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Application of numerical simulation for the analysis and interpretation of pile-anchor system failure

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Abstract. Progressive increase in population causing land scarcity, which is forcing construction industry to build multistory buildings having underground basements. Normally, basements are constructed for parking facility. This research work evaluates important factors which have caused the collapse of pile-anchor system at under construction five star hotel. 21 m deep excavation is carried out, to have five basements, after installation of 600 mm diameter cast in-situ contiguous concrete piles at plot periphery. To retain piles and backfill, soil anchors are installed as pit excavation is proceeded. Before collapse, anchors are designed by federal highway administration procedure and four anchor rows are installed with three strands per anchor in first row and four in remaining. However, after collapse, system is modeled and analyzed in plaxis using mohr-coulomb method. It is investigated that in-appropriate evaluation of soil properties, additional surcharge loads, lesser number of strands per anchor, shorter grouted body length and shorter pile embedment depth caused large deformations to occur which governed the collapse of east side pile wall. To resume work, old anchors are assumed to be standing at one factor of safety and then system is analyzed using finite element approach. Finally, it is concluded to use four strands per anchor in first new row and five strands in remaining three with increase in grouted and un-grouted body lengths.

Keywords: anchor; contiguous pile; stress; deformation; finite; shear; elongation

1. Introduction

Soil anchors system is in progress since third decade of 20th century and lot of advancement have been made in its design, construction methodologies, testing etc. Now a days various temporary and permanent excavation support systems are present to retain backfill material and to prevent the sliding of adjacent structures. The need of this support system arises when deep excavation is carried out below existing ground level to by-pass loose sub soil stratum. According to Terzaghi and Peck (1967), and Tomlinson (2001), excavation that is six meter or beyond in depth should be considered as deep excavation. However, the choice depends on project type, requirement and most importantly on financial cash flow (Ashour and Hamed 2012, Galli and Prisco 2013, Gang *et al*. 2013, Gordon and Mehrangiz 2011). Normally for building projects to have underground parking facilities temporary retention system are adopted using contiguous piles and ground anchors. Their service life is normally not more than two years (Guo *et al*. 2011, Jue *et*

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al. 2014, Kanagasabai *et al*. 2011). However, the permanent soil anchors are used for entire life of the structure.

Mehrangiz and Gordon (2011) stated that the main function of ground anchors is to transfer tensile resisting forces into the groundmass through friction that is generated at surface of grouted body. However, the permanent ground anchors retain the stability of whole system on permanent basis and normally they are corrosion protected (Kee *et al*. 2014, Koichi *et al*. 2014, Lam *et al*. 2014, Loukidis and Salgado 2012, Malek and Alain 2013). According to Szavits (2008), soil anchor is a major part of retention system that acts as a load-carrying component. Anchor as an individual transfer tensile forces to soil mass behind retention piles. Shear strength of backfill soil is utilized to resist tension forces. These tension forces present in anchor are important for static equilibrium between anchor body, structure and the ground mass. With this mechanism, the lateral movement of whole system is restricted within acceptable range (Maosong *et al*. 2011, Mehrangiz and Gordon 2011, Merifield *et al*. 2006, Sivakumar *et al*. 2013).

Alkaya and Yesil (2011) stated that besides anchor, retention pile is another vital structural component that assists in transferring of tensile forces, bending moments and lateral earth pressure applied by back fill material. Retention piles should be rigid enough to minimize ground lateral displacement to acceptable limits (Sofia *et al*. 2011, Suched *et al*. 2013). Anchor inclination also plays an important role on the stability of retention system due to vertical component of load transferred to retention piles after application of lock off loads. Inclination near to horizontal will restrict wall movement to a minimum level. Ground anchors are kept in a range of 15 to 30 degree from horizontal and remaining design is performed accordingly. However depending on the function of soil anchors, Vishwas and Jyant (2011) has categories them in four basic types. Koichi *et al*. (2014) stated that one basic assumption is made during designing of soil anchors that lateral earth pressure applied by backfill is restrained by horizontal component of anchor load. Therefore, pressure applied by backfill is balanced by horizontal component but vertical component remains as it is which enhance shear stresses as excavation is proceeded. This results in deformation of retention system in a very complex manner depending on the yield and flexibility of piles. Other variables such as construction methodologies and unexpected loads at backfill side can enhance lateral earth pressure magnitude that should be carefully considered during design phase. Yong and Mingwen (2011) has examined that movement of trucks, trailers carrying excavated soil, steel, crush, sand etc. can significantly apply a lateral pressure on retention system, and this should be considered in design phase to avoid any collapse during its service life. According to federal highway administration (Sabatini *et al*. 1999) there are normally ten types of potential failure conditions that can occur with pile-anchor system and these should be kept in mind while designing. This research study aims to discuss a collapse of contiguous piling system supported by ground anchors. A very interesting and informative comparison is established between manual and numerical approaches for the design and analysis of pile-anchor system.

2. Scope and objectives

Main purposes to carry out this research work are **(a)** to highlight important geotechnical factors, which governed the collapse of pile anchor system **(b)** to describe failure mechanism of retention system through detail design outputs **(c)** to compare the design reliability of using finite element analysis with manual procedures and to predict the model behavior during different construction phases.

