H24K15	550	553	-0.5	533	542	-1.5	521	530	-1.6	500	507	-1.5	474	481	-1.4	417	423	-1.4	358	363	-1.4	300	304	-1.3	247	250	-1.2
H24K25	426	427	-0.3	410	417	-1.6	399	405	-1.6	379	384	-1.5	355	360	-1.5	304	308	-1.5	252	256	-1.4	204	207	-1.2	161	163	-1.1
H24K35	360	361	-0.1	344	350	-1.7	334	340	-1.7	315	320	-1.5	293	297	-1.5	245	249	-1.5	198	201	-1.4	156	158	-1.2	119	120	-1.0
H24K45	318	318	0.0	302	308	-1.7	292	297	-1.8	274	278	-1.6	253	256	-1.5	208	211	-1.5	165	167	-1.3	126	128	-1.1	93	94	-0.8
H24K55	288	287	0.2	272	277	-1.8	262	267	-1.8	244	248	-1.6	224	228	-1.5	182	184	-1.5	141	143	-1.3	106	107	-1.0	76	77	-0.7
H24K65	265	264	0.3	250	254	-1.8	240	244	-1.8	222	226	-1.6	203	206	-1.5	162	165	-1.5	124	126	-1.3	91	92	-1.0	64	64	-0.5
H24K75	246	245	0.4	232	236	-1.8	222	226	-1.9	205	208	-1.6	186	189	-1.5	147	149	-1.5	111	112	-1.2	80	81	-0.9	55	55	-0.3
H24K85	232	230	0.6	217	221	-1.8	207	211	-1.9	191	194	-1.6	172	175	-1.6	135	137	-1.5	100	101	-1.2	71	72	-0.8	48	48	-0.1
H24K95	219	218	0.7	204	208	-1.9	195	199	-1.9	179	182	-1.6	161	164	-1.6	124	126	-1.5	91	92	-1.1	64	64	-0.7	42	42	0.1
H24K105	208	207	0.8	194	198	-1.9	185	188	-2.0	169	172	-1.6	151	154	-1.6	116	117	-1.5	84	85	-1.1	58	58	-0.6	37	37	0.3
H24K115	199	197	0.9	185	188	-1.9	176	179	-2.0	160	163	-1.7	143	145	-1.6	108	110	-1.5	78	79	-1.1	53	53	-0.5	34	33	0.5
H24K125	191	189	1.0	177	180	-1.9	168	171	-2.0	153	155	-1.7	136	138	-1.6	102	103	-1.5	72	73	-1.0	48	49	-0.4	30	30	0.8
H24K135	184	182	1.1	170	173	-2.0	161	164	-2.0	146	148	-1.7	129	131	-1.6	96	98	-1.5	68	68	-0.9	45	45	-0.3	27	27	1.0
H24K145	178	176	1.1	163	167	-2.0	155	158	-2.0	140	142	-1.7	123	125	-1.6	91	93	-1.5	63	64	-0.9	41	41	-0.2	25	25	1.3
H24K155	172	170	1.2	158	161	-2.0	149	152	-2.1	134	137	-1.7	118	120	-1.6	87	88	-1.4	60	60	-0.8	38	38	-0.1	23	23	1.6
H24K165	167	164	1.3	153	156	-2.0	144	147	-2.1	130	132	-1.7	114	115	-1.6	83	84	-1.4	56	57	-0.8	36	36	0.0	21	21	1.9
H24K175	162	160	1.4	148	151	-2.0	139	142	-2.1	125	127	-1.7	109	111	-1.6	79	80	-1.4	53	54	-0.7	34	34	0.1	19	19	2.2
H24K185	157	155	1.5	144	147	-2.0	135	138	-2.1	121	123	-1.7	106	107	-1.5	76	77	-1.4	51	51	-0.7	32	31	0.3	18	17	2.5
H24K195	153	151	1.6	140	142	-2.0	131	134	-2.1	117	119	-1.7	102	104	-1.5	73	74	-1.4	48	49	-0.6	30	30	0.4	17	16	2.9
H24K205	150	147	1.6	136	139	-2.1	128	130	-2.1	114	116	-1.7	99	100	-1.5	70	71	-1.4	46	46	-0.6	28	28	0.5	15	15	3.2

TABLE 1: Continued.

