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Observational Methods for Predicting Embankment Settlement

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ABSTRAK

Kaedah satu-dimensi Terzaghi diguna dengan meluas untuk menganggar enapan. Persamaan kebezaan diselesaikan dengan membuat andaian yang pekali pengukuhan tidak berubah. Dengan itu, persamaan berbentuk linear (lelurus). Akan tetapi dalam realiti persamaan ini bukanlah linear. Ini adalah kerana kebolehmampatan, kebolehtelapan dan pekali pengukuhan tanah berubah dengan enapan. Oleh yang demikian, kita masih tidak begitu mampu untuk menganggar atau meramal kadar enapan dengan baik. Dalam kertas kerja ini beberapa data enapan jangka masa panjang yang berkualiti tinggi diguna untuk menguji kesahihan beberapa kaedah cerapan, seperti kaedah Hiperbolik dan kaedah Asaoka untuk meramal enapan. Data-data lapangan ini diperoleh daripada benteng cubaan di Tangkak (1987-1996) dan Juru (1990-1992). Berdasarkan rekod enapan benteng di atas tanah-tanah lembut ini, ianya dapat dirumuskan yang enapan diramal menggunakan kaedah Hiperbolik dapat diperbaiki dengan banyak sekiranya data enapan semenjak bermulanya pembinaan digunakan, iaitu selepas kira-kira 50% enapan telah berlaku. Enapan jangka masa panjang yang diramal menggunakan data peringkat awal (iaitu kurang daripada 6 bulan) boleh mengelirukan. Kemampuan kaedah ini juga boleh diperhatikan daripada ciri-ciri lengkung yang dilukis. Sebagai contoh, dalam kes kaedah hiperbolik, didapati sekiranya kehubungan antara t/ρ dan ρ menghampiri satu garisan lurus (linear), maka ramalan yang baik akan diperoleh. Ramalan menggunakan kaedah Asaoka juga diperbaiki sekiranya pangkalan data yang besar digunakan.

ABSTRACT

The one dimensional Terzaghi method is still widely used for prediction of settlement. Its differential equation is solved on the assumption that coefficient of consolidation is a constant, in which case the equation becomes linear. But in reality this equation is non linear because compressibility, permeability and coefficient of consolidation changes with settlement. This is why the capability of predicting the rate of settlement or time-settlement relationship remains rather poor. In this paper a number of high quality long-term field settlement data are used to verify the applicability of the observational methods, namely the hyperbolic and the Asaoka method. The field data were from the Tangkak trial embankment (1987-1996) and the Juru trial embankment (1990-1992). Based on the available settlement record for embankment on soft ground, it can be concluded that the prediction of settlement using the hyperbolic method is significantly improved using the start of construction settlement data, notably after more than 50% of the settlements have occurred. Long-term settlement predicting using the early stage data (6 months or less) could be misleading. The capability of the method can also be diagnosed from the characteristics of the curve plotted. For the case of hyperbolic method, it is evident that if a close linear relation of t/ρ and ρ is obtained, then the prediction is seemingly good. Prediction of settlement using the Asaoka method is also improved using larger settlement database.

Keywords: Asaoka method, hyperbolic method, settlement prediction

INTRODUCTION

The one-dimensional Terzaghi method is still widely used for prediction of settlements. Its differential equation is solved on the assumption that the coefficient of consolidation is a constant, in which case the equation becomes linear. But in reality this equation is non linear because compressibility, permeability and coefficient of consolidation changes with settlement. This is why the capability of predicting the rate of settlement or time-settlement relationship remains rather poor.

Numerous attempts to improve the capability of predicting the magnitude and rate of settlement and excess pore water pressure dissipation by introducing more refined soil models and less restricted assumptions on the parameters describing these models have taken place. These improvements have been proposed by various authors to take into account some of the real conditions that Terzaghi idealised. For example, time dependent loading, variation of soil parameters with change in effective stress, finite (large) strain, submergence of fill and layered systems can be taken into account (Brand and Brenner 1981). However, despite these refinements, predictions of the development of settlement with time using laboratory-derived parameters, for example, coefficient of consolidation, remain speculative. This leads to an interest in studying other methods such as those based on field observations.

