PARAMETRIC SETTLEMENT INVESTIGATION OF MID RISE BUILDINGS UNDER VARYING SOIL PROFILES

Final Year Project 2023

Session: BECE Fall 2019

Project Supervisor: Engr. Shehryar Ahmed

Submitted By

M. Fahad Mehdi

Ghulam Mehr Ali

Usman Fazal

BE Civil Engineering

Abasyn University Islamabad Campus

2023

Certification

This is to certify that **Muhammad Fahad Mehdi (BECE-3194), Ghulam Mehr Ali (BECE-3742)** and **Usman Fazal (BECE-3412)** have successfully completed the final year project **Parametric Settlement Investigation of Mid-Rise Buildings Under Varying Soil Profiles,** at the **Abasyn University Islamabad Campus**, to fulfill the partial requirement of the degree **BE Civil Engineering.**

External Examiner

Engr. Tofeeq Ahmed

[Director & COO, Aryan LLC]

Ahmed

Project Supervisor

Engr. Shehryar Ahmed

[Lecturer]

Head of Department

Dr. Abdul Shakoor

Department of Civil Engineering, Abasyn University Islamabad Campus

Parametric Settlement Investigation of Mid-Rise Buildings Under Varying Soil Profiles

Sustainable Development Goals

Relevant SDG(s) linked with FYDP

SDG No	Description of SDG	SDG No	Description of SDG
SDG 1	No Poverty	SDG 9	Industry, Innovation, and Infrastructure
SDG 2	Zero Hunger	SDG 10	Reduced Inequalities
SDG 3	Good Health and Well Being	SDG 11	Sustainable Cities and Communities
SDG 4	Quality Education	SDG 12	Responsible Consumption and Production
SDG 5	Gender Equality	SDG 13	Climate Change
SDG 6	Clean Water and Sanitation	SDG 14	Life Below Water
SDG 7	Affordable and Clean Energy	SDG 15	Life on Land
SDG 8	Decent Work and Economic Growth	SDG 16	Peace, Justice and Strong Institutions
		SDG 17	Partnerships for the Goals

Range of Complex Problem Solving			
	Attribute	**Complex Problem**	
1	Range of conflicting requirements	Involve wide-ranging or conflicting technical, engineering and other issues.	
2	Depth of analysis required	Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models.	✓
3	Depth of knowledge required	Requires research-based knowledge much of which is at, or informed by, the forefront of the professional discipline and which allows a fundamentals-based, first principles analytical approach.	✓
4	Familiarity of issues	Involve infrequently encountered issues	✓
5	Extent of applicable codes	Are outside problems encompassed by standards and codes of practice for professional engineering.	
6	Extent of stakeholder involvement and level of conflicting requirements	Involve diverse groups of stakeholders with widely varying needs.	
7	Consequences	Have significant consequences in a range of contexts.	✓
8	Interdependence	Are high level problems including many component parts or sub-problems	
Range of Complex Problem Activities			
	Attribute	**Complex Activities**	
1	Range of resources	Involve the use of diverse resources (and for this purpose, resources include people, money, equipment, materials, information and technologies).	✓
2	Level of interaction	Require resolution of significant problems arising from interactions between wide ranging and conflicting technical, engineering or other issues.	✓
3	Innovation	Involve creative use of engineering principles and research-based knowledge in novel ways.	
4	Consequences to society and the environment	Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation.	✓
5	Familiarity	Can extend beyond previous experiences by applying principles-based approaches.	

Abstract

The rapid global urbanization has resulted in a significant increase in the number of mid-rise and high-rise buildings worldwide. This rapid growth is compelling engineers to develop barren land for construction, a process in which the cut and fill phenomena lead to common issues of settlement and liquefaction, causing soil instability and structural failure. The primary objective of this study is to simultaneously analyze the behavior of soil, foundation, and structure while presenting a sustainable approach to mitigate settlement and liquefaction through improvements in foundation and soil stability. The study involved the creation of twenty-four models, each featuring six types of soil profiles paired with various foundation strategies. Static and dynamic analyses were conducted for all 24 models using the 3D modeling tool PLAXIS 3D. he results revealed that extending raft foundations represents an effective and sustainable approach, with an impressive settlement reduction rate of approximately 25% in fine particles and 50% in coarse particles. However, it is important to note that this method may exert increased pressure and load, potentially leading to water expulsion during liquefaction. Consequently, pile-raft foundations exhibited more effective behavior in liquefaction scenarios. The pile raft experienced a minimum amount of liquefaction compared to other foundation types (approximately 40mm during the Kashmir earthquake and 50mm during the Mirpur earthquake). The findings also indicated that soils with coarse particles effectively resist settlement under both static and dynamic loading conditions. The study's analysis of superstructural behavior unveiled an absence of a discernible pattern in the story drift curve and displacement graphs. This phenomenon can be attributed to the soil's inefficiency in transmitting dynamic loads to the superstructure. Importantly, both earthquakes exerted dominant forces in the Y direction. As far as the authors are aware, there have been no prior investigations into the issue of settlement in structures situated on variable slopes and differing soil profiles. Consequently, the primary objective of this study is to conduct an in-depth analysis and provide cost-effective solutions to mitigate structural settlement.

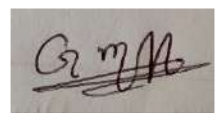
Keywords: Soil settlement, liquefaction, pile raft foundation, structural response, sustainable approach.

Undertaking

I certify that the project **Parametric Settlement Investigation of Mid-Rise Buildings Under Varying Soil Profiles** is our own work. The work has not, in whole or in part, been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/ referred.

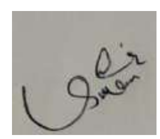
M. Fahad Mehdi

BECE-3194



Ghulam Mehr Ali

BECE-3742



Usman Fazal

BECE-3412

Acknowledgement

We truly acknowledge the cooperation and help made by **Engr. Shehryar Ahmed, Lecturer, Department of Civil Engineering, AUIC.** He has been a constant source of guidance throughout the course of this project. We would also like to thank **Engr. Dr. Zeshan Alam, Managing Director, ZAC Engineers, Islamabad**, for his help and guidance throughout this project.

We are also thankful to our friends and families whose silent support led us to complete our project.

Table of Contents

List of Tables

List of Figures

List of Acronyms

CBD	Central Business District
DEM	Discrete Element Method
DSR	Differential Settlement Ratio
FEM	Finite Element Method
FLAC	Free Lossless Audio Codec
GWT	Ground Water Table
LIR	Load Improvement Ratio
LPI	Liquefaction Capacity Index
RC	Mohr Coulomb model
SPT	Standard Protector Test
SR	Settlement Ratio

Chapter 1

Introduction

Construction in soft soil environments is inherently problematic due to characteristics like weak shear strength, high compressibility, limited permeability, and its malleable consistency (Mohamad et al., 2016). Settlements describe as the soil's downward movement characteristically induced by stress changes due to removal of air and water molecules mostly in filled soil. The total settlement of the ground consists of 3 components: immediate settlement, consolidation settlement and creep settlement. It can cause damage in structures (Coduto, 2001). Settlements come in two main forms: uniform and differential settlement. The mitigation of differential settlement is essential, contingent upon both the specific soil conditions at the construction site and the distribution of loads exerted on the columns that support the building. In contrast, uniform settlement typically poses negligible concerns for a building, but differential settlement has the potential to inflict severe structural damage (Fakharaldin, 2019). Although there may be a scarcity of existing literature in this particular domain, your research endeavors have the potential to fill this void and offer valuable insights to engineers and researchers grappling with challenges related to soil-structure interaction and foundation settlement (Mohamed et al. 2013). Frequently, uncontrolled and excessive settlements can occur over the lifespan of a structure (Lin et al., 2017). Settlement under static loading considered a slow procedure and it may take 10-20 year. However, settlement under dynamic loading have immediate impact on soil. Exiting of water table in upper soil Stata could be more harmful due to liquefaction during earthquake.

Liquefaction occurs when water-saturated, loose granular soils like sands and silts briefly turn liquid-like during earthquake shaking due to increased pore water pressure in the soil particles. In earthquake-prone regions, geotechnical investigations are crucial to ensure the safety and longevity of infrastructure and buildings (Uyanık, 2020). The timing of liquefaction during a seismic event plays a crucial role in determining the performance of structures. Engineers and geotechnical experts take this factor into account when designing buildings and infrastructure in earthquake-prone regions, aiming to enhance their resilience and safety when confronted with ground shaking and liquefaction events (Millen et al., 2020). Analyzing the seismic response of structures situated on liquefiable soil deposits is essential for comprehending and mitigating earthquake-related hazards in areas susceptible to liquefaction. The passage you provided appears to describe a research or investigative endeavor focused on the performance of buildings in Adapazari during the 1999 Kocaeli earthquake, also known as the Izmit earthquake (Millen et al., 2021). The earthquake on February 22nd, although the year isn't mentioned, had a major impact with 181 fatalities and widespread liquefaction and lateral spreading in Christchurch's eastern suburbs and some areas within the central business district (CBD). This description likely relates to the Canterbury earthquake series that began in 2010, accompanied by substantial aftershocks (Cubrinovski et al., 2011). The 2010 decade has been particularly active in terms of destructive earthquakes, i.e., Haiti 2010 (M_w=7.0); Chile 2010 (M_w=8.8), New Zealand 2011 (M_w=6.3) and Japan 2011 (M_w=9.0). The 2010 decade was indeed marked by several significant and destructive earthquakes. Despite advancements in earthquake geotechnical engineering and improved building codes and construction practices, earthquakes continue to cause significant damages and loss of life in seismic-prone regions around the world (Verdugo & González, 2015) As sandy soils age, they become more resistant to liquefaction due to improved grain interlocking and the effects of consolidation and loading history. This increased stability reduces the risk of liquefaction during earthquakes. Engineers and geologists take these factors into account when evaluating soil liquefaction potential in earthquake-prone regions to safeguard structures and infrastructure (Okamura et al., 2019).

Indeed, foundation design involves two essential factors: the soil's ultimate bearing capacity and the acceptable settlement limit for the foundation (Kashap, 2019). Shallow foundations and deep foundations are the two primary categories for foundation systems. Within the category of shallow foundations, the raft foundation, also known as the mat foundation, finds common application in certain soil and load scenarios. These scenarios include instances of high differential settlement in individual spread footings and buildings with significant overturning moments, especially in regions characterized by high seismic activity or featuring complex and irregular superstructures (Hanash et al., 2019). Piles are frequently employed to transmit the load from the superstructure into the subsoil and a strong supporting layer. Lambe and Whitman have underscored that a pile foundation, even when dealing with a single pile, exhibits an exceptionally high level of static indeterminacy (Józefiak et al., 2015; Lambe, T. W., & Whitman, R. V. 1991).

Pile foundations are effective at reducing differential settlement but come 50% higher cost than raft foundations, making them less cost-effective (Hanash et al., 2019). A piled raft, or pile-enhanced raft, blends shallow and deep foundation principles to improve structure performance and cost-efficiency (Guo, W., & Randolph, M. 1999). Piled rafts offer a more balanced and efficient approach to foundation design by combining the load-carrying capabilities of both elements (Shakeel & Ng, 2018).

To the best of authors' knowledge, no study has been conducted to investigate the settlement of structure with variable slopes & soil profiles. Thus, current study is aimed to analyze & recommend economical solutions to avoid settlement of structures.

1.2 Statement of Problem

"Soil filling in land development generally results in weak soil layers that are not feasible to support structures. Such soil conditions require remedies to control settlements which needs huge finances thus, in depth analysis of structure over weak soils is required to reposed economically feasible"

The identified problem targets the **9th Sustainable Development Goa**l for developing **resilient infrastructure** with focus on **economical affordability**.

1.3 Goals/Aims & Objectives

The Overall goal of the research is to look for less expensive measures and strategies to avoid settlement of structure on weak soil.

The specific objectives of this research are

1. To investigate settlement of structure over varying soil layers.
2. To perform liquefaction analysis under extreme seismic excitations.
3. To evaluate structural behavior of building.

1.4 Research Motivation

Population growth leads to urban development at massive scale. Land development requires preparing barren lands with elevations and depression. This creates usually weak grounds that are not suitable for heavy construction.

1.5 Assumption and Dependencies

Scope of work includes analysis of multistory building with different modeling strategies over different soil profile combinations. The static & dynamic analysis will be performed. Results will be evaluated and solution against settlements will be proposed.

This study is limited to

- Only 4 Modeling strategies will be used; a) raft foundation, b) extended raft foundation, c). Pile foundation, d) pile foundation with extended raft as shown in Figure 1.

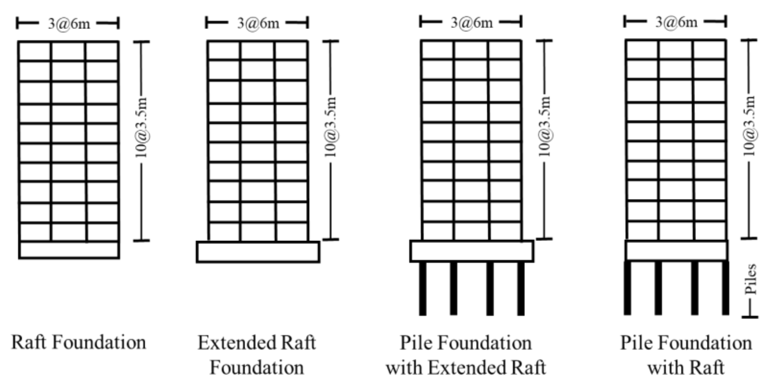


Figure 1: Modeling strategies

- Only 6 soil profiles/combinations will be used as shown in Figure 2.

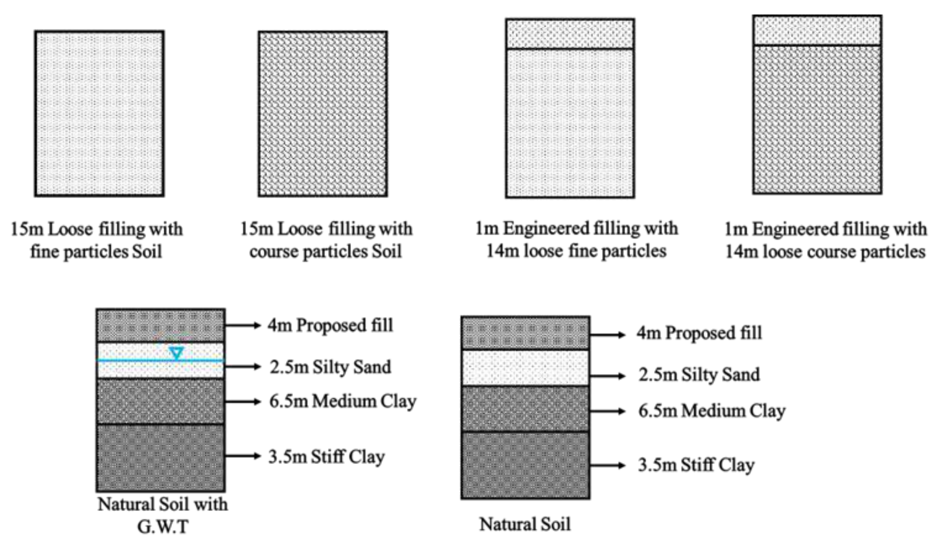


Figure 2: Soil profiles

1.6 Methods

In this research work 24 models have been analyzed. These models consist of 6 type of soil profiles (15m loose filling with fine soil particles, 15m loose filling with course soil particles, 2 m Engineered fill with 13 m fine soil particles, 2m Engineered fill with 13 m course soil particles, Natural soil with various soil layers and Natural soil with water table) underneath the structure. Substructure contained 4 types of foundation (raft foundation, pile foundation, extended raft foundation and pile with extended raft foundation). The superstructure comprises a mid-rise symmetric building with ten stories. The results evaluation includes settlement analysis, liquefaction analysis, and an assessment of the superstructure's behavior under both static and dynamic loading conditions, incorporating liquefaction analysis. Figure 3 shows the methodology.

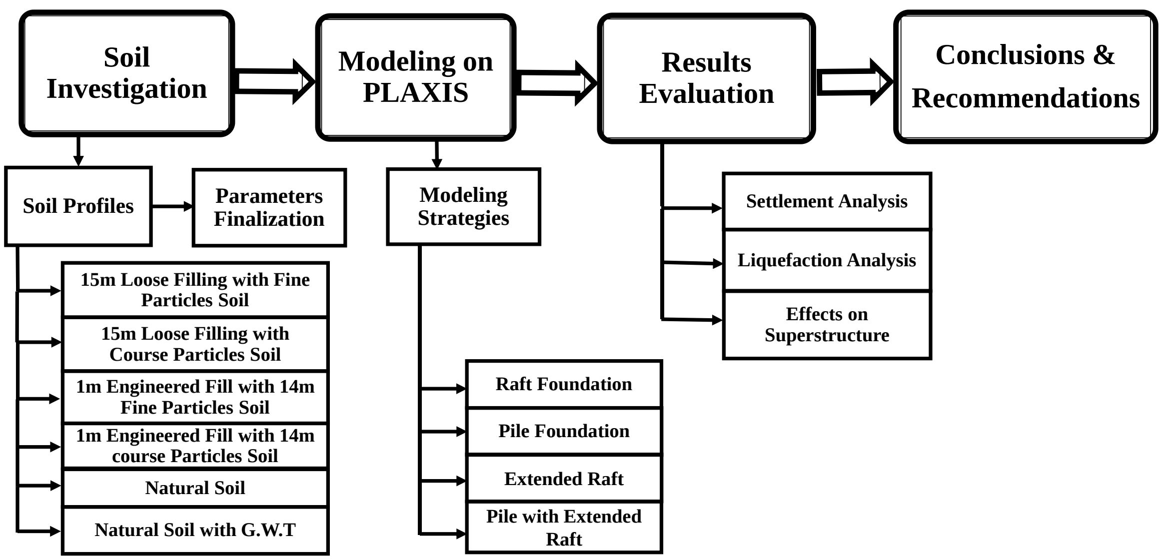


Figure 3: Methodology

1.7 Report Overview

This thesis consists of 5 chapters which are as follows:

Chapter 1 contains introduction, research motivation, problem statement, overall goal specific objective, scope of work and limitation of study, methodology and thesis outlines.

Chapter 2 consists of literature review. It includes background, soil settlement under static and dynamic load, liquefaction of soil due to earthquake and utilization of soil foundation structure interaction for stability of structure and summary

Chapter 3 contains methodology. It consists of parametric investigation of soil samples, modeling strategies and modeling on PLAXIS 3D.

Chapter 4 consists of results extraction from models. It includes settlement analysis, liquefaction analysis and structure behavior.

Chapter 5 includes conclusions & recommendations.

CHAPTER 2

Literature Review

2.1 Background

Soft soil is highly compressible and very weak in shear strength. Static and dynamic structure load causes settlement and chances of structure failure increase. Liquefaction considers more dangerous phenomena and generates sudden settlement during earthquake. Foundation can be classified into two major groups, shallow foundation and deep foundation. Raft foundation is usually utilized where soil and load conditions might lead to high differential settlement for individual spread footings and for buildings with substantial overturning moments in regions of high seismicity or in high irregularity superstructure. Raft foundation use to increase the bearing capacity of soil however when soil is extremely weak to bear the structure load pile foundation provided. Pile foundation cost 50% more than the shallow foundation. In the past few years, there has been an increasing recognition that the use of piles to reduce raft settlements and differential settlements can lead to considerable economy without compromising the safety and performance of the foundation. Pile foundation considered more suitable against the static structure loading and liquefaction.

2.2 Soil Settlement under Static and Dynamic Load

2.2.1 Driving Factors of Soil Settlement

A survey found that structural engineers dominated current design practices, primarily employing traditional methods like the combined stress equation and plate on spring analysis. However, these practices did not yield the most cost-effective results. The survey's findings indicated a need for more fulfilling design outcomes. The results also demonstrated that the plate on pile springs approach, which ignored pile-pile and raft-pile interactions, produced significantly different results compared to 3D FEM analysis. In the 3D FEM model, only 70-80% of building loads were supported by piles, while the raft was positioned in a stiff clay layer. Following the true concept of piled raft foundations could substantially reduce the number of piles needed, with a slight increase in foundation settlement (Amornfa et al., 2012).

When bearing capacity failure is not a concern, it becomes crucial to accurately estimate liquefaction-induced settlement to assess the overall structural performance. Consequently, this paper investigates the dynamic response of shallow foundations on liquefied soils through a comprehensive 3D fully coupled dynamic analysis. The research reveals that the thickness of the soil layer. undergoing liquefaction is a critical parameter. Normalizing with respect to this parameter allows for the elimination of the influence of several other factors. Figure (Gómez-Martínez et al., 2018).

The study's objective is to enhance and validate input parameters for constitutive modeling and enable cost-effective foundation design. To achieve this, a numerical back-analysis was conducted on Eurotheum, a 110-meter-tall building. Thorough measurements have been ongoing from the construction phase to the present. Currently, the observed maximum settlement for EUROTHEUM stands at approximately 3 cm, with ongoing settlement due to consolidation. In contrast, the final settlements calculated using finite element (FE) analysis reach a maximum value of about 5.5 cm (Katzenbach et al., 2005). Figure 4 provides an illustration of the primary factors affecting soil settlement.

