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Research Article

Earth Retention Systems Disasters: Causes and Prevention

Ammad Hassan Khan*

Department of Civil Engineering,
University of Engineering and Technology, Lahore, Pakistan

Abstract: In recent years, the trends of deep excavation for basement construction in high-rise buildings are getting rapid popularity in Pakistan. However, the design and construction specifications of earth retention systems adopted for deep excavation are not yet standardized which have resulted in a number of recent disasters. This paper addresses earth retention system disasters and associated problems observed in design and construction using database of 20 recent projects located at Lahore, Pakistan. Some of these problems are unique to Pakistan, whereas several others are universal. The illustrations of such problems and the preventive measures have been described. It is emphasized that these problems can easily be avoided by adopting effective project management, quality control measures as well as by enforcing the appropriate geotechnical engineering byelaws and specifications in the projects.

Keywords: Earth retention, geotechnical engineering, project management, risk management, design, construction

1. INTRODUCTION

Basement is part of the infrastructure which is constructed below the natural soil level. Deep excavation is a prerequisite for construction of the basement. Appropriate earth retention systems are required to execute deep excavation. Earth retention systems are primarily provided for the protection of workers during deep excavation and construction. In addition, the protection of adjacent infrastructures and utilities are also key consideration for the provision of earth retention system. Numerous types of earth retention systems are available in the industry which include sheet piling, soldier beam and lagging, soil nail and shortcrete, internal bracing (i.e., soil anchors and tie backs), external bracing (i.e., struts, diagonal and rakes), secant and tangent piles, and under pinning [1]. Any particular type of system can be used depending on the soil conditions needing deep excavation. The design as well as construction of each system involves control of multiple parameters deduced from geotechnical, structural, architectural and environmental considerations [2]. The stakeholders involved in earth retention system projects include owner/client, designer, constructor/contractor and supervisor.

Lahore being capital of the Punjab province is the second largest and thickly populated city of Pakistan. Lahore city and its surroundings have been serving as major business and industrial hub in the economic growth of Pakistan. Since 2000, the real estate has been among the prime areas of investment in Lahore. For sustainable housing and commercial demands in Lahore, vertical urban development was adopted as a successful solution by the construction stakeholders. Hence, high-rise multistory buildings have been constructed. After the development of the high rise multistory infrastructures the parking space constraint has emerged as a serious hazard at different locations of the cities. Consequently, the Lahore Development Authority (LDA) has introduced byelaws to address the parking constraint particularly for the high-rise buildings by enforcing the provision of basement parking. As a result, deep excavations and earth retention systems in multi-level basements are

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*Corresponding author: Email: ammadhk@hotmail.com

widespread ongoing construction activities in the city. However, many kinds of disasters have been observed in most of the recent earth retention system projects [3, 4].

The main objectives of this research were to investigate main causes of failures/disasters of earth retention systems by comparing the design and construction practices of locally adapted earth retention systems with international standards. Suitable preventive measures have also been proposed to avoid and minimize such failures in the future.

2. MATERIALS AND METHODS

The objectives of the research were achieved by adopting following methodology:

- Identifying projects in Lahore and its urban vicinity which faced partial or complete failure during design or construction of earth retention system.
- Characterization of typical soil profile of Lahore city up to 15 m and onward depth for determination of suitability of best possible earth retention system for carrying out deep excavation.
- Evaluation of best possible earth retention system for the equivalent soil profiles by comparing the design and construction methodologies adopted in these projects with international standards. This was achieved by carrying out following investigations:
  - o Detailed study of the following project documents;
    - ▪ Prequalification procedure adopted by the client for technical and financial evaluation,
    - ▪ Contract and conditions of contract,
    - ▪ Bill of quantities,
    - ▪ Tendering process,
    - ▪ Project drawings and design documents.
  - o Design and analysis calculations
  - o Detailed evaluation of technical specifications along with byelaws provisions
  - o Detailed meetings with representatives of project stakeholders
  - o Detailed project site visits
- Interviewing different trades of human resources for the assessment of the failure attributions.
- Detailed evaluation of following project practices and its implementation
  - o Human resource management
  - o Equipment and plant management
  - o Procurement management
  - o Financial management
- Data analysis to determine inadequacy in design and construction of earth retention system as well as deep excavation.

3. RESULTS AND DISCUSSION

Case studies of earth retention system taken from twenty multistory commercial building projects located in Lahore city are studied. The list of the projects is tabulated in Table 1.

Table 1. List of high rise projects in Lahore city.

Sr.	Project Name	Sr.	Project Name
1	Tricon corporate center	11	Sherpao Plaza
2	Ahad Tower	12	Lahore City Center
3	Pace	13	Warid Office
4	Haly Tower	14	China Center
5	Pace Hayat	15	Alamgir Tower
6	DHA Mall 1	16	Boulevard Heights
7	Fortress Tower	17	City Tower
8	Mubarak Center	18	DHA Mall 2
9	Liberty Trade Center	19	Alfalah Tower
10	IT Tower	20	MCB Tower

Locations of the project sites in Lahore city are shown in Fig. 1.