A few observational methods based on settlement records are available to predict future settlement behaviour, namely the hyperbolic (Tan 1971; Chin 1975), Velocity (Parkin 1978), and Asaoka (Asaoka 1978) method. Theoretically by extrapolating from observed settlement behaviour, many uncertainties regarding the variability of soil, magnitude and distribution of load can be overcome (Aboshi and Inoue 1986). This new category of settlement analyses is the subject of interest as settlement plates are cheap and can be easily installed.

In this paper a number of high quality long-term field settlement data are used to verify the applicability of the observational methods, namely the Hyperbolic and the Asaoka method. The field data were from the Tangkak trial embankment (1987-1996) and the Juru trial embankment (1990-1992).

THE OBSERVATIONAL METHODS

The Hyperbolic Method

The usefulness of the hyperbolic approach has long been recognised in analysing experimental observations. Tan (1971) made use of the hyperbolic dependence on time of clay undergoing secondary compression and proposed the following relationship:

$$t/\rho = M\,t + C \tag{1}$$

where ρ is the total settlement at any time, t, after the excess pore water pressure has dissipated. M and C are empirical constants. This equation, when plotted with the ratio of t/ρ on the ordinate and time t on the abscissa will give a straight line, the slope of which, M, and the intercept on the ordinate, C. Tan (1971) found the significance of M by writing the equation as follows:

$$1/\rho \;=\; M + C/t \tag{2}$$

When t becomes very large, i.e. $t \rightarrow \infty$, then $1/\,t \rightarrow 0$ and hence $1/\rho = M$. which means the ultimate settlement, $\rho_{ult} = 1/M$.

Chin (1975) also made use of the hyperbolic dependence on time of settlement, and in his case for both the primary and secondary compression. In fact Chin (1978) also used this approach to diagnose the condition of driven piles.

Huat (1996) examined the applicability of the hyperbolic method for predicting embankment settlement using end of construction settlement data and found that the accuracy of the prediction is limited to 1 to 2 years. In this paper, the capability of the method is once again examined but by using settlement data from start of construction.

The Asaoka Method

According to Asaoka (1978), settlement at time, t, (ρ_t) can be expressed as:

$$\rho_t = \beta_o + \beta_1\,\rho_{t-1} \tag{3}$$

This is a time-settlement relationship, which is a linear equation, where β_o is an intercept on the vertical axis, and β_1 is a gradient. As predicted final settlement (ρ_f) is reached, the equation is shown to be equal to:

$$\rho_t = \rho_{t\text{-}1} = \rho_f \tag{4}$$

The settlements plotted ($\rho_{t,}\ \rho_{\ t\text{-}1}$) are for selected time intervals, Δt, which usually ranges between 30-100 days.

THE TRIAL EMBANKMENT

Field data from two trial embankments were considered in this paper. They were Tangkak and Juru trial embankments. Details of these embankments were presented in the symposium organised by the Malaysia Highway Authority in 1989, and in the paper by Huat (1996).

Tangkak Trial Embankment

The Tangkak trial embankment is located at Tangkak in the valley of the Muar rivers, Johor (*Fig. 1*). The subsoil profile beneath the trial is generalised as follows. The upper 17 m consist of soft to very soft silty clay with natural water content 50-120%, liquid limit (w_p) of 40-80% and plastic limit (w_p) of 20-40%. Traces of seashells indicate a marine origin. Underlying this layer is a layer of peat of about 0.5 m thick, followed by some 2 m of sandy clay, which is underlain in turn by a thick deposit of medium to coarse sand with SPT values ranging from 6-50. The undrained strengths obtained from the vane tests showed an almost linear increase of strength below a surface crust, with strength of 9 kPa at 1 m increasing to 36 kPa at 17 m. Results obtained from the odometer tests indicate that the clays are slightly over-consolidated but highly compressible. Values of coefficient of consolidation (c_v) range from 1-10 m^2/yr.