Number	w0 (mm)		w20 (mm)		w30 (mm)		w45 (mm)		w60 (mm)		w90 (mm)		w120 (mm)		w150 (mm)		w180 (mm)	
	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%
H24K215	146	144	1.7	132	135	-2.1	124	127	-2.1	111	112	-1.7	96	97	-1.5	67	68	-1.3
H24K225	143	140	1.8	129	132	-2.1	121	124	-2.2	108	109	-1.7	93	94	-1.5	65	66	-1.3
H28K15	441	439	0.3	427	432	-1.1	419	424	-1.2	404	409	-1.2	386	391	-1.2	347	351	-1.3
H28K25	342	340	0.7	329	333	-1.0	321	325	-1.2	307	311	-1.2	291	295	-1.2	255	259	-1.4
H28K35	290	287	1.0	277	280	-1.0	269	273	-1.2	256	259	-1.3	241	244	-1.3	207	210	-1.4
H28K45	256	253	1.3	244	246	-1.0	236	239	-1.2	223	226	-1.3	209	211	-1.3	177	179	-1.4
H28K55	232	228	1.6	220	222	-1.0	212	215	-1.2	200	202	-1.3	186	188	-1.3	155	158	-1.4
H28K65	214	210	1.8	201	203	-1.0	194	197	-1.2	182	185	-1.3	169	171	-1.3	139	0	-1.4
H28K75	199	195	2.0	187	189	-0.9	180	182	-1.2	168	170	-1.3	155	157	-1.3	127	129	-1.5
H28K85	187	183	2.2	175	177	-0.9	168	171	-1.2	157	159	-1.3	144	146	-1.3	117	118	-1.5
H28K95	177	173	2.4	166	167	-0.9	159	161	-1.2	147	149	-1.3	135	136	-1.3	108	110	-1.5
H28K105	169	165	2.6	157	159	-0.9	150	152	-1.2	139	141	-1.3	127	128	-1.3	101	102	-1.5
H28K115	162	157	2.7	150	151	-0.9	143	145	-1.2	132	134	-1.3	120	122	-1.3	95	96	-1.5
H28K125	155	151	2.9	143	145	-0.9	137	139	-1.2	126	128	-1.3	114	116	-1.3	89	91	-1.5
H28K135	149	145	3.1	138	139	-0.9	131	133	-1.2	121	122	-1.4	109	110	-1.3	85	86	-1.5
H28K145	144	140	3.2	133	134	-0.9	126	128	-1.2	116	117	-1.4	104	106	-1.3	81	82	-1.5
H28K155	140	135	3.3	128	129	-0.9	122	123	-1.3	111	113	-1.4	100	101	-1.3	77	78	-1.5
H28K165	136	131	3.5	124	125	-0.9	118	119	-1.3	107	109	-1.4	96	97	-1.3	73	75	-1.5
H28K175	132	127	3.6	120	121	-0.8	114	116	-1.3	104	105	-1.4	93	94	-1.3	70	71	-1.5
H28K185	128	124	3.8	117	118	-0.8	111	112	-1.3	100	102	-1.4	90	91	-1.3	68	69	-1.5
H28K195	125	120	3.9	114	115	-0.8	108	109	-1.3	97	99	-1.4	87	88	-1.3	65	66	-1.5
H28K205	122	117	4.0	111	112	-0.8	105	106	-1.3	95	96	-1.4	84	85	-1.3	63	64	-1.5
H28K215	119	114	4.1	108	109	-0.8	102	103	-1.3	92	93	-1.4	81	83	-1.3	60	61	-1.5
H28K225	117	112	4.2	105	106	-0.8	99	101	-1.3	90	91	-1.4	79	80	-1.3	58	59	-1.5
H32K15	363	360	0.7	353	355	-0.4	346	349	-0.9	334	339	-1.2	322	326	-1.3	293	297	-1.3
H32K25	282	278	1.2	273	274	-0.2	266	268	-0.8	255	258	-1.2	243	247	-1.3	217	220	-1.4
H32K35	239	235	1.7	230	230	0.0	224	225	-0.7	213	216	-1.3	202	205	-1.4	178	180	-1.4
H32K45	211	207	2.0	203	202	0.2	196	198	-0.7	186	188	-1.3	175	178	-1.4	152	154	-1.4
H32K55	192	187	2.4	183	183	0.3	177	178	-0.6	167	169	-1.3	156	159	-1.4	134	136	-1.4
H32K65	177	172	2.6	168	168	0.4	162	163	-0.6	152	154	-1.3	142	144	-1.5	121	0	-1.4
H32K75	165	160	2.9	157	156	0.5	150	151	-0.5	141	143	-1.3	131	133	-1.5	110	112	-1.5
H32K85	155	150	3.2	147	146	0.6	141	141	-0.5	131	133	-1.3	122	124	-1.5	102	103	-1.5
H32K95	147	142	3.4	139	138	0.7	133	133	-0.5	123	125	-1.3	114	116	-1.5	95	96	-1.5
H32K105	140	135	3.6	132	131	0.8	126	126	-0.4	117	118	-1.3	108	109	-1.5	89	90	-1.5
H32K115	134	129	3.9	126	125	0.9	120	120	-0.4	111	112	-1.3	102	103	-1.5	83	85	-1.5
H32K125	129	124	4.1	121	120	1.0	115	115	-0.4	106	107	-1.3	97	98	-1.6	79	80	-1.5
H32K135	124	119	4.3	116	115	1.1	110	111	-0.3	101	103	-1.4	93	94	-1.6	75	76	-1.5
H32K145	120	115	4.5	112	111	1.2	106	106	-0.3	97	99	-1.4	89	90	-1.6	71	72	-1.5
H32K155	116	111	4.6	108	107	1.3	102	103	-0.3	94	95	-1.4	85	87	-1.6	68	69	-1.5
H32K165	113	107	4.8	105	103	1.3	99	99	-0.2	90	92	-1.4	82	83	-1.6	65	66	-1.5
H32K175	110	104	5.0	102	100	1.4	96	96	-0.2	87	89	-1.4	79	80	-1.6	63	64	-1.5
H32K185	107	101	5.2	99	97	1.5	93	93	-0.2	85	86	-1.4	77	78	-1.6	60	61	-1.5

TABLE 1: Continued.