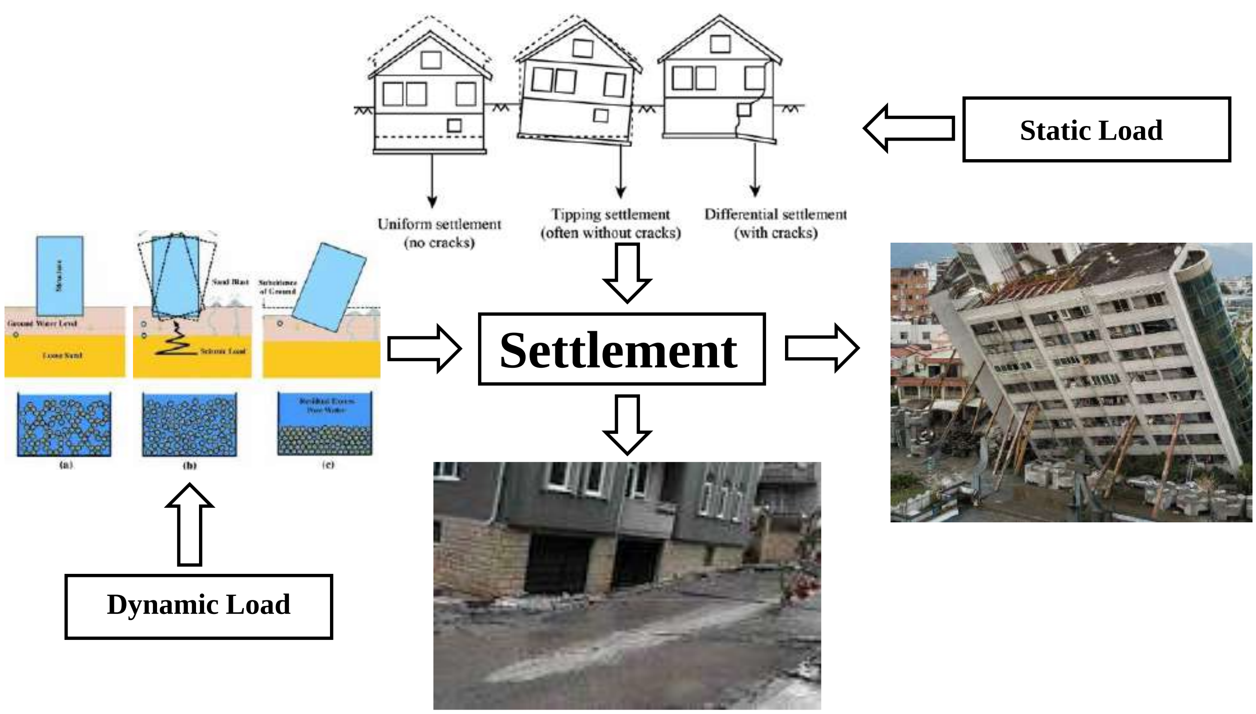


Figure 4: Driving factors of soil settlement

Liquefaction can result in several consequences, including the settlement and tilting of buildings. It can also create flexural demands on structural members due to differential settlement of isolated shallow footings during an earthquake. In this research, we propose representative values for the initial flexural demand of these members caused by differential settlement. These values are determined through simplified modeling of soil and structural variations, coupled with an initial assumption about the distribution of seismic forces. We employ a parametric linear analysis method on a series of planar reinforced concrete frames, and we establish a relationship between the estimated member demand due to differential settlements and the expected demand due to seismic actions at varying intensities. In most instances, our findings suggest that the potential increase in initial member flexural demand due to differential settlements may not be significantly severe when compared to the seismic demand (Gómez-Martínez et al., 2018).

The objective of this study is to connect theoretical and practical aspects when estimating seismic settlements in liquefiable soils with a clay crust. The methodology proposed here provides engineers with a dependable and simplified tool for evaluating potential settlement of strip and rectangle footings during seismic events. Validation against various experimental data sources, including in-situ observations during a significant earthquake event, enhances the methodology's accuracy and suitability for real-world situations (Karamitros et al., 2013).

2.2.2 Structural Vulnerability Due to Settlement

This case study highlights the critical impact of differential settlement on the structural integrity of a 5-storey RC building in Athens, Greece. The absence of tie beams and the soft soil foundation exacerbated the damage, with nearly 70% of the differential settlement occurring before the construction of an adjacent building. The study underscores the importance of proper foundation design, construction quality, and structural maintenance to mitigate such issues. Insights from this case can inform future building practices and help prevent similar incidents in seismic-prone regions like Athens (Anastasopoulos, 2013).

This case study highlights the crucial importance of land governance in the rebuilding of informal settlements after disasters. Through an analysis of two major earthquakes in Haiti and Gujarat, the research underscores the significance of efficient land governance practices in decreasing susceptibility to future calamities. The comparative examination offers valuable understandings and emphasizes key takeaways, including the necessity for reinforcing institutional aspects of land governance and adopting participatory land use planning tools at the local community level. Ultimately, this study adds to the larger discussion on strategies for post-disaster recovery and underscores the pivotal role of land governance in constructing resilient communities (Shrestha et al., 2016).

This summary offers a glimpse into the substantial structural damage caused by the 9-21 Chi-Chi earthquake. It highlights the urgent requirement for enhanced building design practices, specifically emphasizing the inclusion of ductile elements in construction and the avoidance of "soft story" attributes. Additionally, the research encourages the retrofitting of existing structures and the reinforcement of building regulations and public awareness as measures to mitigate future seismic risks. By drawing lessons from past experiences, this overview contributes to the promotion of earthquake preparedness and the strengthening of building resilience in regions prone to seismic activity. Figure 5 displays the extent of building damage during the 9-21 Chi-Chi earthquake (Tsai et al., 2000).

Figure 5: Building damages in 9-21 Chi-Chi earthquake (Tsai et al., 2000)

This research extensively examines the intricacies associated with loess collapsibility and seismic settlement, illuminating the unique mechanisms that trigger these phenomena, even though they share a common metastable microstructure. By drawing attention to both the distinctions and parallels between them, this study enriches our comprehension of these geotechnical hazards and provides valuable guidance for enhancing assessment and mitigation approaches. The results stress the significance of factoring in both collapsibility and seismic settlement when planning and constructing infrastructure in loess regions, ultimately bolstering the resilience and safety of such projects (Yuan & Wang, 2009).

This research offers valuable understanding regarding the successful initiatives to stabilize the foundation of the Leaning Tower of Pisa and its subsequent performance. The noticeable decrease in the rate of northward rotation and induced settlement serves as evidence of the measures' effectiveness. The positive outcomes associated with piezometer measurements and the drainage system underscore the importance of managing groundwater to ensure the structural soundness of historical landmarks. These findings not only play a role in preserving this renowned structure but also provide valuable insights for forthcoming structural engineering projects confronted by comparable difficulties (Burland et al., 2009).

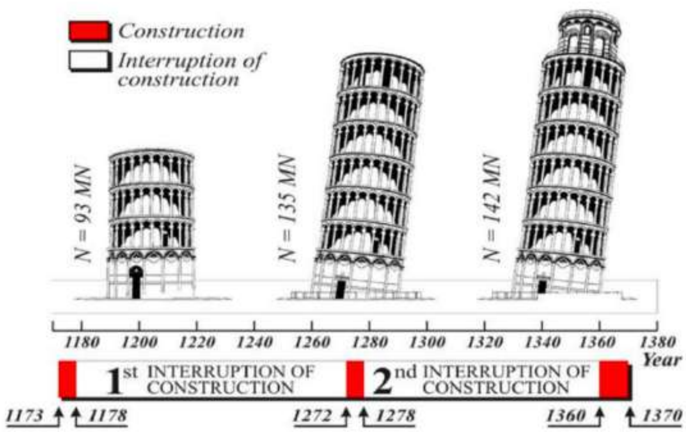


Figure 6: Leaning Tower of Pisa (Burland et al., 2009)

2.2.3 Techniques Used to Avoid Settlement

This paper imparts understanding about the difficulties associated with construction on soft soils in the coastal region of Goa and underscores the significance of employing ground modification techniques. The presented case studies demonstrate the array of soil-related challenges faced, emphasizing the necessity for customized soil modification approaches. The recommendations provided, which cater to both low-rise and high-rise structures, promote secure and sustainable construction practices in this distinctive geotechnical context. The paper also highlights the importance of continual research, monitoring, and environmental considerations in ensuring the enduring performance of structures erected on soft soils in Goa's coastal area (Majik & Savoikar, 2022).

This study highlights the promise of fly ash as a valuable substance for enhancing the load-bearing capacity of weak soils. Through the analysis of different soil types mixed with various proportions of fly ash, the research offers valuable insights into soil stabilization and the management of swelling. The results indicate that fly ash can be a practical solution for construction projects, especially those involving high-rise buildings and infrastructure development, thereby promoting sustainability and cost-effective methods for soil improvement. The study emphasizes the need for continued exploration in this field to advance soil improvement techniques and enhance the performance of structures built on weak soils (Prabakar et al., 2004).

2.3 Liquefaction of Soil Due to Earthquake

2.3.1.1 Structural Collapse During Earthquake

This research brings attention to the significant ground damages caused by liquefaction during the 2010 Chile earthquake, with a specific focus on the seismic vulnerability of tailings dams and the complexities associated with stratified soil layers. The findings highlight the crucial role of proactive measures in disaster prevention and mitigation, especially in regions with a high risk of seismic activity. The study contributes to our understanding of liquefaction hazards and their implications for the safety of infrastructure and the environment. It also emphasizes the ongoing need for research and regulatory actions to strengthen seismic resilience in affected areas, both within Chile and globally. Figure 7 illustrates the occurrence of liquefaction in Muelle Schuster in the city of Valdivia (Verdugo & González, 2015).

Figure 7: Liquefaction in Muelle Schuster at Valdivia city (Verdugo & González, 2015)

In the aftermath of the 2012 Emilia earthquake, an examination was conducted on the impact of liquefaction on structures. This study drew upon data from approximately 1000 personal residential masonry homes across various municipalities affected by the earthquake. The data collection process was led by specialist teams, coordinated by the Italian Department of Civil Safety during the immediate post-earthquake emergency response. The collected data encompassed key details, including the characteristics of the buildings, as well as a comprehensive assessment of the extent and nature of damage to both structural and non-structural components (Di Ludovico et al., 2020).

A recent study assessed the risk of soil liquefaction in Mumbai, a city renowned as India's economic capital and the world's fifth most densely populated metropolis. The study employed a standardized approach, using the Standard Penetration Test (SPT), to evaluate the likelihood of liquefaction across various depths of soil profiles for specific earthquakes with a 2% chance of occurrence within a 50-year timeframe. The assessment covered 142 representative sites within Mumbai, utilizing borehole data from common penetration tests. This research stands as a valuable resource for comprehending and addressing the dangers associated with liquefaction in Mumbai, with a specific focus on areas with reclaimed land. It underscores the imperative role of incorporating geotechnical considerations into urban planning to bolster the city's ability to withstand seismic threats and safeguard its residents and infrastructure (Dixit et al., 2012).

In 2016, a significant earthquake, known as the Meinong Taiwan earthquake with a magnitude of 6.4, struck the southern region of Taiwan. This seismic event resulted in substantial damage, especially in and around Tainan city, including the collapse and severe damage of several buildings, leading to the unfortunate loss of 117 lives. Approximately one month after the earthquake, a five-member team from Learning from Earthquakes (LFE) visited Taiwan with a specific focus on understanding how design practices and seismic mitigation strategies had evolved since the 1999 Chi-Chi earthquake in Taiwan. The LFE team conducted a comprehensive assessment of the earthquake's impact on both buildings and infrastructure, evaluated the response of local authorities, and extracted valuable lessons from their study. Their findings emphasized the critical importance of earthquake-resistant building design and preparedness measures, particularly in regions like Taiwan that are prone to seismic activity. Additionally, there are visual representations of the earthquake's impact, with Figure 2.6 depicting a soft-story collapse resulting from the Meinong Taiwan earthquake, and Figure 8 showing images of the Weiguan building before and after the earthquake, as well as the Xinfu building's condition before the earthquake and the settlement observed in the Xinfu building following the earthquake (Henry et al., 2017).

(a)

(b)

(c)

(d)

Figure 8: Effects of liquefaction; a). Weiguan building before earthquake, b). Weiguan building collapse after earthquake, c). Xinfu building before earthquake & d). settlement in Xinfu building after earthquake (Henry et al., 2017)

The author conducted an experiment analyzing dynamic soil-structure interaction during the 2010-2011 Canterbury earthquake series in Christchurch, where significant damage was attributed to soil liquefaction. They examined well-documented case histories of important structures on fluvial soil with sand and gravel layers. Nonlinear dynamic analyses using FLAC with the PM4 Sand model yielded results aligning with observed responses, recommending this approach to estimate liquefaction-induced building settlement (Luque & Bray, 2020).

2.3.2 Earthquake Leading to Liquefaction

This study focuses on soil liquefaction analysis using two key parameters: cyclic loads induced by earthquakes and soil liquefaction resistance. Its objectives are to determine cyclic load levels, establish a shear resistance ratio based on shear wave speed and earthquake magnitude, and propose a liquefaction assessment method incorporating the shear resistance ratio, cyclic strain ratio, and soil thickness. Testing the method with 315 case records from 22 earthquakes, it demonstrated high reliability in identifying liquefaction potential (100%) and non-liquefaction conditions (66%) but calls for further research in denser soils and deeper deposits to enhance its reliability (Uyanık, 2020).

This study investigates how dry density, initial confining stress, and the degree of liquefaction affect the post-liquefaction shearing behavior of gravelly soil. The results reveal a distinct three-stage stress-strain response pattern post-liquefaction: low strength, extraordinary-linear strength recovery, and sublinear strength recovery. The initial state and previous dynamic stress history notably impact post-liquefaction shearing behavior. Using the Discrete Element Method (DEM), simulations show increased average coordination numbers, oriented contact normals, and reconstructed stress chain backbones during monotonic reloading after liquefaction. These micro-parameter changes reflect the underlying particle interactions across the three macro-mechanical phases of gravelly soil behavior (Wang et al., 2020).

Assessing the impact of earthquake-induced soil liquefaction on structures remains a challenging task in geotechnical earthquake engineering. This research, conducted within the European H2020, delves into this complex issue. It specifically explores the intricate interactions between soil liquefaction and buildings during seismic events. The study underscores the significance of accounting for the presence of structures when evaluating how liquefaction influences the behavior of the soil-structure system. Such insights are invaluable for earthquake engineering and the design of resilient structures in regions prone to seismic activity (Ozcebe et al., 2021).

2.3.3 Remedial Approaches to Mitigate Liquefaction:

The initial section of the paper offers insights into field experiences concerning deep foundations impacted by liquefaction in recent decades. It highlights the primary lessons learned from these encounters. The research paper seems to integrate both theoretical understanding derived from these field experiences and practical insights obtained from physical modeling. Its objective is to tackle the complexities associated with deep foundations and their response to liquefaction during seismic events. This study likely enhances our comprehension of the behavior of deep foundations in liquefiable soils and aids in the formulation of efficient retrofitting strategies to bolster seismic resilience (Abdoun & Dobry, 2002).

This paper conducts an assessment of the lateral response of pile foundations within liquefiable soils, with a focus on seismic conditions. It introduces a pseudo-static analysis method specifically designed for piles situated in liquefiable soil subjected to seismic forces. The study employs three-dimensional (3D) numerical modeling to perform a site response analysis, which helps determine both kinematic loads arising from lateral ground displacements and inertial loads resulting from superstructure vibrations. By comparing numerical results with those obtained from centrifuge tests, the paper concludes that employing p-y curves with varying degradation factors in liquefiable sand yields reasonable outcomes. These p-y curves represent the lateral interaction behavior between soil and piles, serving as a valuable tool for modeling the soil-pile system's behavior during liquefaction (Janalizadeh & Zahmatkesh, 2015).

This study aimed to assess how lateral spreading affects an individual pile located behind a quay wall. To achieve this, a shake-table experiment was conducted on a single pile within a fully saturated sand layer. Before liquefaction, both the soil surface and pile head displacements were minimal. Liquefaction resulted in a significant reduction in soil acceleration. The study calibrated simple methods for analyzing liquefied lateral soil pressure, including uniform and triangular approaches, using experimental data. Subsequently, a Beam on Nonlinear Winkler Foundation model was introduced and compared to the experimental results. The findings demonstrated that the proposed BNWF model provided a more accurate prediction of pile response compared to basic soil pressure methods. To further investigate pile behavior, a parametric study using the BNWF model was conducted. This analysis revealed that greater pile bending stiffness reduces deformation caused by lateral spreading (Su et al., 2016).

2.4 Utilization of Soil Foundation Structure Interaction for Structural Stability

2.4.1 Role of Soil Foundation Structure Interaction in Structures having Shallow Foundation

This paper sheds light on the prevalent problem of ground settlement in construction projects carried out by Malaysia's Public Works Department. This approach is in line with sustainability objectives and offers a potential solution to soil-related challenges in construction endeavors. The study's conclusion reveals that approximately 72% of 252 forensic cases are attributed to ground settlement, while the remaining 28% result from other factors like vibration, erosion, and foundation failures. Furthermore, the research highlights the positive impact of utilizing recycled agricultural waste materials, such as Rice Husk Ash (RHA), in enhancing soil treatment quality and promoting sustainable remediation methods to address these issues (Mohamad et al., 2016).

Engineers often neglect the monitoring of dewatering before excavation in construction projects, which can lead to issues like wall deflection. The conventional monitoring data used in such cases tends to underestimate the environmental impact associated with foundation pit construction. The findings from 35 numerical models reveal that pit deformations experience a rapid initial growth phase in the first few days of dewatering, followed by a continuous decrease in the rate of growth. Moreover, it is observed that wider pits tend to exhibit more pronounced deformations. Interestingly, the research identifies a critical pit width, approximately 40 meters in our study, where pit deformations escalate significantly (with an average increase of approximately 0.03% of Wp). However, when the pit width (Wp) exceeds this critical value, the variations in pit behavior become relatively minor (Zeng et al., 2019).

To ensure a performance-based design remains viable, it's crucial to account for the adverse effects caused by the degradation of shear strength in liquefiable soils. Such degradation can lead to a decline in bearing capacity and the accumulation of seismic settlement in shallow foundations. This study primarily addresses the former effect, focusing specifically on strip and rectangle footings situated above a deep layer of liquefiable soil, with a thinner layer of non-liquefiable clay on top. The research introduces a simplified analytical approach rooted in the composite failure mechanism originally proposed by Meyerhof and Hanna. It also incorporates a reduced friction angle for liquefied sand. Through this analysis, the study identifies a critical thickness for the clay crust, and it's noteworthy that once this threshold is surpassed, subsoil liquefaction no longer significantly impacts the foundation's bearing capacity. Furthermore, the paper underscores the importance of grasping the correlation between the width of the foundation pit and deformations. This understanding proves valuable in optimizing construction practices and proactively addressing potential challenges associated with wall deflection and minimizing the environmental footprint of construction activities (Karamitros et al., 2013).

In the design of various structures, one of the most crucial considerations is the settlement of shallow foundations under earthquake-induced loads and the ensuing consequences. This research delves into this critical issue through a numerical investigation utilizing a 3D dynamic fully coupled u-p analysis. The primary focus is on understanding how different factors impact the settlement of shallow foundations when they are situated on a two-layered soil system. The research outcomes reveal that the presence of a dense layer within the soil can substantially reduce settlement, by as much as 50%, when compared to a uniform liquefiable layer. Consolidating the findings from all the analyses conducted, the study puts forth an equation aimed at estimating the settlement of shallow foundations specifically on subsoils composed of two distinct layers (Ayoubi & Pak, 2017).

In this research, a total of 24 tests were conducted to investigate the settlement behavior of both flexible and rigid raft foundations. These foundations were subjected to varying embedment depths and placed on a substrate of dense sandy soil. The experiments utilized a small-scale building model measuring 200x200mm in dimensions and standing at a height of 320mm. The primary model featured a 10mm reinforced concrete raft foundation with an embedment depth of 23mm for the rigid variant. The testing involved the use of a shaking table technique, with three distinct excitation frequencies—1Hz, 2Hz, and 3Hz—and a displacement amplitude of 13mm. The foundations were positioned at four different embedment depths: 0mm, 50mm (equivalent to 0.25 times the raft side length denoted as 'B'), 100mm (0.5B), and 200mm (B). Importantly, the results revealed that settlement reduction increased gradually with greater embedment depth. For cases where D (embedment depth) equaled B (raft side length), settlement reductions were recorded at

62%, 64%, and 90% for flexible foundations, and 80%, 64%, and 86% for rigid foundations, corresponding to excitation frequencies of 1Hz, 2Hz, and 3Hz, respectively (Hanash et al., 2019).

2.4.2 Settlement Resistance of Pile Foundation

This paper seeks to develop a straightforward and environmentally friendly method for predicting the behavior of large groups of piles. The approach involves using a closed-form equation to estimate the interaction between piles, and this estimation is then applied to predict the performance of extensive pile groups embedded in non-uniform, multi-layered soil media. The outcomes obtained from this contemporary approach are compared extensively with results from previous numerical analyses. The findings demonstrate that the current method for estimating the stiffness of pile groups aligns well with results obtained through rigorous numerical analysis across various layer thickness ratios (H:L) (Guo & Randolph, 1999).

This study investigates how a raft foundation behaves when it is supported by piles designed to reduce settlement. The main objective of this research is to enhance the ultimate bearing capacity, a measure characterized by the load improvement ratio (LIR). Additionally, the study examines the reductions in both average settlement (quantified as the settlement ratio, SR) and differential settlement (represented by the differential settlement ratio, DSR). These experiments are conducted at different slenderness ratios, specifically L/D (length-to-diameter ratio), which are set at values of 20, 30, and 50, respectively. The test results indicate that as the number of settlement-reducing piles increases, the load improvement ratio also increases, and conversely, the differential settlement ratio decreases (El-Garhy et al., 2013).

The analysis found that the greatest settlement happens during excavation when the pile group is placed 0.75 times the excavation depth, even though bending moments are low. Tilting is most significant near the wall but minimal at 0.75 times the depth. Excavation generates excessive negative pore water pressures in the soil. At this depth the settlement is maximum but the bending in piles is minimum so this criterion must keep mind while designing a pile foundation (Shakeel & Ng., 2018).

2.4.3 Pile-Raft Foundation as Sustainable Approach

The purpose of this comparison is to evaluate how the choice of foundation impacts the project's cost. When designing a 200mm thick raft slab for the superstructure, it becomes evident that selecting loose sand with a subgrade reaction of approximately 4800kN/m³ results in structural failure, indicated by excessive deflection exceeding 100mm. Conversely, opting for clay soil with a subgrade reaction of around 12000kN/m³ limits maximum deflection to a mere 4mm. The analysis shows that while a raft foundation constitutes 18% of the total project cost, a pile foundation represents a higher share at 38%. Therefore, from a cost perspective, a pile foundation proves to be an uneconomical choice for this project (Hanash et al., 2019).

S. No	Methodology	Output	References
01	Cost compression between raft and pile foundation for a project.	Raft foundation have 18% of total project cost but in same project pile foundation has 38% cost	Hanash et al., (2019)
02	Cost and suitability of raft and pile foundation for building.	Pile foundation have 54.13% more cost then the raft foundation however pile foundation is safer than raft.	Labidul et al., (2021)
03	Cost compression between raft and pile foundation by quantity and cost estimation.	Pile foundation have 87% cost increment for seismic zone v and 72% cost increment for seismic zone 4 then raft foundation.	(Thiruvengadam et al.)
04	Cost comparison between piled foundation and piled raft foundation by changing configuration of pile-raft.	The cost reduction is 26.56%,49.6% and 41.3% by reducing the number of piles, pile length and raft depth respectively.	(Amornfa et al., 2022)

Table 1: Cost comparison of shallow and deep foundation

This paper delves into the expenses associated with erecting foundations for concrete buildings and aims to determine the most cost-effective foundation type. The building in question has dimensions of 49.25 by 32 feet, and it's situated on soil with a bearing capacity of 3 ksf and a soil settlement allowance of 25 mm. The foundation area covers 1576 square feet and necessitates the installation of 40 piles along with 15 pile caps. Conversely, an alternative approach involves implementing a 2-foot-thick raft foundation at the same location. In this case, each pile foundation comprises a pile cap and one or more piles. Extensive quantity and cost assessments have been conducted for this project. The results clearly indicate a substantial cost disparity of 54.13%, with pile foundations incurring 54.13% more expenses compared to raft foundations (Labidul et al., 2021).