During identification of the projects criteria was made that the projects should be those which must observe constraints of different intensity during design or construction life cycle of earth retention system. The partial design disaster of earth retention system were observed in projects serials 2, 3, 4 and 5 (Table 1). The partial construction failures of earth retention system were recorded in projects serials 6,13,14,15,16,17,18 and 19 (Table

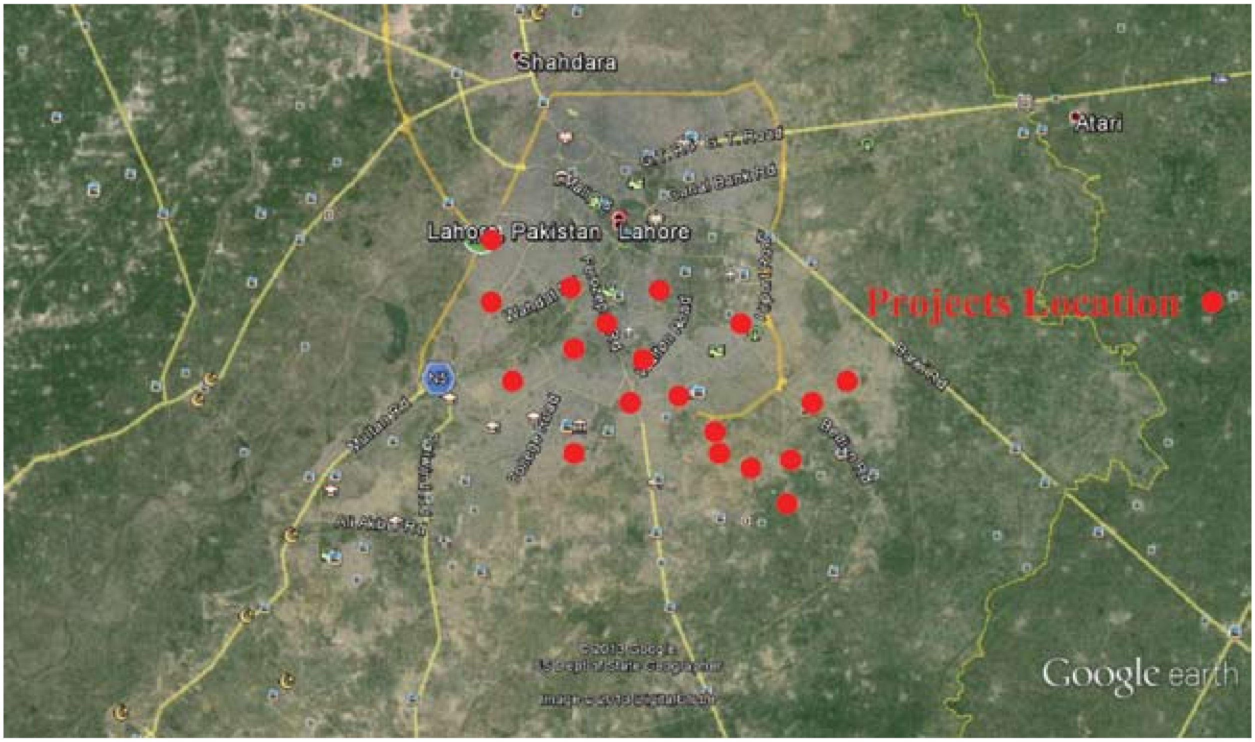

Fig. 1. Location map of the project sites in Lahore city [5].

1) Limited design or construction debacles were noted in rest of the earth retention system projects. The current status of the projects is that the earth retention system disasters were cope down on all projects except two i.e. Alamgir Tower and Sherpao Tower. The construction on these two towers was permanently abandoned after failure of earth retention system.

The soils subjected to deep excavation can be categorized into a typical profile based on the database of the geotechnical data obtained from the projects. The typical soil profile of Lahore city is shown in Fig. 2.

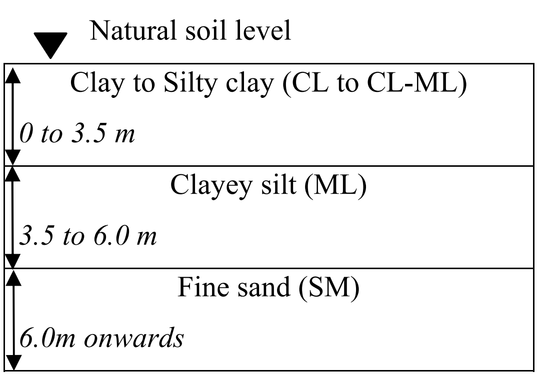

Fig. 2. Typical soil profile in Lahore city.

In such soil profiles (Figure 2), the secant piles earth retention systems are most appropriate for deep excavation [6]. All the projects listed in Table 1 also employed the secant piles earth retention system for deep excavation. Table 2 presents the steps involved in successful completion of earth retention system design and construction based on international standards and specifications [6–9].

Fig. 3 shows physically secant pile earth retention system and its components.