Number	w0 (mm)			w20 (mm)			w30 (mm)			w45 (mm)			w60 (mm)			w90 (mm)			w120 (mm)			w150 (mm)			w180 (mm)		
	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%	DFE	Deal	D%
H32K195	104	99	5.3	96	95	1.6	91	91	-0.2	82	83	-1.4	74	75	-1.7	58	59	-1.5	43	44	-1.0	31	31	-0.6	21	21	0.2
H32K205	102	96	5.5	94	92	1.6	88	88	-0.1	80	81	-1.4	72	73	-1.7	56	57	-1.5	42	42	-1.0	30	30	-0.5	20	20	0.4
H32K215	99	94	5.6	92	90	1.7	86	86	-0.1	78	79	-1.4	70	71	-1.7	54	55	-1.5	40	41	-0.9	28	28	-0.5	19	19	0.5
H32K225	97	92	5.8	89	88	1.8	84	84	-0.1	76	77	-1.4	68	69	-1.7	52	53	-1.5	39	39	-0.9	27	27	-0.4	18	18	0.6
H36K15	305	302	1.1	296	298	-0.7	291	294	-0.9	283	286	-1.1	274	277	-1.2	252	256	-1.4	229	232	-1.3	205	208	-1.3	181	184	-1.3
H36K25	238	234	1.8	229	230	-0.6	224	226	-0.9	216	219	-1.2	208	210	-1.1	188	191	-1.4	167	169	-1.3	146	148	-1.3	126	128	-1.3
H36K35	202	197	2.3	193	194	-0.6	188	190	-0.9	181	183	-1.2	173	175	-1.2	154	156	-1.4	135	137	-1.3	116	117	-1.3	98	99	-1.2
H36K45	179	174	2.8	170	170	-0.5	165	167	-0.8	158	160	-1.2	150	152	-1.2	133	135	-1.5	115	116	-1.3	97	98	-1.3	80	81	-1.2
H36K55	162	157	3.2	153	154	-0.4	149	150	-0.8	142	144	-1.2	134	136	-1.3	117	119	-1.5	100	102	-1.3	84	85	-1.2	68	69	-1.2
H36K65	150	144	3.5	141	141	-0.4	137	138	-0.8	130	131	-1.2	122	124	-1.3	106	0	-1.5	90	91	-1.3	74	75	-1.2	60	60	-1.1
H36K75	140	134	3.9	131	131	-0.3	127	128	-0.7	120	121	-1.2	113	114	-1.3	97	98	-1.5	81	82	-1.3	66	67	-1.2	53	53	-1.1
H36K85	131	126	4.2	123	123	-0.3	119	120	-0.7	112	113	-1.2	105	106	-1.3	90	91	-1.6	74	75	-1.3	60	61	-1.2	47	48	-1.0
H36K95	125	119	4.5	116	116	-0.2	112	113	-0.7	105	107	-1.2	98	100	-1.3	83	85	-1.6	69	70	-1.3	55	56	-1.1	43	43	-0.9
H36K105	119	113	4.8	110	110	-0.2	106	107	-0.7	100	101	-1.2	93	94	-1.3	78	80	-1.6	64	65	-1.3	51	51	-1.1	39	40	-0.9
H36K115	114	108	5.0	105	105	-0.1	101	102	-0.6	95	96	-1.2	88	89	-1.3	74	75	-1.6	60	61	-1.3	47	48	-1.1	36	36	-0.8
H36K125	109	104	5.3	101	101	-0.1	97	98	-0.6	91	92	-1.2	84	85	-1.3	70	71	-1.6	56	57	-1.3	44	45	-1.0	33	34	-0.7
H36K135	105	100	5.5	97	97	0.0	93	94	-0.6	87	88	-1.2	80	81	-1.3	66	68	-1.6	53	54	-1.3	41	42	-1.0	31	31	-0.7
H36K145	102	96	5.8	93	93	0.0	90	90	-0.6	84	85	-1.2	77	78	-1.3	63	64	-1.6	51	51	-1.3	39	39	-0.9	29	29	-0.6
H36K155	99	93	6.0	90	90	0.0	87	87	-0.6	80	81	-1.2	74	75	-1.3	61	62	-1.6	48	49	-1.2	37	37	-0.9	27	27	-0.5
H36K165	96	90	6.2	87	87	0.1	84	84	-0.6	78	79	-1.2	71	72	-1.3	58	59	-1.6	46	46	-1.2	35	35	-0.8	26	26	-0.4
