Forensic Geotechnical Investigation of Settlement Failure of Pile Group Supporting Columns of Conveyor Belt

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Abstract: Forensic Geotechnical Investigation has gained significance among civil engineering professionals as majority of the failures of structures originate from substructure or foundation soil. The forensic studies enable establishing the exact causes for failures and to take up remedial measures to stabilize the structures where ever feasible and help in avoiding similar failures in future constructions by overcoming the deficiencies in geotechnical design of foundations and improving the ground prior to construction if found necessary. The findings of forensic geotechnical investigations of failures of structures are enabling the geotechnical engineers to advise more efficient and safe foundations in different soil conditions and to suggest the post construction care if any to be taken up. The forensic geotechnical investigations not only address the remedial action for overcoming the failures but also provide useful information with regard to causes for failures and the steps to be taken to avoid such failures in future constructions in similar soil conditions. The present paper describes various steps involved in forensic geotechnical investigation and illustrates the same through analysis of settlement failure a pile group supporting columns of conveyor system at one of the locations of material handling in Visakhapatnam port. The investigation revealed the causes for settlement failure of pile group as inadequate soil exploration, insufficient pile length and negative skin friction drag force on pile from soft clay layer. Based on the forensic geotechnical investigation carried out, remedial measures are suggested.

Keywords: Settlement, Pile group, load capacity, Bored cast in-situ pile, Soil investigation, Forensic investigation, Negative skin friction

1. Introduction

Forensic Geotechnical Engineering deals with the investigation/analysis of geotechnical/soil related failures of the structures that occur during/after construction. The forensic study is carried out to identify distress in the structure, the cause of failure and suggest suitable remedial technique for rectification of the problem/failure. The distresses in the structure include cracks, tilts, lateral movement and excessive settlement of structures. The common causes of geotechnical failures are lack of detailed soil investigation, sudden/unexpected changes in ground water profile, inappropriate construction methods adopted in the site etc. (Anirudhan, 2005, Leonards, 1982) Investigation of these kinds of failures is important to address similar issues and prevent possible failures in future. Apart from conventional geotechnical tests, non destructive tests are also required to conduct forensic geotechnical investigation. A well planned forensic investigation includes the following heads (Rao, 2009)

a) Compulsory Tasks

Before establishing cause of failure it is necessary to investigate the condition of the site immediately after failure and record the preliminary observations (Reconnaissance Survey) in order to arrive at the cause of failure. Original soil investigation reports, analysis and design of the structure should be verified and the engineers involved in planning, design, construction and performance monitoring are to be investigated in order to know the design methods and specifications of the material used for construction.

b) Optional Tasks

In case of certain complex engineering failures, standard geotechnical testing alone is sufficient to evaluate the cause of distress. In such cases additional investigations such as non destructive testing of the structural elements are conducted to evaluate quality of construction materials.

c) Analysis and Evaluation of Data

The distress in a structure occurs due to underestimation of loads, lack of sufficient soil investigation data, improper design and construction methods. Certain field and laboratory tests are conducted to characterize the ground and assess the cause of distress in the structure. The data required for the investigation include topography of the site, geological formations such as folds, faults, joints etc. at the site, seismicity of the region, stratification of soil layers, alterations in ground water table, results of field and laboratory studies etc. The load deformation history of the soil is reestablished by conducting data analysis based on mobilization of shear strength, liquefaction potential, critical void ratio of soil existing at the site, limit conditions and partial factors of safety.

d) Conclusions

Conclusions indicate the cause of failure and suggest suitable recommendation.

e) Report

All the data collected during investigation is documented in a easily retrievable format. The report includes all the findings of investigation with supporting documents such as soil investigation reports, meteorological conditions before and after the failure, interviews of persons involved in construction of structure right from planning to the execution stage. It comprises data analysis, investigation methodologies along with their results and conclusions indicating the cause(s) for failure and remedial techniques to be adopted.

The present paper deals with forensic investigation of settlement failure of pile group that occurred during construction phase of conveyor belt system in one of material handling plants at Visakhapatnam Port. The case study illustrates the above described methodology of forensic geotechnical investigation.

