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Probabilistic Analysis of Deep Excavation Design and Construction Practices in Pakistan

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Abstract: Probability analysis provides a sound basis for choosing a course of action against the uncertainties involved in the geotechnical exploration. The modern probabilistic techniques have been successfully applied to classical geotechnical engineering problems such as seepage, settlement, bearing capacity, slope stability in the past throughout the world. This research is more specific towards the application of probabilistic analysis concept in the design and construction of deep excavation, which have emerged as a new trend used in the construction of high-rise buildings in the urban areas of Pakistan specifically. In this research paper, the design and construction data of deep excavation from running construction projects was collected and probabilistic method of analysis was applied for the evaluation of risks, uncertainties, probabilities and cost impacts. From the finding of the results, It is observed that if excessive unplanned risks are taken in design of deep excavations than its cost impact during construction become very high. However if controlled risks are taken in deep excavation construction than that can help in the cost reduction of the project.

Keywords: Probabilistic analysis, risks, geotechnical engineering, deep excavation

INTRODUCTION

Probabilistic analysis is used globally to evaluate the impact of uncertainties and risks taken during the projects execution on its associated activities. Probability theories provide a formal basis for quantifying risks and uncertainties which must not be dealt by engineering judgment (qualitatively).

Soils and rocks are among the most variable of all engineering materials and as such are highly amendable to a probabilistic treatment [1]. Risks and uncertainties in the determination of the in situ geotechnical profiles and material parameters for individual soil layers are one of the most significant problems geotechnical engineering professionals have to cope with. It is important to realize that different sources of uncertainty exist, material parameters varying in a certain but known range may be one of them but simply the lack of knowledge may be the more pronounced one [2].

Risk and reliability analysis is an area of growing importance in geotechnical engineering, where many variables have to be considered. Statistics, reliability modeling and engineering judgment are employed together to develop risk and decision analyses for civil engineering systems. The resulting engineering models are used to make probabilistic predictions, which are applied to geotechnical problems [3]. A formal procedure of geotechnical data evaluation and analysis by mathematical calculations, numeric or computational modeling of all aspects of risks and uncertainties is not a straightforward task. That is why, in common geotechnical engineering practice engineering judgment is pronounced.

Recent theoretical developments and advances [4-16] in probabilistic analysis application techniques and computational modeling allow geotechnical engineers for a more recognized consideration of risks and uncertainties during design and construction. However, it could not replace the role of engineering judgment in the practice of geotechnical engineering.

The horizontal trend of urban development has been the popular expansion mode in Lahore (23rd largest city of world; 2nd largest city of

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Pakistan with a population of over 10 millions and an extended area of 2,491 km) until year 2005. After year 2005 with rapid growth in the economy, real estate becomes one of the most prime areas of investment in Lahore. The rapid shoot in the land prices diverts the direction of the government and private developers towards the vertical urban development thus necessitate the deep excavation [17]. Even until recent times the deep excavation and shoring system adaptation in the industry has been facing numerous challenges and uncertainties. As a result of these uncertainties recent design and construction failures have been observed [18]. In this research an attempt was made to address these challenges and uncertainties by developing an analysis of deep excavation design and construction based on the probabilistic techniques. The deep excavation design and construction related technical and financial data in Lahore from the twenty projects (Table 1) year wise was collected and used for our analysis. Table 1 is showing the list of deep excavation projects in Lahore, Pakistan. Tables 1a & 1b are showing the major causes of failure in design and construction of these deep excavation projects.

Table 1. The list of deep excavation projects in Lahore.

Year	Design Failure Projects	Construction Failure Projects		Successful Projects	
2006	Pace	Alfalah Tower	City Tower	MCB Tower	Tricon Corporate Center
2007	Ahad Center	Alamgir Tower	China Center	Liberty Trade Center	IT Tower
2008	Pace Hayat	Boulevard Heights	Warid Office	Mubarak Center	Sherpao Plaza
2009	Haly Tower	DHA Mall 1	DHA Mall 2	Fortress Tower	Lahore City Center

Table 1(a). Major causes of failure in design projects.

Year	Projects	Type of failure	Major causes of failure	Remarks
2006	Alfalah Tower	Design failure	Inadequate interval between bracing beams, inaccurate bonded and unbonded lengths. Inadequate diameter of anchor piles and undersize reinforcement bars in anchor piles.	Project abandoned
2006	Tricon Corporate Center	Design failure	In adequate geotechnical investigation parameters. Insufficient geotechnical profiling of the adjacent high rise building. In accurate alignment of the anchor piles and multi level tier system.	Project under construction
2007	Alamgir Tower	Design failure	Inadequate spacing between piles, bracing beams. Insufficient grouting in the bonded length of the anchorage system. In appropriate exaction and non exaction lengths of the system	Project abandoned

Table 1(b). Major causes of failure in construction project.