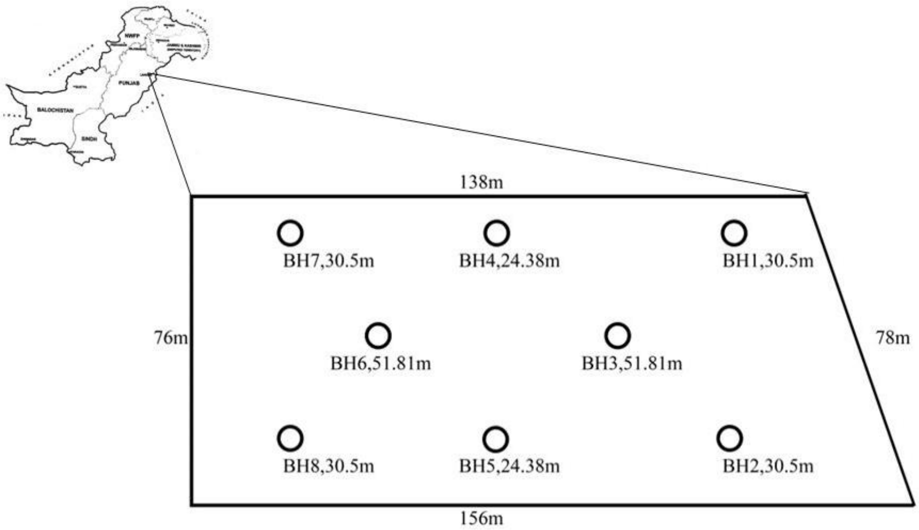


Fig. 1 Project site location and layout

3. Project overview

The five star hotel is planned to have five basements and eleven floors above with covered area of 90,000 m^2. Hotel would have 270 guest rooms, 46 single and duplex apartments and retail spaces. Basement parking facility for 704 cars and 359 motor bikes will be available on its completion. Deep excavation of 21m depth over a plot area of 11,193 m^2 is carried out after installation of 600mm diameter contiguous in-situ concrete piles to its periphery. To retain backfill and piles, soil anchors are installed in between piles as excavation is proceeded. Embedment depth for pile is 5m below excavation bottom level with total pile length as 26 m. Site layout is marked in Fig. 1 with N31°32′28″ and E74°25′18″ which is 3.50 km away from Allama Iqbal International airport, Lahore Pakistan.

4. Geological and geotechnical evaluation of soil stratum

In sub sections, geological stratification of soil and its geotechnical parameters are evaluated based on field and laboratory testing.

4.1 Geological investigation

According to uniform building code, the site is falling under zone 2B with seismic zone factor (Z) as 0.2. Site lies in low to moderate seismicity, which may be subjected to earthquakes of magnitude in range of 3.5 to 6.0 on richter scale. Based on x-ray diffraction major minerals present in soil are quartz, muscovite and clinochlore, which show that the alluvial deposit received sediments from metamorphic origin. Based on borehole logging top 4 m-5 m soil strata contain yellowish brown, stiff to very stiff silty clay mixture. From 5 m-12 m soil is characterized as very loose to loose silty sand with grayish brown color. Soil strata become loose to medium dense after

12 m with variation in color from light grayish to light brown grayish. This layer exists until 22 m after which soil become medium dense to dense until explored depth of 52 m with variation in soil color from light grayish brown to moderate grayish brown.

Water table is not encountered until explored borehole depth while soil investigation work. Soil is mostly in dry condition with low moisture in range of 2% to 4%. Chemical composition of soil indicates that total salt, chloride and sulphate contents vary from 0.039%-0.061%, 0.015%-0.03% and 0.009%-0.018%. pH value for soil varies from 6.9-7.2. Chemical analysis of soil indicates that ordinary portland cement can be utilized for contiguous piles, anchor grouting and anchor concrete blocks. Based on geological evaluation a cross section is drawn in Fig. 2 which shows that no abnormality in backfill behind retention piles. Actual and designed failure planes are established which gives an idea of deficiency in selecting design parameters as detailed in Section 5.

4.2 Geotechnical investigation

Detail geotechnical field and laboratory testing is performed to evaluate soil key parameter for the design of soil anchor retention system (Table 1). Sand replacement tests performed in top layer gives variation in field dry density from 17.8 kN/m^3 to 19.0 kN/m^3 while corresponding moisture content from 3.7% to 4.6%. Natural moisture content (NMC) varies from 4.6% to 6.5% while natural dry densities of undisturbed samples vary from 17.2kN/m^3 to 18.8 kN/m^3. Grain size analysis reflect percent finer #200 sieve varies from 12% to 86% at various depths while consistency varies from non-plastic (NP) to having PI of 10 in Atterberg's limit test. Soil is classified as SM-SP according to unified soil classification system. Specific gravity varies from 2.63 to 2.72 while frictional angle ($\emptyset$) during direct shear test (shearing speed = 1 mm/minute) varies from 24.6° to 32.8° at various depths while soil cohesion varies from 62 kPa to 87 kPa during unconsolidated undrained (UU) triaxial compression tests (rate = 1 mm/min, confining pressure = 100 kPa, 150 kPa, 200 kPa) in top 5 m layer. Coefficient of compression (C_c), calculated between 200 kPa and 400 kPa, varies from 0.0731 to 0.1163 in consolidation test. Based on forgoing test results soil stratum is divided into four layers as mentioned in Table 2. Pile embedment depth, anchor pullout resistance, strands requirement and other parameters are evaluated based on these results during detail finite element analysis. Figs. 3 to 6 give a