2. Details of Failure

One of the Material Handling Firm at Visakhapatnam Port has planned for new storage facility by laying new conveyor belt. The conveyor belt supporting system comprised of RCC Columns erected on pile cap laid on a group of four bored cast-in-situ piles and a horizontal frame work for supporting conveyor belt is laid over the columns. The piles used are of 450mm diameter and 15.5m length based on soil investigation report issued by a private agency. The piles are terminated at 15.5m considering presence of rock based bore log of nearby area. During the executing of the work, two columns supporting the frame work of conveyor belt at a location settled by about 100mm due to self weight as shown in Fig. 1, prior to installation of conveyor belt.

The Material Handling firm has approached Andhra University to investigate in to the problem and to provide technical advice. A site visit has been made to inspect the effected columns and it is observed that the area is stacked by coke up to 4.0m high over a large extent. Further, it is observed that the location is in close proximity to a drain which is 3 to 4m deep. It is understood during the interaction with the concerned officials that the problem of pile group settlement started after stacking of coke material in that area. It is also observed that no exploratory borehole is located within 100m distance from affected area. From the scrutiny of the design documents, it is noticed that the design load on each pile is 650kN. Initial and routine Pile load tests are not performed to check the design load of piles.

Based on the collected information, fresh soil investigation is carried out at the affected pile group location to establish the sub soil information and to estimate allowable load capacity of adopted piles based on termination depth.

3. Details of Soil Investigation

The exploratory borehole used in the forensic study is of 150mm diameter in soil) and 65mm diameter in Rock and terminated at 26.5m length in rock strata after advancing borehole in rock stratum by 4m. The Standard Penetration Tests are conducted at every 0.75m interval up to 3.0m depth and thereafter at every 1.5m intervals up to Rock stratum. The Standard Penetration Tests are performed as per IS 2131-1981. The laboratory tests are carried out on undisturbed, disturbed and SPT samples as per relevant IS codes of practice. The bore log (Table.1) is prepared using field data and laboratory test results of soil samples collected during investigation. The engineering properties of soil at different depths are presented in Table 2.

The bore log revealed that foundation soil at the location consisted of Filled up soil (Clayey sand with Gravel) in top 0.5m depth, Soft Marine Clay, Clayey Gravel, Weathered Rock / SDR, Highly Fractured Rock, Weathered Rock / SDR followed by Hard Fractured Rock. The ground water table is observed at a depth of 2.3m below the ground surface.