Fig. 4 presents the configuration of secant piles earth retention system design in term of its geotechnical design stability [6]. The soils behind the secant piles are subjected to active pressure. The soils under the toe of the secant piles embedded length is subjected to passive pressure.

During detailed investigations of technical and financial documents of each project it was observed that the standardized design and construction procedures for earth retention system was not observed. That led the failures of different intensity during the construction lifecycle of earth retention system. Figure 5 shows the glimpses of failures observed in the projects due to inadequacy in design

Table 2. Major design & construction steps of secant piles earth retention system.

Sr.	Description
A	Site Layout (Surveying)
B	Preliminary Geotechnical Investigation (Selection of number and depth of boreholes with non destructive testing)
C	Detailed Geotechnical Investigation (Drilling of bore holes, In-situ Testing, Laboratory Testing)
D	Determination of Soil Type, Depth and Its Properties (Based on analysis using laboratory and in-situ test results)
E	Geotechnical Secant Pile Design (Pile capacity in term of skin friction and end bearing, Pile depth and interval)
F	Geotechnical Tie Beam Design (Number of tie beams)
G	Geotechnical Anchorage System Design (# of anchor rows, diameter of cable, bonded & unbounded length with inclination)
H	Structural Design of Secant Pile (Pile diameter and reinforcement)
I	Structural Design of Tie Beam (Beam dimensions and reinforcement)

Design — *Design Codes & Technical Specifications* (B–H)

Sr.	Description
J	Drilling of Secant Piles
K	Preparation of Reinforcement Cage of Secant Piles (Cutting & bending)
L	Lowering of Reinforcement Cage of Secant Piles (Through Crane)
M	Casting of Concrete for Secant Piles (Through Trimmy and Crane)
N	Top Level Tie Beam Shuttering
O	Top Level Tie Beam Reinforcement
P	Top Level Tie Beam Concrete Casting
Q	Deep Excavation Level I
R	Mid Level Tie Beam Shuttering
S	Mid Level Tie Beam Reinforcement
T	Mid Level Tie Beam Concrete Casting
U	Mid Level Anchor Bore Hole for Bonded Length
V	Mid Level Anchor Installation
W	Mid Level Anchor Bonded Length Grouting and Clamping
X	Deep Excavation Level II
Y	Bottom Level Tie Beam Shuttering
Z	Bottom Level Tie Beam Reinforcement
α	Bottom Level Tie Beam Concrete Casting
β	Bottom Level Anchor Bore Hole for Bonded Length
γ	Bottom Level Anchor Installation
δ	Bottom Level Anchor Bonded Length Grouting and Clamping
ε	Deep Excavation Level III

Construction — *Quality Control and Assurance* — *Health, Safety, Environment & Loss Prevention Control* (K–δ)

Fig. 3. Components of secant pile earth retention system.

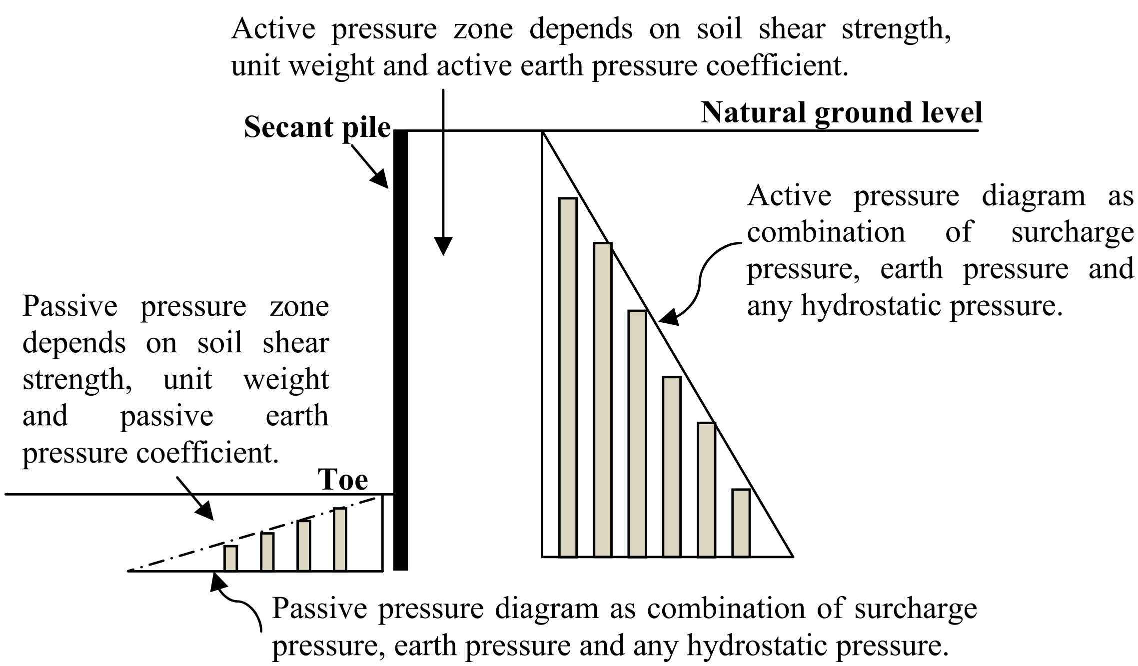

Fig. 4. Soil pressure zones around secant piles for external stability.