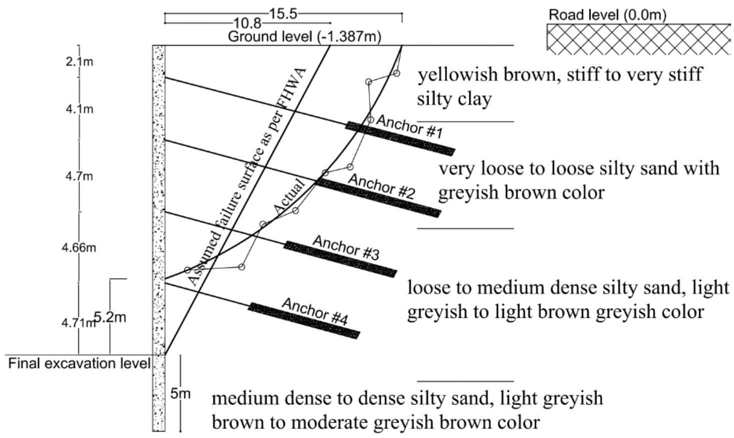


Fig. 2 Geological x-section and failure planes

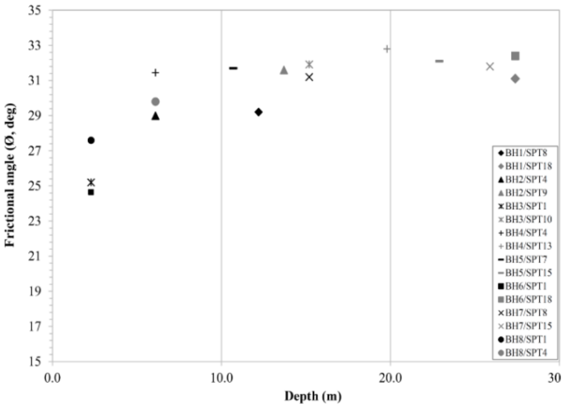


Fig. 3 Friction angle vs depth variation in direct shear test

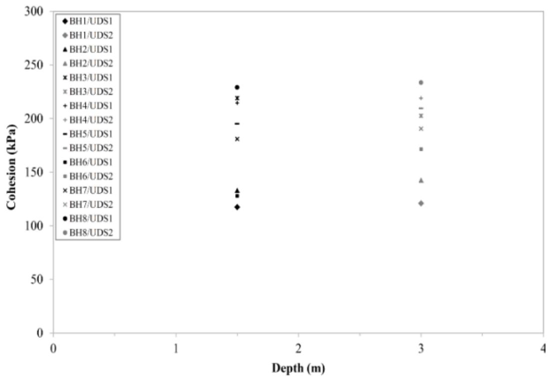


Fig. 4 Cohesion vs depth variation in unconfined compression test

Table 1 Detailed field and laboratory soil investigation test results

BH # -	SPT -	Depth m	NMC %	Natural density γ kN/m³	Passing #200 %	LL %	PI %	Gs -	Sand replacement		Ø (Direct Shear) deg	Triaxial UU		*Cc* (Oedo-meter) -
									w %	γ kN/ m³		Ø deg	C kPa	
1	UDS1/BS1	1.5	6.5	18.4				2.67	4.2	18.7				0.0731
1	1	2.3			68	26	6							
1	UDS2	3.0										13.1	75	
1	4	6.1						2.64						
1	8	12.2									29.2			
1	10	15.2			15	NP	NP							
1	18	27.4									31.1			
1	20	30.5			23	NP	NP							
2	UDS1/BS1	1.5							4.6	19.0		14.7	69	
2	1	2.3			69	25	7							
2	UDS2	3.0	5.5	18.8				2.72	4.1	17.9				0.0963
2	4	6.1									29			
2	6	9.1			20	NP	NP	2.67						
2	9	13.7									31.6			
2	16	24.4			18	NP	NP							
3	UDS1/BS1	1.5	5.2	17.2				2.69	3.9	18.9				0.103
3	1	2.3			73	28	9				25.2			
3	UDS2	3.0										17.5	66	
3	7	9.1			16	NP	NP							
3	9	13.7						2.65						
3	10	15.2									31.9			

Table 1 Continued

BH # -	SPT -	Depth m	NMC %	Natural density γ kN/m³	Passing #200 %	LL %	PI %	Gs -	Sand replacement w %	Sand replacement γ kN/ m³	Ø (Direct Shear) deg	Triaxial UU Ø deg	Triaxial UU C kPa	Cc (Oedo-meter) -
4	UDS1/BS1	1.5							4.0	18.3				
4	1	2.3			70	26	7	2.68						
4	UDS2	3.0	4.8	17.6				2.70				16.8	87	0.093
4	4	6.1									31.4			
4	5	7.6			33	NP	NP							
4	13	19.8									32.8			
4	16	24.4			27	NP	NP							
5	UDS1/BS1	1.5	5.4	17.9				2.68	3.7	18.0		12.6	79	0.1163
5	1	2.3			82	28	9							
5	UDS2	3.0												
5	2	3.1						2.66						
5	4	6.1			13	NP	NP							
5	7	10.7									31.7			
5	15	22.9									32.1			
5	16	24.4			31	NP	NP							
6	UDS1/BS1	1.5							4.3	18.1		16.3	62	
6	1	2.3			86	27	9				24.6			
6	UDS2	3.0	5.8	18.1				2.66						0.1096
6	5	7.6			17	NP	NP							
6	10	15.2						2.67						
6	17	25.9			22	NP	NP							
6	18	27.4									32.4			
7	UDS1/BS1	1.5	4.9	18.6				2.71	3.8	17.8				0.0864
7	1	2.3			83	29	10							
7	UDS2	3.0										19.1	77	
7	8	15.2									31.2			
7	11	19.8			21	NP	NP							
7	15	25.9						2.63			31.8			
7	18	30.5			17	NP	NP							
7	32	48.8			26	NP	NP							
8	UDS1/BS1	1.5							4.4	18.0		15.4	83	
8	1	2.3			85	27	8	2.70			27.6			
8	UDS2	3.0	4.6	18				2.67						0.1063
8	4	6.1			34	NP	NP				29.8			
8	8	16.8			22	NP	NP							
8	20	30.5			12	NP	NP							

SPT blows: 0-7.5 m = 12 blows; 7.5-12.5 m = 25; 12.5-18.5 m = 33; 18.5-24 m = 40; 24-28 m = 50

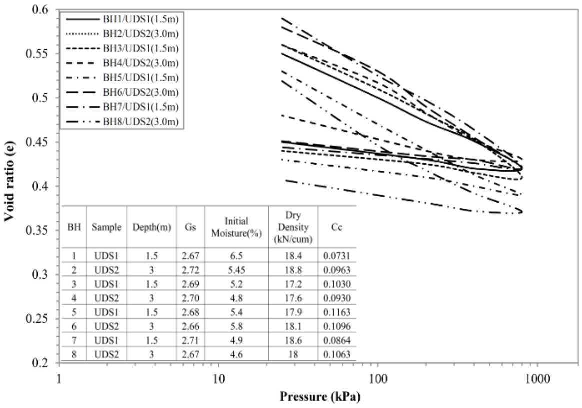


Fig. 5 Consolidation curves during oedometer testd

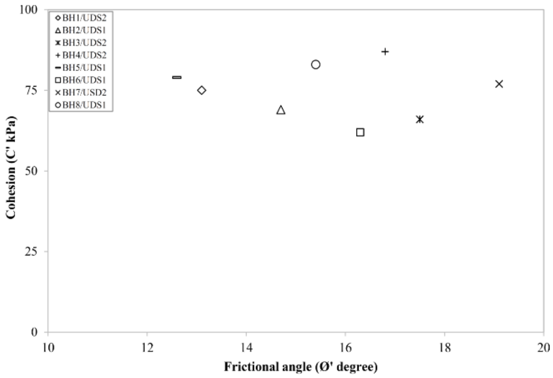


Fig. 6 Cohesion vs. frictional angle for undisturbed samples in UU tri-axial compression test

