Special Topic (II) Final Report

Prediction of Ground Settlement Using Deep Excavation Database

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2022/6/13

Abstract

Hundreds of excavation data history from Sino Geotechnology, Inc. in the past years are collected to establish a database. 2 sets of databases are generated. The first set of this database is based on final stage of every excavation cases. Another set of this database is based on every preliminary stage of each cases. Important variables are taken to account to compare both set of the database. 8 major variable comparison will be shown discussion part. Those details can help to judge whether preliminary stages data can be used and considered as individual cases in the database. Furthermore, two prediction example of the databases are provided to display the comparison of both database prediction. This report provides a reference for engineering projects in Taiwan considering excavation constructions.

1. Introduction

Urban developments of a country are highly supported by recent technologies and studies. Taiwan is an example of developed country with numerous construction done. Number of construction projects will most likely to increase in the future. An excavation database will be a very helpful tool for future engineers, both experienced and unexperienced. Many senior engineers will retire and regeneration is necessary in this field. This database can be used as a thinking foundation of engineers on decision making a construction projects. Through history data, future engineer will have better decision making skill and minimize the chance of mistake that happen in the past.

The first set of databases takes account of a total 233 excavation cases in Taiwan and only consider the last stage of the excavation. This database is previously developed by Lin (2022). The second database was generated based on only 80 excavation cases from the total 233 cases. This database take accounts of every stage which will be generated and discussed whether every preliminary stage can be considered as an individual case. After the second set of the databases are constructed, analysis is done to compare the result of the first database and second database. The main variables that will be discussed are: H_e, H_1, δ_{hm}, S_u, S_a, S_w and will be further discussed in the discussion part. The horizontal displacement is corrected with PSR method and considering the axial force acting. Different cases with different retaining walls (diaphragm wall, sheet pile, and column pile) and construction method (bottom-up and top-down) shows different behavior on several certain variables. Furthermore, example cases will show the prediction accuracy of both database.

2. Description of Research Work

A total of 80 cases was collected to make the database of every stage. Microsoft Excel was used to make the database. Figure 1 shows the sample of the database of case no.1. The following description shows the process of filling the database which also can be referred on figure 1.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	No.	cture	:1,巡	[illegible]	(扶	Scw	year	site	N(coordinate)	E(coordinate)	soil type	linometer in	ation
2	1	DW	1		V		109	區樂群三路	25.0775	121.5676	CL	SID1 (BW)	1
3													2
4													3
5													4
6												SID2	1
7													2
8													3
9													4
10												SID3 (BW)	1
11													2
12													3
13												SID4 (BW)	1
14													2
15													3
16													4

	N	O	P	Q	R	S	T	U	V	W	X	Y
1	B(m)	L(m)	d(m)	SPT-N	Su,avg(kPa)	Su/σv	He(m)	Hw(m)	δh,m(cm)	h,m*PSR(cr	修正差值(cm)	δh,m*(Axial force)(cm)
2	51.35	72.00	36.00	5.00	30.00	0.76	2.10	28.50	0.86		0.00	0.86
3	51.35	72.00	36.00	4.08	28.20	0.58	7.10	28.50	1.00		0.06	1.06
4	51.35	72.00	36.00	3.54	27.13	0.47	10.85	28.50	4.98		-1.83	3.15
5	51.35	72.00	36.00	3.37	26.80	0.43	12.95	28.50	10.36		-2.45	7.91
6	83.80	42.90	20.00	5.00	30.00	0.76	2.10	28.50	0.26	0.26	0.00	0.26
7	83.80	42.90	20.00	4.08	28.20	0.58	7.10	28.50	0.31	0.31	0.05	0.36
8	83.80	42.90	20.00	3.54	27.13	0.47	10.85	28.50	1.88	1.90	0.34	2.24
9	83.80	42.90	20.00	3.37	26.80	0.43	12.95	28.50				
10	58.73	20.00	10.00	5.00	30.00	0.76	2.10	28.50	0.71		0.00	0.71
11	58.73	20.00	10.00	4.08	28.20	0.58	7.10	28.50	0.90		-0.43	0.47
12	58.73	20.00	10.00	3.54	27.13	0.47	10.85	28.50	1.79		0.89	2.68
13	83.80	36.00	18.00	5.00	30.00	0.76	2.10	28.50	1.17		0.00	1.17
14	83.80	36.00	18.00	4.08	28.20	0.58	7.10	28.50	1.29		-1.00	0.29
15	83.80	36.00	18.00	3.54	27.13	0.47	10.85	28.50	3.77		-0.36	3.41
16	83.80	36.00	18.00	3.37	26.80	0.43	12.95	28.50	6.58		0.94	7.52