H36K175	93	88	6.4	85	85	0.1	81	82	-0.5	75	76	-1.2	69	70	-1.3	56	57	-1.6	44	44	-1.2	33	33	-0.8	24	24	-0.3
H36K185	91	85	6.7	82	82	0.1	79	79	-0.5	73	74	-1.2	67	68	-1.3	54	55	-1.6	42	43	-1.2	32	32	-0.8	23	23	-0.2
H36K195	89	83	6.9	80	80	0.2	77	77	-0.5	71	72	-1.2	65	66	-1.3	52	53	-1.6	40	41	-1.2	30	30	-0.7	22	22	-0.1
H36K205	87	81	7.1	78	78	0.2	75	75	-0.5	69	70	-1.2	63	64	-1.4	50	51	-1.7	39	39	-1.2	29	29	-0.7	21	21	0.0
H36K215	85	79	7.3	76	76	0.2	73	73	-0.5	67	68	-1.2	61	62	-1.4	49	49	-1.7	37	38	-1.2	28	28	-0.6	20	20	0.1
H36K225	83	77	7.4	74	74	0.3	71	71	-0.5	65	66	-1.2	59	60	-1.4	47	48	-1.7	36	37	-1.2	27	27	-0.6	19	19	0.2
H40K15	262	258	1.7	254	255	-0.5	250	252	-0.8	243	246	-1.1	236	239	-1.2	220	223	-1.4	202	204	-1.3	183	185	-1.3	164	166	-1.4
H40K25	205	200	2.5	196	197	-0.3	193	194	-0.7	186	188	-1.1	180	182	-1.3	164	167	-1.5	148	150	-1.4	132	133	-1.3	115	117	-1.4
H40K35	174	169	3.2	166	166	-0.2	162	163	-0.6	156	158	-1.1	150	152	-1.3	135	137	-1.5	120	122	-1.4	105	106	-1.4	90	92	-1.4
H40K45	154	149	3.8	146	146	0.0	143	143	-0.5	137	138	-1.1	130	132	-1.3	117	118	-1.6	102	104	-1.4	88	90	-1.4	75	76	-1.4
H40K55	140	134	4.3	132	132	0.1	129	129	-0.4	123	124	-1.1	117	118	-1.3	103	105	-1.6	90	91	-1.5	77	78	-1.4	64	65	-1.4
H40K65	129	123	4.7	121	121	0.2	118	118	-0.4	112	113	-1.1	106	108	-1.3	94	0	-1.6	81	82	-1.5	68	69	-1.4	56	57	-1.3
H40K75	121	115	5.2	113	112	0.3	110	110	-0.3	104	105	-1.1	98	99	-1.4	86	87	-1.7	73	74	-1.5	61	62	-1.4	50	51	-1.3
H40K85	114	108	5.6	106	105	0.3	103	103	-0.3	97	98	-1.1	91	93	-1.4	79	81	-1.7	67	68	-1.5	56	57	-1.4	45	46	-1.3
H40K95	108	102	5.9	100	100	0.4	97	97	-0.2	91	92	-1.1	86	87	-1.4	74	75	-1.7	62	63	-1.5	51	52	-1.4	41	42	-1.2
H40K105	103	97	6.3	95	95	0.5	92	92	-0.2	87	88	-1.1	81	82	-1.4	70	71	-1.7	58	59	-1.5	47	48	-1.3	38	38	-1.2
H40K115	99	93	6.6	91	90	0.6	88	88	-0.2	82	83	-1.1	77	78	-1.4	66	67	-1.7	55	56	-1.6	44	45	-1.3	35	35	-1.2
H40K125	95	89	7.0	87	87	0.6	84	84	-0.1	79	80	-1.1	73	75	-1.4	62	63	-1.8	52	52	-1.6	41	42	-1.3	32	33	-1.1
H40K135	92	85	7.3	84	83	0.7	81	81	-0.1	76	76	-1.1	70	71	-1.4	59	60	-1.8	49	50	-1.6	39	40	-1.3	30	31	-1.1
H40K145	89	82	7.6	81	80	0.8	78	78	0.0	73	73	-1.1	67	68	-1.5	57	58	-1.8	46	47	-1.6	37	37	-1.3	28	29	-1.0
H40K155	86	80	7.9	78	77	0.8	75	75	0.0	70	71	-1.1	65	66	-1.5	54	55	-1.8	44	45	-1.6	35	35	-1.3	27	27	-1.0
H40K165	83	77	8.1	76	75	0.9	73	73	0.0	68	68	-1.1	63	63	-1.5	52	53	-1.8	42	43	-1.6	34	34	-1.2	25	25	-0.9