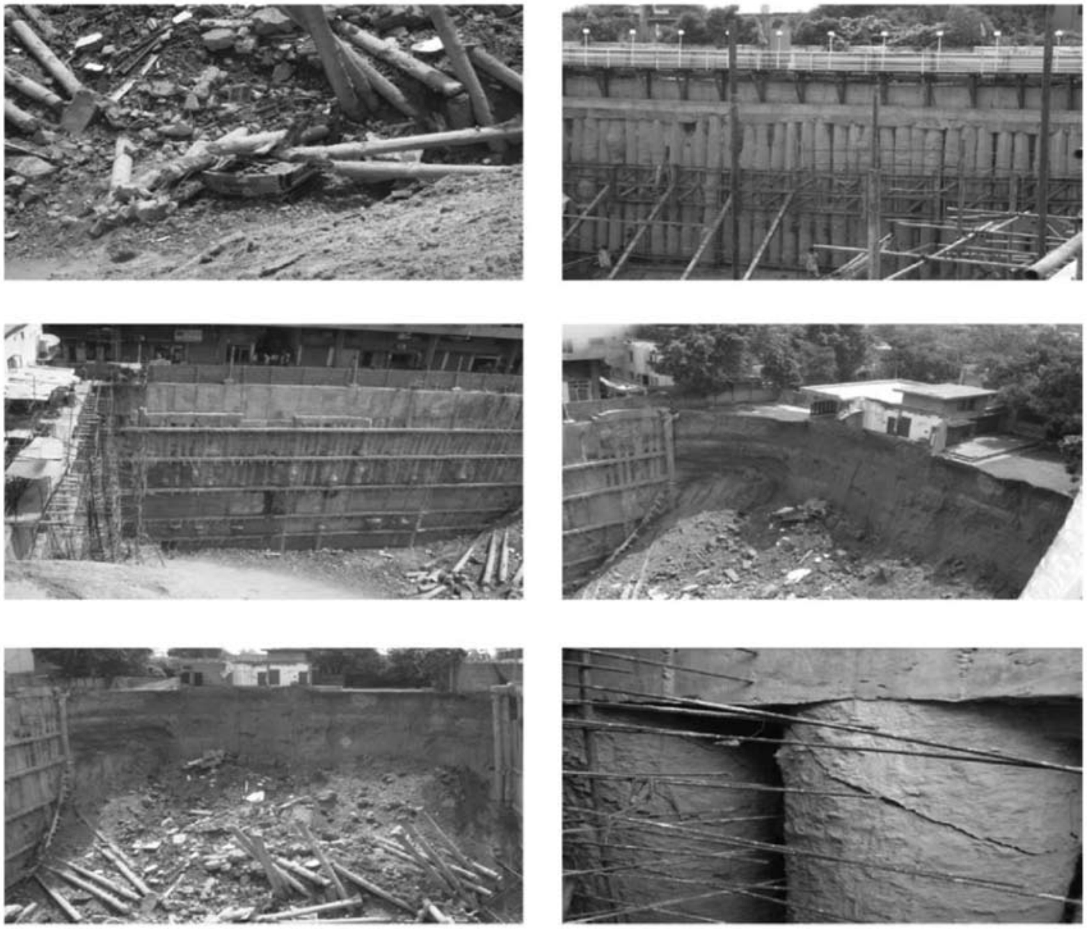

Fig. 5. Earth retention system failures due to design in-adequacy.

of earth retention system.

Table 3 presents a comparison that on each project how the standard design procedures narrated in Table 2 were adopted.

Table 3. Comparative summary of design stages adopted in each investigated project.

Design Sr.	Projects Serial																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
B	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
D	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
E	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
F	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
G	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
H	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
I	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

x (Completely Performed), - (Not Performed), * (Incomplete Performed)

Table 4. Summary of typical values of geotechnical parameters for soil types.

Soil type	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (degree)	Bearing capacity (kPa)	Plasticity index
CL to CL-ML	14 to 19	25 – 50	-	50-70	4 to 7
ML	15-20	-	26 to 30	60-80	0 to 4
SM	16-20	-	28 to 34	65-100	-

In all the investigated projects preliminary geotechnical investigations was skipped (Table 3). The main reason that was probably in the minds of stakeholders in not carrying out that activity was that it was followed by detailed geotechnical investigation. The preliminary geotechnical investigations actually led to planning of scope, schedule and budget of the detailed geotechnical investigations. The absence of preliminary geotechnical investigations led to ambiguities in the methodology for the precise determination of soil types and its requisite design properties. The research has proved that the projects have not been able to achieve complete requirements of detailed geotechnical investigations without preliminary geotechnical investigation [7]. More are the frequency of these ambiguities more severely a project was affected during construction [10]. In all the projects the detailed geotechnical investigation was carried out using standard penetration test (*SPT*). The soil samples retrieved from the *SPT* split spoon samplers were collected for necessary laboratory testing [8]. The minimum requirement of the depth and number of boreholes [6] as per standard for any particular project were not met. Some projects stakeholders gave importance to the findings of geotechnical investigation (controlled risk) while others tried to skip it partially or completely (uncontrolled risk). The projects which have given importance to geotechnical investigations (controlled risk) were saved from potential failures while others who skipped it faced noticeable failures as shown in Figure 5. The design consultant is the stakeholder who took uncontrolled risk of not carrying out geotechnical investigation. Further, the local bye-laws of development authority do not discuss the role of preliminary geotechnical investigation which gives cushion to project stakeholders to skip it completely or partially. The incorporation of preliminary geotechnical investigation in local byelaws can help to avoid the occurrence of disaster events in design of earth retention system in future.