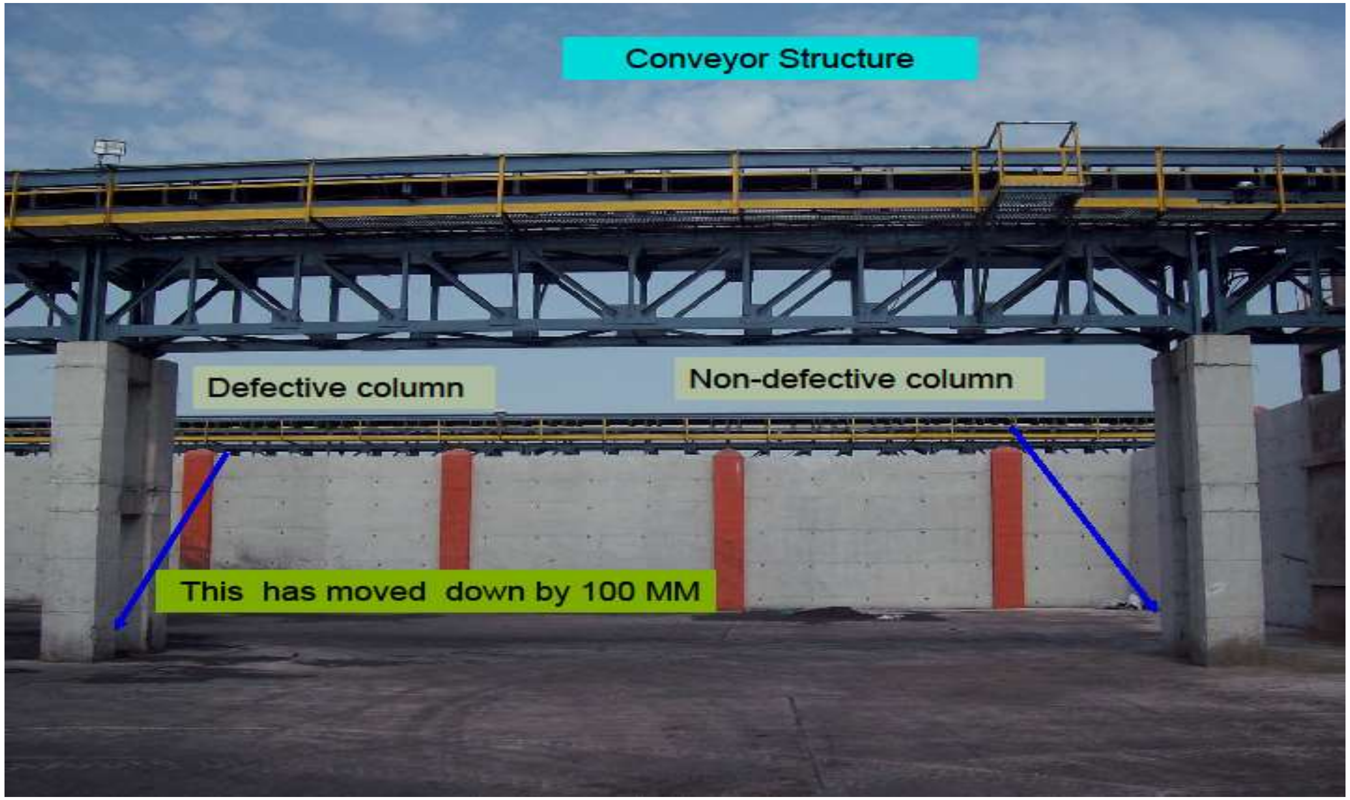

Fig. 1. Settled Columns Supporting Conveyor Structure

Table 1. Bore Log of Affected Location

Location : Visakhapatnam Port Depth of GWT:2.3m					Bore Hole No :BH-1 Depth of Bore Hole :26.5m Type of Boring :Rotary Diameter of Boring :150mm					
Layer Depth (m)	Description	Type	Depth (m)		Blow Count for Penetration of Split Spoon Sampler through			N	CR (%)	RQD (%)
					0-15cm	15-30cm	30-45cm			
0.0-0.5	Filled up soil (Gravelly clayey sand)	DS	0.0	0.5						
0.5-10.0	Soft marine clay	DS	0.5	3.0						
		SPT	3.0	3.45	01	01	02	03		
		DS	3.45	7.5						
		SPT	7.5	7.95	02	02	02	04		
		DS	7.95	10.0						
10.0-13.4	Clayey gravel	SPT	10.5	10.95	09	14	23	37		
		DS	10.95	13.0						
		SPT	13.0	13.4	30	42	Refusal	>100		
13.4-19.0	Soft Disintegrated Rock (SDR)	DS	13.4	14.5						
		SPT	14.5	14.54	Refusal	-	-	>100		
		SPT	16.0	16.45	24	30	35	65		
		SPT	17.5	17.58	Refusal	-	-	>100		
		DS	17.58	19.0						
19.0-22.0	Highly Fractured Rock	SPT	19.0	19.01	Refusal	-	-	>100		
		RCS	19.01	22.0					26.6	0
22.0-22.5	Weathered Rock	DS	22.0	22.5						
22.5-26.5	Fractured Hard Rock	RCS	22.5	24.5					26.4	10.5
		RCS	24.5	26.5					32.8	14.6

Notations: DS : Disturbed sample SPT: Standard Penetration Test
N: Standard Penetration Resistance RCS: Rock Core Sample
RQD: Rock Quality Designation CR: Core Recovery