A complex engineering challenge involves modeling a raft foundation as a plate using the Mindlin concept, while representing the soil and piles as Winkler and coupled springs, respectively. The objective is to minimize differential settlement by optimizing the positions of the piles. Employing the Response Surface Method (RQP) implies that this process is iterative, with pile positions adjusted iteratively to achieve the best solution. Such analyses are standard in geotechnical engineering and structural design, ensuring the safety and stability of foundations through meticulous pile placement adjustments (Kim et al., 2001).

In this research, a comprehensive three-dimensional finite element analysis is conducted, employing infinite elements. The primary objectives are to assess the consolidation rate of piled rafts, compute the magnitude of differential deflections, and track the development of associated moments in the raft over time. Based on the obtained results, it is feasible to reasonably predict the settlement of a full-scale structure using this method and anticipate the gradual accumulation of moments over time. Additionally, the study includes a comparison with approximate methods that simplify the piles, soil, and raft as a unified material block, considering equivalent properties for both the individual piles and the soil situated between them (Small & Liu, 2008).

There has been hesitancy in adopting piled rafts on soft clay due to worries about excessive settlement and inadequate bearing capacity. This research delves into the three-dimensional response of a piled raft on soft clay through numerical investigation utilizing a 3D finite element method. The analysis encompasses a model accounting for the interaction between piles and soil.

A range of numerical analyses was executed, varying pile lengths and configurations for a square raft under vertical loading. The findings suggest that strategically positioning a limited number of piles can potentially enhance both the bearing capacity and settlement performance of the raft foundation (Lee et al., 2010).

The mentioned study aims to collect in-depth knowledge about piled raft foundations. To attain this objective, researchers carried out a nonlinear three-dimensional finite element analysis, employing a computational modeling technique that incorporated a pile-soil slip interface model. They systematically investigated a range of factors, including diverse pile placements, quantities of piles, depths of piles beneath the raft, and various types of loading. The aim was to gain enhanced insights into how these variables impact the performance of piled raft foundations. Figure 9 illustrates an eco-friendly approach to piled raft foundations (Cho et al., 2012).

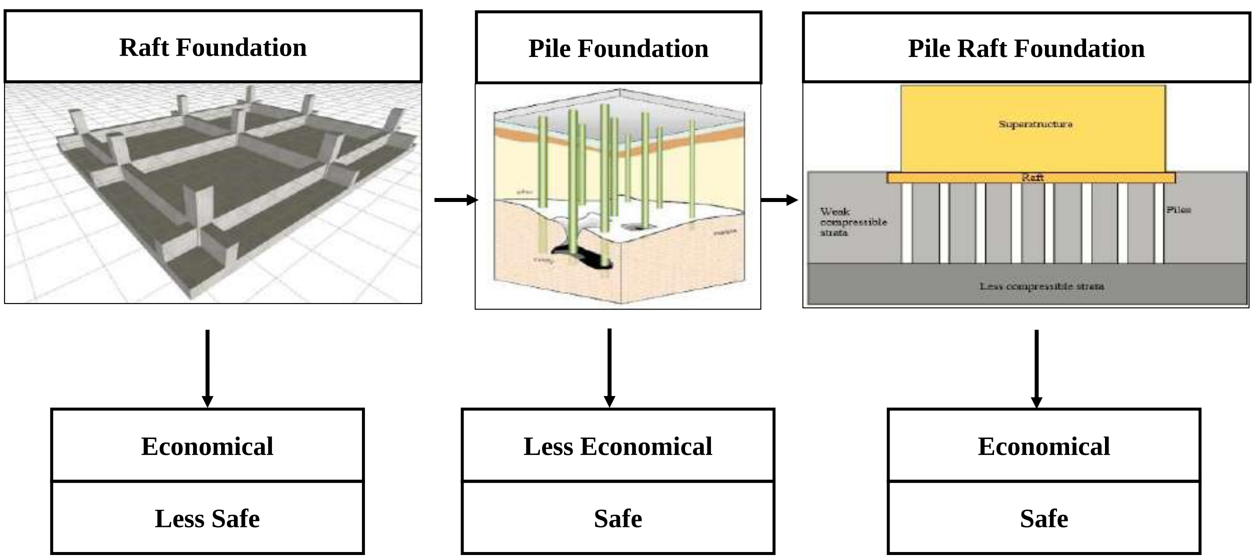


Figure 9: Pile-Raft Foundation as Sustainable Approach

A method was developed to analyze piled-raft foundations under vertical loads while considering interaction effects. It treats the raft as a plate supported by piles and soil. The ultimate pile group capacity is considered in settlement calculations under large vertical loads. Experimental models of 16-pile and 9-pile rafts in silica sand were tested in a centrifuge. Results were compared with the proposed method and PLAXIS 3D, showing good agreement, affirming its potential. The method highlights that within pile capacity, piles dominate piled raft behavior, while beyond capacity, the raft governs (Nguyen et al., (2013).

2.5 Summary

Soft soil considered highly compressible and very weak in shear strength. Static and dynamic structure load causes settlement which increase the probability to fail the building, settlement and soft soil is highly compressible and has very weak shear strength. Both static and dynamic structural loads can induce settlement, increasing the risk of building failure, particularly with respect to settlement and liquefaction. These issues can be mitigated by enhancing soil stability and the foundation system. Foundations are broadly categorized as shallow or deep. Raft foundations are typically employed in scenarios where soil conditions and applied loads may lead to significant differential settlement, especially for individual spread footings and buildings with substantial overturning moments in regions prone to high seismic activity or with irregular superstructures. Raft foundations help improve soil bearing capacity. However, in cases where the soil's strength is extremely insufficient to support structural loads, pile foundations are recommended, albeit at a higher cost. In recent years, there has been a growing recognition that using piles to reduce raft settlements and differential settlements can result in significant cost savings without compromising foundation safety and performance. Pile foundations are particularly effective against static structural loading and in liquefaction-prone areas. Combining both pile and raft foundations can be an efficient approach as it enhances load distribution while addressing settlement and liquefaction concerns

CHAPTER 3

Methodology

3.1 Background

Both static and dynamic structural loads contribute to ground settlement, increasing the risk of building failure. Liquefaction, particularly during earthquakes, exacerbates this issue. Foundations are broadly categorized into shallow and deep foundations. Shallow foundations are employed when the soil near the surface can adequately support the load. However, in regions where soil conditions lead to significant differential settlement, especially for individual spread footings, or in buildings with substantial overturning moments, raft foundations come into play. They are also favored in areas of high seismic activity or where irregular superstructures pose challenges. Raft foundations serve to enhance the soil's bearing capacity, spreading the load over a wider area. Conversely, when the soil is exceptionally weak and cannot bear the structural load sufficiently, deep foundations like pile foundations are utilized. Although pile foundations offer robust support, they come at a higher cost compared to shallow foundations. In recent years, a noteworthy trend has emerged in acknowledging the potential for substantial cost savings by combining piles with raft foundations. This innovative approach effectively mitigates raft settlements and differential settlements without compromising safety or foundation performance. Pile foundations are particularly suitable for countering static structural loads and safeguarding against the detrimental effects of liquefaction.

3.2 PLAXIS 3D Program:

PLAXIS 3D, engrained in the finite element method, is vital for complex geotechnical analyses addressing stability, deformation, and groundwater flow. It's a potent tool for complex engineering problem-solving. It excels in both static and dynamic modeling, utilizing advanced constitutive models to replicate complex soil and rock behaviors. It also simplifies model setup for geotechnical professionals (Al-Taie et al., 2019). The program was used to pretend the experimental work and complex geotechnical problems, find the cause of settlement or slop stability (Gündüz, 2008). It accommodates various boundary conditions, including pore water flow and vertical/horizontal movements. For optimal drainage, the program permits the incorporation of zero lines for excess pore pressure in the design (Montgomery & Karstunen, 2009). The program offers various material models, including Mohr-Coulomb, Linear Isotropic Elasticity, Hardening-Soil, and Soft Clay. The Mohr-Coulomb (MC) model, known for its elastic perfectly plastic behavior, requires defining parameters such as shear strength (c), internal friction angle (ϕ), Poisson's ratio (υ), modulus of elasticity (Es), and angle of dilatancy (ψ) for early deformation assessments (Gündüz, 2008).

3.3 Data Collection

3.3.1 Parametric Investigation of Soil Profiles

In this research presentation, two distinct material models were applied to analyze various soil profiles in the PLAXIS 3D software. PLAXIS 3D is software used for numerical simulation, wherein the interaction between the soil and the foundation structure is examined through three-dimensional finite element analysis. A specific material model designed for soft soils was employed for soil profiles consisting of both soft clay and stiff clay. The study included the determination of the physical parameters required for characterizing both soft and stiff clay soils, which played a key role in the analysis process. Table 3.1 shows the input parameters proposed by (Özhan et al., 2016). A second soil model, following the Mohr-Coulomb model (MC), was employed to analyze loose sand with fine particles, coarse sand, and engineered fill soil. This model was chosen to examine the stress-strain behavior of the soil. The study involved conducting physical parameter analyses for both loose fine sand and coarse soil. Table 3.1 also contain input parameters for both loose fine sand and coarse soil conducted by (Alimohammadi et al., 2013). PLAXIS 3D software required parametric value for cohesion and void ratio which was not presented by (Özhan et al., 2016) and (Alimohammadi et al., 2013). A standard parametric value conducted by (Braja D, 2008) has been use for void ratio and cohesion. Kappa used to stimulate the clavier behavior and input parameters was conducted by (Hassan, 2019). Table 2 shows the input parameters and physical properties for loose fine sand, loose coarse sand, soft clay, stiff clay and engineered filled soil.

Soil Types	Un sat. unit Weight	Sat. unit Weight	Stiffness Factor	Cohesion	Frictional Angle	Dilatancy Angle	Void Ratio	Passion Ratio	Over consoled. Ratio	Keppa	Lambda	-	References
Parameters	γ_{unsat}	γ_{sat}	E_{oed}	C	φ	Ψ	E	V_u	OCR	K_o	λ*	k*	
Unit	KN/m³		KN/m²	Kpa	o	o	-	-	-	-	-	-	
Loose Sand Fine Particles	16	19.4	15000	1	31	1	0.4	0.2	-	-	-	-	Özhan et al., 2016)
Loose Sand Course Particles	19	20.4	60000	1	40.5	10.5	0.35	0.2	-	-	-	-	
Medium Clay	18	18	10000	1	30	0	1	0.15	1	0.5	0.1	0.2	(Alimohammadi et al., 2013)
Stiff Clay	18	18	10000	1	30	0	1	0.15	1	0.5	.035	.007	
Engineered Filled	18.8	21	20000	1	44	22	0.35	0.2	-	-	-	-	(Saygili et al.)

Table 2: Input parameters for soil materials used in the Model

3.3.2 Substructure Input Parameters

The substructure comprises shallow and deep foundations, utilized in various modeling approaches. Shallow foundations include a 0.975 m thick mat foundation with an area of 18 x 18 m^2 for raft models and 19 x 19 m^2 for extended raft models, all sharing the same thickness. In contrast, pile-raft and extended pile-raft combined footings match the area and thickness of the raft foundation. The deep foundation incorporates pile foundations employed in various modeling strategies. Each column incorporates a single pile with a diameter of 0.75 m and a length of 10 m. This pile dimension remains consistent for both combined pile-raft foundations and piles utilized with extended raft models. The specific pile input parameters are detailed in Table 3, sourced from project specifications (AbdelSalam et al., 2011).

Parameters	Soil Types		Unit
	Clay	Sand	
Stiffness (E).	15000	10000	KN/m^2
Pile Length	10	10	Meters
Pile diameter	0.975	0.975	Meters
Skin friction	754	388	Kilonewton
Base resistance	943	485	Kilonewton

Table 3: Input parameters for pile foundation (AbdelSalam et al., 2011)

3.3.3 Superstructure Dimensions

A mid-rise symmetric building is constructed with various types of foundations to accommodate varying soil profiles. The building comprises ten stories, each with a height of 3.5 meters, organized into four grids with 6-meter spacing in both the x and y directions. The structural elements include (600 x 600) mm columns situated at each grid intersection, (300 x 600) mm beams, and a 150 mm thick plate used as the roof slab.

PLAXIS 3D considers the self-dead load of structural members, which is determined based on the unit of concrete. Additionally, external loads have been assigned to the building, following the Building Codes of Pakistan 2007. These loads consist of a dead load of 4.74 KN/m2, a roof dead load of 1.896 KN/m2, a live load of 3.79 KN/m2, and a roof live load of 1.896 KN/m2. These specifications ensure that the building is constructed and analyzed in accordance with the appropriate structural and safety standards The structure also underwent the Kashmir earthquake in 2007 and the Mirpur earthquake in 2019 to study its dynamic response.

3.4 Experimental Work

3.4.1 Procedure of Modeling in PLAXIS 3D

In the numerical simulation, the three-dimensional finite element program PLAXIS 3D is used to analyze the interaction between the soil and the foundation structure. Soil modeling involves creating boreholes to represent various soil profiles with appropriate input parameters and soil models. Furthermore, the modeling process assigns structural elements based on the elastoplastic behavior of concrete. Mesh generation and node selection are crucial for calculations. Stage construction is performed to distribute results gradually, and seismic loading is applied to analyze the behavior of both the soil and the structure under dynamic loads. Figure 10 illustrates the modeling procedure in PLAXIS 3D.

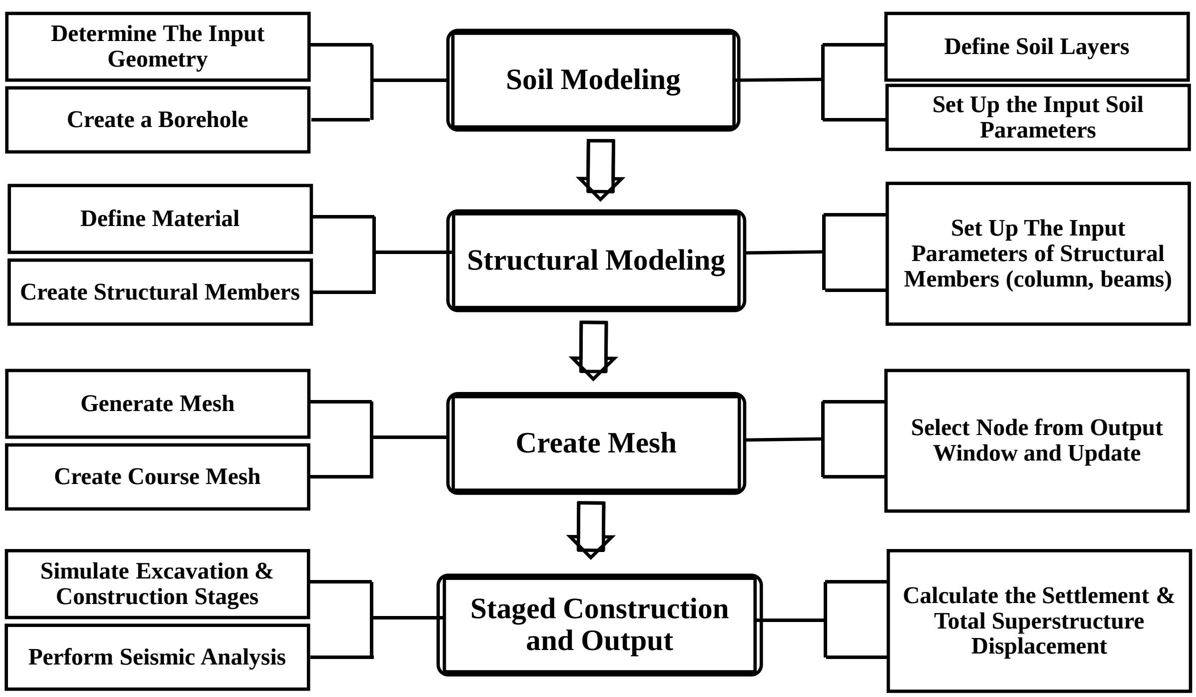


Figure 10: Procedure of modeling in PLAXIS 3D (Hassan, 2019)

3.4.2 Soil Modeling:

The parameters presented in Tables 2 were utilized to create six soil profiles for four different foundation strategies in PLAXIS 3D. The Mohr-Coulomb constitutive model (MC) was selected for analyzing the stress-strain behavior of loose fine sand and loose coarse sand presented in figure 11. The dimension of the loose fine sand soil model is (50 x 50 x 15) meters in the X, Y, and Z directions. Similarly, the second soil profile, containing loose coarse sand, shares the same dimensions of (50 x 50 x 15) meters in the X, Y, and Z directions. Engineered fill soil overlays the third and fourth soil profiles. These third and fourth soil profiles share dimensions of (50 x 50 x 14) meters for both loose fine sand and coarse sand soil models, with an additional (50 x 50 x 1) meter of engineered fill overlay in the X, Y, and Z directions. The last two soil profiles are also considered as part of the study (Donald P Coduto, 2001) The soil profiles consist of both soft and stiff clay, with the soft soil material model simulating more challenging conditions. The natural soil extends (50 x 50) meters in the X and Y directions, comprising 3.5 meters of engineered fill, 2.5 meters of silty sand, 6 meters of medium clay, and 3 meters in the Z direction. In the last soil profile, the groundwater table is situated 6 meters deep within the natural soil. To evaluate liquefaction potential, a comparative analysis is conducted between the natural soil and the natural soil with a groundwater table. Soil boreholes measuring (11 x 11) meters are created and extended in each direction to observe complete contours of soil deformation. Figure 11 shows six soil profiles used in this study.

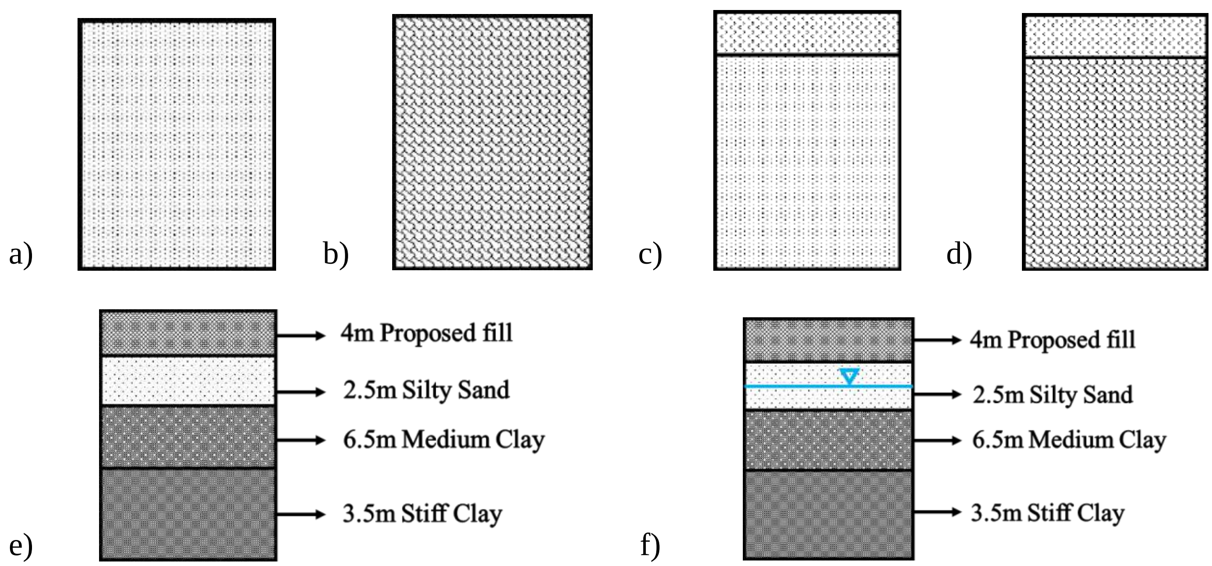


Figure 11: Soil profiles; a). 15 m Loose Filling with Fine Particles, b). 15 m Loose Filling with Course Particles, c). 2m Engr. Filled with 13 m Loose Filling with Fine Particles, d). 2m Engr. Filled with 13 m Loose Filling with Course Particles, e). Natural Soil, f). Natural Soil with GWT

3.4.3 Structural Modeling

In this research, a total of twenty-four models have been developed, integrating six different soil profiles as discussed in section 3.4.2. In the structural modeling, two primary materials are employed: embedded beams for beams and columns (where vertical beams serve as columns) and plates for rafts and slabs. Both materials exhibit an elastoplastic behavior similar to concrete.

A plate assumed to be a raft foundation is being considered as a concrete material, albeit not a standard one. Typically, a raft foundation is a type of foundation that spreads the load from a structure over a large area and is used when the soil is weak. While it might share some similarities with concrete in terms of distribution of loads and support, it's not an actual material in the conventional sense. If you're trying to simulate its behavior, you might approximate its characteristics to those of concrete for modeling purposes, like assuming a similar unit weight and elastic-plastic behavior. This would be an oversimplification, of course, but might serve for certain theoretical or computational analyses.

The plate material set properties are likely detailed, including characteristics such as, yield strength, area and concrete-like elastoplastic behavior. The material properties specific to embedded beams used for beams and columns, ultimate strength, moment of inertia, cross-sectional area and other elements pertinent to their structural behavior. These models are analyzed using four distinct foundation strategies: a) Raft foundation: The first foundation type consists of a (18 x 18 x 0.975) m plate with elastoplastic behavior. b) Pile-raft foundation: The second model involves a (18 x 18 x 0.975) m raft with sixteen 10m-long piles located under each column. c) Extended raft foundation: For this foundation type, the dimensions used are (19 x 19 x 0.975) m, and it can be used either as a separate foundation or in combination with pile-raft foundations. Table 3.2 presents the input parameters for the pile foundation, which were derived from the study conducted by AbdelSalam et al. (2011), and includes relevant base resistance and skin friction values. Figure 12 shows the four modeling strategies use for modeling.