	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI
1	H1(m)	Ew(t/m²)	t(m)	Iw (m4)	havg(m)	Est(MN/m²)	Ast(cm²)	s(m)	Sa(MN/m)	Sw
2	1.00	2509980.00	0.7	0.03		204000.00				
3	3.00	2509980.00	0.7	0.03		204000.00				
4	17.50	2509980.00	0.7	0.03	5.43	204000.00	1002.80	6.42	3186.47	82.52
5	19.50	2509980.00	0.7	0.03	4.32	204000.00	1002.80	6.42	3186.47	205.99
6	1.50	2509980.00	0.7	0.03		204000.00				
7	1.00	2509980.00	0.7	0.03		204000.00				
8	16.50	2509980.00	0.7	0.03	5.43	204000.00	1002.80	6.42	3186.47	82.52
9		2509980.00	0.7	0.03	4.32	204000.00	1002.80	6.42	3186.47	205.99
10	1.00	2509980.00	0.7	0.03		204000.00				
11	1.00	2509980.00	0.7	0.03		204000.00				
12	16.50	2509980.00	0.7	0.03	5.43	204000.00	1002.80	6.42	3186.47	82.52
13	1.00	2509980.00	0.7	0.03		204000.00				
14	1.00	2509980.00	0.7	0.03		204000.00				
15	18.50	2509980.00	0.7	0.03	5.43	204000.00	1002.80	6.42	3186.47	82.52
16	19.00	2509980.00	0.7	0.03	4.32	204000.00	1002.80	6.42	3186.47	205.99

Figure 1. Database of case no.1

The first set of data that were recorded are the type of retaining wall, construction method, ground improvement involvement, presence of buttress wall, year, coordinate location, and type of soil. The type of retaining structures are diaphragm wall, sheet pile, and column pile. The construction method involves either bottom up or top down method.

The second set of data involves the site dimension, soil properties, and surface settlement. First, every inclinometer SID and SIS, for some of the cases, are recorded and also classify whether the inclinometer location is between a buttress wall, cross wall, or free. The next data is the total excavation stages. The length (L) and width (B) of the site is measured as well as the distance of the inclinometers to the nearest separating wall or edge (d). The soil properties: SPT-N, Su_{avg}, and $S_u/\sigma v$ are collected and calculated every stage. In other words, the value of these three variables varies every stage because the depth of each excavation stage takes account the generate the average value of each stage. The next column shows the excavation depth of each stages (H_e) and the length of the supporting system (H_w). The next column displays the maximum horizontal displacement (δ_{hm}) that was recorded in the monitoring data. The next column is the modified horizontal displacement (δ_{hm} PSR) due to corner effect. Wu et al. (2013) collected 22 actual excavation cases in Taipei and pointed out that the deformation of the retaining wall measured at a distance d from the corner ($\delta_{hm}(d)$) is related to the length of the excavation. H_e deformation of the retaining wall increases with the distance from the corner. Generally, the actual position of the maximum deformation of the retaining wall occurs at L'/2. Therefore, the deformation is corrected with formula in figure 2. After that, the maximum deformation is corrected once more where axial force is taking account on the retaining wall. The displacement was corrected through these following steps: 1. The depth of the first support will be the benchmark point. 2. Find the monitoring value after excavation of each stage and find the difference with the benchmark depth. 3. Correct the displacement by adding the difference to the place with the largest change. Lastly, the depth where the maximum displacement happened was recorded as H_1.

$$\frac{\delta_m(d)}{\delta_m^*} = \frac{\delta_1 + \delta_2(d)}{\delta_1 + \delta_2^*} \approx \frac{\delta_2(d)}{\delta_2^*} \approx 16\left(\frac{d}{L'}\right)^4 - 32\left(\frac{d}{L'}\right)^3 + 16\left(\frac{d}{L'}\right)^2$$

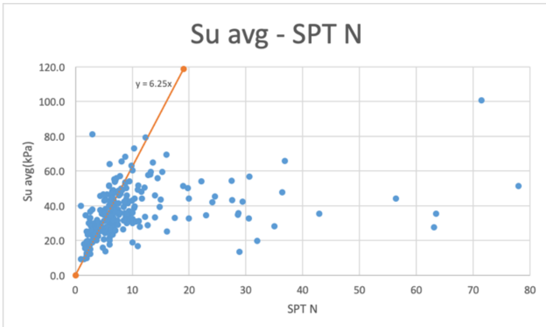
Figure 2. Maximum horizontal displacement correction due to corner effect