TABLE 1: Continued.

Number	w0 (mm)		w20 (mm)		w30 (mm)		w45 (mm)		w60 (mm)		w90 (mm)		w120 (mm)		w150 (mm)		w180 (mm)										
	DfE	Dcal	D%	DfE	Dcal	D%	DfE	Dcal	D%	DfE	Dcal	D%	DfE	Dcal	D%	DfE	Dcal	D%									
H40K175	81	75	8.4	73	73	0.9	70	70	0.1	65	66	-1.1	60	61	-1.5	50	51	-1.8	40	41	-1.6	32	32	-1.2	24	24	-0.8
H40K185	79	73	8.7	71	71	1.0	68	68	0.1	63	64	-1.1	58	59	-1.5	48	49	-1.9	39	39	-1.6	30	30	-1.2	23	23	-0.8
H40K195	77	71	8.9	69	69	1.0	67	66	0.1	62	62	-1.1	57	58	-1.5	47	48	-1.9	37	38	-1.6	29	29	-1.2	22	22	-0.7
H40K205	76	69	9.2	68	67	1.1	65	65	0.1	60	61	-1.1	55	56	-1.5	45	46	-1.9	36	37	-1.6	28	28	-1.2	21	21	-0.7
H40K215	74	68	9.4	66	65	1.2	63	63	0.2	58	59	-1.1	54	54	-1.5	44	45	-1.9	35	35	-1.6	27	27	-1.1	20	20	-0.6
H40K225	72	66	9.7	65	64	1.2	62	62	0.2	57	58	-1.1	52	53	-1.5	42	43	-1.9	34	34	-1.6	26	26	-1.1	19	19	-0.5
H44K15	228	224	2.1	223	222	0.5	219	219	-0.3	212	215	-1.0	206	209	-1.2	194	196	-1.3	179	182	-1.3	164	166	-1.4	149	151	-1.3
H44K25	178	173	3.0	173	171	0.9	169	169	-0.1	163	164	-1.0	157	159	-1.3	145	147	-1.3	132	134	-1.3	119	121	-1.4	106	107	-1.3
H44K35	152	146	3.8	146	144	1.3	142	142	0.1	137	138	-0.9	131	133	-1.3	120	122	-1.4	108	109	-1.3	96	97	-1.4	84	85	-1.4
H44K45	135	129	4.4	129	127	1.6	125	125	0.3	120	121	-0.9	114	116	-1.4	104	105	-1.4	92	94	-1.3	81	82	-1.5	70	71	-1.4
H44K55	122	116	5.0	117	115	1.8	113	113	0.4	108	109	-0.9	103	104	-1.4	92	94	-1.4	81	82	-1.3	70	71	-1.5	60	61	-1.3
H44K65	113	107	5.5	107	105	2.1	104	103	0.5	98	99	-0.9	94	95	-1.4	84	0	-1.5	73	74	-1.4	63	64	-1.5	53	54	-1.3
H44K75	106	100	6.0	100	98	2.3	96	96	0.6	91	92	-0.9	86	88	-1.4	77	78	-1.5	67	68	-1.4	57	57	-1.5	47	48	-1.3
H44K85	100	94	6.4	94	92	2.5	90	90	0.8	85	86	-0.9	81	82	-1.5	71	72	-1.5	61	62	-1.4	52	52	-1.5	43	43	-1.3
H44K95	95	88	6.8	89	87	2.7	85	85	0.9	80	81	-0.9	76	77	-1.5	66	67	-1.5	57	58	-1.4	48	48	-1.5	39	40	-1.3
H44K105	90	84	7.2	85	82	2.9	81	80	1.0	76	77	-0.9	72	73	-1.5	63	63	-1.5	53	54	-1.4	44	45	-1.5	36	37	-1.2
H44K115	86	80	7.6	81	79	3.1	77	77	1.0	73	73	-0.9	68	69	-1.5	59	60	-1.5	50	51	-1.4	41	42	-1.5	33	34	-1.2
H44K125	83	77	8.0	78	75	3.3	74	73	1.1	69	70	-0.9	65	66	-1.6	56	57	-1.6	47	48	-1.4	39	39	-1.5	31	32	-1.2
H44K135	80	74	8.3	75	72	3.5	71	71	1.2	66	67	-0.8	62	63	-1.6	54	54	-1.6	45	46	-1.4	37	37	-1.5	29	30	-1.2
H44K145	78	72	8.6	72	70	3.6	69	68	1.3	64	64	-0.8	60	61	-1.6	51	52	-1.6	43	43	-1.4	35	35	-1.5	28	28	-1.1
H44K155	75	69	9.0	70	67	3.8	66	66	1.4	62	62	-0.8	57	58	-1.6	49	50	-1.6	41	41	-1.4	33	33	-1.5	26	26	-1.1
H44K165	73	67	9.3	68	65	3.9	64	63	1.5	60	60	-0.8	55	56	-1.6	47	48	-1.6	39	40	-1.4	31	32	-1.5	25	25	-1.0
H44K175	71	65	9.6	66	63	4.1	62	62	1.5	58	58	-0.8	53	54	-1.7	45	46	-1.6	37	38	-1.4	30	30	-1.5	23	24	-1.0
H44K185	69	63	9.9	64	62	4.2	61	60	1.6	56	56	-0.8	52	53	-1.7	44	45	-1.6	36	36	-1.4	29	29	-1.5	22	22	-1.0
H44K195	68	62	10.1	62	60	4.4	59	58	1.7	54	55	-0.8	50	51	-1.7	42	43	-1.6	35	35	-1.4	27	28	-1.5	21	21	-0.9
H44K205	66	60	10.4	61	58	4.5	58	57	1.7	53	53	-0.8	49	50	-1.7	41	42	-1.6	33	34	-1.4	26	27	-1.5	20	20	-0.9
H44K215	65	59	10.7	60	57	4.6	56	55	1.8	52	52	-0.8	47	48	-1.7	40	40	-1.6	32	33	-1.4	25	26	-1.5	19	19	-0.8
H44K225	64	57	11.0	58	56	4.8	55	54	1.9	50	51	-0.8	46	47	-1.8	39	39	-1.7	31	32	-1.4	24	25	-1.4	19	19	-0.8

Note. (a) D^{FE} and D^{cal} stand for the deflection values obtained by the finite element method and the Winkler model, respectively (unit: mm); (b) $D^{\%}$ represents the relative deviation of the D^{FE} and D^{cal} .

FIGURE 1: Layout of measuring points.

FIGURE 2: FE model of pavement thin slab. (a) Stress of concrete slab. (b) Displacement under H28K125 working condition.

TABLE 2: Parameters adopted in the parametric study.

Parameter	Value
Slab thickness h (mm)	20–44 at an interval of 4
Modulus of subgrade reaction k (MN/m ³)	15–225 at an interval of 10

$$w(r) = \frac{qR}{kl} \int_0^\infty \frac{J_0((r/l)t)J_1((R/l)t)}{1+t^4} dt, \quad (1)$$

where $w(r)$ represents the deflection value at the distance of r away from the load center (m); q is the circular uniform load (Pa); R stands for the radius of load acting surface (m); l represents the radius of relative stiffness (m), which can be calculated by equation (2) according to Ioannides [12]; J_0 is the zero-order Bessel function; J_1 is the first-order Bessel function; r is the distance of a measurement point away from the load center (m); and t stands for the integral variable.

$$l = \left(\frac{Eh^3}{12(1-\mu^2)k} \right)^{1/4}, \quad (2)$$

where E represents the elastic modulus of pavement slab (Pa) and μ represents Poisson's ratio.