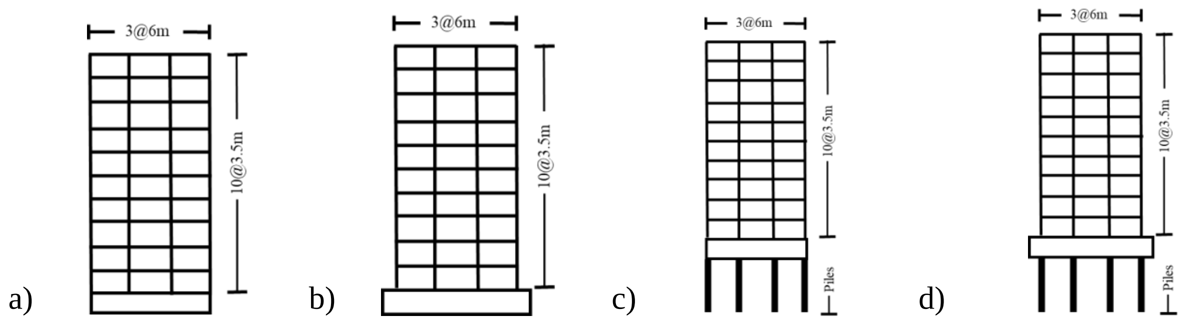


Figure 12: Modeling strategies use for modeling; a) Raft, b) Extended Raft, c) Pile-Raft, d) Pile with Extended Raft

3.4.4 Mesh Generation

A mesh is generated by selecting the 'mesh' option, and then a window appears where we choose a medium mesh for soil and structure degradation. Mesh generation has a very useful option that takes a fine mesh where forces are maximum and considers a coarse mesh where forces are not as significant. After that, an output window opens for choosing three nodes: (0,0,0), (16,16,0), and (16,16,35) for result analysis. Mesh generation and node selection are crucial for calculations.

3.4.5 Staged Modeling & Outputs Extraction

Stage construction is a fundamental aspect of PLAXIS 3D modeling, enabling engineers to break down the complex modeling process into distinct phases. This phased approach is critical for a comprehensive evaluation of results and understanding how a system behaves over time. In a typical PLAXIS 3D model, six phases are employed:

1. Initial Phase: This phase establishes the model's initial conditions, including soil layers and properties, forming the foundation for subsequent phases.
2. Phase 1 - Execution: In this stage, construction activities like excavation, compaction, or ground improvement are simulated to account for changes in the soil due to these activities.
3. Phase 2 - Raft Footing and Walls: This phase focuses on modeling raft footing and underground walls within the excavation area, considering their interactions with the surrounding soil.

4. Phase 3 - Structural Modeling: Structural components such as beams, columns, and slabs are added in this phase, refining the model's geometry and addressing structural interactions.
5. Phase 4 - Load Assignment: Loads, including dead loads, live loads, and other static forces, are assigned to the structure. This phase assesses how the building behaves under these applied loads.
6. Phase 5 - Seismic Response: Phase 5 introduces dynamic effects by applying displacement multipliers to assess the structure's response during seismic events. This phase adds a dynamic aspect to the otherwise static conditions in the earlier phases.

Once these construction stages are defined, the analysis process begins. PLAXIS 3D employs an iterative method to calculate stress distributions at various nodes within the model. The software takes into account soil-structure interactions, boundary conditions, and loading conditions specific to each phase. The results offer valuable insights into how the structure responds to different construction stages and loads.

By dividing the modeling process into phases and systematically analyzing each one, PLAXIS 3D enables engineers to conduct realistic and reliable assessments of a project's performance under a range of conditions. This approach helps in making informed decisions, optimizing designs for safety and stability, and ensuring that the structure can withstand the forces it will encounter during construction and its operational life.

3.5 Dynamic Loading

The devastating seismic event known as the 2005 Kashmir earthquake, or the South Asia earthquake, occurred on October 8, 2005, in the region of Azad Kashmir in Pakistan and parts of Indian-administered Jammu and Kashmir. It registered a magnitude of 7.6 on the Richter scale and had a depth of approximately 10 kilometers (6.2 miles). The epicenter of the earthquake was situated near the town of Muzaffarabad in Pakistan-administered Kashmir. This earthquake is considered one of the worst natural disasters in the history of both Pakistan and the broader Indian subcontinent, resulting in a tragic toll. The earthquake claimed the lives of over 70,000 individuals, left more than 80,000 injured, and rendered more than two million people homeless. Early estimates from the World Bank and the Asian Development Bank indicated that the total cost of reconstructing damaged infrastructure and facilitating rehabilitation efforts exceeded five billion dollars in direct losses.

Results from damage surveys conducted in the Azad Jammu and Kashmir region of Pakistan, specifically in Mirpur, following a moderate earthquake on September 24, 2019, have provided significant insights. The earthquake's epicenter was situated near the city of Mirpur at a depth not exceeding 10 kilometers, considered shallow in seismological terms. A moment magnitude of 6.0 indicates a moderate to strong earthquake on the Richter scale. Earthquakes of this magnitude have the potential to cause significant shaking and damage to structures, particularly if they are located near the epicenter. Notably, ground surface rupture was observed in close proximity to the epicenter, an occurrence attributed to the release of seismic energy at these shallow depths. This observation holds importance in understanding the seismic activity and its impacts within the affected area. The earthquake resulted in several casualties, with reports of both deaths and injuries. Figure 13 shows the data of Kashmir and Mirpur Earthquake.

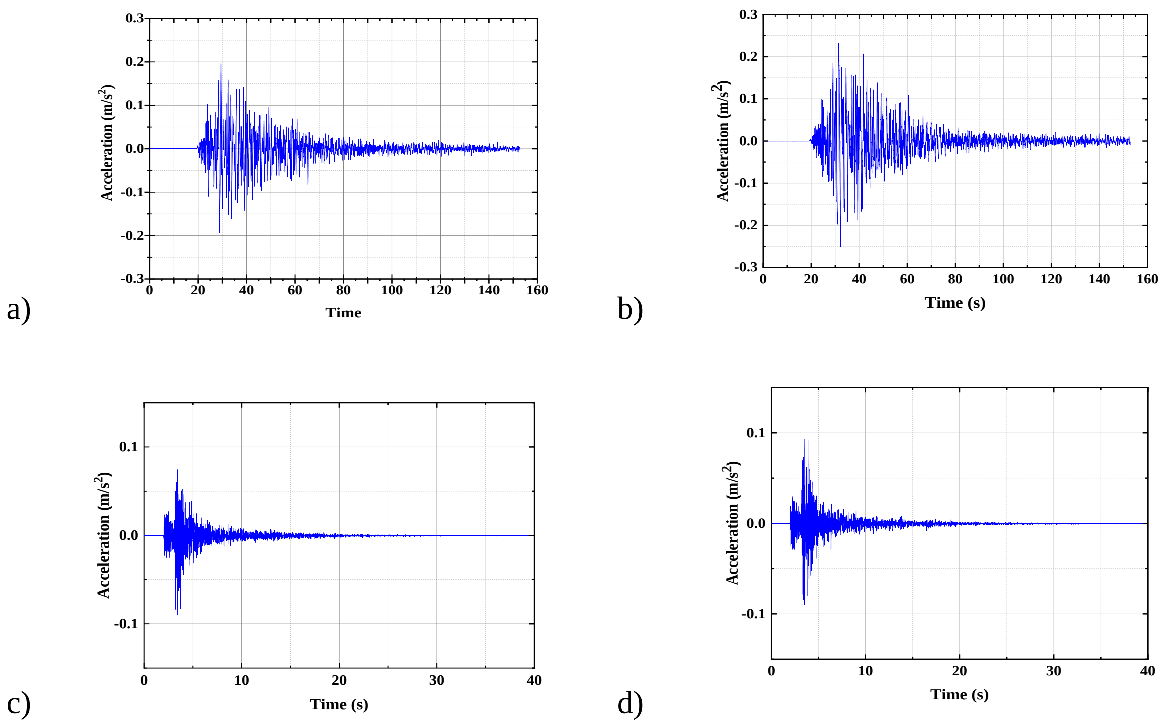


Figure 13: Earthquake Graphs; a). Kashmir earthquake in X direction, b). Kashmir earthquake in Y direction, c). Mirpur earthquake in X direction, d). Mirpur earthquake in Y direction

CHAPTER 4

Results Analysis & Discussions

4.1 Background

In this research work twenty-four models have been model. These models contain of six type of soil profiles (15m loose filling with fine soil particles, 15m loose filling with course soil particles, 2m Engineered fill with 13 m fine soil particles, 2m Engineered fill with 13 m course soil particles, Natural soil with various soil layers and Natural soil with water table) underneath the structure. Substructure contained four types of foundation (raft foundation, pile foundation, extended raft foundation and pile with extended raft foundation). Static and dynamic analysis took place for 24 models. Results based on settlement analysis, liquefaction analysis and structural damages for these twenty-four models.

4.2 Settlement Analysis

This study aimed to investigate the influence of diverse foundation types and soil profiles on settlement outcomes. Predictions were generated for a variety of foundation types, encompassing raft, extended raft, pile-raft, and pile with extended raft. Each of these foundations underwent comprehensive analyses, including static settlement analysis and dynamic analysis, in response to two distinct seismic events (Kashmir and Mirpur) across a spectrum of soil profiles. The primary objective was to compare settlement results for each soil profile and assess their impact on individual foundation types.

Notably, the findings highlighted that the raft foundation demonstrated the highest settlement values, designating it as the least favorable foundation type in terms of settlement performance. This discovery contributes valuable insights for optimizing foundation choices in seismic-prone regions. It underscores the significance of carefully considering both foundation type and soil profile in construction planning, emphasizing the need for tailored approaches to mitigate settlement issues and enhance the overall resilience of structures in earthquake-prone areas. This comprehensive understanding is crucial for informing engineering practices and improving the seismic performance of structures in vulnerable regions. The table 4 shows the settlement of each static and dynamic case.

Soil	Foundation	Settlement (m)			Settlement Reduction (%)		
		Static	Kashmir	Mirpur	Static	Kashmir	Mirpur
15m Loose Soil with Fine Particles	Raft	0.4688	0.9298	1.03	0%	0%	0%
	Extended Raft	0.3464	0.8634	0.9866	5%	7%	4%
	Pile-Raft	0.4614	0.8626	0.9138	1%	7%	11%
	Pile Extended Raft	0.3447	0.7152	0.728	27%	23%	29%
15m Loose Soil with Course Particles	Raft	0.3034	0.486	0.566	0%	0%	0%
	Extended Raft	0.1307	0.312	0.3307	69%	36%	42%
	Pile-Raft	0.1879	0.4432	0.5129	28%	9%	9%
	Pile Extended Raft	0.1278	0.2495	0.2556	70%	49%	55%
2m Engineered Fill & 13m Loose Soil with Fine Particles	Raft	0.4085	0.6939	0.7628	0%	0%	0%
	Extended Raft	0.2696	0.6635	0.6939	34%	4%	9%
	Pile-Raft	0.1971	0.6329	0.721	52%	9%	5%
	Pile Extended Raft	0.2599	0.5656	0.583	36%	18%	24%
2m Engineered Fill & 13m Loose Soil with Course Particles	Raft	0.3296	0.5865	0.6511	0%	0%	0%
	Extended Raft	0.1781	0.4212	0.4315	46%	28%	34%
	Pile-Raft	0.3246	0.5708	0.629	2%	3%	3%
	Pile Extended Raft	0.1704	0.3518	0.3585	48%	40%	45%

Table 4: Settlement results and settlement reduction percentage.

Table 4 shows in the case of 15 meters of loose soil with fine particles, the maximum settlement values for a raft foundation are 0.4688 meters under static loading, 0.9298 meters during the Kashmir earthquake, and 1.03 meters in the Mirpur earthquake, with no settlement reduction observed. Conversely, the pile with an extended raft foundation exhibits more favorable settlement results, with values of 0.3447 meters under static loading, 0.7152 meters during the Kashmir earthquake, and 0.728 meters in the Mirpur earthquake, along with settlement reductions of 27%, 23%, and 29%, respectively. Pile-raft and extended-raft foundations experience moderate settlement occurrences.

Table 4 shows that for the situation involving 15 meters of loose soil with coarse particles, the settlement in a raft foundation reaches extreme values of 0.3034 meters under static loading, 0.486 meters during the Kashmir earthquake, and 0.566 meters in the Mirpur earthquake, with no observed settlement reduction. Conversely, the pile with an extended raft foundation demonstrates the most appropriate results in settlement analysis, with values of 0.1278 meters under static loading, 0.2495 meters during the Kashmir earthquake, and 0.2556 meters in the Mirpur earthquake. These are accompanied by significant settlement reductions of 70%, 49%, and 55%, respectively, for static loading, the Kashmir earthquake, and the Mirpur earthquake. The pile-raft foundation exhibits a lower settlement reduction rate, while the extended-raft foundation also achieves an impressive settlement reduction rate of 69%, 36%, and 42%.

Table 4 shows that in a scenario involving 15 meters of loose soil with fine particles, the settlement in a raft foundation is notably high, reaching values of 0.3296 meters under static loading, 0.5865 meters during the Kashmir earthquake, and 0.6511 meters in the Mirpur earthquake, with no observed settlement reduction. In contrast, the pile with an extended raft foundation demonstrates the most favorable settlement results, registering values of 0.2599 meters under static loading, 0.5656 meters during the Kashmir earthquake, and 0.583 meters in the Mirpur earthquake. These results come with settlement reductions of 36%, 18%, and 24%, respectively, for static loading, the Kashmir earthquake, and the Mirpur earthquake. When assessing the results for a scenario with 2 meters of engineered fill and 13 meters of loose soil with fine particles, a notable difference becomes evident between the pile-raft and extended-raft foundations. Specifically, the pile-raft foundation displays a more efficient static settlement reduction rate of 52%, surpassing the extended-raft and pile with extended raft foundations.

Table 4 presents the corresponding results for the scenario involving 2 meters of engineered fill and 13 meters of loose soil with coarse particles. In this context, settlement in a raft foundation reaches extreme values of 0.4085 meters under static loading, 0.6939 meters during the Kashmir earthquake, and 0.7628 meters in the Mirpur earthquake, with no observed settlement reduction. Conversely, the pile with an extended raft foundation exhibits the most suitable results in settlement analysis, registering values of 0.2599 meters under static loading, 0.5656 meters during the Kashmir earthquake, and 0.583 meters in the Mirpur earthquake. These results are accompanied by settlement reductions of 47%, 40%, and 45%, respectively, for static loading, the Kashmir earthquake, and the Mirpur earthquake. Pile-raft and extended-raft foundations display moderate settlement amounts in this situation.

The analysis of the data presented in Table 4 unravels a compelling pattern in foundation performance. Raft foundations consistently exhibit notably higher settlement values compared to other foundation types. However, among the considered alternatives, the pile-raft foundation emerges as a more effective solution for mitigating settlement issues than the conventional raft foundation. While an improvement, the pile-raft foundation doesn't quite reach the superior performance level exhibited by the extended raft and pile with extended raft options.

The standout performer in this analysis is undeniably the pile with an extended raft foundation. This foundation type consistently demonstrates the most favorable settlement outcomes across a diverse array of soil profiles. Its remarkable ability to minimize settlement to the greatest extent in every scenario underscores its suitability for maintaining structural stability and integrity in various soil conditions. This finding suggests that, when contemplating foundation options, serious consideration should be given to the pile with an extended raft foundation, particularly in areas prone to settlement concerns or where maintaining structural integrity is of paramount importance. This insight contributes valuable information for informed decision-making in construction practices, emphasizing the need for tailored foundation choices based on specific site conditions.

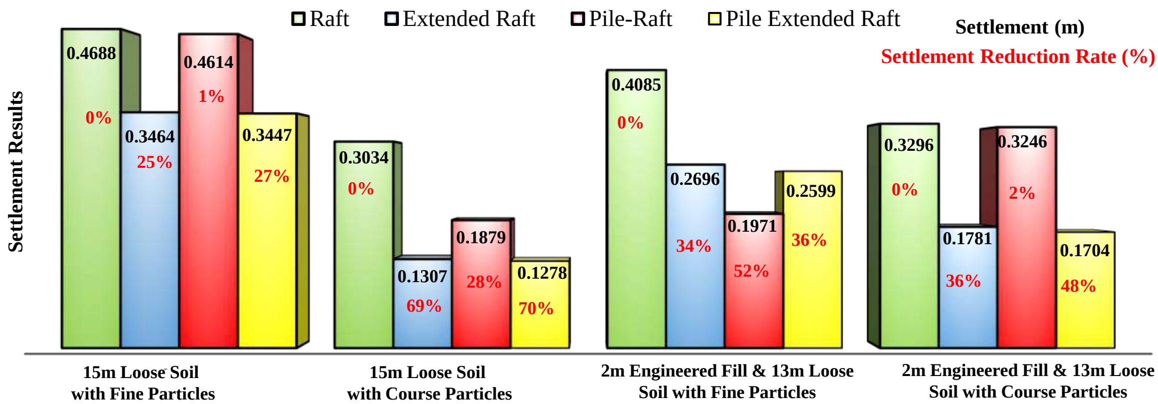


Figure 14: Settlement analysis under static loading

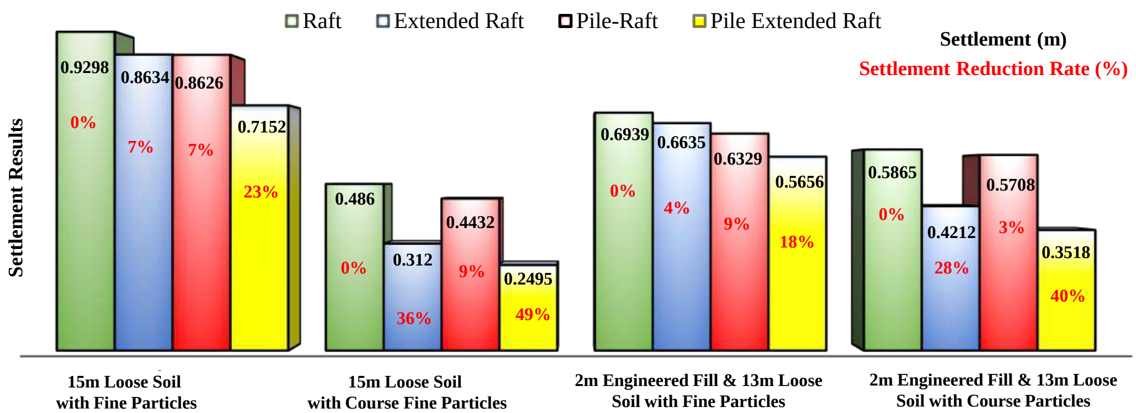


Figure 15: Settlement analysis under dynamic loading Kashmir earthquake

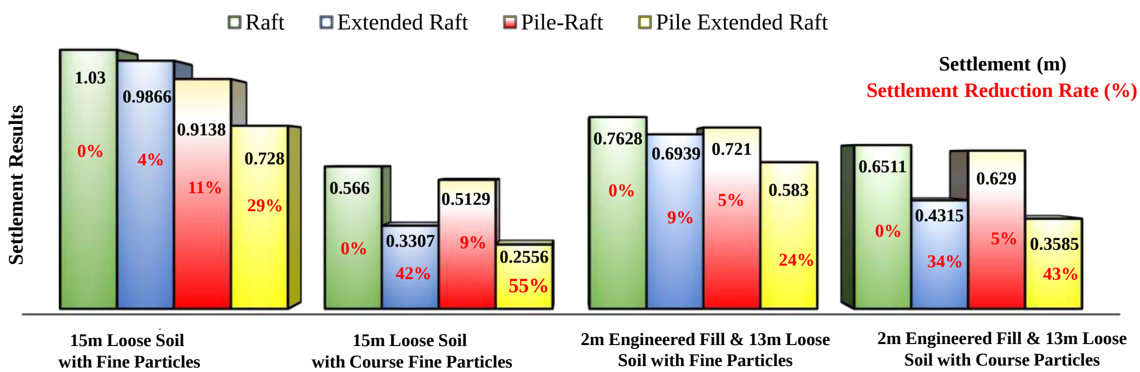


Figure 16: Settlement analysis under dynamic loading Mirpur earthquake

Figure 14 shows settlement variations in different soil combinations alongside various foundation types under static loading. This comparison reveals that coarse particles significantly enhance the soil's bearing capacity. Settlement analysis under static loading yields the most favorable results for soil containing coarse particles. Additionally, a 2-meter overlay of engineered fill soil increases the soil's bearing capacity and stability, making it better suited for supporting heavy structures. Soil with coarse particles exhibits a larger Dilatancy angle, providing greater stability. Coarse particle soil has a stiffness factor of 60,000 KN/m^2, which is higher than that of fine particles (15,000 KN/m^2) and engineered fill soil (20,000 KN/m^2). Consequently, it performs better compared to fine soil and engineered fill soil. When comparing foundation types under static loads, Figure 14 highlights that the pile with an extended raft foundation has the most significant impact on reducing settlement. While pile-raft and raft foundations aim to improve soil bearing capacity under heavy structures, an extension in the raft yields better results than both the raft and pile-raft.

Figure 15 demonstrates the settlement differences among various soil profiles and foundation types during the Kashmir earthquake of 2005. Based on the results, coarse particles contribute to enhancing the soil's bearing capacity. Settlement analysis, particularly under static loading, yields the most appropriate outcomes for soil containing coarse particles. The stiffness factor is a crucial element in soil with coarse particles, enabling it to effectively dampen earthquake vibrations when subjected to heavy structural loads. Pile with extended raft foundations demonstrates the most favorable results in cohesive soil under Kashmir earthquake conditions. However, it's worth noting that the behavior of different foundations on fine soil doesn't exhibit significant variations, which should be taken into consideration.

In Figure 16, the settlement disparities among different soil combinations and foundation types during the Mirpur earthquake of 2019 are evident. Notably, coarse particles, even under dynamic loading conditions, provide the most suitable results for soil stability. Additionally, the introduction of 2 meters of engineered fill soil enhances the soil's bearing capacity and overall stability, making it better equipped to support heavy structures. The results also highlight that the influence of dynamic loading on soil with fine particles exhibits only minimal variations across various foundation types.

4.3 Settlement Contours:

Contours are a representation of the quality of an outline or the characteristics of a bounding surface, indicating whether it is smooth, jagged, curving, or sharply angled. In the context of settlement analysis, settlement contours serve as outlines where lines with similar characteristics signify consistent settlement effects within soil layers. These contours are invaluable for discerning variations in load transfer throughout different soil profiles. The configuration of settlement contours relies on several factors, including soil type, load distribution, load modes (static or dynamic), and foundation type. Settlement contours also play a pivotal role in identifying critical points within both the foundation and the soil. Furthermore, contours are instrumental in distinguishing between differential settlement (varying settlement across the foundation) and uniform settlement (consistent settlement across the foundation).