The third set of data involve information regarding to the strutting system. The Modulus of diaphragm wall is stated as E_w and its thickness was stated as t. Moment of inertia of the retaining wall is I_w and h_{avg} is the average height of the excavation depth section which is separated by the struts. As for the steel struts information, E_{st} shows the modulus of the steel, A_{st} represents the area of the steel section, and s shows the average spacing of the steel strut on the excavation site. Last two variables that are counted are S_a and S_w. S_a is the axial stiffness of the strut which is calculated by dividing the product of modulus and area of the steel with the spacing. S_w is the stiffness of the strutting system which is defined as product of modulus and area of the retaining system divided by the h_{avg} to the power of four. Ou (2016) stated that the stiffness of strut will contribute to the shape of wall deformation. Excavation with high strut stiffness will produce maximum wall deformation near the excavation surface. On the other hand, excavation with low strut stiffness will produce maximum wall deformation near the top of retaining wall.

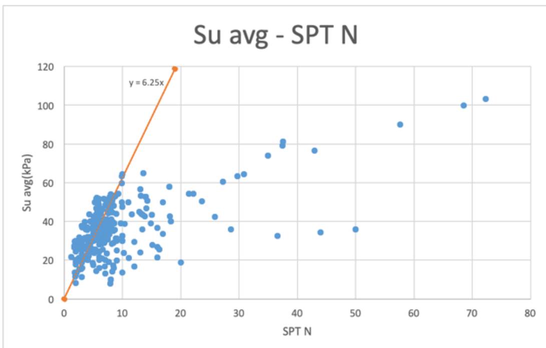
3. Parameters Comparison and Analysis

After completing every stage database, it is compared with the final stage database which is already generated formerly. A total of 8 variables comparison will be discussed in the following section.

1. $S_{u\ avg}$ – SPT N



Final Stage

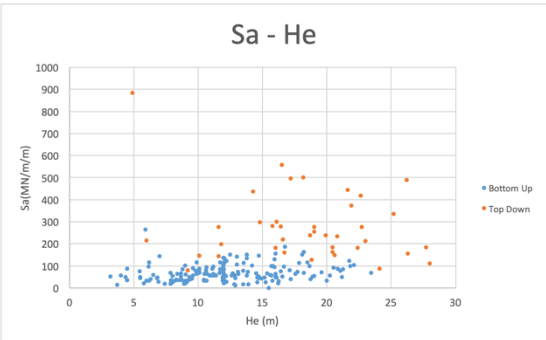


Every Stage

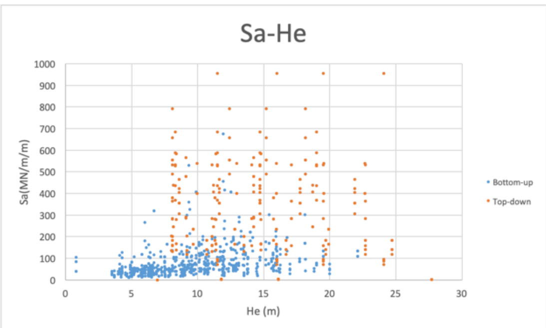
Figure 3. Comparison of $S_{u\ avg}$ – SPT N

According to the result on figure 3, both final stage and every stage graphs shows similar trend. Most of the cases are limited with SPT N in range of 0-10, moderate amount of cases in range of 10-20, and few cases above 20. Most cases have a S_u value ranges from 10-60 kPa and few cases above 60. Most of the cases follows the trend line y=6.25x which means generally cases with ground condition of a certain SPT N value have an undrained shear strength value of 6.25 times the SPT N.