2.4.2. Verification. To evaluate the accuracy of the FE model, the FE results were compared with the corresponding theoretical deflection values calculated with MATLAB under 154 working conditions according to the Winkler foundation model formula, as shown in Table 1. Only part of deflection data were selected to illustrate the difference of theoretical and simulated value of deflections, as depicted in Figure 3. The variables D^{FE} and D^{cal} represent the deflection values obtained by the numerical simulation and theoretical calculation, respectively.

FIGURE 3: Comparisons of deflections between FE simulations and theoretical calculations.

It can be seen from Table 1 and Figure 3 that the difference between the simulated value and the theoretical value is rather small, and the deviations of the points within 20–150 cm away from the load center are even lower than 5%. Moreover, the deviation decreases first and then increases with the increment of slab thickness, and it increases with the modulus of subgrade reaction. For the slab with a thickness of 0.24–0.40 m, the deviations are all lower than 10%. However, when the slab thickness exceeds or is lower than a specific value and with the increment of the modulus of subgrade reaction, the deviation between the two methods gradually increases. For example, when the thickness of the slab is 0.44 m, the maximum deviation of the measurement point in the load center is 10.96%, and the deviation of the measuring point at the location of 180 cm away from the load center is 11.82% on the slab with the thickness of 0.2 m. The reason is probably that the Winkler foundation model was initially developed based on the thin slab theory, and the thick slab may be squeezed vertically at the loading point, resulting in the measurement deviation. The accuracy of the predicted solution may be extensively degraded for the slab with a relatively high modulus of subgrade reaction. Furthermore, there was no interaction between different points, as assumed in the Winkler foundation model. However, weak interactions can be detected in the FE model. When the thickness of the slab was relatively thin, the cumulative deviation may bring a significant error for the farthest point away from the loading point with the increase of the modulus of subgrade reaction due to the weak interaction. Therefore, to ensure the accuracy of verification and the rationality of the model parameters being relative to the engineering application, it is suggested that the optimal range of the slab thickness is 0.24–0.40 m.

3. Refined Deflection Basin Area Index Method

3.1. General Description. Ioannides [12] has illustrated that the deflection basin area index A_w (see equation (3)) was a geometric property of the deflection basin, which can be calculated based on the by dividing the basin into several fine trapezoids as shown in Figure 4. Then, A_w is normalized by the deflection value w of the designated measuring point, which can be applied to describe the geometric information of the deflection basin:

$$A_w = \frac{s}{2w} [w_0 + 2(w_1 + w_2 + \cdots w_{n-1}) + w_n], \quad (3)$$

where s represents the distance between two adjacent measuring points (m); w is the deflection of the designated measuring point (m); and w_i is the deflection of measuring point i (m).

Based on the elastic foundation slab model theory, the deflection basin area index method is a back-calculation approach that determines the pavement structural parameters as per the deflection value. The back-calculation process can be stated as follows. According to equations (1) and (2), the deflection value at a certain point is determined by the calculations of qR/k and $1/l \int_0^\infty (J_0((r/l)t)J_1((R/l)t)/(1+t^4))dt$. However, it is difficult to calculate the modulus of subgrade reaction k and the radius of relative stiffness l in practical engineering simultaneously. To separate these two variables, the deflection basin area index A_w becomes a necessity, and the relationship between A_w and l can be established. Then, according to the expression of the deflection coefficient $w(l)$, the equations of the modulus of subgrade reaction k and the elastic modulus of pavement slab E are also available, which are induced by the following equations:

$$k = \frac{qR}{w(r_0)} w(l), \quad (4)$$

where $w(r_0)$ is the deflection value at r_0 away from the load center (m) and $w(l)$ stands for deflection coefficient which is equal to $1/l \int_0^\infty (J_0((r/l)t)J_1((R/l)t)/(1+t^4))dt$.

$$E = \frac{12(1-\mu^2)kl^4}{h^3}. \quad (5)$$

3.2. Existing Deflection Basin Area Index Methods

3.2.1. Method Introduction. So far, the conventional deflection basin area index methods with satisfactory accuracy mainly include MH/T 5024-2009 [13], Strategic Highway Research Program (SHRP) 4-in, SHRP 5-outer, US Air Force (USAF) 6-outer, and SHRP 7-in method [24]. It should be noted that the number represents the number of measuring points, and the following label of “in” and “outer” means the near-side measuring points (measurement ranges within the load center) and far-side measuring points (measurement ranges beyond the load center), respectively. Figure 5 shows the layout schemes of measuring points of several theories mentioned above.

FIGURE 4: Calculation diagram of the deflection basin area.

FIGURE 5: Layout schemes of measuring points. Layout scheme of (a) MH/T 5024-2009 [13], (b) Cheng et al. [19], and (c) SHRP 7-in [24].

Cheng et al. [19] have analyzed the accuracy of back-calculation of the five deflection basin area index methods mentioned above for pavement structural parameters and reported that the results of the far-end measuring points were more accurate. Furthermore, it has also been observed that sufficient measuring points and a reasonable form of best-fitting formula can significantly improve the accuracy of prediction. In addition, for the reason that most of the existing methods cannot incorporate the deflection information of each measurement point, Lin et al. [15] developed a revised deflection basin area index method to overcome this deficiency using the point-by-point fitting method [9] based on the traditional deflection basin area index method. The results revealed that the new method can provide more reasonable back-calculation results. However, this method requires multiple iterations of the distribution, which makes the calculation process quite complicated.