As geotechnical investigations were not completely carried out on most of the projects

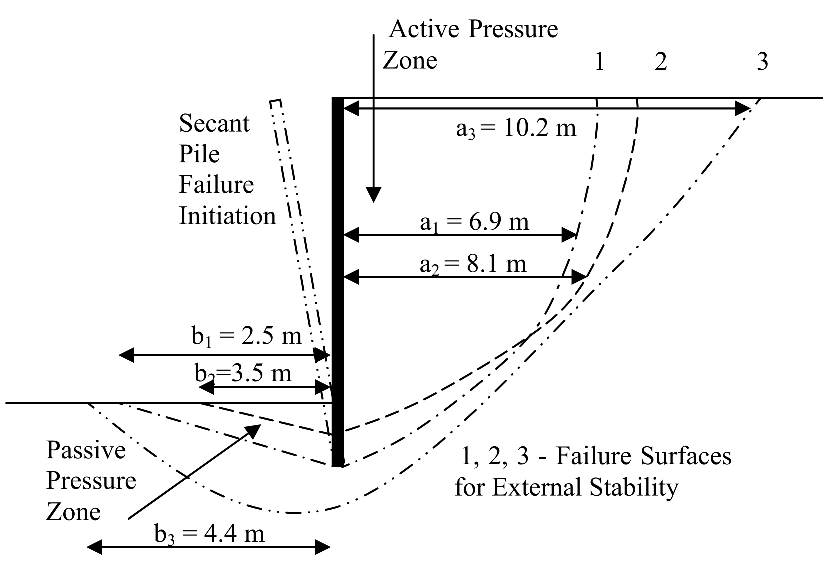

Fig. 6. Limits of critical zone lengths around secant piles for external stability.

therefore the designers deduced geotechnical parameters based on assumptions (uncontrolled risk). The typical range of basic geotechnical engineering parameters [8] for the soil types reported in Figure 1 is summarized below in Table 4.

In order to select the best possible combination from the range of geotechnical parameters (Table 4) to be used in design external stability check has been applied. For the external stability of earth retention system [6], there are three possible modes of occurrence that can initiate the failure of secant piles as shown in Figure 6. For a secant pile of 0.5 m diameter and 20 m length (5 m embedded and 15 m non-embedded which is mostly employed earth retention system secant pile dimensions) the three possible failure modes distances from the head and toe of the secant piles determined [6] using typical parameters combinations described in Table 4.

The lengths (a_1, a_2, a_3, b_1, b_2, b_3) reflect the limits of critical soil zones around the secant piles with respect to its stability (Fig. 6). Failure surface 3 was observed based on lower limit of geotechnical parameters (Table 4). Failure surface 1 was found using upper bound values of the geotechnical parameters (Table 4). Failure surface 2 was observed from the average of the geotechnical parameters described in Table 4. In actual on most of the projects no clear failure surface pattern (1, 2 or 3) was observed. A combination of patterns was noticed. However, the minimum and maximum limits of lengths described in Figure 6 were observed. Hence, the selection of geotechnical parameters from any reference is a complex phenomena and even an experience professional cannot do it precisely.

Structural design of the earth retention system components were carried out for all the projects. The structure design of earth retention system need parameters deduced from geotechnical investigation like soil cohesion, soil friction angle, bearing capacity, pile end bearing, pile shaft resistance, soil unit weight etc [8]. It can be seen from Table 4 that there are three possibilities of assumptions (uncontrolled risk) which structure engineer have with him; use minimum value, use maximum value or use average value in absence of actually determined value of geotechnical parameter. Table 5 shows different possibilities of assumptions a structure engineer has for geotechnical parameters and impact of these assumptions on different components of earth retention system [6].

Table 5. Summary of possible earth retention system components using different combinations of geotechnical parameters.