Table 2 Design comparison of pile-anchor system before and after collapse

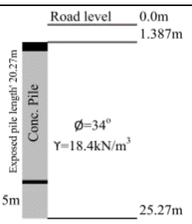
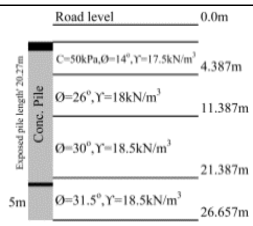
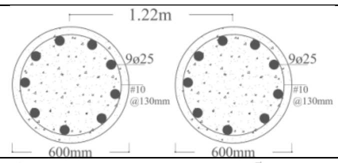
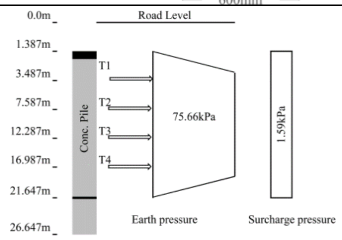
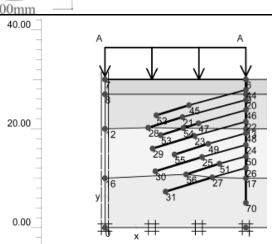
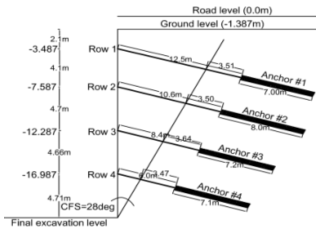
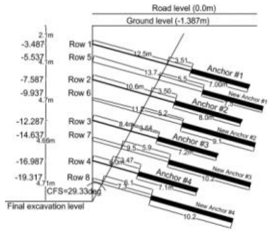
Sr. no.	Design aspects	Units	Design before collapse	Design after collapse
1	Design approach	-	FHWA geotechnical engineering circular no 4 (June' 1999)	Plaxis 2D assisted with FHWA and Canadian design approach
2	Soil geotechnical properties	-		
3	Loading condition	-	Surcharge pressure = 5.5 kPa GWT is below excavation level	Surcharge pressure = 15 kPa GWT is below excavation level
4	Contiguous pile design			
5	Apparent lateral earth pressure diagram	-		
6	Anchor design load	tons	DL1 = 32, DL2 = 38, DL3 = 40, DL4 = 40	DL1' = 35, DL2' = 45, DL3' = 48, DL4' = 48
7	Anchor inclination	deg	15	15
8	Anchor c/c spacing	m	1.22 m c/c	1.22 m c/c

Table 2 Continued

Sr. no.	Design aspects	Units	Design before collapse				Design after collapse			
9	Anchor diameter	mm	150				150			
10	Critical failure surface (CFS) angle from vertical	deg	45-Ø /2 from final excavation level				45-Ø /2 from final excavation level			
11	Anchor length	row	1st	2nd	3rd	4th	1st	2nd	3rd	4th
11-a	Un-grouted	m	12.5	10.6	8.4	6.0	13.7	11.2	9.5	7.3
11-b	Grouted	m	7.0	8.0	7.2	7.1	7.5	9.1	10.2	10.2
11-c	Total	m	19.5	18.6	15.6	13.1	21.2	20.3	19.7	17.5
11-d	Anchor length beyond CFS	m								
12	No of strands per anchor	No	3	4	4	4	4	5	5	5
13	Ultimate friction value	kPa	130/fos(2) = 65				100/fos(2) = 50			
14	Soil-grout interface friction	kPa	95 115		98 117		100 100		100 100	
15	Total no of anchors	no	1,503				1,016			
16	Total no of piles anchored	no	364				268			
17	Total no of anchor blocks	no	1,503				1,016			
18	Anchor locking load	ton	75% of anchor design load				75% of anchor design load			
19	Performance test	no	Not performed				57 anchors are tested			

comprehensive look on variation of soil frictional, shearing and consolidation properties along explored depth at different levels.

Foregoing geological and geotechnical evaluation indicate that soil anchors would lie mainly in cohesionless stratum consisting of silty sand with compactness ranging from loose to medium dense to dense state.

5. Retention system design - before collapse

600 mm diameter and 25.27 m deep cast insitu contiguous concrete piles are installed at plot periphery with center-to-center spacing as 1.2 m. Structural design for piles is done using ACI code with adequate amount of steel to have sufficient moment resistance and vertical bearing capacity. Retention piles are rotary bored and casted using 45 MPa ready-mix concrete. Before collapse, ground anchor system is designed according to federal highway authority manual. Single soil layer is assumed behind retention piles with frictional angle as 34°, surcharge pressure of 5.5 kPa and pile embedment depth as 5 m. Road top level is assumed as zero (0.0 m) which start 25 m

away from pile cap contributing no traffic load effect on ground anchors. Pile cap top level is -1.387 m. Based on this, four anchor rows are designed to retain pile and backfill material with three strands per anchor in first row and four strands per anchor in next three rows. Anchors are installed between centers of two adjacent piles with center-to-center spacing as 1.2 m. However, the detail design results are given in Table 2.