4.3.1 Under Static Loading

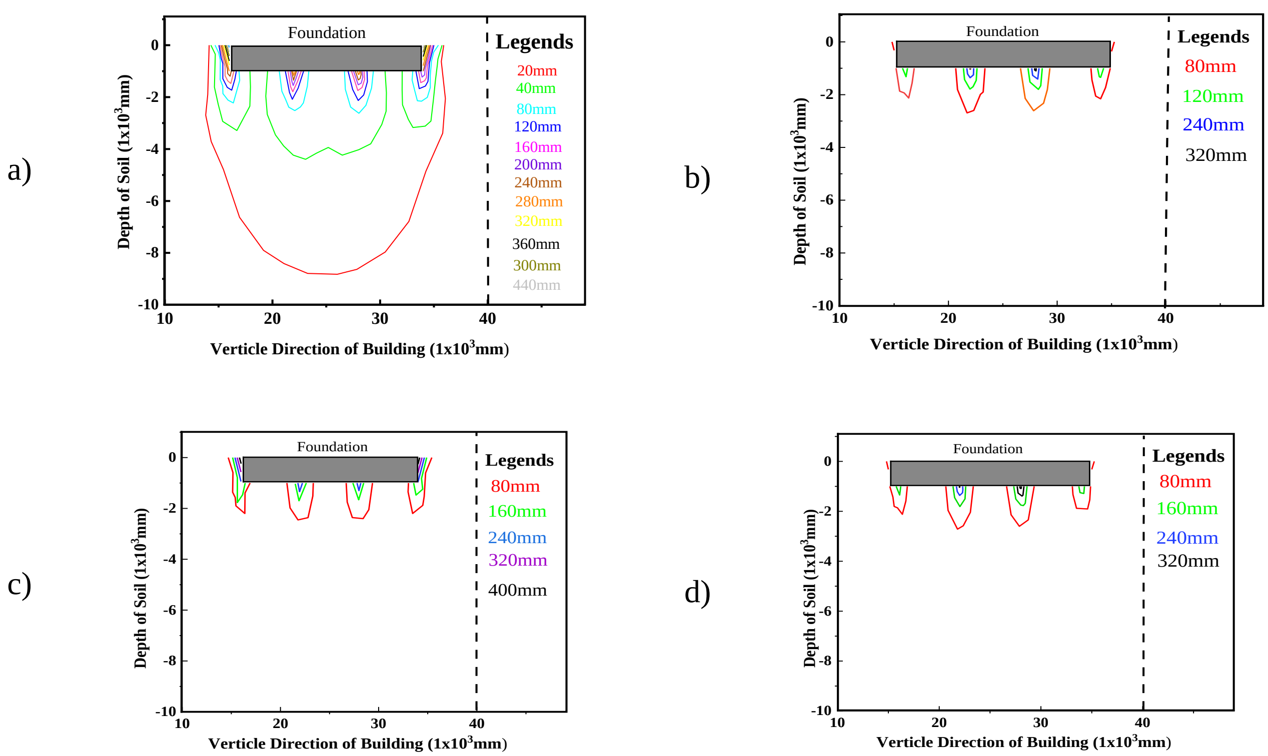


Figure 17: Static Settlement in 15m loose soil with fine particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft

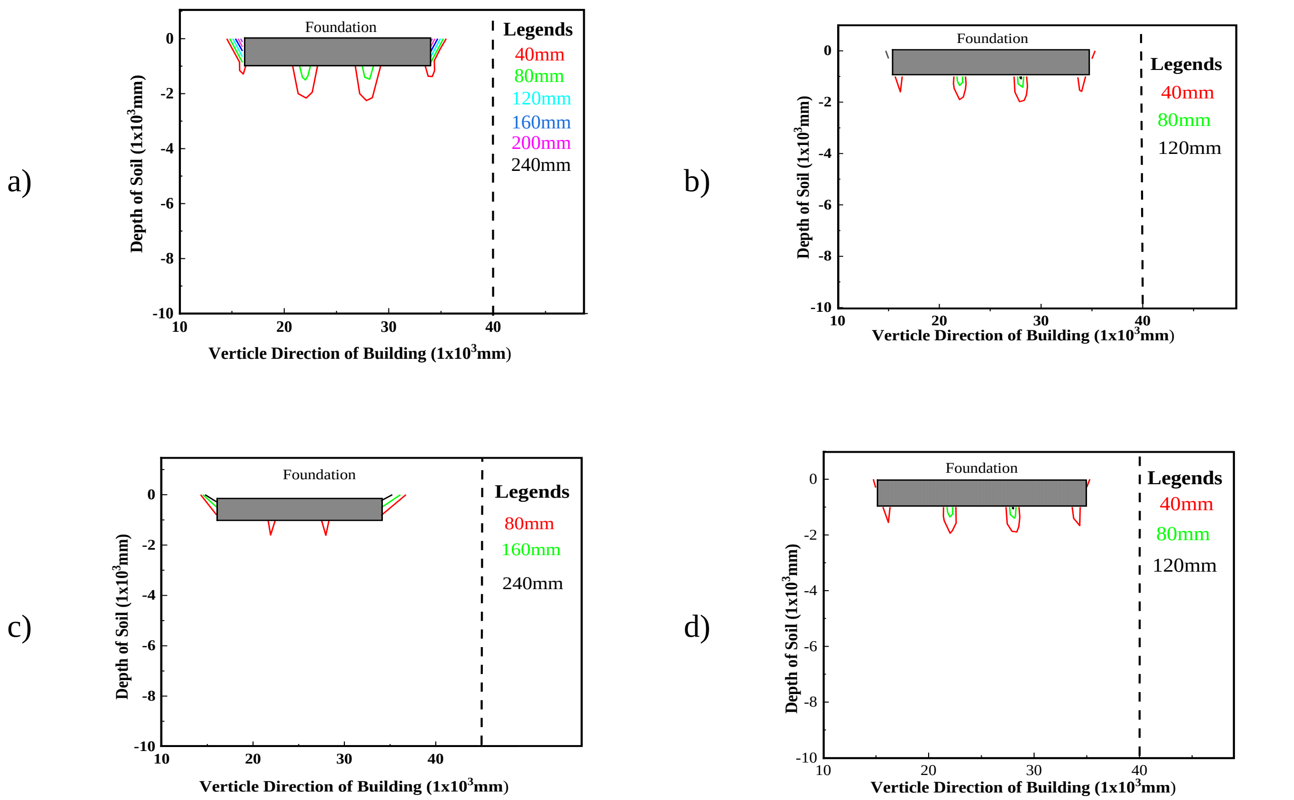
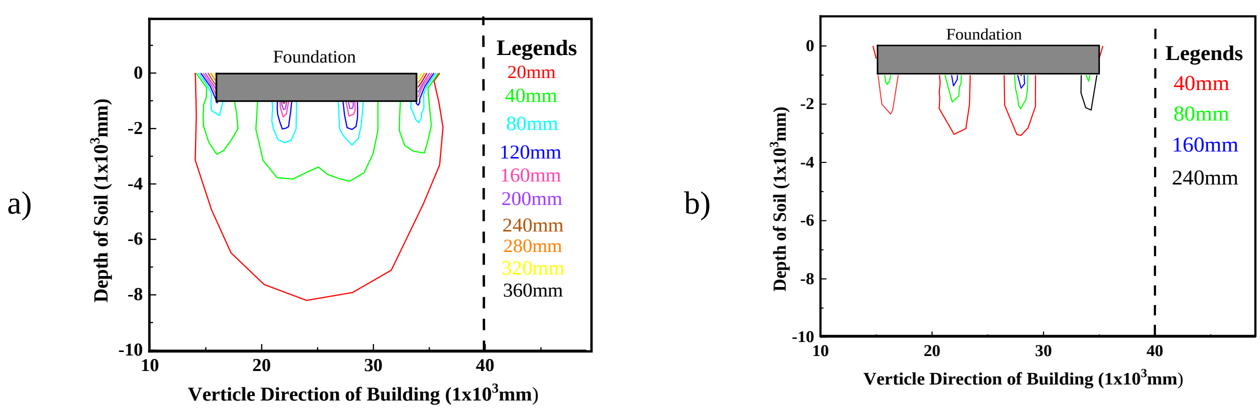


Figure 18: Static Settlement in 15m loose soil with course particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft



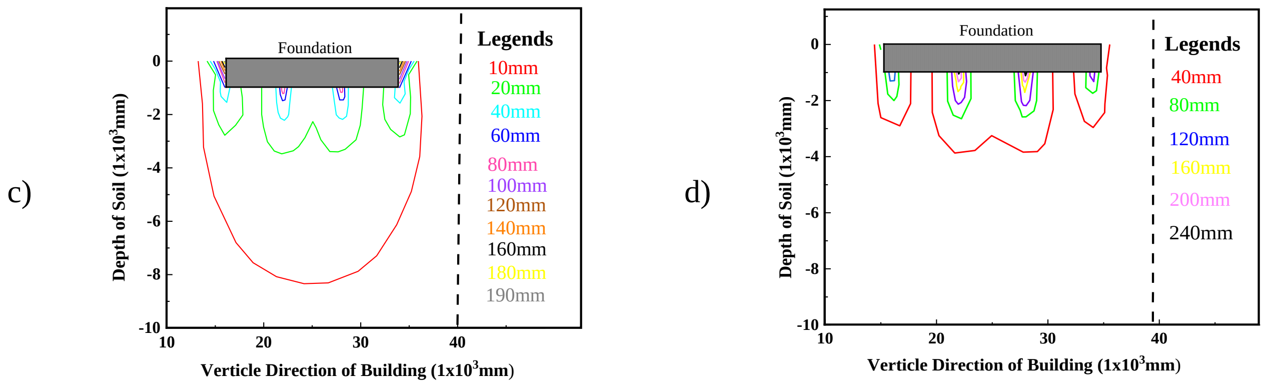


Figure 19: Static Settlement in 2m Engineered fill 13m loose soil with fine particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft

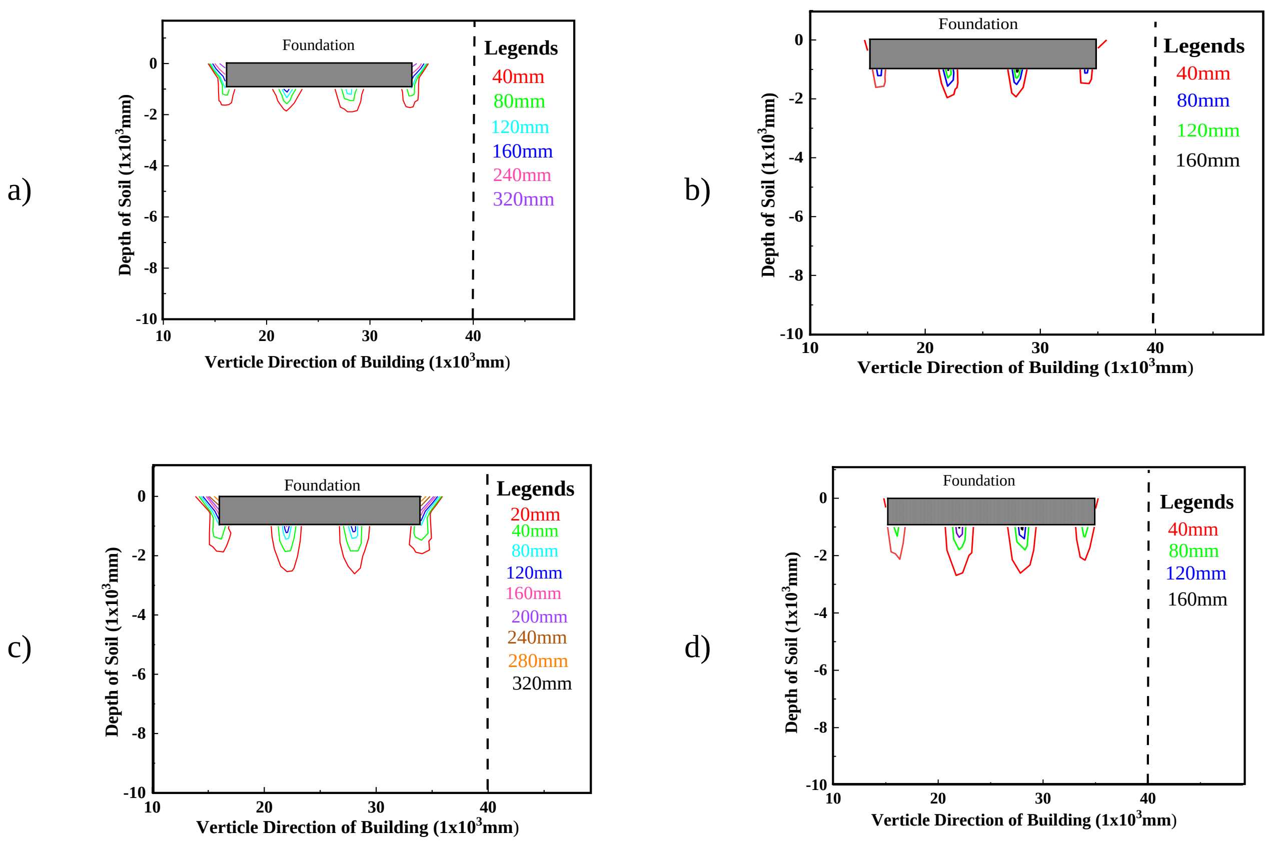


Figure 20: Static Settlement in 2m Engineered fill 13m loose soil with course particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft

Figure 17 shows that the most ineffective settlement results occur in 15m loose soil with fine particles under static loading. A raft foundation is not considered a suitable approach for mitigating settlement under heavy structures in this scenario, as it experiences a significant settlement of 0.480 meters under the middle columns. Conversely, the extended raft foundation, in both deep and shallow configurations, is chosen as the best alternative for mid-rise buildings, with a settlement of 320mm under the middle columns.

In Figure 18, it is evident that the most effective settlement results occur in the case of 15 meters of loose soil with course particles under static loading. A raft foundation, in this scenario, is not considered a suitable approach for mitigating settlement under heavy structures, given its significant settlement of 0.240 meters under the middle columns. Conversely, the extended raft foundation, in both deep and shallow configurations, emerges as the best alternative for mid-rise buildings, with a settlement of 0.12 meters observed under the middle columns.

Figure 19 provides clear evidence of moderate settlement when dealing with a scenario involving 2 meters of engineered fill atop 13 meters of loose soil containing fine particles under static loading conditions. A raft foundation is deemed unsuitable for effectively mitigating settlement beneath heavy structures, as it exhibits substantial settlement of 0.360 meters under the middle columns. In contrast, pile raft foundations are considered a best option in this soil condition, resulting in a settlement of 0.19 meters. On the other hand, the extended raft foundation, available in both deep and shallow configurations, stands out as the moderate choice for mid-rise buildings, with a minimal settlement of 0.24 meters observed under the middle columns.

Figure 20 shows that under static loading conditions, presents clear evidence of increased settlement when faced with a scenario that involves 2 meters of engineered fill atop 13 meters of loose soil containing coarse particles. In this context, a raft foundation is found to be unsuitable for effectively mitigating settlement beneath heavy structures, as it exhibits a substantial settlement of 0.360 meters under the middle columns. Conversely, pile raft foundations are regarded as a more moderate option in this specific soil condition, resulting in a settlement of 0.32 meters. In contrast, the extended raft foundation, available in both deep and shallow configurations, emerges as the superior choice for mid-rise buildings due to its minimal settlement of 0.16 meters observed under the middle columns.

The settlement results in various soil conditions and under static loading reveal distinctive patterns. In the scenario with 15 meters of loose soil containing fine particles, a raft foundation proves highly ineffective for mitigating settlement under heavy structures, with a substantial settlement of 0.480 meters observed under the middle columns.

Conversely, the extended raft foundation, available in both deep and shallow configurations, is deemed the most suitable option for mid-rise buildings, demonstrating minimal settlement of 0.320 meters under the middle columns. In contrast, when facing 15 meters of loose soil with coarse particles, the raft foundation is again unsuitable for heavy structures, showing significant settlement of 0.240 meters under the middle columns. Yet, the extended raft foundation shines as the optimal choice for mid-rise buildings, offering minimal settlement of 0.12 meters. Similarly, in the case of 2 meters of engineered fill on 13 meters of loose soil containing fine particles, the raft foundation underperforms for heavy structures with substantial settlement of 0.360 meters, while pile raft foundations present a more moderate option with 0.19 meters of settlement. However, the extended raft foundation remains the middle-ground choice for mid-rise buildings, exhibiting minimal settlement of 0.24 meters.

In the scenario involving 2 meters of engineered fill on 13 meters of loose soil with coarse particles, the inadequacy of the raft foundation becomes evident, experiencing substantial settlement of 0.360 meters. In contrast, pile raft foundations provide a more moderate solution, with a settlement of 0.32 meters. However, the extended raft foundation, available in both deep and shallow configurations, emerges as the optimal choice for mid-rise buildings, showcasing minimal settlement at 0.16 meters. This underscores the critical importance of tailoring the choice of foundation to specific soil conditions and structural requirements. The findings emphasize that a one-size-fits-all approach is insufficient, and thoughtful consideration of factors such as soil composition and building height is necessary. By selecting the appropriate foundation type, in this case, the extended raft foundation, engineers can effectively manage settlement and ensure the structural integrity of mid-rise buildings in the given soil conditions. This insight reinforces the need for site-specific analyses in construction planning to optimize foundation choices and mitigate settlement-related challenges.

4.3.2 Under Dynamic Loading

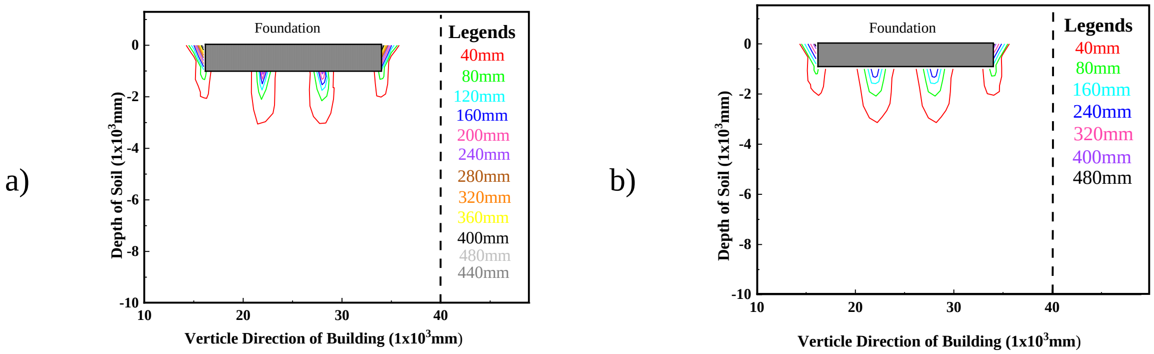


Figure 21: Dynamic settlement on 15m loose soil with course particles raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

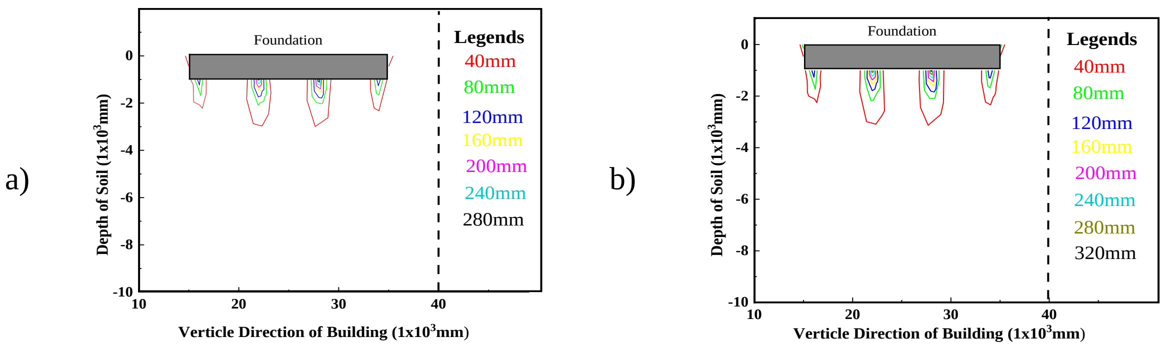


Figure 22: Dynamic settlement on 15m loose soil with course particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

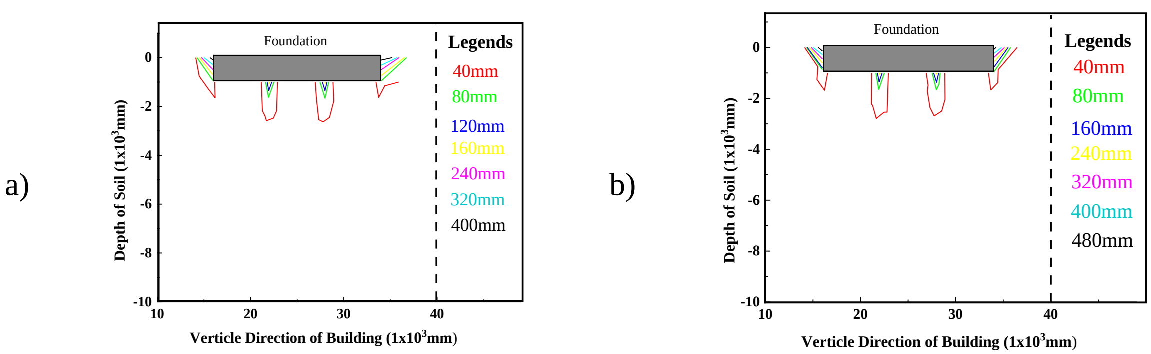


Figure 23: Dynamic settlement on 15m loose soil with course particles under pile-raft foundation; a). Kashmir earthquake, b). Mirpur earthquake

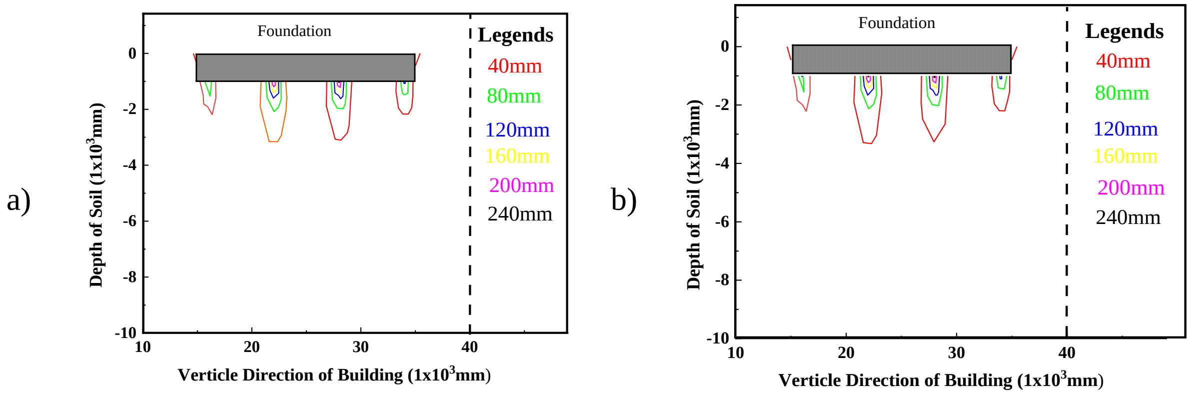


Figure 24: Dynamic settlement on 15m loose soil with course particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

Figure 21 reveals that for a scenario involving 15 meters of loose soil with coarse particles and a raft foundation, both the Kashmir and Mirpur earthquakes yield the same settlement value of 0.48 meters. However, it's evident that the contours in the Mirpur scenario show a deeper and more pronounced effect on the 15 meters of loose soil with coarse particles under the raft foundation. This implies that the Mirpur earthquake scenario could have a more significant impact on the soil and foundation system, potentially leading to increased soil disturbance or structural challenges compared to the Kashmir earthquake scenario.