Year	Projects	Type of failure	Major causes of failure	Remarks
2007	China Center	Construction failure	The deep excavation carried out with out the installation of anchors and multilevel tier system only top tie up beam provided. Inappropriate implementation of HSE and QA/QC systems.	Project under construction
2007	Liberty Trade Center	Construction failure	The deep excavation carried out with out the installation of anchors, multilevel tiers and top tie up beam. Inappropriate implementation of HSE and QA/QC systems.	Project under construction
2007	Sherpao Plaza	Construction failure	The deep excavation carried out with out the top tie up beam. Inappropriate implementation of HSE and QA/QC systems.	Project abandoned

The geotechnical investigation for the design of deep excavation and shoring in all above projects was based on field testing (SPT - ASTM D1586) and relevant laboratory testing (Natural Moisture Content Deteremination (ASTM D2216), sieve analysis test (ASTM D422), direct shear test (ASTM D3080), unconfined compression test (ASTM D2166), Atterberg limits test (ASTM D4318), etc).

The design and construction failure photographs are shown in Fig. 1(a) & 1(b).

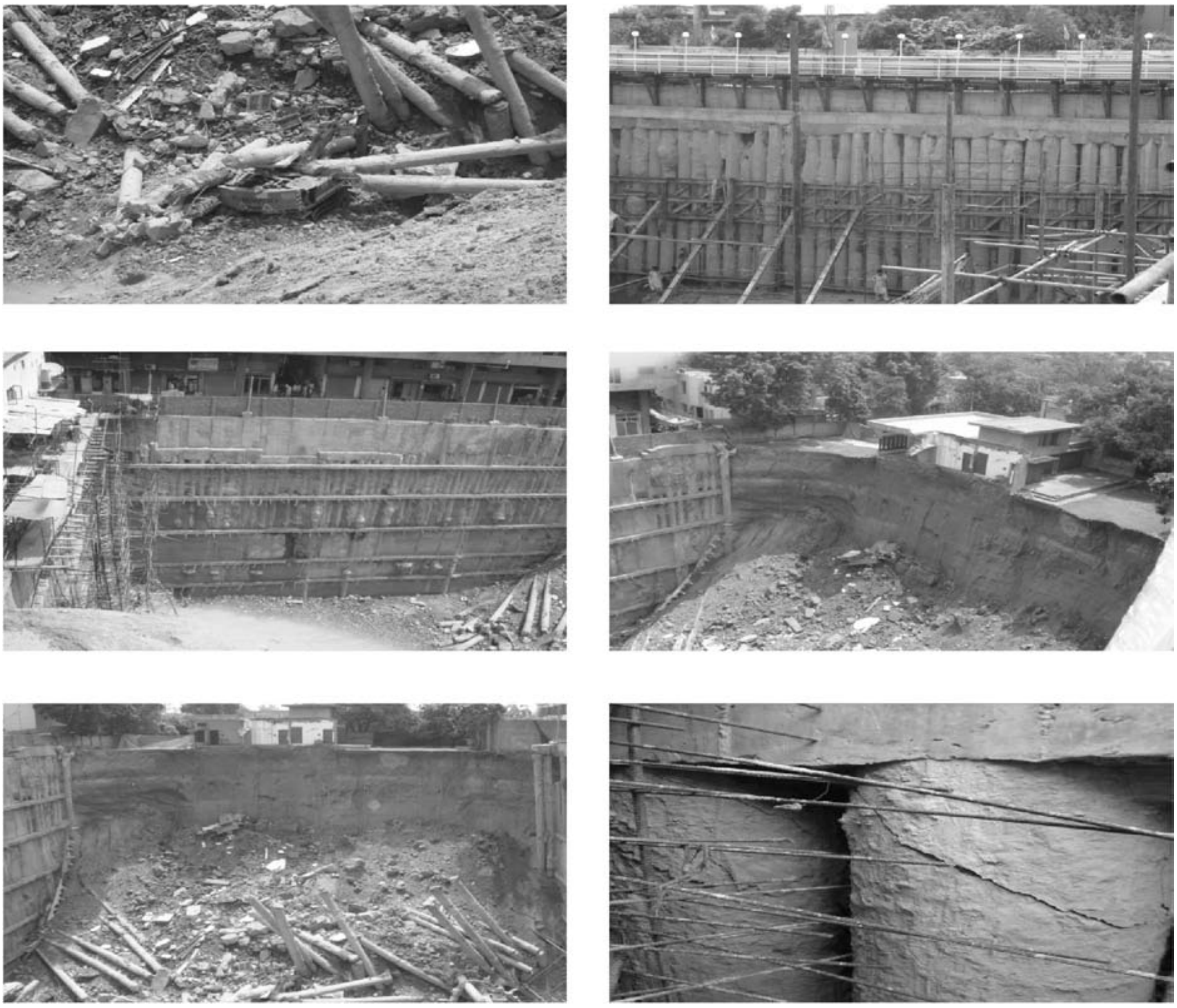

Fig.1(a). Design failure sites.

The major risks taken in the design and construction failure projects are shown in Table 2.

Application of Probability Theory for Deep Excavation

Probability theory is based on engineering mathematics associated with random analysis of variables, processes and events. The human made activities involving quantitative analysis are largely dependent on the concepts of probability theory for its analysis. In geotechnical engineering we mainly encounter such random phenomena for which basic mathematical analysis is not enough to analyze the event or activity; this necessitates the application of probability theory in geotechnical engineering i.e. deep excavations.