6. Reasons for sudden collapse of pile-anchor system

Few months after construction, east side retention pile system suddenly collapsed (Fig. 7) but giving allowance for workers to rush away from underneath causing fortunately no fatality. The collapse was sudden giving no prior evidence with respect to pile wall deflection, anchor strand breaking and crack at top of backfill behind pile cap. Physical survey shows that east side is having 129 piles out of which 97 piles are collapsed. The failure is extended about 15.5 m away from top of pile cap by making a slope that broke the piles at 4 m-6 m from top of final excavation level. However, the retention pile samples showed that pile reinforcement, steel grade and concrete quality are as per design requirements. Following are the important reasons, which have caused sudden collapse of pile-anchor system:

(a) Collapsed side was having steel rebar stock (Fig. 7(c)) placed close to pile cap from adjacent under construction building which contributing an additional surcharge of 9.5 kPa. System collapse is occurred due to immense over burden, which is not considered during design phase.

(b) Recovered samples of grouted body and anchor strand from the debris indicate that anchor strand has elongated and grouted body has slipped/broken as evident from Fig. 7(d) due to excessive steel surcharge. A cross section is enclosed in Fig. 2 giving an idea of failure surface and extent of failure. Fortunately, other retention walls remain secured due to existing ramp, which provided a good lateral support.

(c) Performance and pull out tests are not performed to check the design capacity of ground anchors after installation. However, anchors are stressed to design load only and locked at 75% of design load.

(d) According to FHWA, the ultimate friction values in medium dense and dense sand are 100 kPa and 130 kPa respectively. Soil-grout interface friction (design load over surface area of grouted body) is calculated based on design load which is coming 95 kpa-117 kPa considering safety factor of two. It is below the ultimate friction value (130 kPa) in dense sand. Refer to case I of finite element analysis (Table 4) the top two anchor rows are failed to have grout-soil interface friction between 66-70 kPa. It is less than the ultimate friction value in medium dense sand. It caused the breaking/slippage of grouted body due to incorrect evaluation of soil parameters.

(e) Determination of critical failure plane is also dependent on soil frictional properties. Short estimate of un-grouted body length probably has caused the actual failure plane to pass through/close to the grouted body.

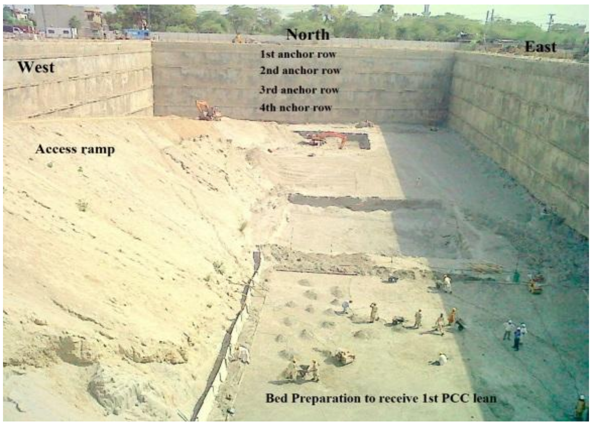
7. Failure mechanism of pile-anchor system

Failure mechanism of this collapse is well elaborated using theoretical relationships in sub sections.

7.1 Based on inappropriate selection of soil properties

Soil geotechnical parameters un-comprehensively evaluated before collapse considering single soil layer with constant frictional angle (Ø) as 34°. However stratum based on soil investigation comprises of four layers whose compactness, strength and frictional properties varies with depth. Variation in these properties has significant impact on pull out resistance of anchor, anchor load carrying capacity and grain-to-grain contact of soil particles. Before collapse this factor is ignored by assuming that soil have constant geotechnical properties along the depth. This make an overestimate of anchor load transfer rate, development of frictional resistance at periphery of grouted body and anchor ultimate load carrying capacity. Moreover, the location of critical failure plane for design of grouted and un-grouted body length depends on frictional angle (Φ) using following relationship

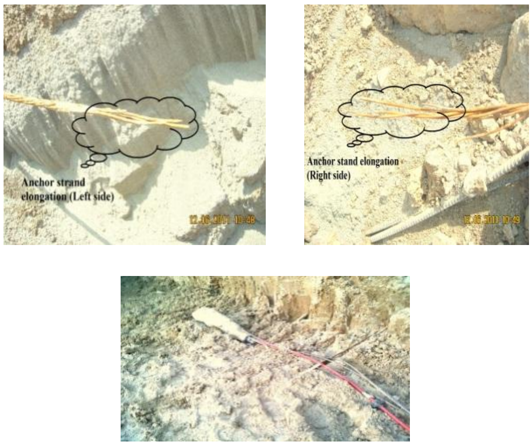
$$\alpha = \tan^{-1}(45+\Phi/2) \qquad (1)$$



(a) View before collapse

(b) Collapse of eastern pile-anchor system

(c) Steel stack beside eastern wall



(d) Strand and grouted body condition after collapse

Fig. 7 Project aspects before and after collapse of pile anchor system

Assumption of higher soil frictional angle keeps failure plane closer behind pile wall. This in turn gives shorter anchor length. Therefore this has caused slippage of grouted mass (Fig. 8) due to insufficient soil frictional resistance and underestimation of grouted and un-grouted body length.

7.2 Based on additional surcharge loads

During initial design only surcharge load due to traffic is considered and no addition is made for adjacent building surcharge, steel rebar presence, effect of moving earth dump trucks and trailers. With consideration of these additional surcharge loads, the value has been increased from 5.5 kPa to 15 kPa. Underestimate of surcharge loads give lower anchor force values against actual anchor loads which is evident from following relation

$$\Lambda\sigma_h = K \cdot qs \tag{2}$$

Where;

$\Delta\sigma_h$ is the increase in lateral earth pressure due to the vertical surcharge load, *qs* (in kPa)

K = earth pressure coefficient

Therefore, calculation and provision of less strands against actual requirement has caused anchor strand to elongate and break ultimately (Fig. 8).