Figure 22, shows that an extended raft foundation on 15 meters of loose soil with coarse particles, it becomes clear that both the Kashmir and Mirpur earthquakes result in consistent settlement values of 0.32 meters and 0.36 meters, respectively. These findings suggest that the Mirpur earthquake had a more substantial impact on the extended raft foundation compared to the Kashmir earthquake. Consequently, it indicates that the Mirpur earthquake scenario may have a more significant effect on the soil and foundation system, potentially resulting in greater soil disturbance or structural challenges compared to what was observed during the Kashmir earthquake.

Figure 23 shows that 15 meters of loose soil containing coarse particles with a pile raft foundation, it's illustrated that both the Kashmir and Mirpur earthquakes result in an identical settlement value of 0.40 meters. However, in the Mirpur scenario, the contours depict a more pronounced and deeper impact on the 15 meters of loose soil with coarse particles beneath the raft foundation. This observation suggests that the Mirpur earthquake scenario might exert a more significant influence on the soil and foundation system, potentially resulting in greater soil disturbance or presenting more substantial structural challenges compared to the Kashmir earthquake.

Figure 24, reveals the examination of 15 meters of loose soil containing coarse particles with a pile and extended raft foundation, both the Kashmir and Mirpur earthquakes yield an identical settlement value of 0.24 meters. Nevertheless, in the Mirpur scenario, the contours reveal a more pronounced and deeper impact on the 15 meters of loose soil with coarse particles beneath the raft foundation. This observation implies that the Mirpur earthquake scenario could exert a more significant influence on the soil and foundation system, potentially resulting in increased soil disturbance or structural challenges compared to the Kashmir earthquake.

In the challenging scenario of 15 meters of loose soil containing coarse particles, the most effective solution is the combination of a pile foundation with an extended raft system, consistently demonstrating the lowest settlement value of 0.24 meters. This integrated approach proves superior for both Kashmir and Mirpur earthquake scenarios, providing enhanced stability and minimal settlement. In contrast, the traditional raft foundation underperforms in this context, with a settlement value of 0.48 meters, making it unsuitable for such soil conditions.

While the extended raft and pile-raft foundations exhibit moderate settlement results, the observation that the Mirpur earthquake scenario results in more pronounced and deeper impacts on the 15 meters of loose soil with coarse particles beneath the raft foundation suggests greater challenges. These challenges include increased soil disturbance and structural concerns compared to the Kashmir earthquake. This underscores the significance of considering specific seismic conditions and soil profiles in foundation design, ensuring resilient structures capable of withstanding diverse earthquake scenarios and minimizing settlement-related risks.

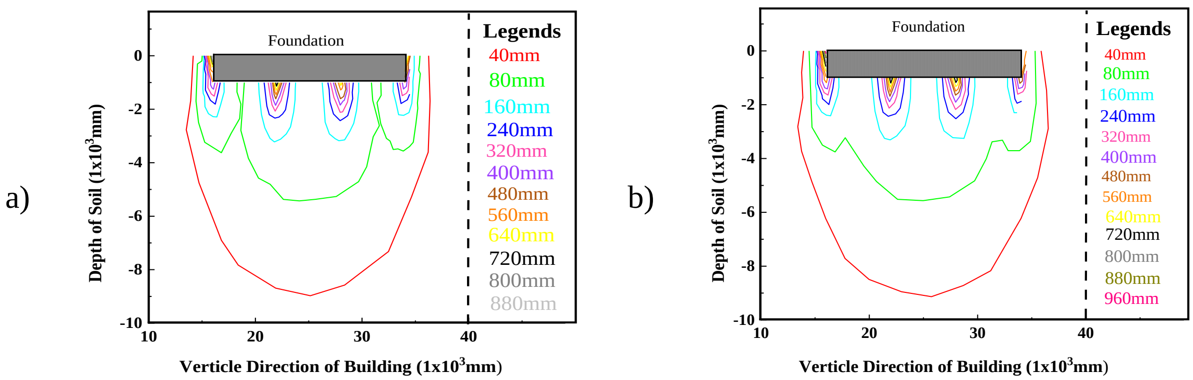


Figure 25: Dynamic settlement on 15m loose soil with fine particles raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

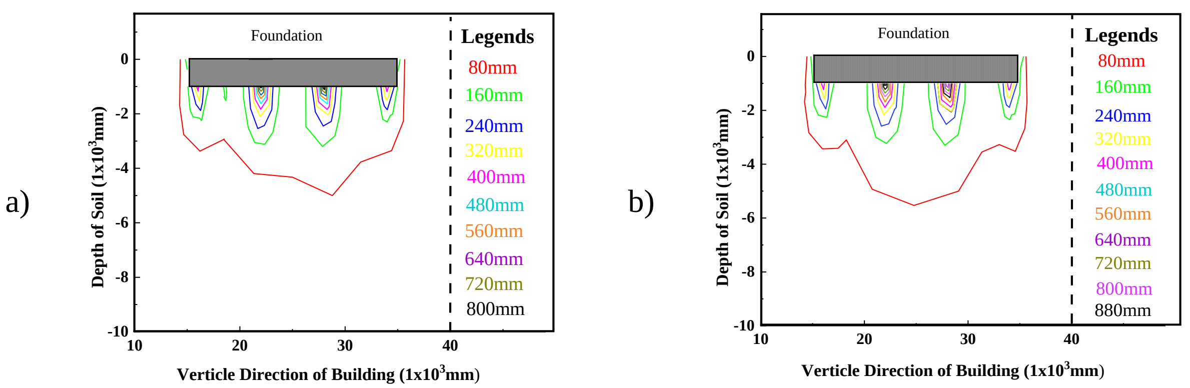


Figure 26: Dynamic settlement on 15m loose soil with fine particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

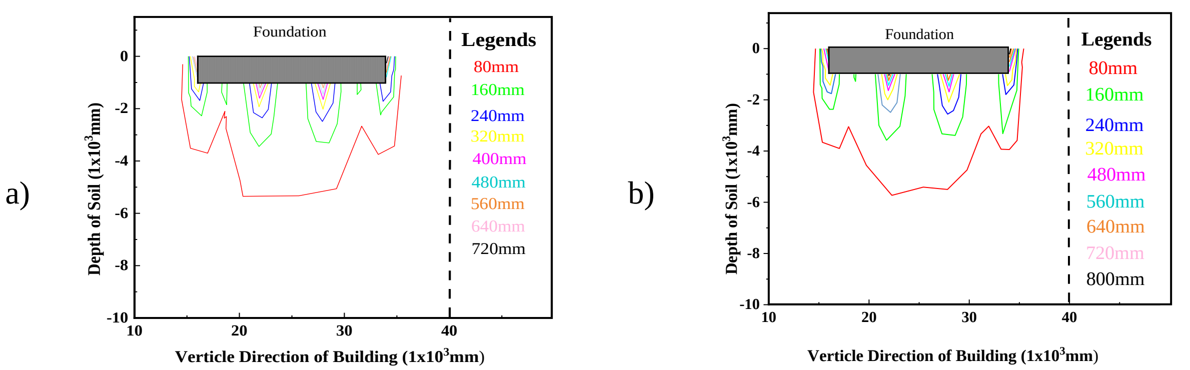


Figure 27: Dynamic settlement on 15m loose soil with fine particles under pile-raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

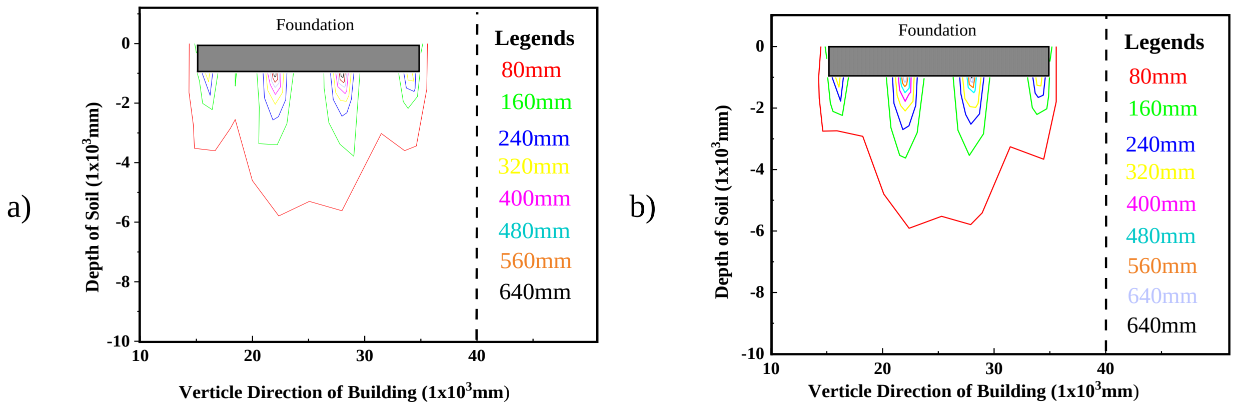


Figure 28: Dynamic settlement on 15m loose soil with fine particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

Figures 25 and 26 show consistent settlement values of 0.880 meters for the Kashmir and 0.960 meters for Mirpur earthquakes on a raft foundation, while the extended raft experienced 800 meters of settlement for the Kashmir quake and 880 meters for Mirpur. This indicates that the Mirpur earthquake had a more significant impact on the raft and extended raft, potentially suggesting greater soil disturbance and structural challenges compared to the Kashmir earthquake on a 15-meter loose soil foundation with fine particles

Figures 27 and 28 provide insights into a scenario where there are 15 meters of loose soil with fine particles. In this context, both the pile raft and extended raft foundation exhibit identical settlement values of 0.72 meters and 0.64 meters for both the Kashmir and Mirpur earthquakes. Additionally, the contour patterns in both earthquake figures suggest that they apply a similar level of pressure on the soil

When dealing with a challenging scenario of 15 meters of loose soil containing fine particles, the most effective solution is the use of a pile with extended raft foundation, consistently demonstrating the lowest settlement value of 0.64 meters. This combination proves to be the preferred choice for both Kashmir and Mirpur earthquake scenarios, offering superior stability and minimal settlement. So, for loos soil with fine particles is to be suggested to provide pile to transfer load deep to minimize the settlement and expansion in raft use to increase the bearing capacity of soil. Although pile raft and extended raft have same settlement value sop consider to be moderate alternative. And pile with extended raft consider the best option for loose soil with fine particles.

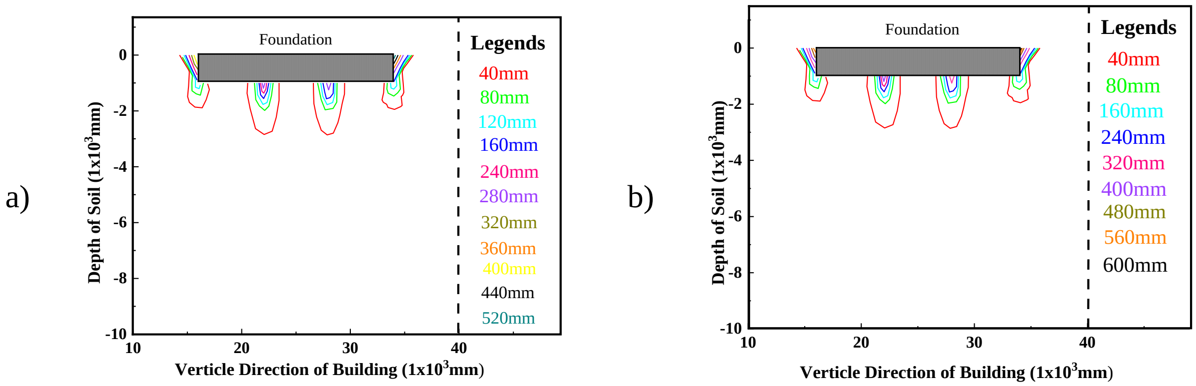


Figure 29: Dynamic settlement on 2m Engineered fill 13m loose soil with course particles under raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

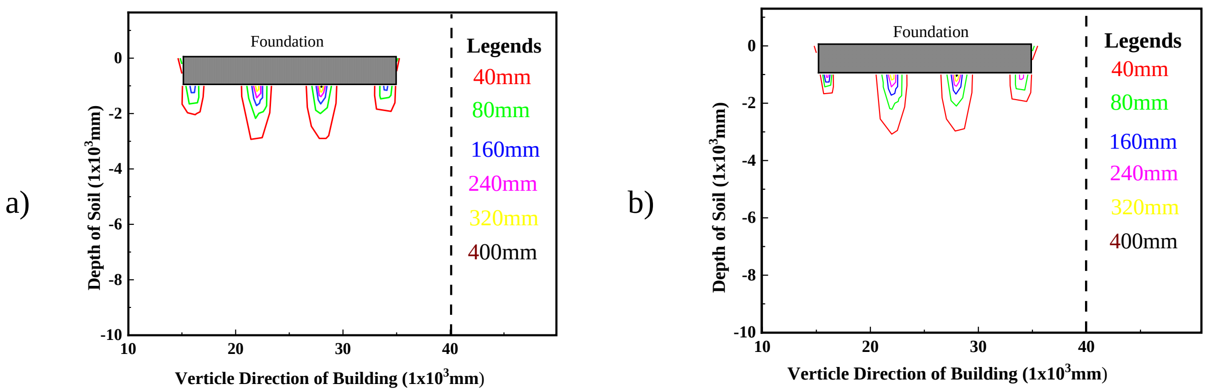


Figure 30: Dynamic settlement on 2m Engineered fill 13m loose soil with course particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

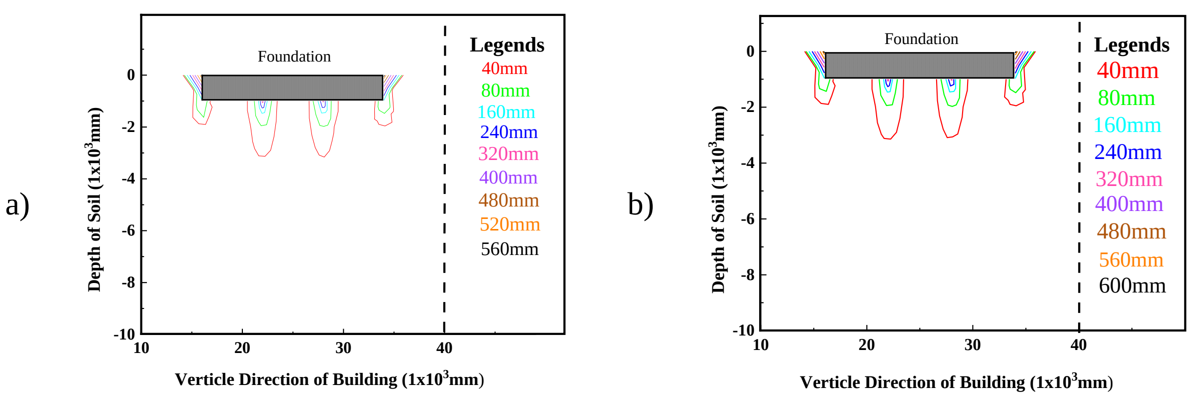


Figure 31: Dynamic settlement on 2m Engineered fill 13m loose soil with course particles under pile-raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a) b)

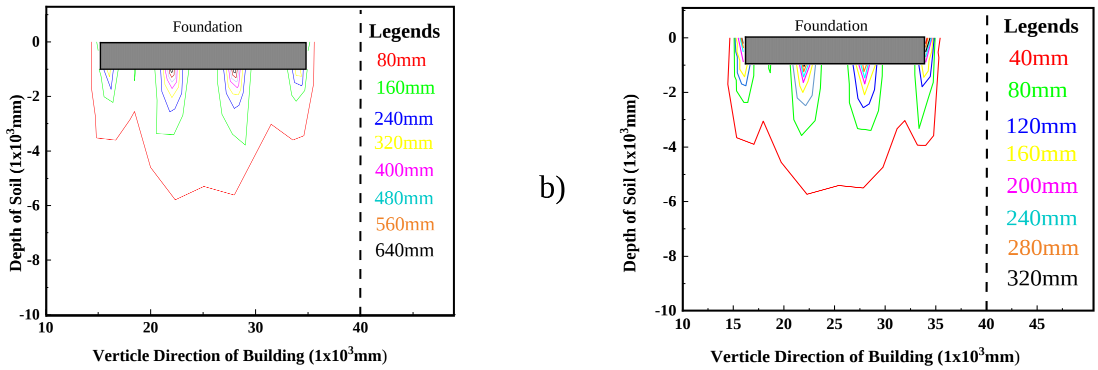


Figure 32: Dynamic settlement on 2m Engineered fill 13m loose soil with course particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

Figures 29 reveal consistent settlement values of 0.520 meters for the Kashmir earthquake and 0.60 meters for the Mirpur earthquake when a raft foundation is employed. This indicates that the Mirpur earthquake had a more significant impact on both the raft and extended raft foundations, potentially suggesting greater soil disturbance and structural challenges compared to the Kashmir earthquake in the context of a foundation consisting of 2 meters of engineered fill and 13 meters of loose soil with coarse particles.

Figures 30 and 31 provide insights into a scenario where there is 2 meters of engineered fill atop 13 meters of loose soil with coarse particles. In this context, both the pile raft and extended raft foundations demonstrate identical settlement values of 0.6 meters for both the Kashmir and Mirpur earthquakes. Additionally, when employing a pile with an extended raft, the settlement value is 0.4 meters for both earthquakes, as shown in Figures 32. The contour patterns in both earthquake figures suggest that they exert a similar level of pressure on the soil

The most effective solution is employing a pile with an extended raft foundation, consistently yielding the lowest 0.32-meter settlement. This proves optimal for both Kashmir and Mirpur earthquake scenarios, ensuring stability and minimal settlement. For 2 meters of engineered fill atop 13 meters of loose soil with coarse particles, it's advisable to use piles to transfer loads deep and consider expanding raft usage to enhance soil bearing capacity. While the pile raft and extended raft show the same settlement value, they are moderate alternatives.

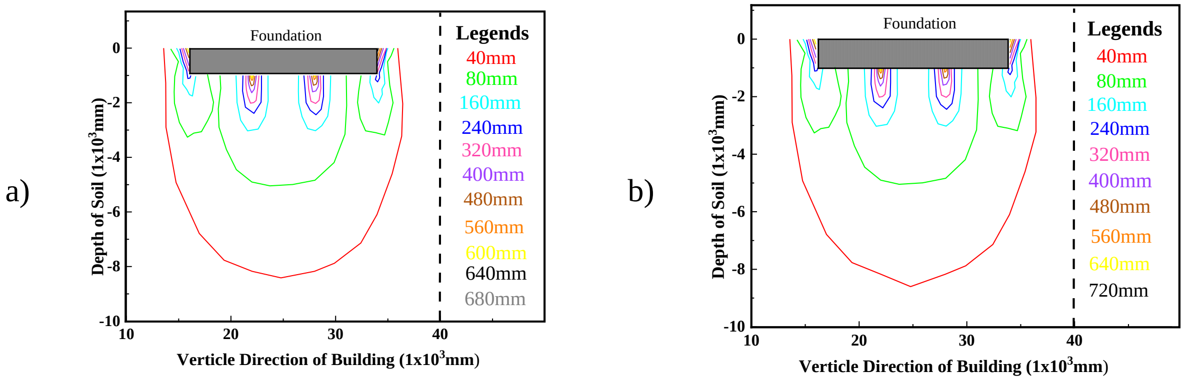


Figure 33: Dynamic settlement on 2m Engineered fill 13m loose soil with fine particles under raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

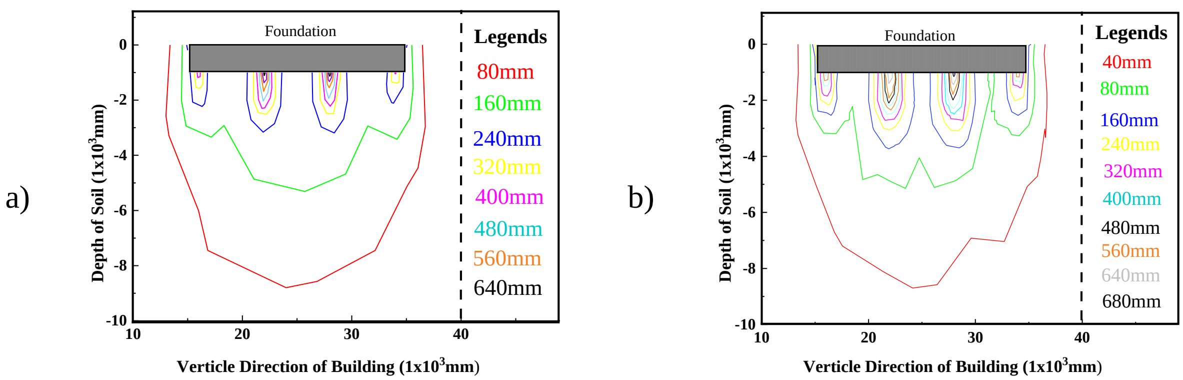


Figure 34: Dynamic settlement on 2m Engineered fill 13m loose soil with fine particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

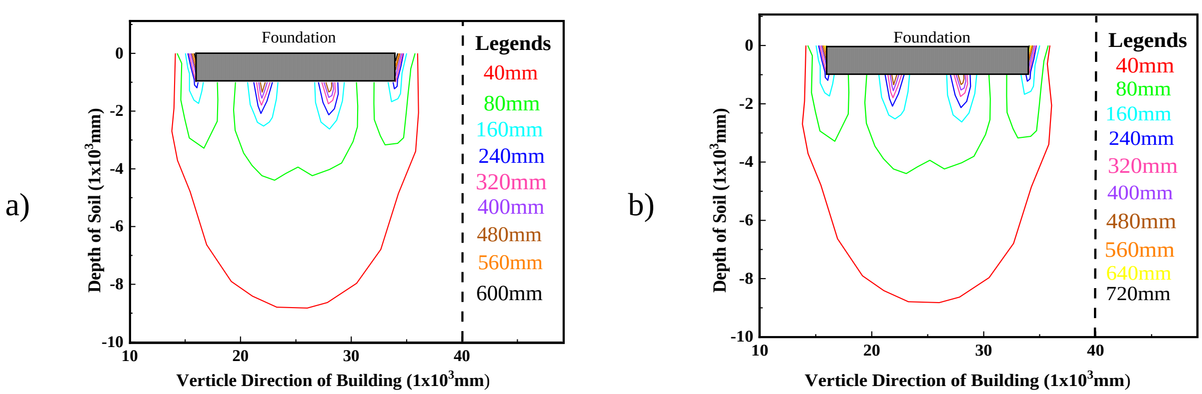


Figure 35: Dynamic settlement on 2m Engineered fill 13m loose soil with fine particles under pile-raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

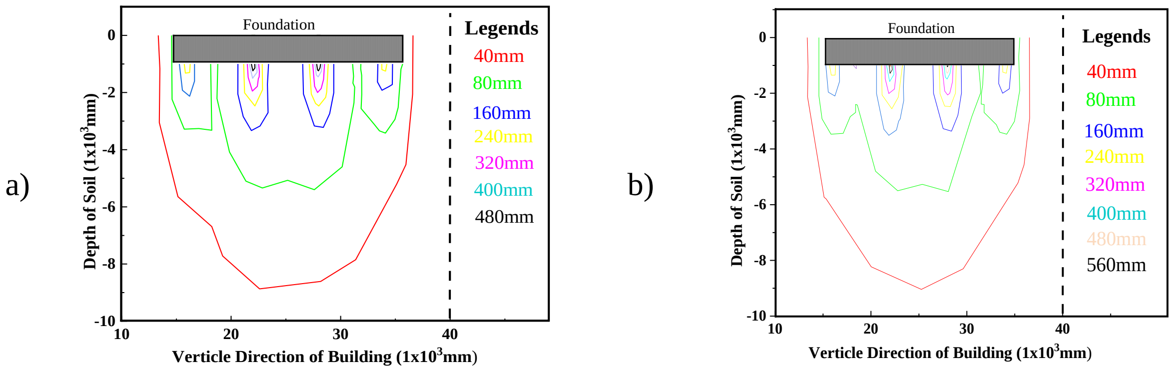


Figure 36: Dynamic settlement on 2m Engineered fill 13m loose soil with fine particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

Figures 4.33 and 4.35 depict consistent settlement values of 0.680 meters for the Kashmir earthquake and 0.720 meters for the Mirpur earthquake on a raft foundation. Conversely, the pile raft experienced 0.6 meters of settlement for the Kashmir quake and 0.72 meters for Mirpur. However, Figure 36 reveals that a pile with an extended raft achieved more favorable results, with settlements of 0.28 meters for the Kashmir quake and 0.32 meters for Mirpur. These findings suggest that the Mirpur earthquake had a more pronounced impact on both the raft and extended raft foundations, potentially indicating increased soil disturbance and structural challenges compared to the Kashmir earthquake in the context of a foundation consisting of 2 meters of engineered fill and 13 meters of loose soil with fine particles.