The deep excavation comprise of two events i.e. design and construction. The design event comprise of following processes i.e. geotechnical exploration, laboratory testing and report and geotechnical design. The construction event comprise of following processes i.e. anchor piles casting, level 1 excavation, level 1 anchor beam casting and anchor installations, level 2 excavation, level 2 anchor beam casting and anchor installation, level 3 excavation.

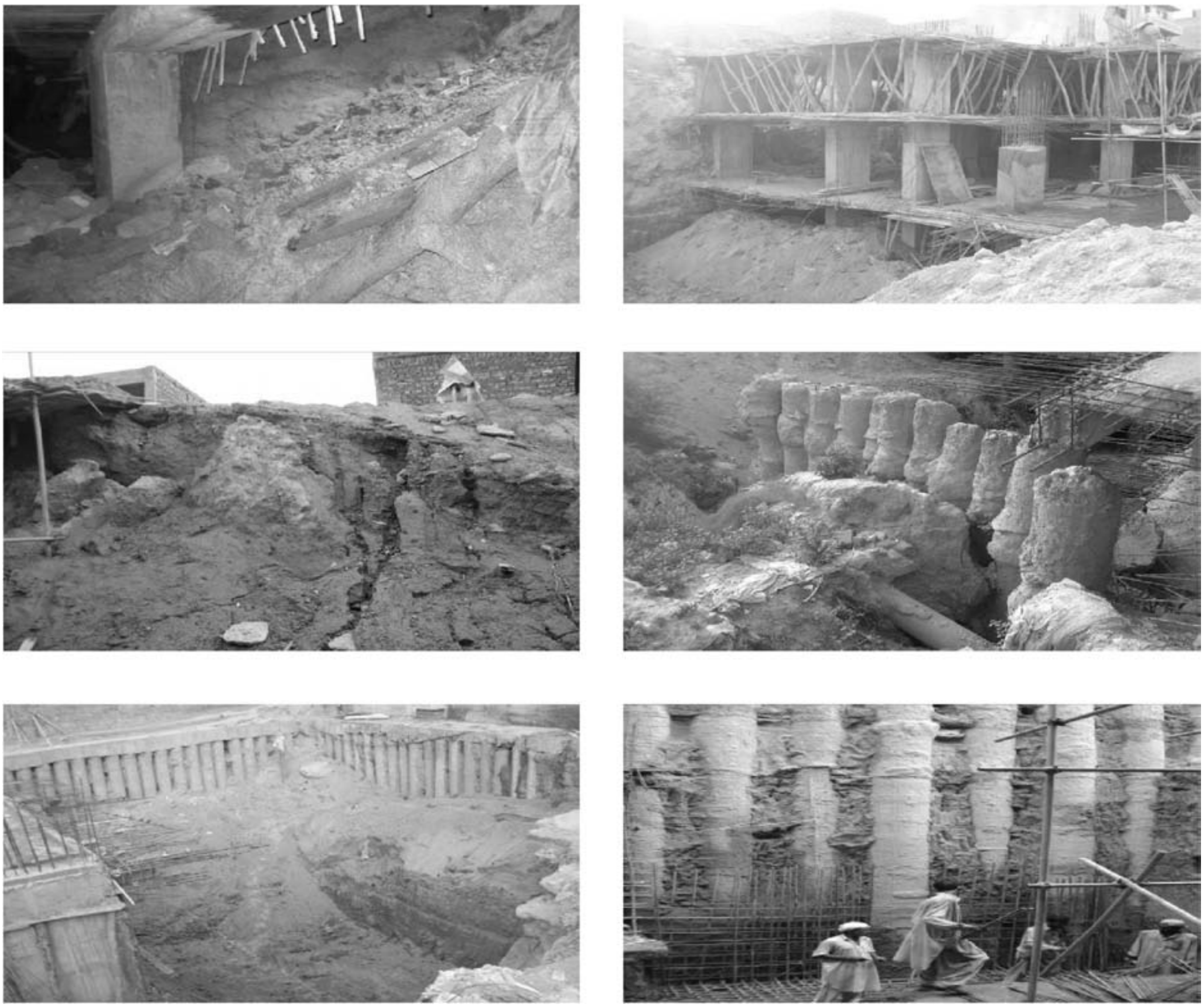

Fig. 1(b). Construction failure sites.

Table 2. Risks identified in the design and construction failure projects.

Phase	Risks Identified
DESIGN	Insufficient geotechnical exploration
	Safety factors in foundation design
	Safety factors in bracing design
	Insufficient technical staff employed
	Bye laws violation
	Credibility & commitment
	Inexperience designer
CONSTRUCTION	Deep excavation with inappropriate or without anchor installation
	Safety
	Health
	Environment
	Loss prevention
	Quality assurance and quality control
	Inexperience contractor
	Financial impacts

The major variables associated in the design process include field testing (SPT), relevant laboratory testing (natural moisture content determination, sieve analysis, Atterberg limits, direct shear test, unconfined compression test etc). The major variables associated in construction process include marking and lay out, excavation manual or mechanical (type of excavator, size of bucket, wheel or chain type, boom length), disposal of excavated material (manual or mechanical (type of truck, capacity of truck, with or without jacking system, need for disposal), drilling for anchor piles (type of machine – straight or reverse rotary, control of caving, steel fixing for reinforcement cage, lowering of cage through crane, concreting – through conventional mixer or batching plant, casting of concrete through conventional trimmy or concrete pump, anchor beams, steel fixing, shuttering and casting, type and size of anchor, bonded and unbonded anchor length, type of chemical for bonding).