7.3 Based on shorter pile embedment depth

Before collapse pile embedment depth is estimated based on Brooms and Wang-Reese method by considering passive pressures acting below the base of excavation. This gives embedment depth as 5 m (24% of excavated height). However analysis is made for embedment depth based on canadian foundation engineering manual (Fig. 9) which gives pile embedment depth as 9 m (43% of excavated height) to support 21m deep excavation using following equation

$$z = (K_pD^2\text{-}K_a\,(H+D)^2)/((K_p\text{-}K_a)(H+2D)) \tag{3}$$

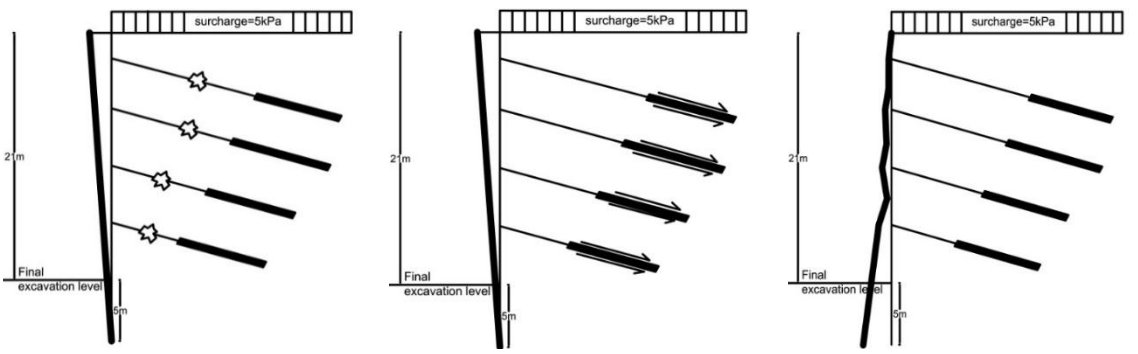
Where;

D = pile embedment depth in meter

H = pile height above final excavation level (meter)

K_a, K_p = active and passive earth pressure coefficient respectively

z = distance from bottom tip of pile where sum of all moments become zero (meter)



(a) Anchor tensile failure (b) Pullout failure of grouted body (c) Insufficient pile passive capacity

Fig. 8 Plausible failure mechanism of pile anchor system

Shorter pile embedment depth has significant impact on ultimate loads to be carried by single strand and provide less passive resistance (Fig. 8). Elongation and ultimate break is observed due to less strands per anchor.

8. Finite element analysis for pile-anchor system - after collapse

After collapse, re-engineering of whole system is performed using finite element method. For this purpose, the system is modeled in Plaxis and analyzed using mohr-coulomb approach. The structure is modeled in such a fashion that already installed old anchors are assumed to be standing at one factor of safety (F.O.S.).

8.1 Calculation Phases and material properties for finite element analysis

Finite element calculations are performed in seven phases namely (a) piles and surface loads are activated; (b) first cluster of excavation is de-activated; (c) first anchor geogrid (grouted body) and node-to-node anchor (un-grouted body) is activated; (d) second cluster of excavation is de-activated; (e) 2^{nd}, 3^{rd} and 4^{th} anchor geogrid and node-to-node anchor is activated; (f) third cluster of excavation is de-activated; (g) 5^{th}, 6^{th}, 7^{th} and 8^{th} anchor geogrids and node-to-node anchors are activated. Material parameters adopted for finite analyses are summarized in Table 3a and 3b considering four layers of soil behind pile wall. Soil interface reduction factor is taken as 0.9 to cover any abnormality during laboratory testing work. Backfill material is assumed to have four layers with properties as evaluated during field and laboratory testing (Table 1).

8.2 Cases for finite element analysis

Finite element analysis (FEA) is performed considering mainly four cases as numerated below:

Case I:
Case I-A: single soil layer (Ø = 34°), pile embedment depth = 5 m, old anchors active, surcharge = 5.5 kPa,
Case I-Ai: single soil layer (Ø = 34°), pile embedment depth = 5 m, old anchors active, surcharge = 15 kPa,
Case I-B: single soil layer (Ø = 34°), pile embedment depth = 9 m, old anchors active, surcharge = 5.5 kPa,

Case II:
Case II-A: four soil layer, pile embedment depth = 5 m, old anchors active, surcharge = 15 kPa,
Case II-Ai: four soil layer, pile embedment depth = 5 m, old anchors active, surcharge = 5.5 kPa,
Case II-B: four soil layer, pile embedment depth = 9 m, old anchors active, surcharge = 15 kPa,

Case III:
Case III-A: four soil layer, pile embedment depth = 5 m, new anchors active, surcharge = 15 kPa,
Case III-B: four soil layer, pile embedment depth = 9 m, new anchors active, surcharge = 15 kPa,

Case IV:
Case IV-A: four soil layer, pile embedment depth = 5 m, all anchors active, surcharge = 15 kPa,
Case IV-B: four soil layer, pile embedment depth = 9 m, all anchors active, surcharge = 15 kPa.

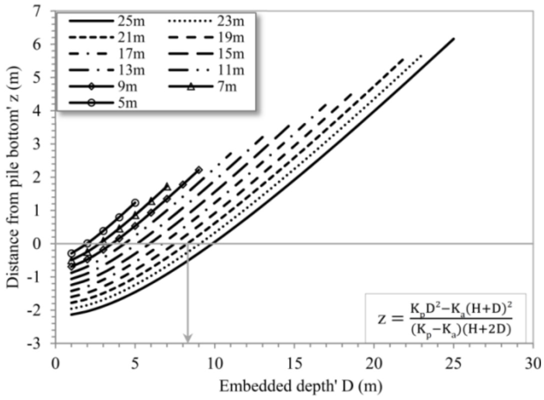


Fig. 9 Estimate of pile embedment depth using canadian approach

Table 3A Soil and interface properties

Layer number	Name (units)	1	2	3	4
Material type	type	Clayey silt	Silty sand	Silty sand	Silty sand
Material model	model	Mohr Coulomb			
Type of material behavior	type	Drained			
Soil un-saturated unit weight	γunsat(kN/m^3)	17.5	18	18.5	18.5
Soil saturated unit weight	γsat (kN/m^3)	19	20	21	21
Horizontal permeability	Kx (m/day)	0.5	0.5	0.5	0.5
Vertical permeability	Ky (m/day)	0.5	0.5	0.5	0.5
Young's modulus	Eref (kN/m)	5,000	20,000	26,000	32,000
Poisson's ratio	v (-)	0.33	0.34	0.35	0.35
Cohesion	cref (kN/m^2)	50	1	1	1
Frictional angle	Ø (degree)	14	26	30	31.5
Dilatancy angle	Ψ (degree)	0	0	0	0
Interface reduction factor	Rinter (-)	1.0	1.0	1.0	1.0