Table.2. Engineering Properties of Soil at Bore Hole

Depth (m)	Description of strata	ISC	Type of sample	Grain size Analysis			Plasticity characteristics			ρ (g/cc)	NMC (%)	FSI (%)	C (t/m^2)	Ø (Deg)
				G (%)	S (%)	F (%)	w_L (%)	w_p (%)	I_p (%)					
0.0—0.5	Filled up soil (Gravelly clayey sand)	SC	DS	20	38	42	34	21	13	-	-	-	-	-
0.5—10.0	Soft marine Clay													
0.5-3.45	-do-	CH	SPT	01	30	69	63	32	31	2.02	65.5	60	1.6	12
3.45-7.5	-do-	CH	DS	00	25	75	58	28	30	-	-	-	-	-
7.5-10.0	-do-	CH	SPT	00	22	78	60	28	32	2.01	61.6	50	1.8	10
10.0—13.5	Clayey gravel	GC	SPT	43	32	25	43	24	19	2.28	25.8	35	1.2	29
13.5—19.0	SDR													
13.5-14.5	-do-	-	DS	29	48	23	32	20	12	2.22	20.7	-	-	-
14.5-14.54	-do-	-	SPT	Sample inadequate for analysis										
16.0-16.45	-do-	-	SPT	20	52	28	31	19	12	2.20	15.8	10	-	-
17.5-17.58	-do-	-	SPT	No sample recovered										
17.58-19.0	-do-	-	DS	25	55	20	28	19	09	-	-	-	-	-
19.0-22.0	Highly Fractured Rock													
19.0-19.01	-do-	---	SPT	No sample recovered										
19.0-22.0	-do-	---	RCS	Rock cores =recovered with CR 26.6% and RQD = Nil										
22.0-22.5	Weathered rock	GC	DS	59	13	28	30	19	11	-	7.5	-	-	-
22.5-26.5	Fractured Hard Rock													
22.5-24.5	-do-	---	RCS	Rock cores recovered with CR= 24.4% and RQD =10.5% with unconfined compressive strength of 3210t/m^2										
24.5-26.5	-do-	---	RCS	Rock cores recovered with CR= 32.8% and RQD =14.6% with unconfined compressive strength of 3450t/m^2										

Notations:

G : Gravel
S : Sand
F : Fines
W_l : Liquid Limit
Wp : Plastic Limit
Ip : Plasticity Index
ISC : Indian Standard Soil Classification Symbol
ρ : In-situ Density
NMC : Natural water content
C : Cohesion
Φ : Angle of Internal Friction

4. Analysis of Pile Settlement Problem

The pile load capacity of used pile of 450mm diameter and 15.5m length to support the columns of conveyor belt is determined based on established sub soil properties at affected location as per IRC 78-2014. As SDR strata is observed to have varying stiffness and consistently refusal is also not observed, skin friction contribution from clayey gravel overlying the SDR layer is also considered in load capacity evaluation. Load capacity in skin friction from clayey gravel is determined as per IS 2911 part 1 (Section 2) – 2010.

Allowable load capacity is determined as

$$Q_a = (R_e/3)+(R_{af}/6)+(Rs/2.5) \qquad \text{…………… (1)}$$

Where, Re = ultimate capacity in end bearing = $9C_{ub}.A_b$

R_{af} = ultimate capacity in side socket shear= $C_{us}.A_{s\,2} + r_s.A_{s1}$

Rs = Ultimate capacity in skin friction in clayey gravel

C_{ub} = Average shear strength below base of pile over a depth of 2 times diameter of pile

C_{us} = ultimate shear strength along socket length

r_s = ultimate skin friction resistance in clayey gravel

A_{s1}= surface area of pile in clayey gravel layer

A_{s2}= surface area of pile in SDR stratum.

In SDR layer, N value is considered as 60 and accordingly shear strength or cohesion of SDR is taken as 400 kN/m^2 as per IRC 78-2014. The ultimate skin friction resistance (kN/m^2) in clayey gravel is determined as "2**N**". In marine clay, the ultimate skin friction resistance is determined as 0.9 times undrained cohesion (kg/cm^2) of soil, which is taken as $1/16^{th}$ of '**N**' value (=3). The ultimate skin friction resistance (r_s) in clayey gravel and soft marine clay has been taken as 74 kN/m^2 and -17kN/m^2 respectively. A factor of safety of 2.5 has been used to arrive at allowable skin friction resistance in clayey gravel. Deduction for downward drag due to negative skin friction of soft marine clay (is made in evaluation of load capacity of pile. The details of load capacity estimation are presented in Table 2. Downward drag force is determined by multiplying ultimate skin friction resistance in soft clay layer with corresponding surface area of pile.