Fig 1: Location of Tangkak trial embankment

Construction of the embankments commenced in early 1987, and the whole project was the subject of a symposium sponsored by the Highway Authority in 1989. One of the embankments, i.e. the 3 m high control embankment, is analysed in this paper.

Juru Trial Embankment

The Juru trial embankment is located some 10 km south of Butterworth, in the northern part of Peninsular Malaysia, about 600 km north of the Tangkak trial (*Fig. 2*). The site of the trial embankment is between km 4.9 to km 5.2 of the Butterworth-Jawi route of the North-South expressway. The area is low-lying with original ground level varying from 0.2 m to 0.7 m above mean sea level.

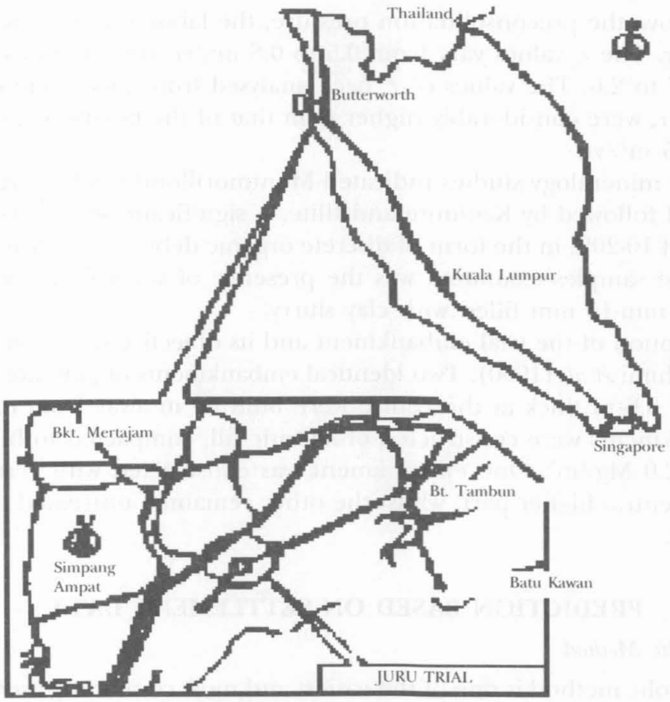

Fig. 2: Location of Juru trial embankment

A comprehensive site investigation was carried out in 1990 to determine the subsoil profile and properties of the trial site. The investigation revealed the presence of a desiccated upper crust of about 1.5 m thick. Beneath the upper crust is a layer of very soft silty clay of about 12.5 m thick. The clay has been identified as part of the Holocene marine deposits formed after the last period of low sea level between 15,000 to 18,000 years ago. Below the clay stratum is a layer of loose to medium dense sand of about 2 m thick, which is underlain in-turn with residual soil deposit. The clay is of high plasticity with liquid limit in the range of 80-120%, plasticity index of 40-80%, and with moisture content close to the liquid limit. The densities of the clay are typically low of the order of 1.35 – 1.40 Mg/m^3.

Field vane measurements show an almost linear increase in undrained strength (S_u) from about 10 kPa below the surface crust to about 30 kPa at depth 12 m. The vane strength-effective vertical stress ($S_u/\ s'_v$) ratio being around 0.6 except for isolated higher values in the crust. Sensitivity of the clay is modest, ranging from 3.5 to 5.0. From the odometer tests, the clay is shown to be lightly over-consolidated but highly compressible.

The initial void ratio (e_o) is high, typically 3.0 to 3.5. The compression ratio, ($c_c/1 + e_o$) is in the region of 0.4 to 0.6 for most of the deposit except in and just below the upper crust. Tests were carried out to establish the coefficient of consolidation in both the vertical (c_v) and horizontal (c_h) directions. For pressure above the preconsolidation pressure, the laboratory c_v varies from 0.3 to 0.4 m^2/yr. The c_h values vary from 0.5 to 0.8 m^2/yr, the ratio of c_h/c_v ranges between 1.7 to 2.0. The values of c_h back analysed from piezocone dissipation test, however, were considerably higher than that of the laboratory, with values of 3.5 to 4.5 m^2/yr.