3.2.2. Method Evaluation. Based on the database mentioned above, the accuracy of the methods of MH/T 5024-2009 [13], SHRP 7-in [24], Cheng et al. [19], and Lin et al. [15] is systematically evaluated in this section. Nine groups of representative working conditions are compared. The results are presented in Figure 6 and Table 3. It should be noted that the calculated value of the modulus of subgrade reaction k is adopted to assess the accuracy.

As illustrated in Figure 6, although the methods of SHRP 7-in [24] and MH/T 5024-2009 [13] adopted similar layout schemes on the near-end measuring points, smaller back-calculation deviations are detected for the former method. This is because that the measuring points in SHRP 7-in [24] method are arranged intensively near the loading point, where the slope of deflection basin curve is significantly changed to fully capture the shape of deflection basin, resulting in a higher accuracy compared with MH/T 5024-2009 [13]. Since the far-end measuring points were used in Cheng et al. [19] method to conduct the back-calculation process, the predicted errors decrease obviously due to the reason stated before. For these methods except for Lin et al. [15], the deflection value of a specific measuring point was applied to standardize the deflection basin area index A_w . Thus, when the information of the specific measuring point is inaccurate, considerable errors of the predicted results may emerge, and the back-calculation process may become unstable as well. Moreover, if the deflection value normalizes the deflection basin area index at different measuring points, multiple-solution problems need to be considered as well. To avoid these potential problems, Lin et al. [15] have calculated the back-calculation results by minimizing the deviations as the objective function, which exhibits the best performance among all selected methods, as represented in Figure 6. However, low efficiency and complex calculations faced by this method means that it cannot be applied directly in practical engineering.

3.3. Proposed Method. To balance the accuracy of prediction and calculation complexity, seven locally intensive far-end measuring points were adopted with the positions of 30 cm,

45 cm, 60 cm, 90 cm, 120 cm, 150 cm, and 180 cm away from the load center, as shown in Figure 7. Besides, the average $\bar{w}$ of all the above points was applied directly to determine the deflection basin area index A_w and the resulting modulus of subgrade reaction k was recalculated as well (equations (6)–(8)). The most evident advantage of this method was that the information of deflection of all measuring points can be considered to make the predicted results more accurate and stable and to avoid the multiple-solution problem effectively.

$$A_w = \frac{0.15}{2\bar{w}} [w_{30} + 2w_{45} + 3w_{60} + 4(w_{90} + w_{120} + w_{150}) + 2w_{180}], \quad (6)$$

where w_j is the deflection of measuring point j (m) and j represents the distance from the load center (m).

$$\bar{w} = \frac{1}{7} (w_{30} + w_{45} + w_{60} + w_{90} + w_{120} + w_{150} + w_{180}), \quad (7)$$

$$k = \frac{qR}{\bar{w}} w(l). \quad (8)$$

Based on the deflection results from FE simulations under different working conditions (including different modulus of subgrade reaction k and different thickness of pavement slab h), the expression on the radius of relative stiffness l was obtained by regression analyses [25] with equations (2) and (6), as presented in equation (9); next, the deflection coefficient $w(l)$ was regressed through equations (8)–(9), as presented in equation (10). Figures 8 and 9 show that the trend almost coincides with the simulation results with R^2 being equal to 0.9927 and 0.9995, respectively. It should be noted that, under all working conditions, the deflection results of the slab with a certain thickness are represented by the same label, and the number following the letter “H” refers to the thickness of the slab. X represents all working conditions under this plate thickness.

$$l = 0.0036e^{(A_w^{4.60338})} + 0.52495, \quad (9)$$

$$w(l) = 0.1945e^{(-1.90595l)} + 0.00908. \quad (10)$$

4. Comparison with Engineering Data

4.1. Data Source. An airport in northern China was selected to obtain practical deflection results. The runway is 2200 m in length and 45 m in width, including two vertical contact lanes and six parking aprons. The airport is located on the frozen soil area, and the soil layers are topsoil/miscellaneous fill, fine sand, silty clay, and bedrock (moderately and strongly weathered granite) [26], respectively. The runway of the airport has a severe frost boiling problem due to the freeze-thaw effect and constant impact loads. Thus, the HWD deflection test has been carried out on the existing pavement to assess the safety grade of the airport, as shown in Figure 10, which covered all functional regions, as listed in Table 4.

FIGURE 6: Deviation comparison of existing deflection basin area index methods.

TABLE 3: Comparison of existing deflection basin area index methods.

Number	MH/T 5024-2009 [13] (%)	SHRP 7-in [24] (%)	Cheng et al. [19] (%)	Lin et al. [15] (%)
H28K45	34.89	18.45	11.43	9.01
H28K65	36.62	20.72	9.77	7.12
H28K85	36.81	22.65	7.8	6.59
H32K45	30.33	18.46	11.16	8.42
H32K65	34.63	20.72	9.92	7.34
H32K85	36.26	22.65	8.54	6.69
H36K45	23.22	21.22	11.25	8.03
H36K65	30.53	23.83	11.21	7.55
H36K85	33.85	25.50	10.18	7.02
Average	33.02	22.06	10.38	7.51

FIGURE 7: Layout scheme of measuring points in the proposed method.

4.2. Verification Results. To verify the rationality of the proposed method, the actual deflection data of each functional area of the airport were randomly selected to examine the back-calculation accuracy of the new proposed approach and three other methods developed by MH/T 5024-2009 [13], Cheng et al. [19], and Lin et al. [15]. Based on the

measuring data of deflections, the deflection basin area index A_w can be determined by equation (6). Then, the radius of relative stiffness l and the deflection coefficient $w(l)$ were obtained by the proposed equations as well, and the modulus of subgrade reaction k and elastic modulus of pavement slab E can also be derived by equations (8) and (5), respectively.