The data of success or failure in the projects was collected from client organizations with consent of design consultants purely for research and analysis purpose. The yearly rate of success, design failure and construction failure is represented by figure above. The trend shows that initially the design and construction failure projects rate was high which decreased gradually with the passage of time. The rate of success of design and construction was low initially but it also gradually improved.

The deep excavation as event (E) can happen in “h” (way of success or failure of event) ways out of a total of “n” (possibly equally likely ways of event). In the analysis deep excavation design and construction was taken as two independent events (E* & E^) in each project. The design and construction nomenclature are with superscript of * and ^ respectively.

The probability of occurrence of success and failure in various design events are shown in Table 3(a), 3(b) and 3(c).

Table 3(a). The success and failure probability in geotechnical exploration (SPT, drilling of bore holes, collection of UDS, etc).

Year	E*	h*	n*	p*	q*	p*+q*
2006	5	2	4	0.5	0.5	1
2007	5	2	2.86	0.7	0.3	1
2008	5	2	2.5	0.8	0.2	1
2009	5	2	2	1	0	1

Table 3(b). The success and failure probability in laboratory testing (NMC, UCCT, Sieve Analysis, Atterberg’s Limits, Direct Shear Test, etc).

Year	E*	h*	n*	p*	q*	p*+q*
2006	5	2	3.33	0.6	0.4	1
2007	5	2	2.86	0.7	0.3	1
2008	5	2	2.5	0.8	0.2	1
2009	5	2	2	1	0	1

Table 3(c). The success and failure probability in reporting (report writing, geotechnical design, FOS, etc).

Year	E*	h*	n*	p*	q*	p*+q*
2006	5	2	2.86	0.7	0.3	1
2007	5	2	2.5	0.8	0.2	1
2008	5	2	2.5	0.8	0.2	1
2009	5	2	2	1	0	1

The success and failure probability in various construction events are shown in Table 4(a), 4(b) and 4(c).

Table 4(a). The success and failure probability in anchor piles casting.

Year	E^	h^	n^	p^	q^	p^+q^
2006	5	2	4	0.5	0.5	1
2007	5	2	4	0.5	0.5	1
2008	5	2	3.33	0.6	0.4	1
2009	5	2	2.5	0.8	0.2	1

Table 4(b). The success and failure probability in excavation.

Year	E^	h^	n^	p^	q^	p^+q^
2006	5	2	4	0.5	0.5	1
2007	5	2	4	0.5	0.5	1
2008	5	2	3.33	0.6	0.4	1
2009	5	2	2.5	0.8	0.2	1

Table 4(c). The success and failure probability in anchor installation.

Year	E^	h^	n^	p^	q^	p^+q^
2006	5	2	4	0.5	0.5	1
2007	5	2	2.86	0.7	0.3	1
2008	5	2	2.86	0.7	0.3	1
2009	5	2	2.22	0.9	0.1	1

where,

$$p = \Pr\{E\} = h/n \quad (1)$$

$$q = 1 - \Pr\{E\} \quad (2)$$

p, q are the success and or failure variables of deep excavation design (SPT, various laboratories testing etc) and or construction (drilling, anchoring, shoring, deep excavation etc).

These variables are discrete in nature and are based on various uncertainties and risks discussed above. The deep excavation design and construction events are dependent on each other. Thus using the concept of empirical probability, conditional probability of dependent events and mutually exclusiveness of the events are evaluated as shown in Table 5 and Table 6 below.

Table 5. Conditional probability and mutually exclusiveness of dependent events in the design of deep excavations.

Year	E*	Pr . E*	Pr . F*	Pr . F*/E*	Pr . E*- F*	Pr . E* . Pr . F*/E*	Pr . F* . Pr . F*/E*	Pr . E*+F*
2006	15	0.60	0.40	0.67	0.20	0.400	0.267	1.00
2007	15	0.73	0.27	0.36	0.47	0.267	0.097	1.00
2008	15	0.8	0.2	0.25	0.6	0.200	0.050	1.00
2009	15	1	0	0	1	0	0	1.00

Table 6. Conditional probability and mutually exclusiveness of the dependent events in the construction of deep excavation.