2. S_a – H_e



Final Stage

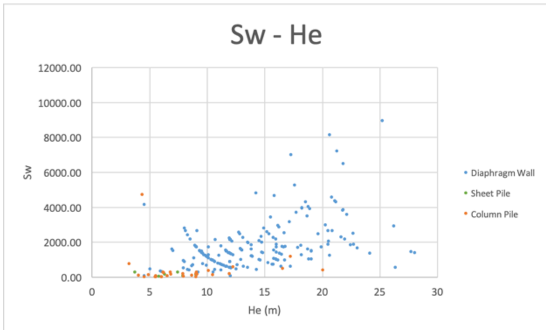


Every Stage

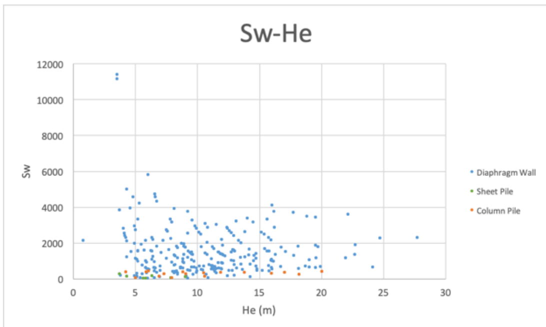
Figure 4. Comparison of S_a-H_e

From figure 4, both final stage and every stage graphs show similar behavior for bottom up (blue) cases. The S_a is limited to roughly 200 MN/m/m even though few cases in every stage graph exceeds the value. As for top down (orange) cases, both shows scattering results of S_a with different H_e, final stage cases lie between S_a = 100-550 while every stage cases lies between S_a = 100-1000. Top down cases on every stage graph seems to have a pattern at a certain H_e because the value of S_a in one case is the same for all the stages, resulting a same S_a plot with different H_e.

3. S_w – H_e



Final Stage

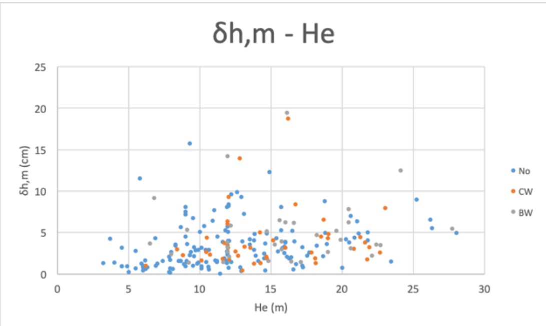


Every Stage

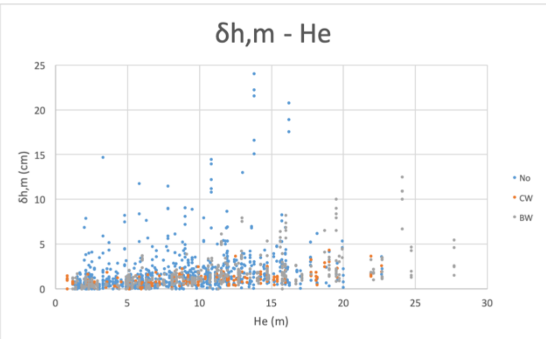
Figure 5. Comparison of S_w-H_e

Referring to figure 5, both final stage and every stage graphs show similar behavior. For cases using diaphragm wall (blue) as the reinforcement system, the stiffness of the strutting systems varies up to 4000 t/m2 with some cases exceeds the value. For column pile (orange) and sheet pile (green) reinforcement system, the stiffness generally varies below 500 t/m2. Comparing with H_e value, the final stage graph shows a scattering points starting from $H_e = \pm 7.5$ m, but the every stage graph already shows scattering points pattern starting from $H_e = \pm 4$ m. This is reasonable because the second graph also records the preliminary stages of the excavation which produce points at lower H_e value. The points with high value of S_w is caused by low value of h_{avg}.

4. δ_{hm} – H_e



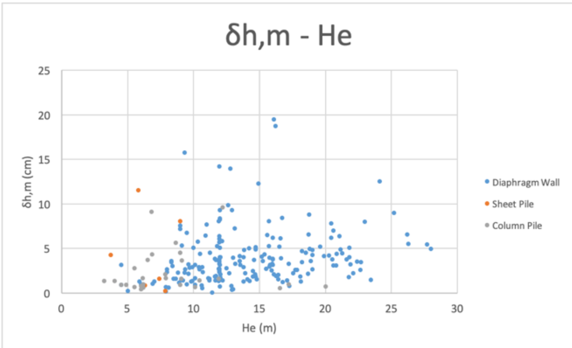
Final Stage



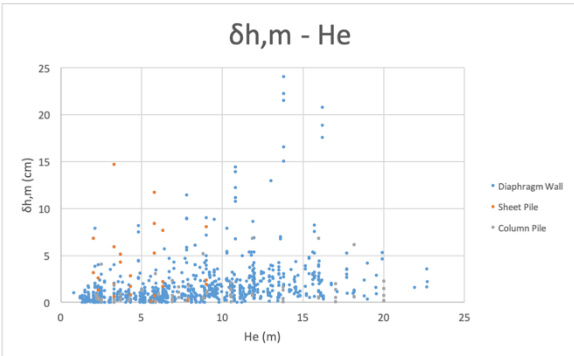
Every Stage

Figure 6. Comparison of δ_{hm} – H_e part 1

From figure 6, final stage and every stage graph show different behavior. For cases without cross wall or buttress wall (blue), both graph shows the maximum deformation mostly varies to 5 cm and some up to 10 cm. For cases with cross wall (orange), final stage cases graph shows scatter results of maximum deformation up to 20 cm, but in every stage cases, the maximum deformation doesn't exceed 5 cm. For cases with buttress wall, the final stage cases show variation of results just like the cases without any walls. However, the every stage cases show majority of the deformation doesn't exceeds 2.5 cm and the rest vary in results as well.