Earth retention system components	Soil Parameters		
	Case A, Friction Angle = 28^0, Unit Weight = 16.5 kN/m^3	Case B, Friction Angle = 31^0, Unit Weight = 17 kN/m^3	Case C, Friction Angle = 34^0, Unit Weight = 18 kN/m^3
Secant pile diameter (m)	0.75	0.60	0.50
Secant pile length (m)	25	23	20
Secant pile reinforcement (Number and diameter of steel bar)	8 , 25 mm	7, 25 mm	6, 25 mm
Top tie beam dimension (width and height in m)	0.8 x 0.8	0.65 x 0.65	0.55 x 0.55
Top tie beam reinforcement (Number and diameter of steel bar)	6, 25 mm	5, 25 mm	4, 25 mm
Anchor beam dimension (width and height in m)	0.4 x 0.4	0.35 x 0.35	0.25 x 0.25
Anchor beam reinforcement (Number and diameter of steel bar)	6, 12 mm	5, 12 mm	4, 12 mm
Anchor bonded length (m)	5	4	3
Anchor unbounded length (m)	10	8	6
Anchor diameter (mm)	75	60	50

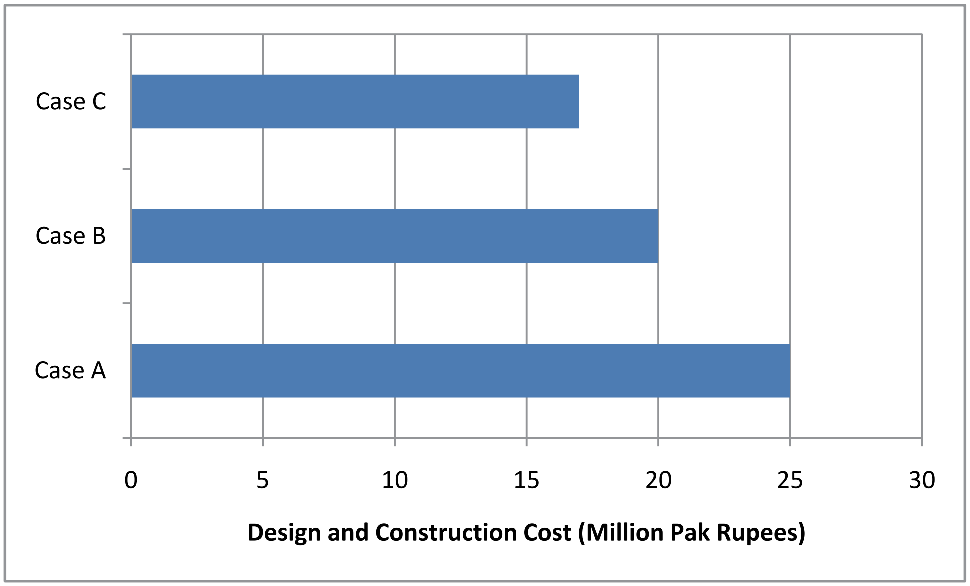

Fig. 7. Cost comparison of three cases for typical unit of earth retention system.

Fig. 7 presents a comparison of cost (for a set of earth retention system having 10 secant piles rest same as in the configuration shown in Fig. 3) for each case described in Table 5 using to date construction practices and material rates [12].

The Case A (minimum combination of geotechnical parameter) resulted in undersize and Case C (maximum combination) led to oversize of earth retention system in comparison to Case B (average choice) (Table 5, Fig. 7). The Case B (average combination) is uneconomical with reference to Case A (minimum) and undersize with respect to Case C (maximum) combination. This approach to use assumed geotechnical parameters in structure design of earth retention system may lead the design system either to failure or will make structure uneconomical. It can further be seen from Table 5 and Figure 7 that selection of any combination of geotechnical parameter for structure design of earth retention system is a complex phenomenon. Even for an experienced structure engineer it is cumbersome unless supported by logical preliminary and detailed geotechnical investigation. Additionally, local byelaws of development authority do not address the liability of geotechnical and structure earth retention system design on any design stakeholder [4]. That led to various discrepancies in practice of earth retention system design. The liability of structure as well as the geotechnical earth retention system design should be attributed by development authorities to ensure its safe practice. As per existing local bye laws structure engineers designing any project is always kept liable for his design. However, no liability is attributed to him for the design of earth retention system; this may be the most probable reason that structure engineer take categorical risk of earth retention system design with no or incomplete geotechnical design parameters.

The implementation of construction procedures during each project in comparison with standard construction practice (Table 2) are given in Table 6.

Fig. 8 shows glimpses of construction failures in earth retention system projects.

Drilling of secant piles (J) were carried out in all the projects by rotary drilling machines. The drilling was not carried out as per recognized drilling practices [7]. The verticality, invertness and stability of boreholes were neither maintained nor verified on any project by contractors. It led to the overconsumption of the concrete in secant piles resulting in cost overrun in the activity for owner.

The reinforcement steel (serials K, O, S, Z) bars were not provided in secant piles and tie / anchor beams according to design and technical specifications of the projects. In some projects the verticality of the cage was not maintained and in others the qualities as well as quantity of steel bars

Table 6. Summary of construction activities adopted in each investigated project.