Year	E*	Pr . E*	Pr . F*	Pr . F*/E*	Pr . E*- F*	Pr . E* . Pr . F*/E*	Pr . F* . Pr . F*/E*	Pr . E*+F*
2006	15	0.50	0.50	1.00	0.00	0.500	0.500	1.00
2007	15	0.57	0.43	0.76	0.13	0.433	0.331	1.00
2008	15	0.63	0.37	0.58	0.27	0.367	0.212	1.00
2009	15	0.83	0.17	0.20	0.67	0.167	0.033	1.00

RESULTS

The analysis results reflect that the success in design and construction is showing the invert trend in comparison with failure in design and construction over the passage of time. The trend of the design and construction success of deep excavation is increasingly improved in Lahore. Meanwhile, the trend of the design and construction failure of deep excavation is decreased as shown in Fig. 2(a) and Fig. 2(b).

The analysis results also reflect the improvement trend in the probability of design and construction success of deep excavation practice in Lahore. The increasing difference in the dependency of mutual exclusiveness of the deep excavation events on conditional probability is also recognized as shown in Fig. 3 and Fig. 4.

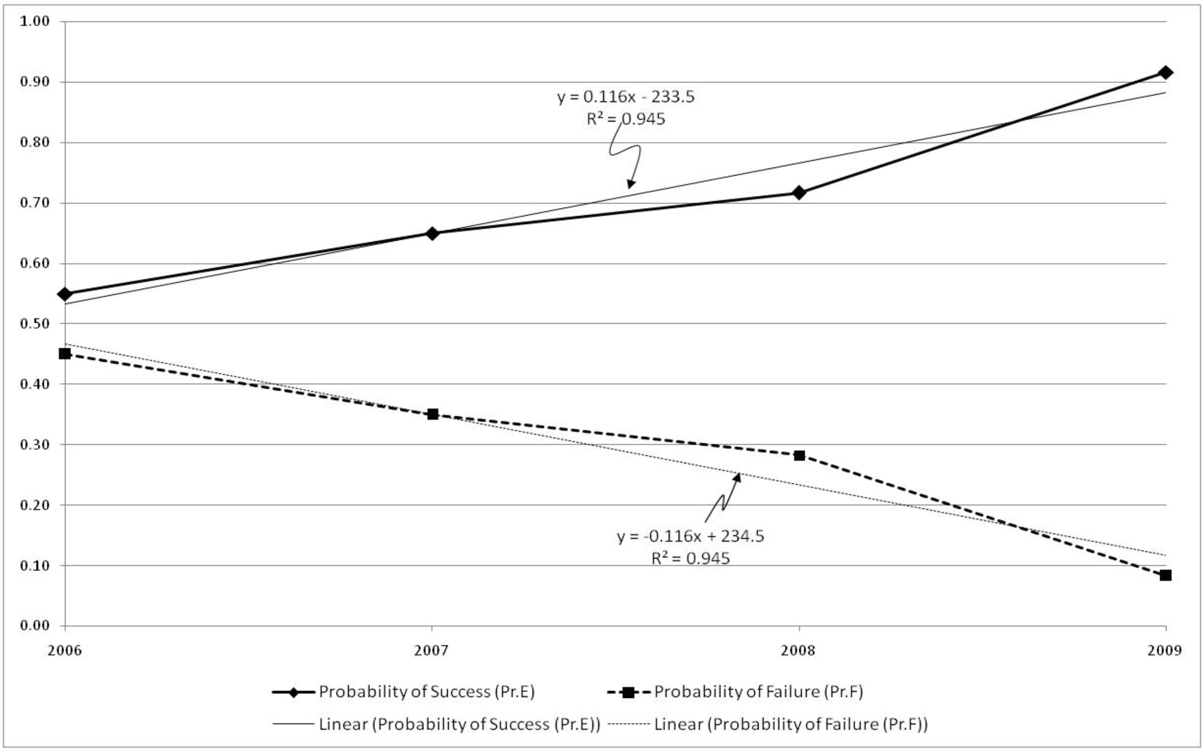

Fig. 2(a). Overall probability of success and failure for projects in Lahore.