The clay mineralogy studies indicated Montmorillonite as the predominant clay mineral followed by Kaolinite and Illite. A significant organic content was noted, about 10-20% in the form of discrete organic debris. A feature frequently seen in most samples examined was the presence of vertical and sub vertical holes of 10 mm-15 mm filled with clay slurry.

A description of the trial embankment and its objective has been presented by Wan Hashimi *et al.* (1990). Two identical embankments of plan area of 100 m x 56 m and 3.6 m thick at the centre were built 60 m away from each other. The embankments were constructed of lateritic fill, compacted to bulk density of around 2.0 Mg/m^3. One embankment was constructed with vertical drain under the central higher part, whilst the other remained untreated and served as a control.

PREDICTION BASED ON SETTLEMENT DATA

The Hyperbolic Method

The Hyperbolic method is one of the easiest and most commonly used methods for predicting future performance based on available settlement data. The availability of an eight year settlement record as in the case of the Tangkak trial embankment offers a rare opportunity to examine the accuracy of the hyperbolic method of prediction. While the Juru trial, which is on a completely different test site, provides a basis for comparison, it also offers an opportunity to test whether the same observational method can be used to predict settlements for the case of vertical-drains-treated embankment.

Tables 1, 2 and 3 summarise comparisons of the predicted and measured end of construction settlement of the Tangkak embankment. Note that settlement gauges S2, S5 and S8 were all centre line settlement gauges. Predictions are made based on end of construction settlement data of 3 months, 6 months, and 1, 2, 3, 4 and 5 years. As concluded by Huat (1996), a reasonable prediction (but not necessarily 'good') can only be made based on the 2 year data. A good prediction is arbitrarily defined as that with a discrepancy of within 10% of the measured values. Predictions made using the early stage data (< 3 months), however, consistently under-predict the settlements. A similar trend of behaviour is also observed by Hudson (1991).

Tables 4, 5 and 6 summarise comparisons of the predicted and measured settlements of the same embankment but using settlement data from start of construction. As shown in the table below, the prediction capability is significantly enhanced by using data from start of construction, especially based on the 2 year data onward. However, the predictions of future settlements using early stage data (< 6 months) can be misleading.

TABLE 1
Comparison of predicted and measured end of construction settlement of Tangkak embankment (gauge S2)

t_r	¼	½	1	2	3	4	5	6	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
¼		69	99	125	137	144	148	152	158	164	166
½			148	249	323	378	423	458	550	646	686
1				324	436	528	604	668	849	965	1163
2					357	415	458	494	583	675	718
3						423	469	506	600	690	740
4							469	505	600	690	740
5								513	610	710	754
Actual settlement (mm)	45	90	170	290	370	435	485	500			

Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm

TABLE 2
Comparison of predicted and measured end of construction settlement of Tangkak embankment (gauge S5)

t_r	¼	½	1	2	3	4	5	6	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
¼		56	68	77	81	83	84	85	86	87	88
½			160	265	377	390	430	460	547	630	665
1				227	273	303	325	341	378	410	424
2					320	365	398	425	480	550	573
3						394	434	466	540	623	655
4							443	476	559	643	677
5								492	583	676	714
Actual settlement (mm)	50	95	160	270	350	416	470	488			

Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm

Based on the degree of consolidation, it appears from examining the data presented that some 50% of consolidation must occur before the predictions become more reliable. In another words, one to two years must be given in order to harvest good results (Huat 2002).