Const. Sr.	Projects Serial																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
J	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
K	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
L	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
M	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
N	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
O	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
P	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Q	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
R	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
S	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
T	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
U	*	*	*	*	*	-	*	*	*	*	*	*	-	-	-	-	-	-	-	*
V	*	*	*	*	*	-	*	*	*	*	*	*	-	-	-	-	-	-	-	*
W	*	*	*	*	*	-	*	*	*	*	*	*	-	-	-	-	-	-	-	*
X	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Y	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Z	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
α	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
β	*	*	*	*	*	-	*	*	*	*	*	*	-	-	-	-	-	-	-	*
γ	*	*	*	*	*	-	*	*	*	*	*	*	-	-	-	-	-	-	-	*
δ	*	*	*	*	*	-	*	*	*	*	*	*	-	-	-	-	-	-	-	*
ε	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

x (Completely Performed), - (Not Performed), * (Incomplete Performed)

were not adhered as per technical specifications or design. It has been observed that around 5 to 10 % of the reinforcement steel bars were reduced in piles/beams in comparison to originally designed bars. The major objective probably in reducing quality and quantity of steel was to curtail the unit cost of activity which was the serious risk by contractor in perspective of the construction project execution ethics.

As per international practice the casting of concrete for secant piles should be through weight batching from concrete batching plant [7]. However, in most of the projects that casting was carried out by conventional concrete mixers through volume batching. In addition the types (coarse and fine) and ratio of concrete ingredients remained out of control by contractors. That led to the attaining of concrete strength lower than the design. The records of compressive strength of different cubes and cylinders casted from the concrete samples of secant piles reflect that the volume batched concrete showed around 10 to 20% lesser strength than the design. This was an uncontrolled risk taken by contractor in the project.

In most of the projects, the wooden shuttering material (N, R, Y) was used in place of steel. That resulted in under/over compaction and improper dimension achievement of beam members.

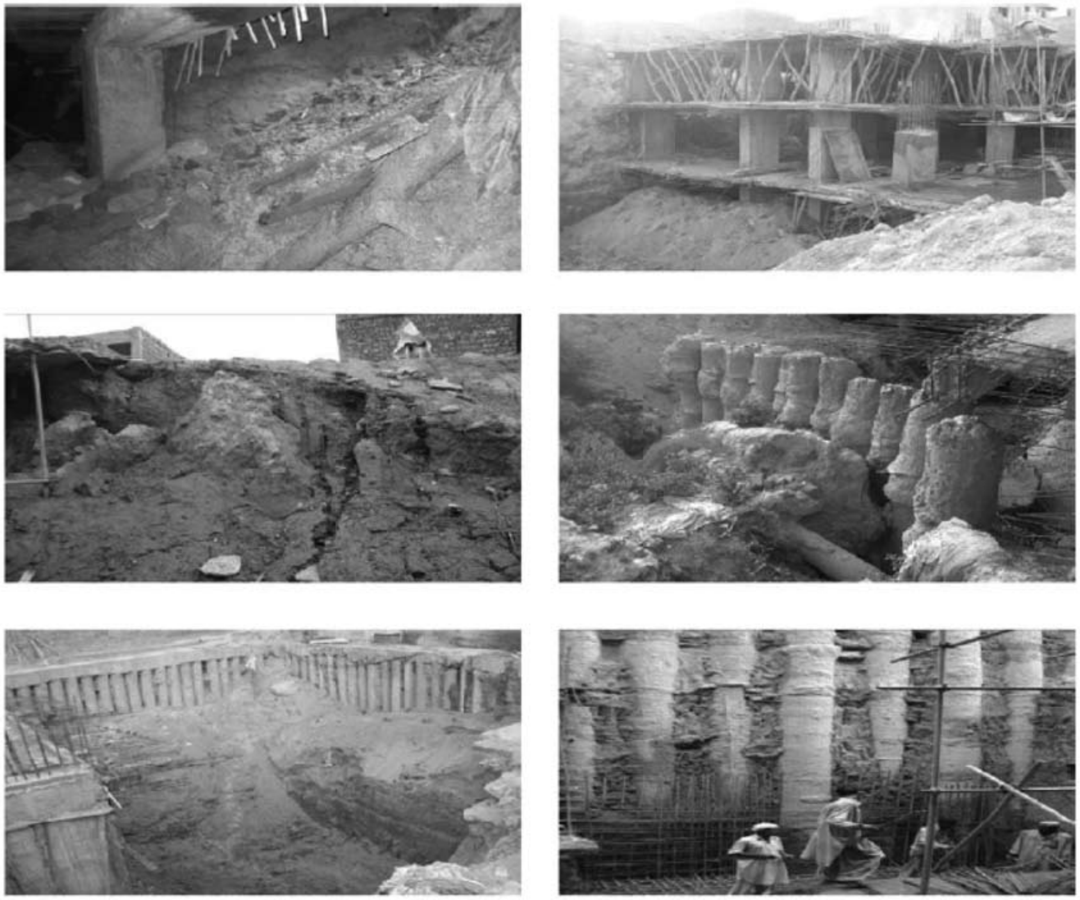

Fig. 8. Glimpses of earth retention system construction failure.

This was reflected through the origination of honeycombing on the beam surfaces at different location. The concrete earth retention beams casted with inappropriate shuttering by contractors led to reduce compressive strength of concrete than the originally anticipated in design. The shuttering quality compromise was another uncontrolled risk taken by contractor.