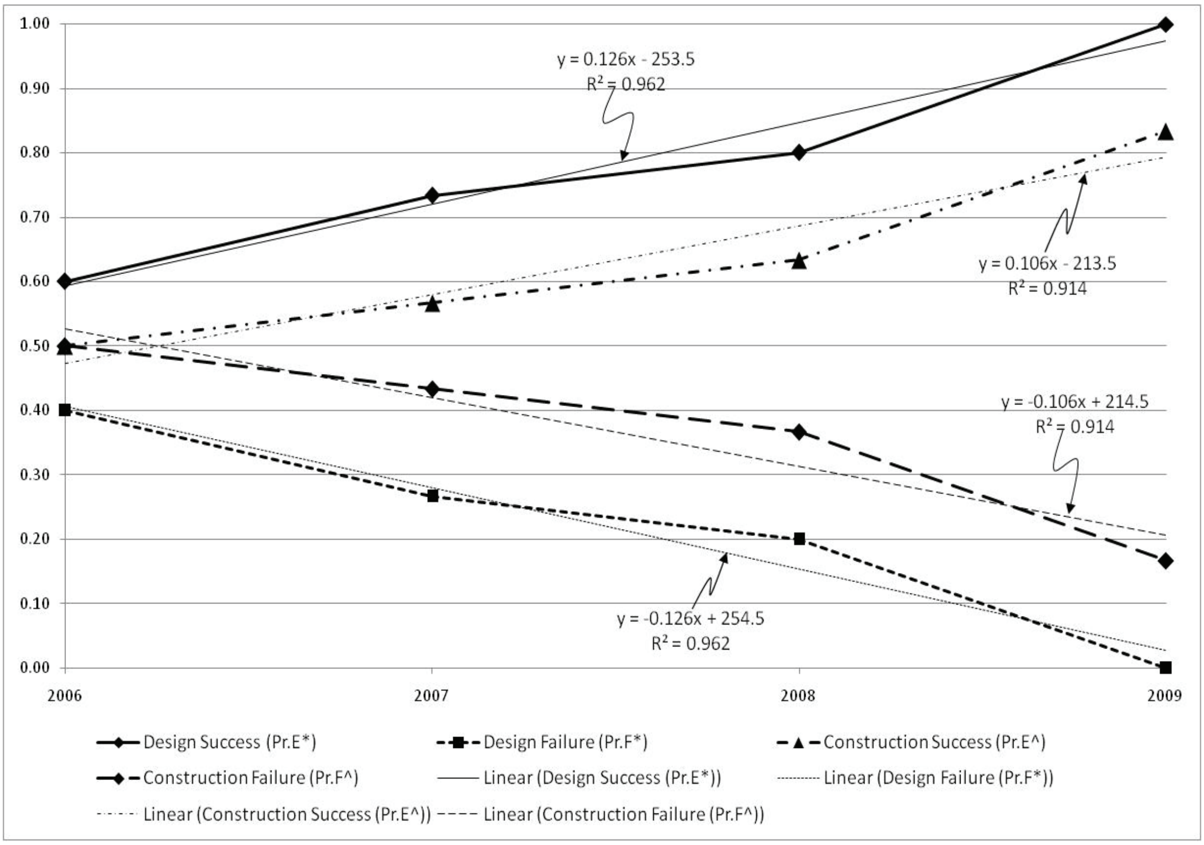

Fig. 2(b). Design/construction success/failure cumulative probability.

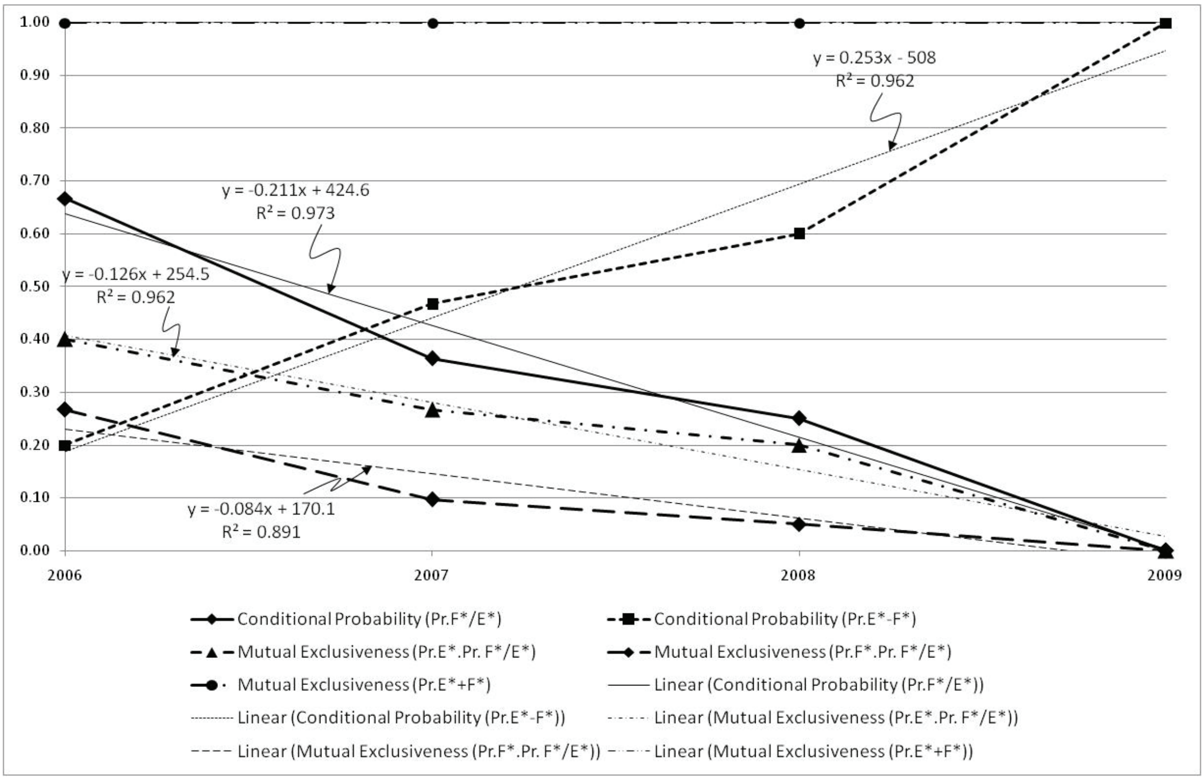

Fig. 3. Design conditional probability along with events mutual exclusiveness.