TABLE 3
Comparison of predicted and measured end of construction settlement of Tangkak embankment (gauge S8)

t_c	¼	½	1	2	3	4	5	6	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
¼		53	59	64	65	66	67	67	68	68	69
½			123	161	179	190	197	202	213	220	230
1				174	194	205	214	219	230	240	250
2					293	326	349	367	408	445	459
3						378	432	440	501	561	585
4							440	456	525	593	619
5								483	564	645	677
Actual settlement (mm)	50	100	160	280	360	415	480	490			

▨ Indicates a prediction within 10% of measured value
t_c = time after end of construction (in year)
ρ = predicted settlement in mm

TABLE 4
Comparison of predicted and measured start of construction settlement of Tangkak trial embankment (gauge S2)

t_o	¼	½	1	2	3	4	5	6	7	8	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
¼		744	918	1041	1089	1115	1131	1142	1150	1156	1165	1182	1188
½			820	901	932	948	958	965	969	973	978	986	992
1				1092	1185	1238	1272	1296	1313	1326	1346	1386	1400
2					1089	1158	1204	1236	1261	1379	1306	1365	1385
3						1192	1233	1262	1283	1299	1324	1374	1392
4							1267	1306	1335	1357	1389	1460	1485
5								1228	1259	1283	1318	1395	1423
6									1350	1386	1434	1542	1581
Actual settlement (mm)	550	670	835	1010	1150	1230	1300	1350	1390	1400			

▨ Indicates a prediction within 10% of measured value
t_c = time after end of construction (in year)
ρ = predicted settlement in mm

TABLE 5
Comparison of predicted and measured start of construction settlement of Tangkak trial embankment (gauge S5)

t_o	1/4	1/2	1	2	3	4	5	6	7	8	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
1/4		781	952	1069	1115	1139	1155	1165	1173	1178	1186	1203	1208
1/2			837	911	939	954	963	969	973	976	984	990	993
1				1027	1108	1153	1183	1203	1218	1229	1245	1279	1292
2					1117	1178	1218	1246	1267	1283	1306	1355	1373
3						1202	1238	1263	1282	1297	1317	1362	1377
4							1267	1302	1329	1349	1379	1444	1467
5								1335	1370	1400	1442	1534	1568
6									1431	1467	1521	1643	1688
Actual settlement (mm)	550	700	850	1040	1167	1239	1316	1381	1394	1413			

Indicates a prediction within 10% of measured value
t_c = time after end of construction (in year)
ρ = predicted settlement in mm

TABLE 6
Comparison of predicted and measured start of construction settlement of Tangkak trial embankment (gauge S8)

t_o	1/4	1/2	1	2	3	4	5	6	7	8	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ	ρ
1/4		766	924	1029	1071	1092	1106	1115	1121	1126	1134	1148	1153
1/2			837	911	939	953	962	968	973	976	981	991	994
1				979	1044	1079	1101	1116	1128	1136	1148	1174	1182
2					1197	1267	1314	1346	1371	1389	1417	1475	1496
3						1252	1297	1328	1353	1371	1397	1454	1474
4							1252	1289	1317	1339	1371	1439	1464
5								1254	1282	1303	1335	1402	1426
6									1338	1353	1375	1421	1437
Actual settlement (mm)	550	700	850	1040	1170	1250	1320	1390	1400	1420			

Indicates a prediction within 10% of measured value
t_c = time after end of construction (in year)
ρ = predicted settlement in mm

Tables 7 and 8 summarise the comparisons of predicted and measured end of construction settlement of the Juru embankments. The measured settlements were taken at the centre of the embankment. As noted by Huat (1996), the observation in this case is only limited to $1^1/_2$ years, but the trend of behaviour is nevertheless quite similar to the above. Long-term settlement predicted based on the early stage data is small compared with that over a larger base.

TABLE 7
Comparison of predicted and measured end of construction settlement of Juru embankment - control section

t_r	¼	½	1	1½	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ
¼		450	550	600	700	715	720
½			600	665	820	840	845
1				715	970	1000	1010
Actual settlement (mm)	201	490	625	750			

▨ Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm

TABLE 8
Comparison of predicted and measured end of construction settlement of Juru embankment – treated section

t_r	¼	½	1	1½	10	20	30
		ρ	ρ	ρ	ρ	ρ	ρ
¼		620	830	930	1180	1205	1215
½			840	950	1205	1235	1245
1				1005	1330	1370	1380
Actual settlement (mm)	369	640	890	1020			

▨ Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm

Tables 9 and 10 show comparisons of the predicted and measured settlement of the Juru embankment using the start of construction settlement data. It is of interest to note that the early stage data (both 3 and 6 months in this case) gave negative time – settlement relationship because of the large increment of cumulative settlements, while the rest appears to be good to the limit of the available data, i.e. for the next year in this case. Having examined all the cases presented, it appears that the capability of the hyperbolic method to predict future settlement is highly dependent on the characteristics of the graph plotted. A good prediction is only possible if the curve of the plotted graph is very close to a linear relationship.