Final Stage

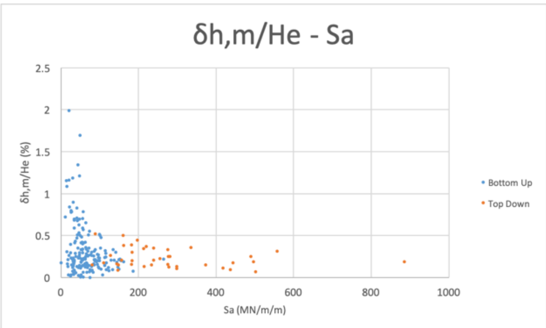


Every Stage

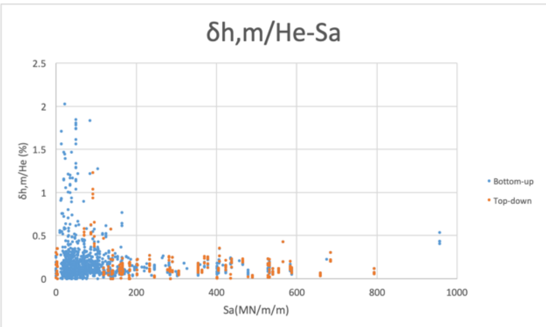
Figure 7. Comparison of δ_{hm} – H_e part 2

From figure 7, final stage and every stage graph show different behavior. For cases diaphragm wall (blue), both graph shows the maximum deformation mostly varies to 5 cm and some up to 10 cm, small amount of cases exceeds 10 cm. For cases with sheet pile (orange), final stage cases graph shows scatter results of maximum deformation up to 12 cm, but in every stage cases, the maximum deformation goes further to 15 cm. For cases with column pile (grey), the final stage cases show variation of results just like the cases with sheet pile. However, every stage cases show majority of the deformation doesn't exceeds 2.5 cm and small amount vary just like sheet pile cases.

5. δ_{hm}/H_e – S_a



Final Stage

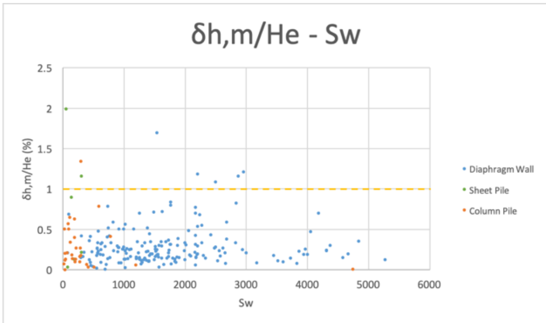


Every Stage

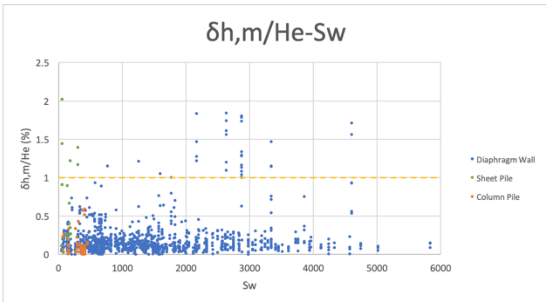
Figure 8. Comparison of δ_{hm}/H_e – S_a

According to figure 8, both final stage and every stage graphs show similar behavior. The normalized maximum deformation lies majorly below 0.5%. Some of bottom up (blue) cases shows normalized maximum deformation value up to 2%, but top down (orange) cases shows less points that lies above 0.5% since majorly doesn't exceeds that value. Top down cases show higher axial stiffness of strut which varies above ± 180 MN/m/m, while almost all bottom up cases stay below ± 180 NM/m/m.