Table 3B Properties of contiguous piles (plate), anchor rod (node-to-node anchor) and grouted body (geogrid)

Parameter	Name	Units	Pile	Anchor rod	Grouted body
Type of behavior	Material type	-	Elastic	Elastic	Elastic
Normal stiffness	EA	kN/m	1.20 × 10+7	2 × 10+5	1 × 10+15
Flexural rigidity	EI	kNm^2/m	1.2 × 10+5	-	-
Pile diameter	d	m	0.6	-	-
Weight	w	kN/m/m	8.3	-	-
Poisson's ratio	v	-	0.15	-	-
Rayleigh factor	α	-	0	-	-
	β	-	0	-	-
Spacing out of plane	Ls	m	-	1.22	-
Maximum force	Fmax. comp	kN	-	1 × 10+15	-
	Fmax. tens	kN	-	1 × 10+15	-

8.3 Anchor length and pile embedment depth

Grouted body and strand lengths for old anchors are kept same for comparison purpose (Table 2). However, for new anchors, lengths are initially estimated using FHWA manual based on the location of critical failure slip plane. Instead of relying on Brooms and Wang-Reese method for the calculation of pile embedment length, canadian foundation engineering manual is referred for the calculation of distance (z) based on the principle of static equilibrium. To support excavation height (H) of 21 m, data is plotted (Fig. 5) between pile embedment depth (D) and distance (z) which gives embedment depth as 8.302 m. Calculated length is increased by 8% to have appropriate safety margin for passive resistance against active pressures. Anchor pullout capacity is also estimated using canadian approach with minimum one factor of safety. 13 mm diameter strands requirement per anchor is established based on ultimate breaking strength as mentioned in ASTM A416 for grade 1860 considering 60% margin for pre-stressing.

8.4 Finite element results and discussion

Effect of surcharge pressure, anchor length and pile embedment depth is critically analyzed using plaxis to determine anchor forces at each level. Detail comparative results are presented in Table 4, which shows significant impact of surcharge magnitude, pile embedment length, soil frictional properties on strand requirement, anchor pullout capacity and grouted body length. For case I, assuming single layer ($\emptyset = 34°$) with old anchors, safety factor against pullout resistance is below one for first two anchor rows giving allowance for grouted body to slip along its plane. Case II, assuming four layers with old anchors, also giving safety factor below one for first three rows in case of embedment depth as 5 m and for two rows in case of 9m embedment depth. From case I and II it is deduced that length of grouted body is not sufficient to provide required pullout resistance against applied loads. Therefore, in third case grouted body lengths are increased by 7.2, 13.8, 41.7 and 43.7% for four new anchor rows. Safety factor above one is obtained against anchor pullout resistance for all four rows and number of strands is estimated based on calculated anchor forces. However, for comparison purpose one analysis is performed by activating all eight-anchor rows and considering four soil layers (case IV). Significant safety margin is obtained against anchor pullout resistance even at 5m pile embedment depth and strands requirement even less than case III-A. With respect to difficulties in installation of anchors at eight different levels, case III-A is adopted to have anchors at four different levels with four strands in first level and five in remaining three levels. Pile embedment depth (5 m) is fixed as it has already been installed. However for case III-B, embedment depth of 9 m, would give an allowance to reduce one strand per anchor in first two rows with reasonable safety factor against anchor pullout resistance. External stability of pile anchor system in cohesionless soil is less critical compared with soft cohesive soil in which rotational failure passing below the base of pile is most dominant. Water table is not encountered during excavation and pile installation even at 26 m depth due to drawdown. Therefore piping which look to be critical for basal instability in cohesionless soil is not observed with sheet pile system. 44.4% reduction in extreme horizontal displacement pile (δ_x) is observed for case III-A compared with case II-A due to increase in grouted body length and number of strands while 41% reduction is obtained with increase in pile embedment length from 5 m to 9 m.

Based on finite element analysis, it is concluded that evaluation of actual soil parameters, consideration of expected surcharge loads, strand requirement with respect to actual loading, reasonable anchor grouted and pile embedment lengths are most important controlling factors for the safe geotechnical design of contiguous pile anchor system in cohesionless soil.

Table 4 Detail finite element analysis results

Case #	A-B-C-D	Parameter	Anchor no.							
			1st	2nd	3rd	4th	5th	6th	7th	8th
		X	23		31		31.83		31.83	
1-A	1-5-5.5-old	Y	2.4		3.2		3.3		3.3	
		Z	0.74		0.93		1.19		1.53	
		X	21.9		31.3		32.2		32.3	
1Ai	1-5-15-old	Y	2.26		3.24		3.33		3.34	
		Z	0.77		0.93		1.17		1.51	
		X	18.9		29.8		29.9		30	
1B	1-9-5.5-old	Y	2.0		3.1		3.1		3.1	
		Z	0.90		0.97		1.26		1.62	
		X	28.8		38		38.5		38.7	
II-A	4-5-15-old	Y	2.98		3.99		3.98		3.98	
		Z	0.59		0.75		0.98		1.26	
		X	28.2		37.1		37.2		38.6	
II-Ai	4-5-5.5-old	Y	2.92		3.84		3.84		3.98	
		Z	0.6		0.78		1.02		1.26	
		X	24		34.6		35.7		36.1	
II-B	4-9-15-old	Y	2.48		3.57		3.67		3.76	
		Z	0.71		0.84		1.06		1.34	
		X		35		45		48		48
III-A	4-5-15-new	Y		3.29		4.30		4.60		4.60
		Z		1.01		1.08		1.48		2.13
		X		28.47		37.9		41.9		42
III-B	4-9-15-new	Y		2.94		3.92		4.33		4.33
		Z		1.08		1.16		1.57		2.27
		X	11.4	12.7	13.1	17.8	20.5	27.5	31.6	45.4
IV-A	4-5-15-all	Y	1.21	1.31	1.35	1.84	2.12	2.84	3.26	4.69
		Z	1.44	2.43	2.22	2.47	1.84	2.39	1.54	2.1
		X	10.3	11.8	12.6	17.4	20.3	26.5	31.3	43.5
IV-B	4-9-15-all	Y	1.07	1.22	1.36	1.80	2.09	2.74	3.24	4.57
		Z	1.64	2.61	2.24	2.53	1.86	2.48	1.55	2.14