In some of the projects, deep exaction (Q, X, ε) was carried out using mechanical excavator. The excavated material was transported from the site location through dump trucks. While on others it was manually executed and excavated material was transported from the site through the two sided bags loaded on donkeys. The mechanical method was quick but costly. The manual method was cheaper but time consuming. Both methods have merits and demerits. However, both were risk free as far as quality or procedure of carrying out of activity was concerned [10, 11].

In most of the projects, the diameter of the anchors, bonded/unbounded lengths of anchors were not used (U, V, W, β, γ, δ) by contractors as originally anticipated in design. The quality and application of the grouting epoxy and clamping materials used was also not up to mark. The methodology of manual anchor boring at certain inclination angle was also slack. The non standardized anchors installation was key risk taken by contractor on the project.

The construction shortcomings discussed above referred to the inadequacy of project management and lack of quality control and assurance on the projects. Further excessive risks taken on the projects referred to out of control risk management which is extremely dangerous practice for the construction projects. Due to design or construction shortcomings described above the projects originally anticipated costs overran as shown in Fig. 9.

The projects at serial nos. 2, 3, 4 and 5 (Table 1) which faced partial design disaster of earth retention

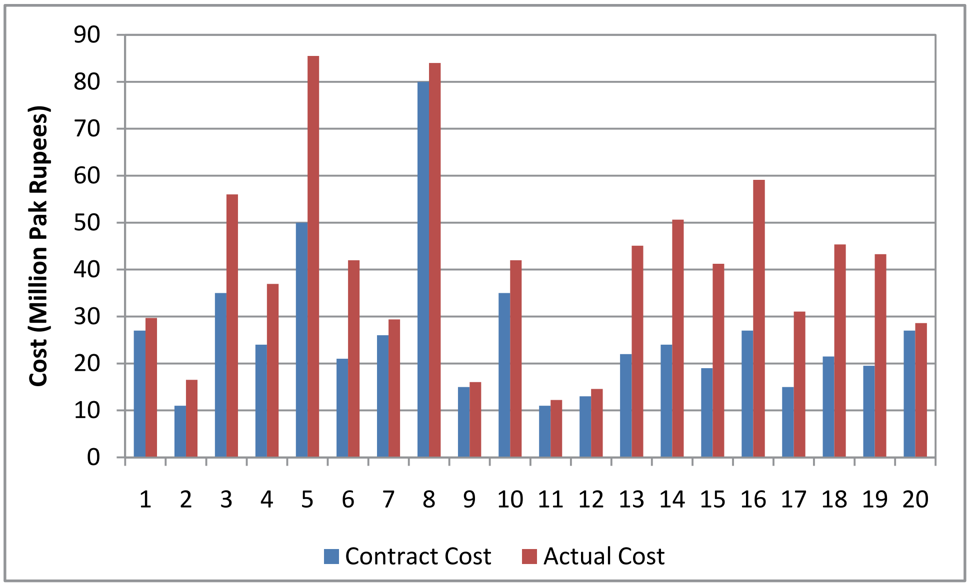

Fig. 8. Glimpses of earth retention system construction failure.

system showed 50 to 70 % increase in its original contract cost of earth retention at completion after necessary rehabilitations (Fig. 9). The partial construction failures of earth retention system in projects serials 6,13,14,15,16,17,18 and 19 (Table 1) finished in almost more than double of the original cost of earth retention at completion after repair. In significant cost variation was observed in cost of earth retention in remaining projects which faced limited design or construction debacles.

4. CONCLUSIONS

The earth retention system disasters were caused primarily due to insufficiency in the existing byelaws of the local development authorities. In addition, lack of implementation of geotechnical engineering, project management and risk management practices were also the major reasons of disasters.

The main geotechnical engineering design and construction factors that caused the failures were inappropriate spacing of anchor piles, deficient anchors installation methodology, underestimating the soil behavior and pressures, incomplete understanding of geotechnical design / implementation. The major project management design and construction factors those contributed failures were deficient constructability, improper deep excavation methodology and lack of quality control / assurance during design / construction. The key risk management features that led to the failure include improper risks management, insufficient risks identification and lack of precautionary measures after taking uncontrolled risks.

5. RECOMMENDATIONS

Based on this study, the following recommendations are proposed as prevention measures to avoid future disasters in earth retention systems:

1. Local byelaws of development authorities should incorporate the implementation of preliminary geotechnical investigations prior to detailed geotechnical investigation.
2. Structure engineer should design the earth retention system structure after incorporation of necessary geotechnical parameters deduced from preliminary and detailed geotechnical investigations. Earth retention system design should be verified though a structure stability certificate by the local development authorities. The certificate should be mutually signed by professional geotechnical and structural engineer.
3. Geotechnical design of earth retention system must be carried out using actual parameters deduced from preliminary and detailed

geotechnical investigation otherwise either the design will be under design or uneconomical. Local development authorities should also impose liability on geotechnical engineer for design safety of earth retention system.

4. The owner/client of the project should hire the advisory services from licensed professional construction individuals or enterprises. The historic or surrounding geotechnical data can only be used as reference during feasibility. However, independent geotechnical investigation should be carried out before detailed design of earth retention system for the project.

6. ACKNOWLEDGEMENTS

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