6. δ_{hm}/H_e – S_w



Final Stage

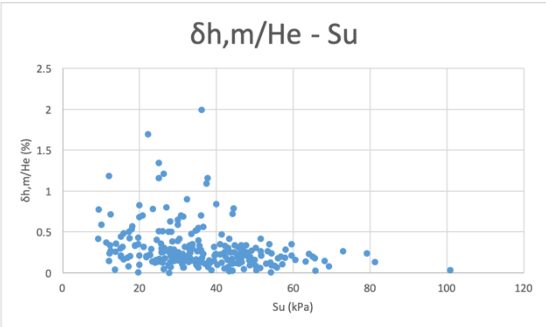


Every Stage

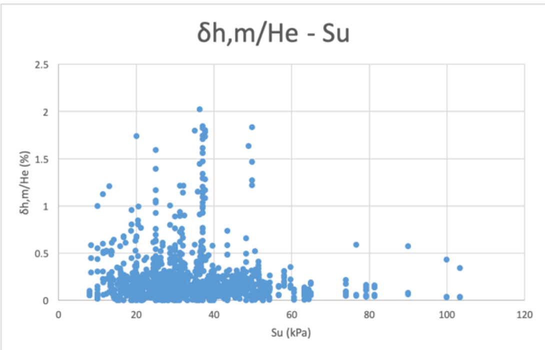
Figure 9. Comparison of δ_{hm}/H_e – S_w

From figure 9, both final stage and every stage graphs show similar behavior. For cases supported by diaphragm wall (blue), the cases with normalized maximum deformation less than 0.5% have various stiffness of strut mostly up to 2000 t/m2 and gradually decreasing until 5000 t/m2. Cases with normalized maximum deformation above 0.5, the value of S_w scatters and don't have a certain pattern. For cases supported with both sheet pile (green) and column pile (orange), the strut stiffness doesn't exceed ± 500 t/m2. In every stage graph, it is clearly shown column pile have noticeable greater S_w (almost up to ± 500 t/m2) difference compared to sheet pile that ranges only 50-300 t/m2.

7. δ_{hm}/H_e – S_u



Final Stage

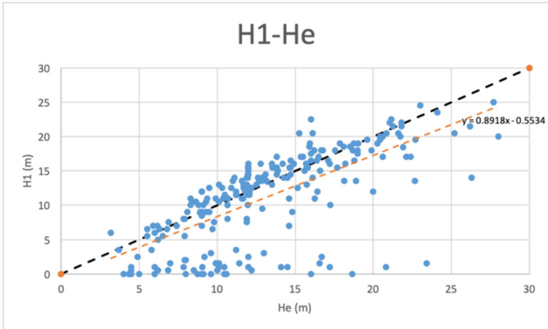


Every Stage

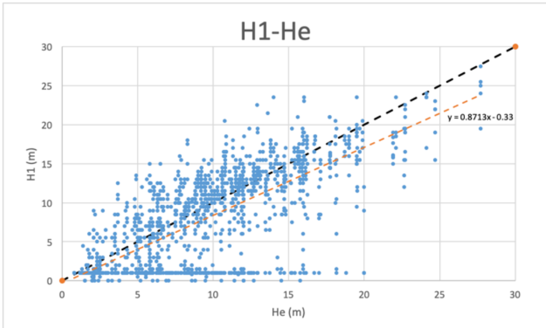
Figure 10. Comparison of δ_{hm}/H_e – S_u

Referring to figure 10, both final stage and every stage graphs show similar behavior. For cases with normalized maximum horizontal displacement below 0.5 have an undrained shear strength value ranges from 10-60 kPa and few cases with S_u value greater than 60 kPa. Cases with normalized maximum horizontal displacement larger than 0.5 have a scattering value of S_u ranges from 10-50 kPa.

8. $H_1 - H_e$



Final Stage



Every Stage

Figure 11. Comparison of H_1-S_u

Both final stage and every stage graphs show similar behavior. Regression line (orange) is made on both graph and both follows a very similar trend line. The gradient of the line is slightly below y=x line (black) which means most of the cases experienced maximum deformation at the depth in which the same as the excavation depth. This is more accurately judged from the final stage of the case, while preliminary stages graph leads to a more scattering plot, but the gradient of the regression line only have a difference of 0.02x. Points that lie on H_1=0 m means the deformation type of the wall is spandrel type instead of concave type. According to Hsieh and Ou (1998), spandrel type of surface settlement is related to cantilever type of wall deformation while concave type of surface settlement is related to deep inward type of wall deformation.

4. Case Prediction Example and Discussion

After completing the database, case example is done to understand the reliability of the 2 databases. According to Lin (2002), 2 case examples are taken, which includes new case and a specific case the established database. All cases on each database are distributed on real time maps with their respective location. Figure 12 shows the search model of the database based on location.