A = No of soil layer; *B* = pile embedment (m); *C* = surcharge (kPa); *D* = anchor type activated
X = design load (ton); *Y* = no of strands per anchor;
1st, 3rd, 5th, 7th = old anchors; 2nd, 4th, 6th, 8th = new anchors
Z = factor of safety against anchor pullout resistance $= \frac{Par = \sigma z'.As.Ls.\alpha g}{Anchor\ force}$

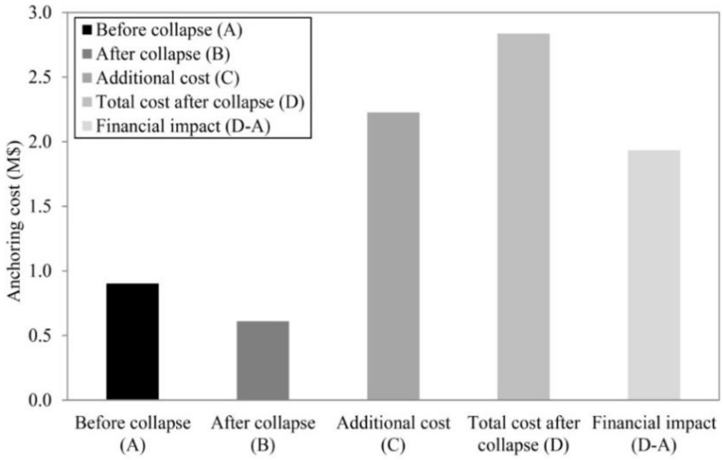


Fig. 10 Project financial impacts after collapse

9. Design implication and financial impacts

After performing re-engineering analysis, soil anchor design is implemented. Working plate form is prepared of soil embankment all around the periphery and proceeded with boring, tendon lowering, primary grout, water injection, anchor block installation, final grout, stressing, anchor locking, installation of welded wire fabric (WWF) and shotcreting.150 mm diameter hole is drilled at designed angle of 15° to required design depth (Table 2) using manual auger method. A crew of two persons is engaged to drill a borehole. After completing drilling process primary grout containing water cement slurry with w/c ratio as 0.45 is injected using 20 mm diameter PVC pipe to fill the drilled bore until grouted length. After 3 hours, the high-pressure pipe is connected with pressure pump to initiate the process of water injection. This process fractures the grouted mass formed during primary grouting and develop grooves over its surface. After 10 hours, the high-pressure grout pipe is connected with grout pump and slurry with w/c ratio as 0.45 is pumped at a pressure of 30 bars to fill all the fractured surfaces. After 14 days from the performance of final grout or after the lapse of 7 days from the pouring of anchor block concrete, whichever comes later, anchors are stressed to design load using hydraulic jack and then each anchor is locked at 75% of the design load. Anchor block cage fixing and concrete pouring is performed after final grout and before anchor stressing. 57 anchors are tested for proof load test and results are satisfactory without slippage of grouted body and breaking of anchor strands. Project financial impacts due to this incident are well summarized in Fig. 10 which shows that the project cost is enhanced by 1.93 M$ in total. This additional cost overrun covers increase in preliminaries, additional site and head office expenses and execution of revised anchor design, which is merely attributed to the factors as, highlighted in Section 6.

10. Conclusions

Important findings of this research work are concluded as below:

- This research study investigates and evaluates main causes, which governed the collapse of pile-anchor system. Important geotechnical aspects for this collapse are shorter contiguous piles embedment depth, underestimate of surcharge loads, incorrect evaluation of soil geotechnical parameters, lesser no of strands per anchor, shorter length of grouted and un-grouted body.

- Consideration of single soil layer has mobilized grouted body to slip along its plane giving factor of safety below one.
- Load transfer rate of anchor is merely dependent on soil friction properties based on which length of grouted and un-grouted body is estimated.
- Provision of short grouted lengths provides less skin friction to develop required pullout resistance.
- Canadian approach is more reliable for initial estimate of contiguous pile embedment length in cohesionless soil based on the principle of static equilibrium.
- Short embedded length not provided adequate passive resistance to active applied loads, which increased anchor loads and caused anchor strands to elongate and break after utilizing their full capacity.
- Finite element analysis (2D) using mohr-columb approach is quick to predict the model behavior during different phases of construction.

At the end, this sort of research comparison on actual happening would definitely aid designers; researcher and contractors to safely design and execute pile-anchor system for given sub-soil conditions.

11. Recommendations

Plaxis 2D is deficient to provide true three dimensional stress states and soil structure interaction so model can be analyzed in Plaxis 3D where real stress distribution, deformation, soil structure interaction and stability analysis can be evaluated more comprehensively. It is recommended to use canadian approach compared with federal highway method for the manual design of contiguous pile anchor system. Special attention should be made if water table is encountered and where soil conditions change abruptly i.e. half-grouted length is falling in clay and half in sand stratum. Overall stability of pile anchor system become more critical due to the presence of phreatic water level above excavation base that develops piping phenomenon. Special attention should be made on the design life of temporary anchor system and sub structural work must come up before its expiry.

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