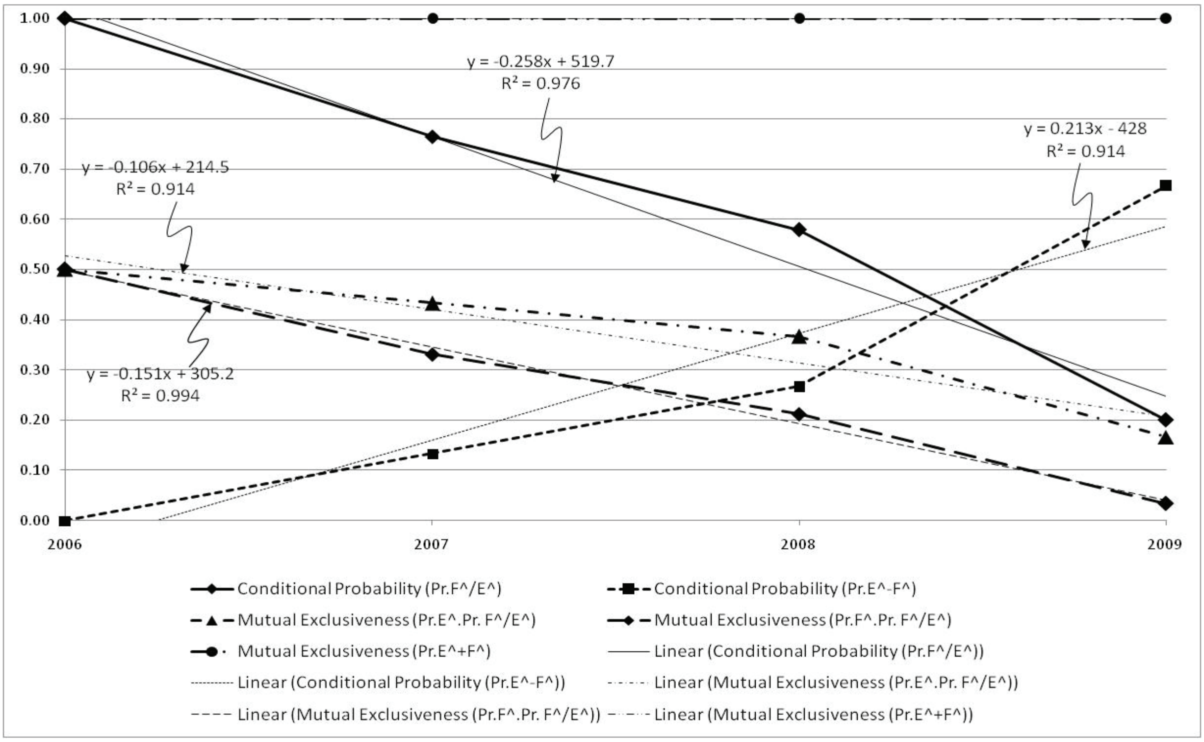

Fig. 4. Construction conditional probability along with events mutual exclusiveness.

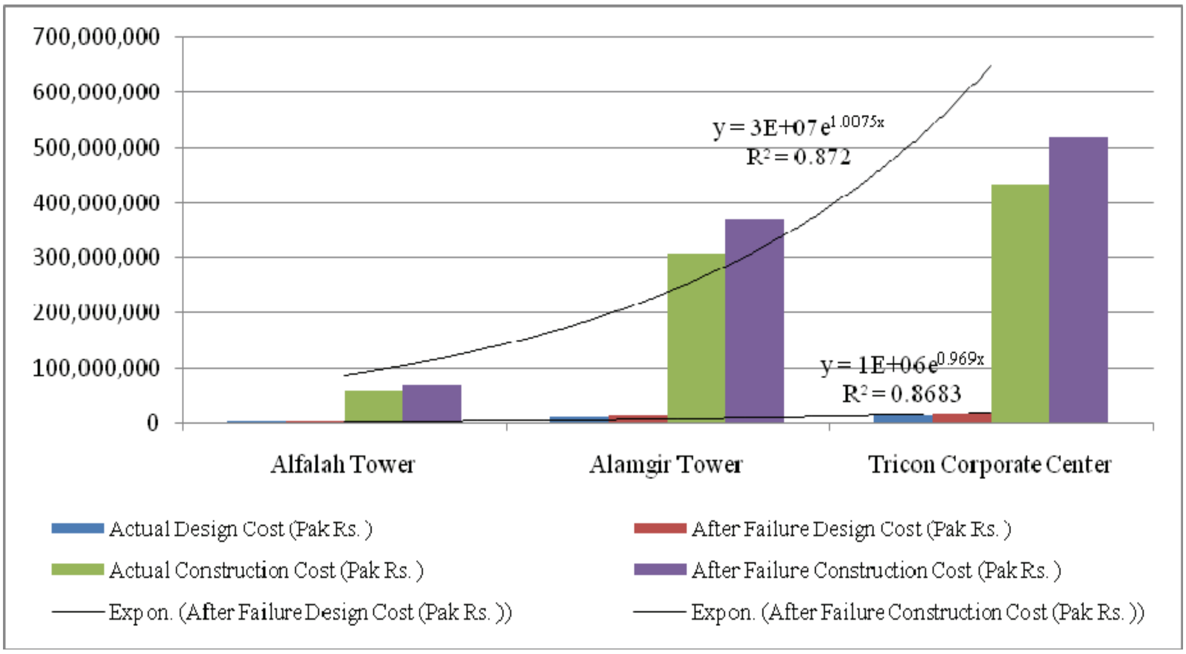

Fig. 5. Comparison of the design and construction cost of the design failure project before and after failure (Source: Project Tender Documents).