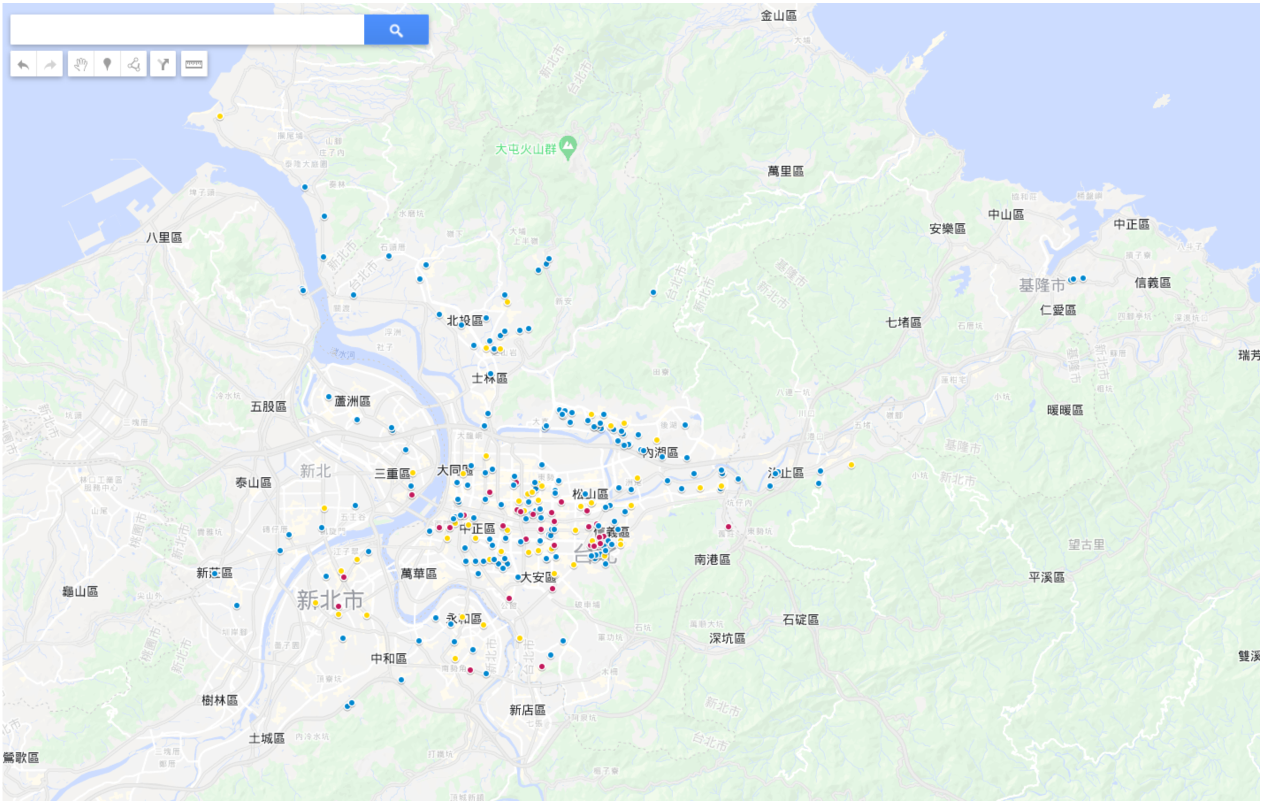


Figure 12. Search model of the database based on location

To use this model, user need to input a specific point of designated location. The search distance is based on radius of 0.3km, 0.5km and 1.5km around a designated case. Note that 0.5km radius will include 0.3km results and 1.5km radius will include 0.3km and 0.5km results, as shown in figure 13. According to the input location, search in the database will give the user the wall displacement. The displacement will be the average displacement from all data covered in a certain radius as in the formula shown in figure 14.

Figure 13. Search method of the database

$$\delta_{h,m} = \frac{\sum_{i=1}^{n} \delta_{hm,1} + \delta_{hm,2} + \delta_{hm,3}}{\sum_{i=1}^{n} n}$$

Figure 14. Average displacement calculation from all data points in a certain range

The first prediction example is shown in figure 15. This case is not in the database or in other words it is a new case. The monitored maximum displacement is 1.8 cm which is shown in the figure. The left table shows the result using final stage database and the right table shows the result using every stage database. User will first input the location of the site which is shown with column written "N" and "E", also the excavation height of that case which is written "He". Below the user input, "NO AM" is written to show that this case has no such ground improvement, additional buttress wall or cross wall, etc. Both final stage and ever stage databases don't have any data up to radius of 0.5km around the inserted location. For radius of 1.5km, final stage case database shows 9 cases captured in that range and every stage case database have 41 cases. The average displacement for the first database is 4.17 cm, while the second database result is 2.1 cm. Through this result, every stage database shows a good performance with a small over predict on displacement value which is 0.3 cm difference. On the other hand, final stage database displays contrast result in which the difference of the displacement around 2.3 cm, more than double the monitored data.