In Figures 4.34 shows a scenario featuring 2 meters of engineered fill atop 13 meters of loose soil with fine particles, extended raft foundations exhibit identical settlement values of 0.72 meters for both the Kashmir and Mirpur earthquakes. The contour patterns in both earthquake figures suggest that they exert similar levels of pressure on the soil.

Comparing contours, the most effective solution is a pile with an extended raft, offering minimal settlement (0.32m for Mirpur, 0.28m for Kashmir) in both earthquake scenarios. For 2 meters of engineered fill over 13 meters of coarse particle loose soil, using piles for load transfer and considering expanded raft usage is recommended. While the pile raft and extended raft have similar settlement values, they are moderate options.

4.4 Liquefaction Analysis

Liquefaction is the separation of water and soil particles caused by dynamic excitation and vibrations during an earthquake, allowing water to be squeezed out and resulting in sudden settlement. To investigate the effects of liquefaction on foundations, a comparison was made between the results of a multi-layered soil with a groundwater table (G.W.T) and without G.W.T. Predictions were conducted for different foundation types, including raft, extended raft, pile-raft, and pile with extended raft. Each foundation underwent dynamic analysis for two earthquakes, Kashmir and Mirpur, across various soil profiles. The results were compared to assess the impact of liquefaction on each foundation type. Raft foundations exhibited the highest liquefaction susceptibility, with a liquefaction reduction factor considered as 0%. Table 4.2 presents the dynamic liquefaction cases and liquefaction reduction rates for each foundation.

Description	Foundation Type	Settlement in Non-Liquefiable Soil		Settlement in Liquefiable Soil		Liquefaction Analysis	
		Kashmir	Mirpur	Kashmir	Mirpur	Kashmir	Mirpur
Settlement/ Liquefaction in Meters	Raft	0.8353	0.9234	0.8934	0.9824	0.0581	0.059
	Extended Raft	0.7242	0.7749	0.7837	0.8486	0.0595	0.0737
	Pile-Raft	0.7474	0.8571	0.7859	0.9043	0.0385	0.0472
	Pile Ext- Raft	0.6968	0.7103	0.7632	0.7803	0.0664	0.07
Settlement / Liquefaction Reduction Rate	Raft	0%	0%	0%	0%	0%	0%
	Extended Raft	13%	16%	12%	14%	-2%	-25%
	Pile-Raft	11%	7%	12%	8%	34%	20%
	Pile Ext- Raft	17%	23%	15%	21%	-14%	-19%

Table 5: Settlement/liquefaction analysis in liquefiable and no liquefiable soil.

Table 5, shows that considering non-liquefiable soil conditions, the raft foundation experiences maximum settlement values of 0.8353m and 0.9234m for the Kashmir earthquake and

Mirpur earthquake, respectively, with no observed settlement reduction. Conversely, the pile with an extended raft foundation yields the most favorable settlement results, measuring 0.6968m and 0.7103m for the Kashmir earthquake and Mirpur earthquake, along with settlement reduction rates of 17% and 23%, respectively. Moderate settlement reduction rates are observed for pile-raft and extended-raft foundations in non-liquefiable soil. However, when assessing the settlement results in liquefiable soil, it becomes evident that pile-raft foundations experience only 5% liquefaction. In contrast, pile with extended raft and extended raft foundations exert more pressure on liquefiable soil during earthquake vibrations, leading to a higher liquefaction rate of 9% in these two foundation types.

Table 5 also shows that the pile with extended raft foundation achieves an impressive settlement reduction rate in liquefiable soil, with settlement values of 0.7632m and 0.7803m for the Kashmir earthquake and Mirpur earthquake, accompanied by settlement reduction rates of 15% and 21%, respectively. However, the liquefaction resistance ability of this foundation type is not optimal. The results of liquefaction analysis show that the reduction in pile-raft settlements is 17% and 23% for the Kashmir earthquake and Mirpur earthquake, respectively. Therefore, pile-raft appears to be a suitable approach for addressing liquefiable soil conditions and is a preferable choice for providing foundation stability in such situations.

A pile raft foundation is ideal for liquefiable soil because it uses piles to transfer loads to deeper, stable layers, preventing liquefaction. In contrast, a pile with an extended raft is better suited for non-liquefiable soil. This design increases the foundation's area, distributing loads more effectively and reducing the risk of differential settlement. However, using an extended raft in liquefiable soil could indeed exacerbate liquefaction due to the larger footprint, potentially compromising stability. Therefore, the choice depends on the soil conditions to ensure the foundation's safety and performance.

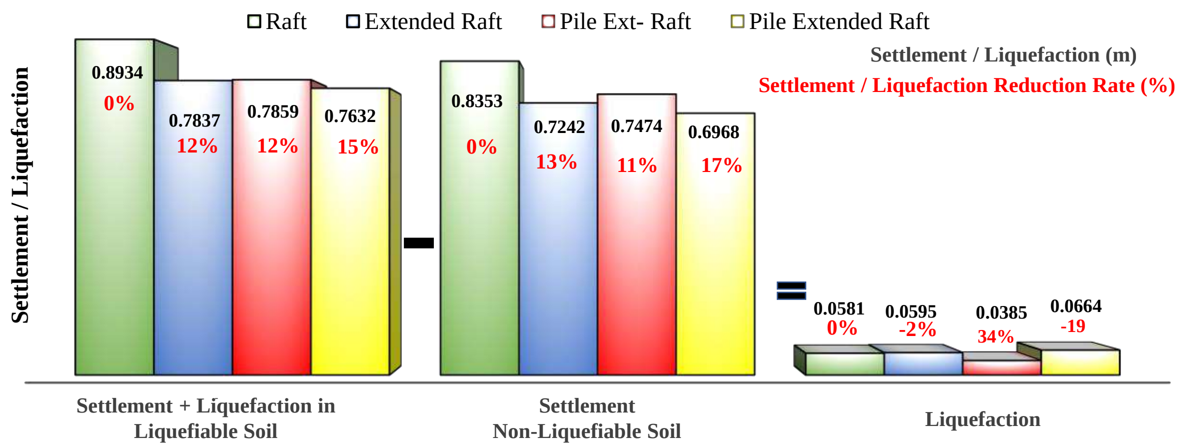


Figure 37: Settlement / Liquefaction analysis under dynamic loading Kashmir earthquake

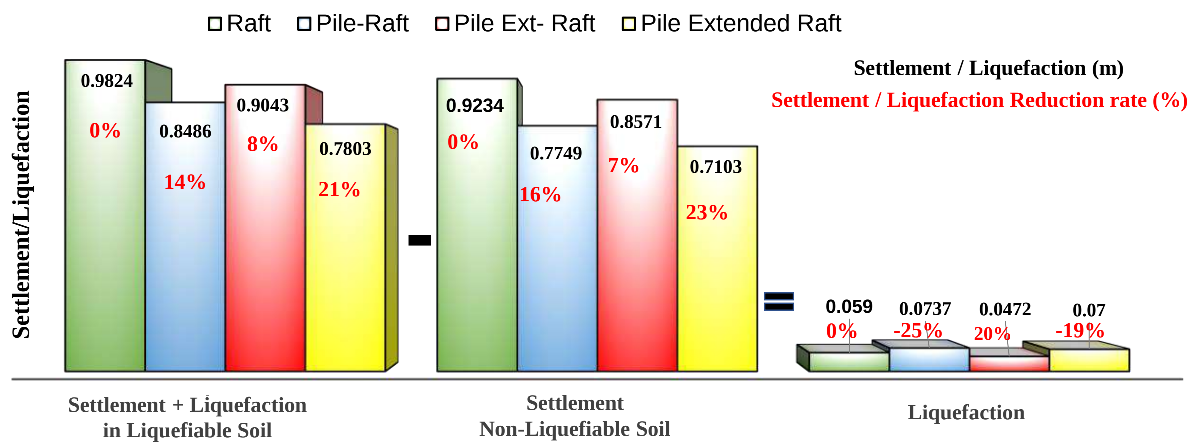


Figure 38: Settlement / Liquefaction analysis under dynamic loading Mirpur earthquake

Figure 37 illustrates settlement differences between liquefiable and non-liquefiable soils under various foundation types during the 2005 Kashmir earthquake. The findings highlight the positive impact of coarse particles on soil bearing capacity. Settlement analysis, particularly in liquefiable soil containing coarse particles, yields the most favorable results. Pile foundations with extended rafts performed exceptionally well in cohesive soil during the earthquake, while extended rafts in liquefiable soil experienced reduced reduction rates, possibly due to increased liquefaction susceptibility caused by raft extension. Notably, pile raft foundations proved highly effective in reducing liquefaction with a 34% reduction rate, contrasting with pile foundations with extended rafts and extended rafts that exhibited unexpectedly higher liquefaction. These results emphasize the significance of foundation choice in seismic-prone areas.

Figure 38 presents a similar study, focusing on settlement differences between liquefiable and non-liquefiable soils under various foundation types during the Mirpur earthquake. Like the previous findings, this study underscores the positive influence of coarse particles on soil bearing capacity. Settlement analysis, particularly in liquefiable soil with coarse particles, yields favorable outcomes. Pile foundations with extended rafts demonstrated exceptional performance in cohesive soil during the earthquake. However, extended rafts in liquefiable soil exhibited reduced reduction rates, potentially attributed to increased liquefaction susceptibility from raft extension. Remarkably, pile raft foundations proved highly effective in reducing liquefaction, achieving a 20% reduction rate, in contrast to pile foundations with extended rafts and extended rafts, which unexpectedly showed higher liquefaction rates.

These results underscore the critical role of foundation selection in earthquake-prone regions. The liquefaction analysis highlights the pile raft as the most suitable option in liquefiable soil, primarily owing to its smaller surface area, which exerts less pressure on the liquefiable soil during earthquakes. However, a holistic consideration of both settlement and liquefaction results reveals that pile foundations with extended rafts offer a superior reduction in settlement compared to pile raft foundations.

In conclusion, if liquefaction is the dominant concern, the highly recommended approach is the use of pile raft foundations. The reduced surface area minimizes the impact on liquefiable soil during seismic events. Conversely, if settlement takes precedence as the primary consideration, then pile foundations with extended rafts prove preferable. This approach, while addressing liquefaction concerns, also provides a notable reduction in settlement values, enhancing overall stability. The decision between these approaches should be informed by a thorough understanding of the specific geological and seismic conditions of the site. Tailoring the foundation choice to the unique characteristics of the soil and anticipated seismic activity ensures optimal performance and resilience against settlement and liquefaction challenges, contributing to the longevity and safety of the constructed structures in the given environment.

4.4.1 Liquefaction Contours under static loading

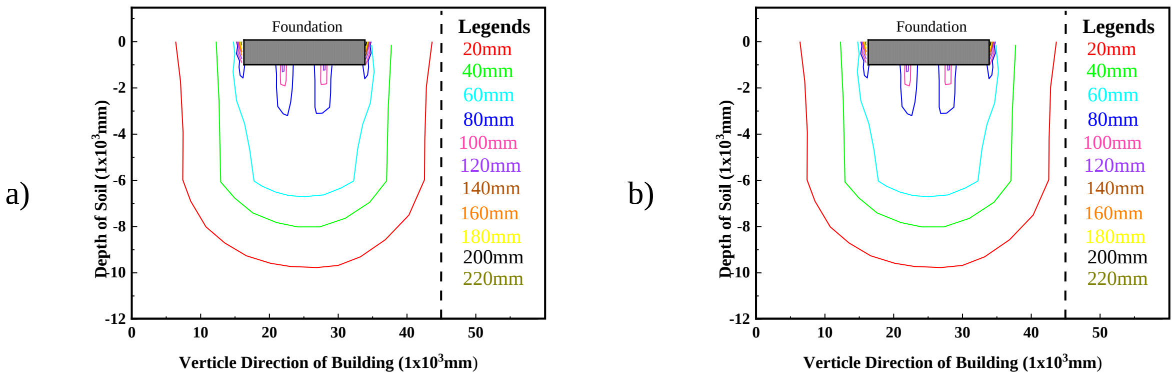


Figure 39: Static settlement under raft foundation; a) non-liquefiable soil, b) liquefiable soil

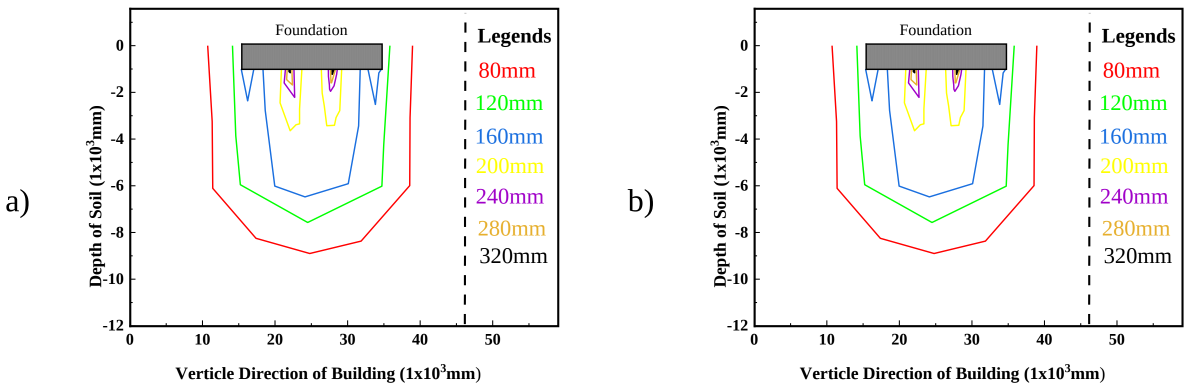


Figure 40: Static settlement under extended raft foundation; a) non-liquefiable soil, b) liquefiable soil

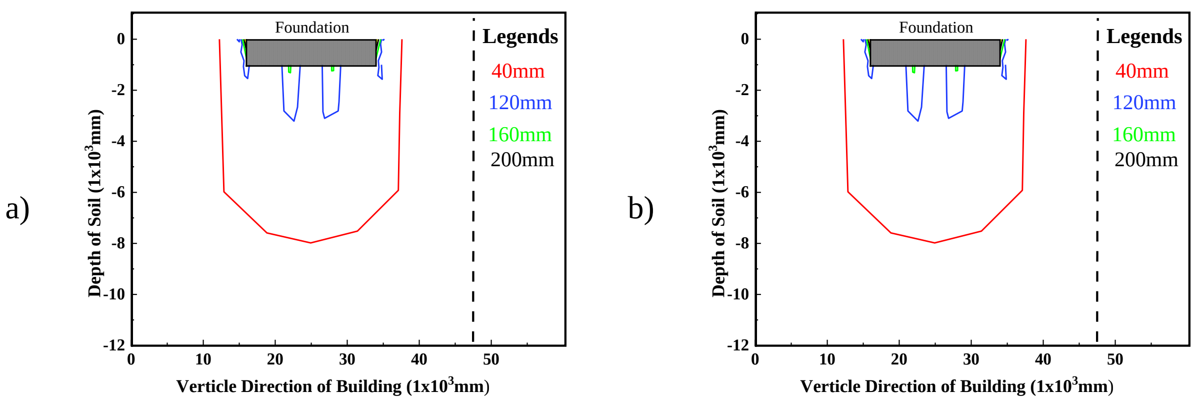
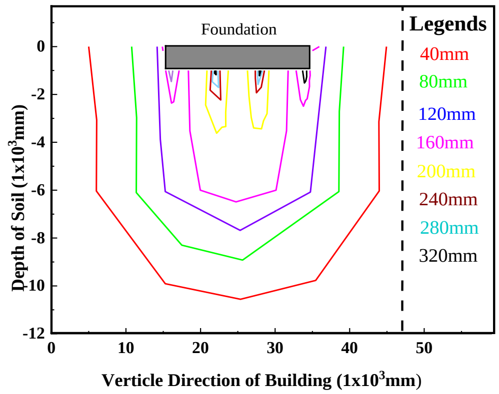


Figure 41: Static settlement under pile-raft foundation; a) non-liquefiable soil, b) liquefiable soil

a)



b)

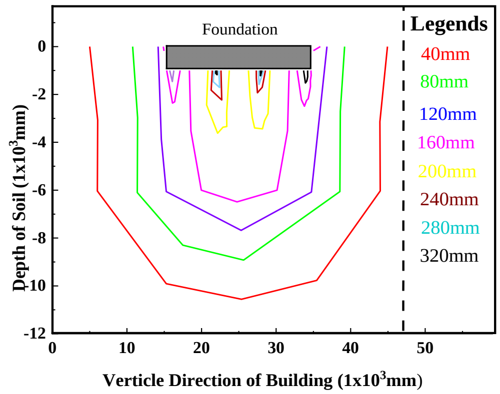


Figure 42: Static settlement under pile with extended raft foundation; a) non-liquefiable soil, b) liquefiable soil

After analyzing the data, it is evident that liquefaction settlement in a raft foundation under static loading is 0.22 meters for both earthquakes as shown in Figure 39. Figure 40 shows, liquefaction settlement in an extended raft foundation under static loading is 0.32 meters for both earthquakes. In Figure 41, liquefaction settlement in a pile raft foundation under static loading is 0.2 meters for both earthquakes. Lastly, Figure 42 illustrates that liquefaction settlement in a pile with an extended raft foundation under static loading is 0.32 meters for both earthquakes. Consequently, the data suggests that pile foundations exhibit superior performance under static loading conditions.

Based on the results, it is evident that liquefaction does not occur under static loading conditions. This conclusion is drawn from the fact that settlement results are the same in both natural (non-liquefiable) soil and natural soil with a groundwater table (liquefiable soil). Liquefaction typically takes place under dynamic loads, such as those generated during earthquakes or rapid construction processes that induce vibration and cyclic loading. Under static loading conditions, where the applied load remains constant over time, liquefaction is far less likely to occur. In such static loading situations, the excess pore water pressure in the soil does not significantly increase, allowing the soil to maintain its strength and stability.