TABLE 9
Comparison of predicted and measured start of construction settlement of Juru embankment – control section

t_o	¼	½	1	1½	2	10	20	30
				ρ	ρ	ρ	ρ	ρ
¼								
½								
1				▨ 1099	▨ 1198	1485	1532	1549
1½					▨ 1203	1499	1548	1565
Actual settlement (mm)	420	659	953	1101	1234			

▨ Indicates a prediction within 10% of measured value
t_c = time after end of construction (in year)
ρ = predicted settlement in mm

TABLE 10
Comparison of predicted and measured start of construction settlement of Juru embankment – treated section

t_o	¼	½	1	1½	2	10	20	30
				ρ	ρ	ρ	ρ	ρ
¼								
½								
1				▨ 1938	▨ 2200	3008	3162	3217
1½					▨ 1937	2356	2426	2405
Actual settlement (mm)	425	962	1602	1848	1991			

▨ Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm

The Asoaka Method

Tables 11, 12 and 13 summarise comparisons of the predicted and measured settlement of the Tangkak embankment. Predictions were made based on settlement data of 1, 2, 3, 4 and 5 years and time interval Δt of 60 days. A good prediction, as in the above, is arbitrarily defined as that of within 10% of the measured values. As shown in the tables below, predictions made based on 1 year or so data are good at least for the next 5 years. Using a larger database significantly enhances the prediction capability.

TABLE 11
Comparison of predicted and measured settlement of Tangkak trial embankment (gauge S2)

t_r	1	2	3	4	5	6
		ρ	ρ	ρ	ρ	ρ
1		303	376	421	450	467
2			377	424	453	472
3				440	475	498
4					488	515
5						541
6						
Actual settlement (mm)	170	290	370	435	485	500

Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm
Time interval, Dt = 60 days

TABLE 12
Comparison of predicted and measured settlement of Tangkak trial embankment (gauge S5)

t_r	1	2	3	4	5	6
		ρ	ρ	ρ	ρ	ρ
1		287	362	412	445	466
2			377	435	475	503
3				422	458	482
4					482	514
5						519
6						
Actual settlement (mm)	160	270	350	416	470	488

Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm
Time interval, Dt = 60 days

TABLE 13
Comparison of predicted and measured settlement of Tangkak trial embankment (gauge S8)

t_r	1	2	3	4	5	6
		ρ	ρ	ρ	ρ	ρ
1		293	379	441	484	515
2			377	434	473	500
3				437	477	505
4					515	555
5						537
6						
Actual settlement (mm)	160	280	360	415	480	490

Indicates a prediction within 10% of measured value
t_r = time after end of construction (in year)
ρ = predicted settlement in mm
Time interval, Dt = 60 days

CONCLUSION

Based on the available settlement record for embankment on soft ground, it can be concluded that the prediction of settlement using the hyperbolic method is improved by using the start of construction settlement data, notably after more than 50% of the settlements have occurred. Long-term settlement predicted using the early stage data (<6 months) could be misleading. The capability of the method can also be diagnosed from the characteristic of the curve plotted. For the case of hyperbolic method, it is evident that if a close linear relation of t/ρ and ρ is obtained, then the prediction is seemingly good.

Prediction of settlement made using the Asaoka method is also improved using a larger settlement database.

Using the hyperbolic method, the advantage is that it can use the start of construction settlement data. Prediction can therefore be made after 1 year or so from start of construction. The Asaoka method uses the end of construction settlement data and prediction can only be made after the end of construction, which usually takes between 1-2 years. In this respect, the hyperbolic method holds an advantage of being able to predict future settlement at an earlier time.

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