case	大同區大龍國小校舍新建
from	Design Procedure for Deep Excavation with Diaphragm Wall
type	國立臺北科技大學碩士論文
aximum displacement(cm)	1.8

no data means:
At this distance (EX:0.3KM、0.5KM、1.5KM), there is no matching data.

	final stage		
		N	E
	location(user input)	25.073895	121.51681
	He(m)	10.95	
	NO AM (no use auxiliary method)		
	displacement (cm)	No data	
cases numder in 0.3km	distance < 0.3 km	No data	
	displacement (cm)	No data	
cases numder in 0.5 km	distance < 0.5 km	No data	
	displacement (cm)	4.17	
cases numder in 1.5km	distance < 1.5 km	9	

	every stages		
		N	E
	location(user input)	25.07389468	121.5168102
	He(m)	10.95	
	NO AM (no use auxiliary method)		
	displacement (cm)	No data	
cases numder in 0.3km	distance < 0.3 km	No data	
	displacement (cm)	No data	
cases numder in 0.5 km	distance < 0.5 km	No data	
	displacement (cm)	2.1	
cases numder in 1.5km	distance < 1.5 km	41	

Figure 15. First prediction example

The second prediction example is shown in figure 16. Different from the first case, this case is taken from the existing case in the database. The layout of the calculation is the same layout with previous figure. The monitored maximum displacement is recorded 4.47 cm. The location point and excavation height was inserted by the user. Also differs from the first case, this excavation case uses cross wall on the site. Both final stage database and every stage database don't have any data until a radius range of 0.5 km. On radius range of 1.5 km, final stage database has 2 cases included and every stage database has 4 cases. The average displacement for the first database is 2.98 cm, while the second database result is 3.89 cm. Unlike over prediction on first case, both case under predict for this case. However, it has a similarity with previous example in which every stage database predicts better than final stage database. Every stage database has a difference of roughly 0.5 cm, while final stage database prediction almost shows 1.5 cm difference.

case	台北市松壽路 11號						
from	our database						
type	our database	The case was removed					
aximum displacement(cm)	4.47						
	final stage				every stages		
		N	E			N	E
	location(user input)	25.037041	121.567162		location(user input)	25.03704079	121.5671618
	He(m)	21.25			He(m)	21.25	
	CW (use cross wall)				CW (use cross wall)		
	displacement (cm)	No data			displacement (cm)	No data	
cases numder in 0.3km	distance < 0.3 km	No data		cases numder in 0.3km	distance < 0.3 km	No data	
	displacement (cm)	No data			displacement (cm)	No data	
cases numder in 0.5 km	distance < 0.5 km	No data		cases numder in 0.5 km	distance < 0.5 km	No data	
	displacement (cm)	2.98			displacement (cm)	3.89	
cases numder in 1.5km	distance < 1.5 km	2		cases numder in 1.5km	distance < 1.5 km	4	

Figure 16. Second prediction example

The summary of both prediction example can be seen in figure 17. From these two prediction example, it can be concluded that every stage database predicts displacement of the assigned case better than final stage database. This is clearly shown by the difference of displacement predicted by both database with the monitored displacement. Other reasoning is every stage database has more point data in the same range of radius compared to final stage database. More data being added will leads to a lower standard deviation, in which leads to a more accurate prediction. Take note that the total of cases in final stage database in 233, while every stage cases only have 80 cases. An even more accurate result might be generated if every stage database is further extended until case no. 233.

	PREDICTION EXAMPLE 1	PREDICTION EXAMPLE 2
Displacement from Monitoring Data (cm)	1.8	4.47
Displacement from Final Stage Database (cm)	4.17	2.98
Displacement from Every Stage Database (cm)	2.1	3.89
Total data points inside the radius Final Stage Database	9	2
Total data points inside the radius Every Stage Database	41	4

Figure 17. Summary of both prediction example

5. Conclusions

Based on this study, some conclusions can be drawn:

1) All 8 variables that were being compared in both database shows good agreement, in which both database has similar behavior and can be further compared with prediction example.
2) Through 2 prediction example done, every stage database shows lesser gap value with the monitoring data, which means better displacement prediction compared to final stage database.
3) More data points on a certain range of radius is most likely to generate a more accurate displacement result because lower standard deviation will be obtained.

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