Table 2. Details of load capacity estimation of affected pile

Soil layer	Thickness (m)	Allowable load capacity in	
		in skin friction/ side socket shear (kN)	End bearing (kN)
Soft marine clay	10.0	-240.3	---
Clayey gravel	3.5	146.5	---
SDR	2.0	188.6	190.9

The allowable load capacity after accounting for downward drag from soft marine clay is determined as 286 kN as permanent liner is not provided around the piles. Ignoring downward drag from soft marine clay, the allowable load capacity of piles with PVC casing in soft clay zone is about 526 kN. Since dumping of material is done at the area, the downward drag force developed on the pile surface which resulted in low allowable load capacity of 286 kN against the required design load capacity of 650kN. Hence, the settlement of pile group occurred.

5. Remedial Action

In view of the prevailing situation, it is advised to install new piles to support the columns of conveyor belt by terminating the piles in fractured hard rock available at 22.5m by maintaining a minimum socketing length of 'd', where 'd' is the diameter of pile. Hence, Pile length of 23m is considered.

Allowable load capacity of suggested pile

Ultimate load capacity of pile with termination in Fractured hard rock is determined as

$$Q_u = R_e + R_{af} = k_{sp}.q_c.d_f.\mathbf{A_p} + \mathbf{A_s.c_{us}} \qquad \text{..................(2)}$$

Allowable load capacity of pile is determined as $Q_a = (R_e/3)+(R_{af}/6)$

Where , K_{sp} is an empirical constant =0.3 for (CR+RQD)/2 = 0.3

q_c= average unconfined compressive strength of rock below base of pile for a depth of twice the diameter of pile = 3200 t/m^2

d_f= depth of factor = 1+0.4×(length of socket/diameter of pile) with a maximum value of 1.2

C_{us} = ultimate shear strength of rock in socket length in Mpa = $0.225\sqrt{q_c}$

For socketing length of "d", depth factor is determined as 1.2. For unconfined compressive strength of rock, q_c = 32MPa, ultimate side socket shear resistance in rock is determined as 1.27MPa. Ultimate side socket shear resistance in SDR is taken as 66.7 kN/m^2 corresponding to N=60. Side socket shear contribution is considered over "6d" length (=2.7m) of pile above tip.

The details of allowable vertical Compression load Capacity estimation of 450mm dia. and 23.5 m length pile at location are tabulated in Table 3.

Table 2. Details of load capacity estimation of suggested pile

Soil layer	Thickness (m)	Allowable load capacity in		Allowable load capacity	
		in skin friction/ side socket shear (kN)	End bearing (kN)	Considering negative skin friction effect	with usage of Permanent casing
Weathered Rock	2.25	212.2	---	717.6	957.9
Fractured hard Rock	0.45	134.7	611		

The allowable load capacity of suggested pile is more than the required design pile load capacity of 650kN. Hence, it is adequate for supporting the columns of conveyor belt system.

6. CONCLUSIONS

Based on the present forensic investigation of affected pile group supporting columns of Conveyor belt, the following conclusions are drawn.

1. The settlement failure of pile group is due to inadequate sub soil investigation and termination of pile in weathered rock of varying stiffness instead of fractured hard rock.
2. Downward drag on pile surface from soft clay due to stacked coke has resulted in settlement of pile as permanent liner is not placed around the pile.
3. Routine pile load tests at the affected location where proper soil investigation is not done could have helped in modifying pile size /length and avoided the failure.
4. The need for extending soil exploration beyond 3m depth in to rock is realized as there can be thin layers of fractured rock sandwiched in weathered rock material, particularly in sites adjacent to natural drains.
5. Conduction of initial tests and routine tests is mandatory in projects where large numbers of piles are used.
6. The fractured hard rock at the affected location is available at 23m depth below ground surface from fresh soil investigation carried out.
7. The columns of the conveyor belt are to be supported on fresh bored cast in-situ piles of 450mm diameter and 23.5m length.

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