FIGURE 8: Relationship between A_w and l . FIGURE 9: Relationship between l and $w(l)$.

Therefore, the theoretical value of deflection calculated by equation (1) as per the above structural parameters was adopted to compare it with the actual measurement value, and the difference between the two values is shown in Figure 11 and Table 5.

As shown in Figure 11, the methods developed by Cheng et al. [19] and MH/T 5024-2009 [13] possess a lower accuracy and unstable predictions, which indicates that the information of the specific measuring point adopted to

FIGURE 10: Schematic diagram of HWD deflection measurement.

TABLE 4: Information of pavement structure for the airport.

Region	Functional area	Pavement type	Load (kN)
Runway	1800 m from east to west	Cement concrete	70
	400 m from west to east		
Contact lane	A contact lane B contact lane	Cement concrete	70
Parking apron	A parking apron B parking apron	Cement concrete	70

FIGURE 11: The deviation sum of deflection.

standardize A_w may have a great impact on the back-calculation results in the conventional deflection basin area index methods. For the proposed method and method developed by Lin et al. [15], more stable results can be obtained because all measuring points are considered. Moreover, the new method proposed in this study exhibits the better performance with the lower predicted errors and

TABLE 5: Verification of four methods.

Measuring point	w_0 (mm)	w_{20} (mm)	w_{30} (mm)	w_{45} (mm)	w_{60} (mm)	w_{90} (mm)	w_{120} (mm)	w_{150} (mm)	w_{180} (mm)	Elastic modulus E (GPa)				Modulus of subgrade reaction k (MN/m ³)				Sum of errors (um)			
										Proposed	MH/ T5024- 2009 [13]	Cheng et al. [19]	Lin et al. [15]	Proposed	MH/ T5024- 2009 [13]	Cheng et al. [19]	Lin et al. [15]	Proposed	MH/ T5024- 2009 [13]	Cheng et al. [19]	Lin et al. [15]
H28-1	125	118	115	107	100	84	69	56	42	43.67	40.50	45.28	39.46	63.42	61.71	60.83	67.43	11.58	43.21	18.88	13.96
H28-2	185	178	174	164	155	133	111	90	74	33.61	33.49	35.97	32.57	35.86	32.28	33.49	38.18	16.10	99.01	32.14	15.14
H28-3	133	128	125	118	110	94	78	63	48	45.00	43.96	45.95	42.23	52.63	47.86	50.77	54.44	11.53	69.58	20.73	13.38
H28-4	125	118	116	108	101	86	72	57	45	45.73	43.16	47.55	44.52	59.66	56.49	56.96	63.44	11.98	54.76	20.71	14.48
H32-1	135	127	125	117	110	94	79	64	51	30.58	27.73	31.84	29.94	51.65	49.91	49.10	54.81	14.46	64.47	25.14	15.92
H32-2	116	110	108	102	96	82	68	58	45	37.33	33.97	38.83	33.28	56.78	54.49	53.95	64.47	12.29	59.48	21.87	14.36
H32-3	128	122	119	112	105	89	74	61	48	30.97	29.33	32.90	31.04	55.68	52.44	52.43	58.04	11.72	59.31	21.10	14.00
H32-4	109	104	101	95	88	74	61	49	37	33.07	32.08	34.81	30.44	72.12	67.81	68.72	75.13	8.66	41.18	14.72	12.09
H36-1	107	103	100	96	90	78	69	58	48	34.50	31.14	36.32	32.89	50.47	50.33	47.58	54.93	11.93	43.25	20.48	14.34
H36-2	113	109	106	102	97	84	73	63	53	33.69	32.45	36.63	35.57	45.65	45.67	42.23	43.81	12.73	23.72	20.91	14.69

higher computed efficiency compared with the method developed by Lin et al. [15], which is more convenient for the practical engineering application.

5. Conclusions

FE modeling was adopted to simulate the pavement structure in this study, and the study on parameter was also carried out to develop a new deflection basin area index. The main conclusions that can be drawn as follows:

- (1) By comparing the deflection values gained from FE simulation with the theoretical values calculated by the Winkler foundation response model, increasing deviations are observed with the increment of the modulus of the subgrade reaction when the pavement slab is either too thick or thin. Thus, considering the accuracy of the FE method and the actual demands of practical engineering, the suitable range of slab thickness for pavement structural parameters in the back-calculation process is suggested to be 0.24–0.4 m.
- (2) Based on the established database, the back-calculation results of several existing deflection basin area index methods reveal that the increase of local measuring points under the same layout scheme can improve the accuracy of back-calculation results. Moreover, using the average deflection of all measuring points instead of a specified point during the normalized procedure, the back-calculation will become more stable, and the multiple-solution problem can also be alleviated.
- (3) According to the deflection database obtained by FE simulation under different working conditions, a refined deflection basin area index method is proposed. The actual measuring data from an airport in northern China is applied to verify the rationality of the new method. Comparisons between the test results and theoretical predictions illustrate that the new method possesses a higher accuracy and efficiency, which may provide valuable guidance for the practical engineering application.

Data Availability

The data used in this paper are all from the finite element simulation and engineering measurement mentioned in the study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

Acknowledgments

This research was supported financially by the National Natural Science Foundation of China (grant no. 41702320).

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