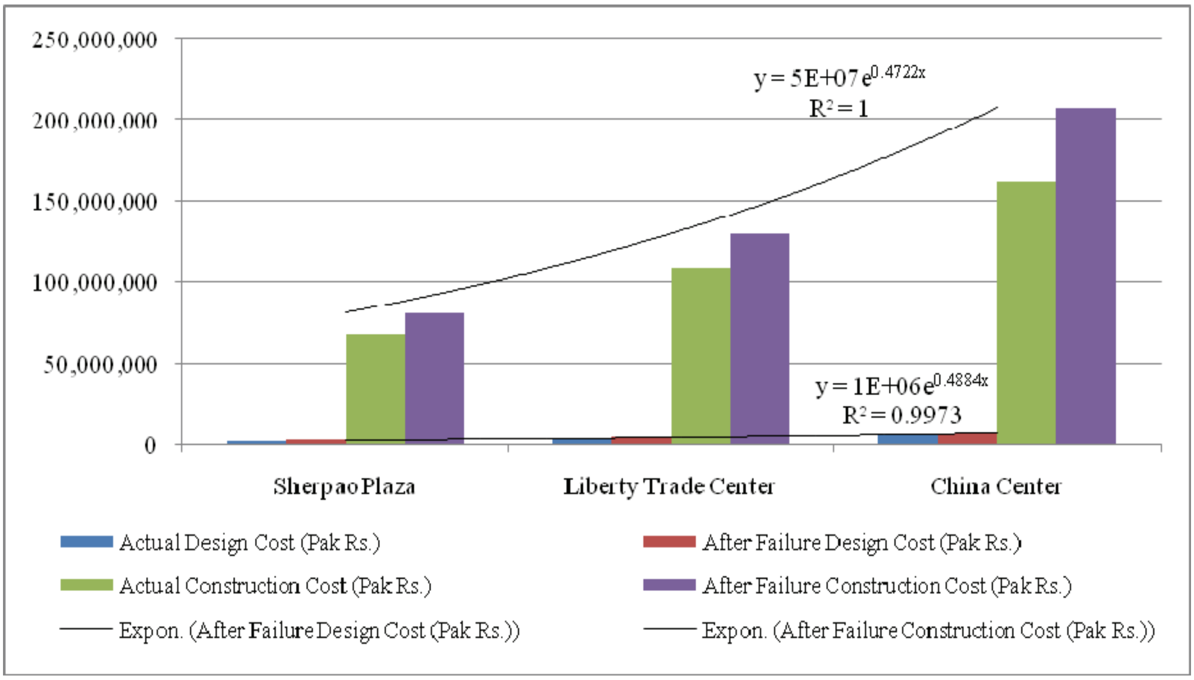

Fig. 6. Comparison of the design and construction cost of the construction failure project before and after failure (Source: Project Tender Documents).

Based on the probability analysis the impact of the uncertainties and risks on the projects are established. This is presented through a cost comparison established between the actual cost of the design and construction project with the cost after failure of the design and construction projects as shown in Fig. 5 & 6.

CONCLUSIONS

The faults observed in huge deep excavation design and construction projects must be carefully analyzed for the benefit of the researchers and engineers, including those responsible for the success/failure so that these defects are taken care of in all ongoing and future similar design and construction projects. The major conclusions based on this research are:

- The historic or surrounding geotechnical data can only be used as reference during feasibility, however before detailed design independent geotechnical investigation should be carried out for the deep excavation project.
- The projects where the reliability in the performance and implementation of conventional geotechnical field investigation and laboratory testing is inappropriate, in such cases the modern field exploration techniques (curtailing the frequency of laboratory testing) i.e flat rigid piston dilatometer(ANDMT), cone penetration test (CPT) or pressuremeter test may be employed.
- The geotechnical design, construction and supervision enterprises previous work experience of similar deep excavation projects should be carefully considered in its selection.
- The organizational structure and project control during the construction is required to delegate the authority and assess the variation in deep excavation project scope, schedule and budget.
- The presence and importance of professional geotechnical engineer in foundation engineering, anchor system, tieback, lagging, deep excavation, geotechnical investigation should not be over ruled.
- The building approval authority should not allow any deep excavation construction until the design of deep excavation is prepared and vetted by a professional geotechnical engineer.
- Risks in geotechnical design and construction at the cost of economy should be curtailed.
- Economy at the cost of quality should not be the ideology in certain functional disciplines of deep excavation projects, i.e., geotechnical; however, it can be achieved in other allied disciplines e.g., architectural.

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