4.4.2 Liquefaction Contours under Dynamic Loading

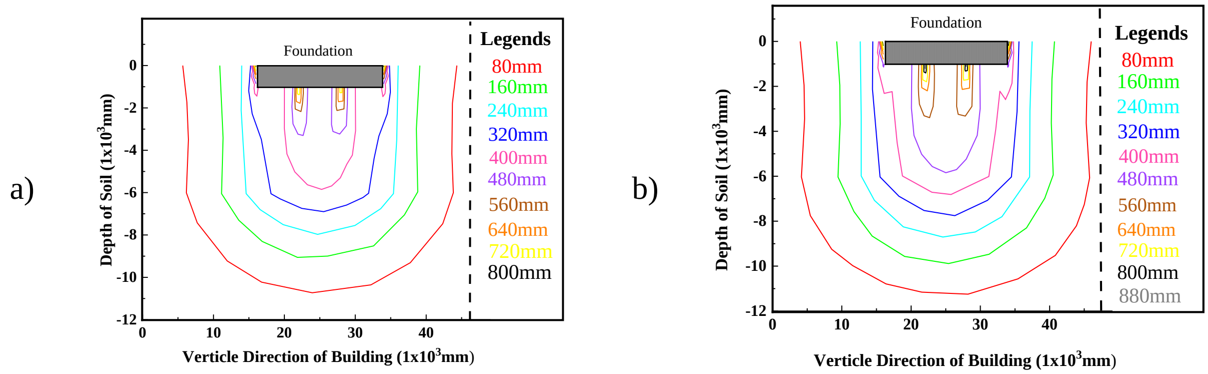


Figure 43: Dynamic settlement on raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

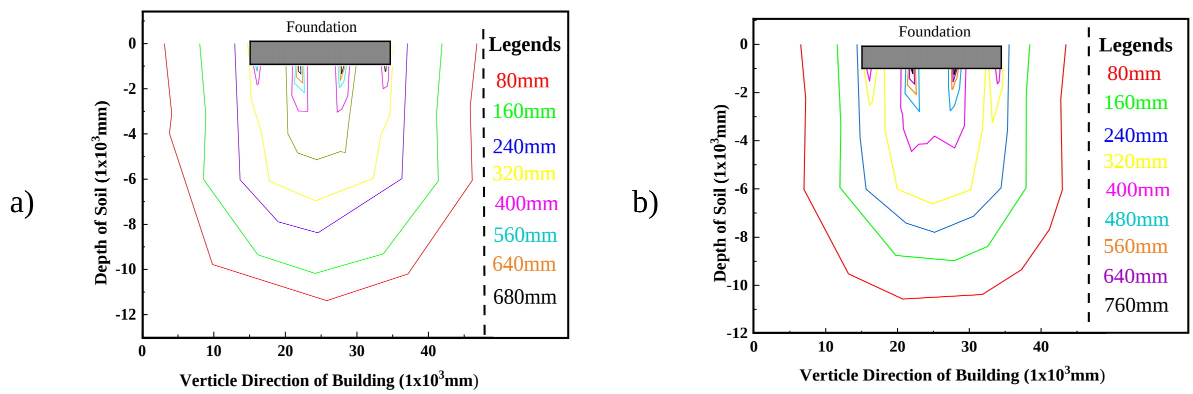


Figure 44: Dynamic settlement on pile-raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

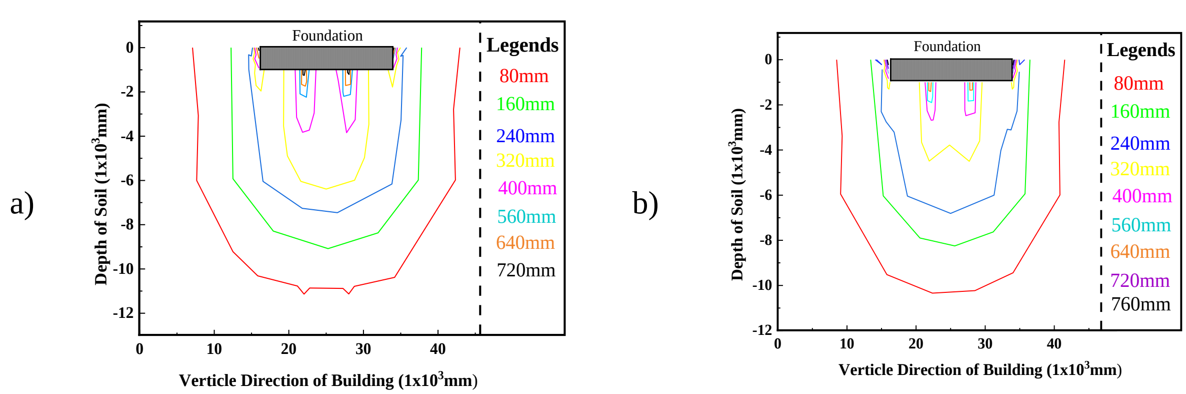


Figure 45: Dynamic settlement on pile-raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

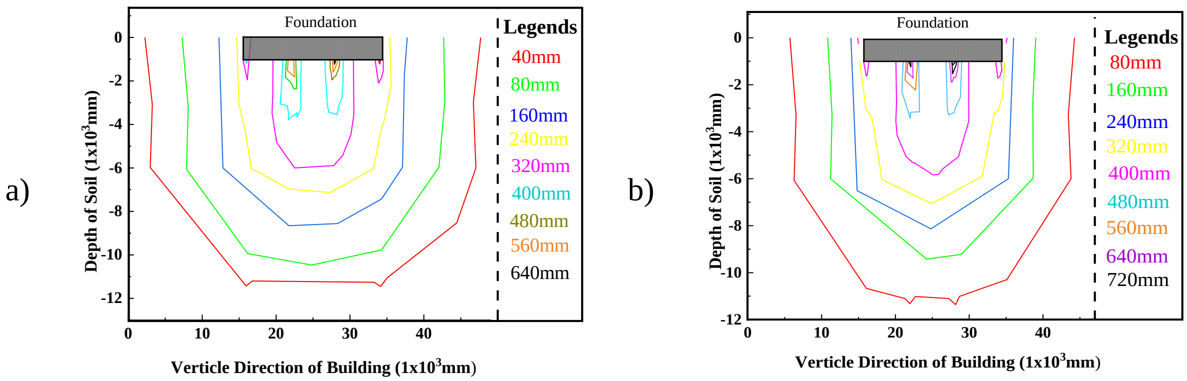


Figure 46: Dynamic settlement on pile with extended raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

Figure 43 illustrates that the settlement in non-liquefiable soil measures 0.8 meters, while in liquefiable soil, it amounts to 0.88 meters when considering a raft foundation subjected to the Kashmir earthquake. This disparity in settlement values signifies that liquefaction has occurred within the raft foundation area, resulting in an additional 0.08 meters of soil deformation compared to the non-liquefiable soil. Consequently, this earthquake-induced liquefaction has led to more pronounced soil deformation beneath the raft foundation, which may have implications for the stability and performance of structures supported by it. Engineering assessments and potential mitigation strategies should be considered in such seismic-prone regions to address these settlement challenges effectively.

Figure 44 demonstrates that, under the influence of the Kashmir earthquake, the settlement in non-liquefiable soil measures 0.68 meters, whereas in liquefiable soil, it reaches 0.76 meters for an extended raft foundation. This discrepancy in settlement values indicates the occurrence of liquefaction within the area covered by the extended raft foundation, resulting in an additional 0.08 meters of soil deformation compared to non-liquefiable soil. Unfortunately, it's important to note that the extended raft foundation does not effectively mitigate liquefaction; it still experiences the same amount of liquefaction-induced deformation. This phenomenon raises concerns regarding the stability and performance of structures supported by the extended raft foundation under seismic conditions.

Figure 45 illustrates, the impact of the Kashmir earthquake on soil settlement. In areas with non-liquefiable soil, settlement measures 0.72 meters, whereas in regions with liquefiable soil, it extends to 0.76 meters when employing a pile raft foundation. This difference in settlement values signifies that liquefaction has taken place within the area supported by the pile raft foundation, resulting in an additional 0.04 meters of soil deformation compared to non-liquefiable soil. Importantly, table 4.2 reveals that pile rafts boast an impressive liquefaction reduction factor of 34%, affirming their suitability for use in liquefiable soil conditions. This data strongly underscores the effectiveness of pile foundations in mitigating settlement caused by liquefaction.

Figure 46 shows, the effects produced by the Kashmir earthquake, depicts settlement measurements in non-liquefiable and liquefiable soils. In areas with non-liquefiable soil, the settlement is 0.64 meters, while in regions with liquefiable soil, it rises to 0.72 meters when utilizing a pile with an extended raft foundation. This disparity in settlement values signals the presence of liquefaction within the zone supported by the pile with an extended raft foundation, causing an additional 0.08 meters of soil deformation compared to non-liquefiable soil. It's unfortunate to note that the extended raft foundation doesn't effectively counteract liquefaction; it still experiences the same level of liquefaction-induced deformation. Despite its notable success in achieving settlement control in non-liquefiable soil, the pile with an extended raft foundation does not address liquefaction. Therefore, in cases where liquefaction is not the primary concern, the pile with an extended raft foundation is more suitable for natural soil conditions.

Based on the liquefaction analysis results on Kashmir earthquake, it is advisable to option for a pile raft foundation when the risk of liquefaction is a substantial concern. Pile rafts provide superior stability and load-bearing capacity in such conditions. Conversely, when liquefaction is not a dominant or critical factor in the site's geotechnical conditions, a simpler and cost-effective solution like a pile with an extended raft can be a more suitable choice for the foundation design, offering a balanced approach that aligns with the specific ground conditions and engineering requirements of the project.

a) b)

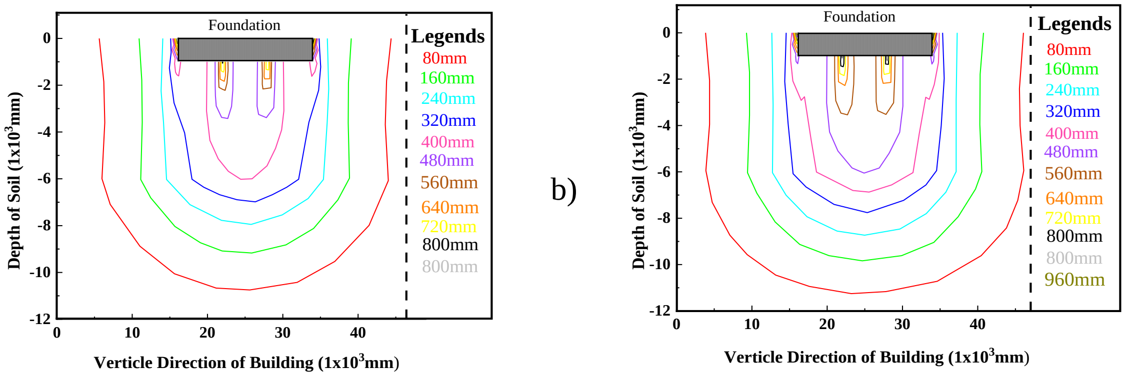


Figure 47: Dynamic settlement on raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable

a) b)

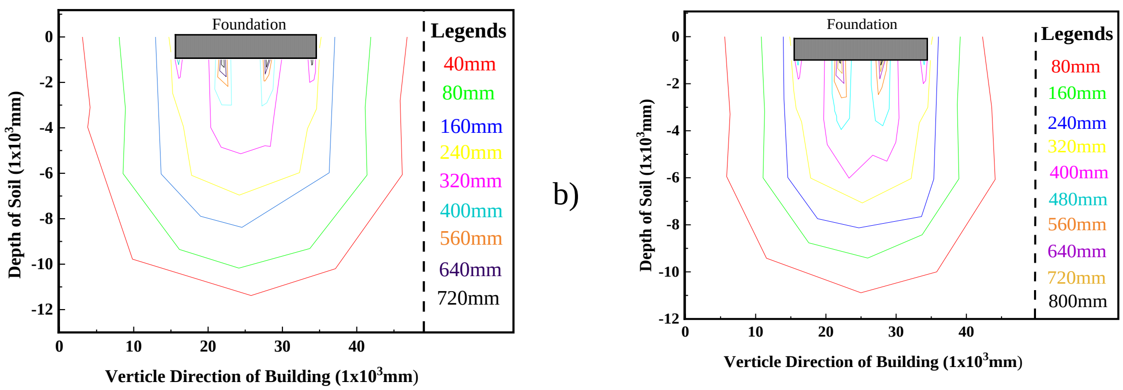


Figure 48: Dynamic settlement on pile-raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable soil

a) b)

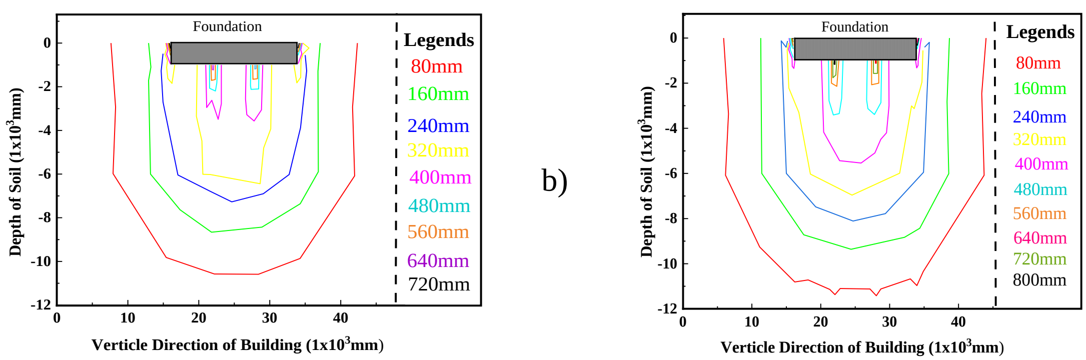


Figure 49: Dynamic settlement on pile-raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable soil

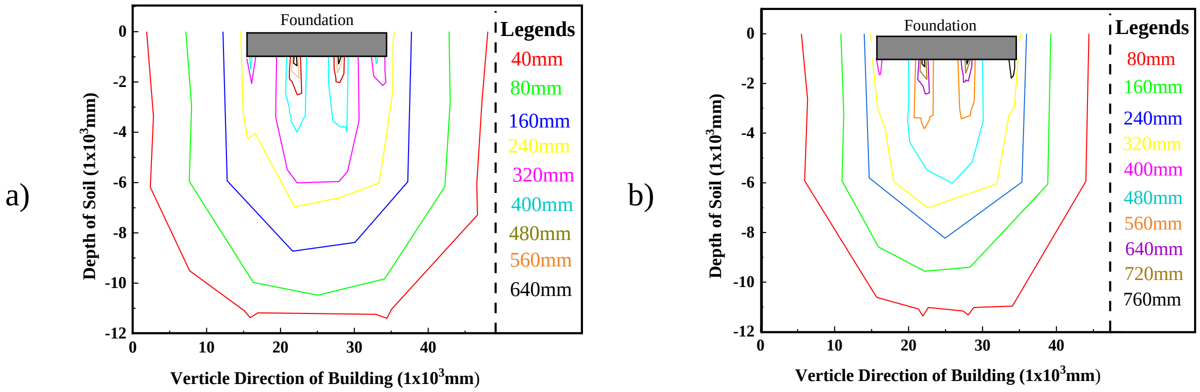


Figure 50: Dynamic settlement on pile with extended raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable soil

Figure 47 illustrates that, during the Mirpur earthquake, settlement in non-liquefiable soil measures 0.8 meters, whereas in liquefiable soil, it reaches 0.96 meters with a raft foundation. This discrepancy highlights liquefaction within the raft foundation area, resulting in an additional 0.08 meters of soil deformation compared to non-liquefiable soil. Consequently, this earthquake-induced liquefaction exacerbates soil deformation beneath the raft foundation, potentially affecting the stability and performance of structures it supports. Effective engineering assessments and mitigation strategies should be considered in seismic-prone regions to address these settlement challenges.

In Figure 48 shows, the settlement in non-liquefiable soil measures 0.72 meters under Mirpur earthquake, but in liquefiable soil with an extended raft foundation, it extends to 0.8 meters. This difference indicates liquefaction within the extended raft foundation area, causing an additional 0.08 meters of soil deformation compared to non-liquefiable soil. Unfortunately, it's crucial to note that the extended raft foundation does not effectively mitigate liquefaction-induced settlement; it still experiences the same level of deformation. This phenomenon raises concerns about the stability and performance of structures supported by the extended raft foundation during seismic events.

Figure 49 shows, the impact of the Mirpur earthquake on soil settlement. In non-liquefiable soil areas, settlement measures 0.72 meters, while in regions with liquefiable soil, it also reaches 0.72 meters with a pile raft foundation. This disparity indicates liquefaction within the pile raft foundation area, causing an additional 0.04 meters of soil deformation compared to non-liquefiable soil, as shown in table 3. Importantly, table 5 reveals that pile rafts have an impressive liquefaction reduction factor of 34%, confirming their suitability for use in liquefiable soil conditions. This data underscores the effectiveness of pile foundations in mitigating settlement due to liquefaction.

In Figure 50 show that, the settlement measurements in non-liquefiable and liquefiable soils under Mirpur earthquake are depicted. In non-liquefiable soil, settlement is 0.64 meters, but in regions with liquefiable soil with a pile and an extended raft foundation, it rises to 0.72 meters. This difference signals the presence of liquefaction within the zone supported by the pile with an extended raft foundation, causing an additional 0.08 meters of soil deformation compared to non-liquefiable soil. Regrettably, the extended raft foundation does not effectively counteract liquefaction, experiencing the same level of liquefaction-induced deformation. Despite its success in controlling settlement in non-liquefiable soil, the pile with an extended raft foundation does not address liquefaction. Therefore, in cases where liquefaction is not the primary concern, the pile with an extended raft foundation is more suitable for natural soil conditions.

The liquefaction analysis results for both the Kashmir and Mirpur earthquakes advocate for the adoption of a pile raft foundation when the risk of liquefaction is a significant concern. Pile rafts demonstrate superior stability and load-bearing capacity in conditions prone to liquefaction. Their design, with a reduced surface area, minimizes the pressure on liquefiable soil during seismic events, making them highly effective in mitigating liquefaction-related risks. Conversely, in scenarios where liquefaction is not a dominant or critical factor in the site's geotechnical conditions, opting for a simpler and cost-effective solution like a pile with an extended raft becomes a more suitable choice for foundation design. The extended raft, while addressing settlement concerns, provides an effective and economical alternative, aligning with the specific ground conditions and engineering requirements of the project. This dual approach recognizes the importance of tailoring foundation choices to the specific challenges presented by the geological and seismic characteristics of the site. It reflects a pragmatic and risk-based strategy, ensuring that the selected foundation type optimally addresses the anticipated challenges while considering cost-effectiveness and engineering efficiency. This nuanced decision-making process contributes to the overall resilience and performance of structures in earthquake-prone regions.

4.5 Structural Behavior

Structural displacement refers to the movement or shifting of a building or structure from its original position. This movement can occur due to various factors, including natural forces and structural failures. Settlement, heave, sliding, tilting, and seismic forces are common causes. Settlement involves gradual downward movement of a foundation due to soil compression, while heave is upward movement caused by soil expansion. Sliding is horizontal movement, often due to unstable soil or foundation issues, and tilting involves a structure leaning due to uneven settling. Seismic forces during earthquakes can also cause structural displacement, posing significant risks.

Earthquakes generate ground motions that lead to dynamic forces acting on buildings and structures. These forces cause lateral displacement, which can be both translational (side-to-side) and rotational (angular). Structural displacement under earthquake loading refers to the movement or shifting of a building or structure from its original position when subjected to the ground motion and forces generated by an earthquake. Earthquakes exert lateral forces on structures due to the sudden release of energy in the Earth's crust, resulting in dynamic and often unpredictable movements

Story drift is a fundamental concept in structural engineering that refers to the horizontal displacement or movement between adjacent floors or stories of a building when subjected to seismic events, strong winds, or other external forces. It quantifies the extent to which one story shifts relative to the story above or below it, serving as a crucial metric for assessing structural performance under lateral loads. Seismic forces and wind loads impose lateral pressures on buildings, prompting them to sway or deform. Story drift is particularly significant in structural engineering, especially in regions prone to earthquakes and high winds. Excessive story drift can have detrimental consequences, including structural damage, discomfort for building occupants, and impaired functionality. Engineers carefully analyze and design structures to limit story drift within acceptable parameters. Various structural elements, such as bracing systems and dampers, are employed to enhance a building's ability to withstand lateral forces, mitigating the risk of excessive story drift. Ensuring structural integrity against horizontal displacements is imperative for constructing resilient buildings in earthquake-prone and windy regions, contributing to both safety and the long-term functionality of the structures.

4.5.1 Structural Displacement Graphs

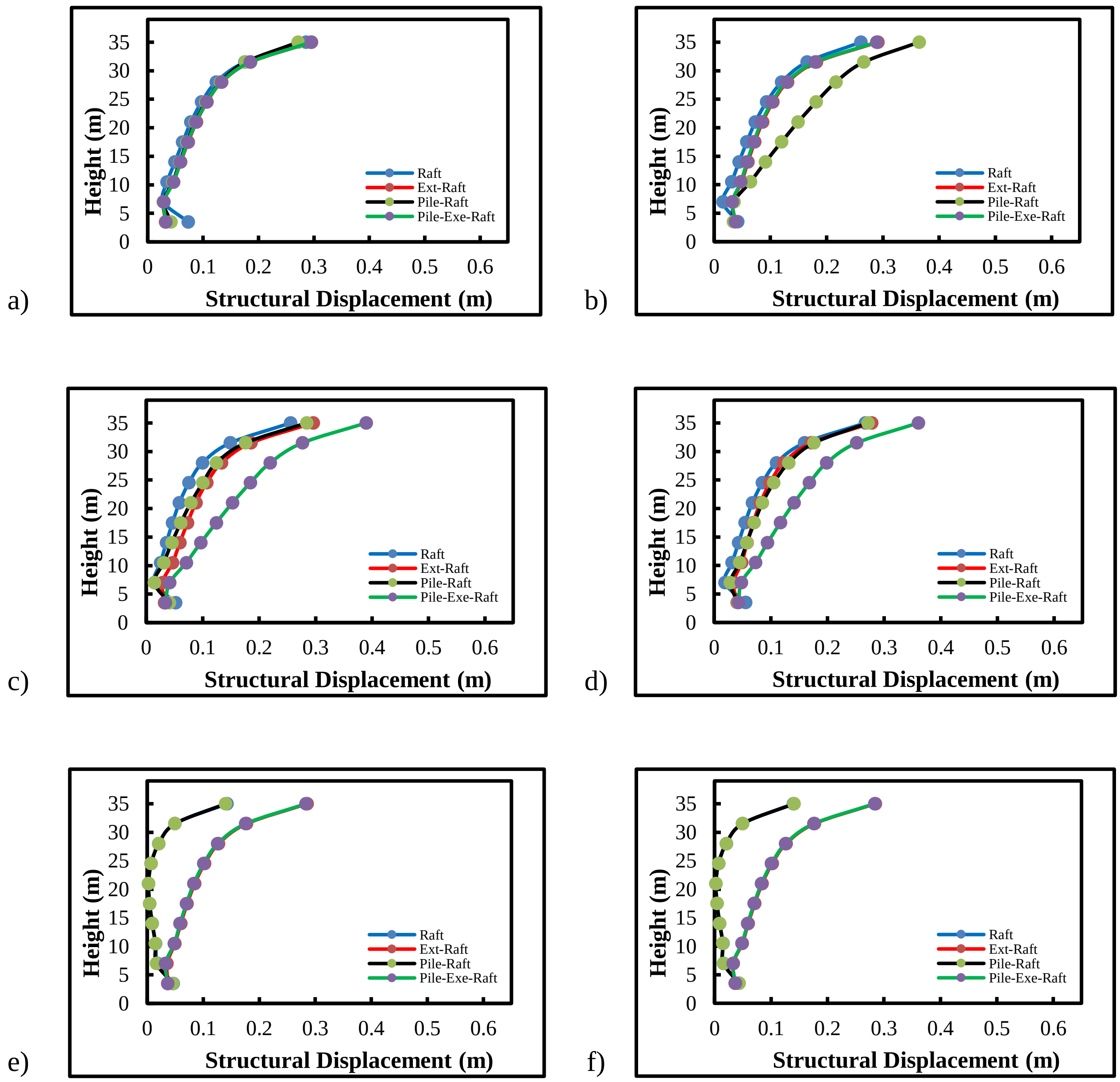


Figure 51: Structural displacement under Kashmir earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 51a illustrates that during the Kashmir earthquake, 15 meters loose soil with fine particles experienced slightly more significant effects on the extended raft and pile with extended raft in the X direction. Figure 51b shows that coarse particles have the same impact on these two foundations and experience more displacement than fine particles. Structures supported by extended raft foundations suffered greater structural displacement in the fine particle soil, measuring 0.2957 meters within the extended raft. Additionally, the pile raft experienced a maximum displacement of 0.3645 meters in coarse particle soil. The conclusion is that the extended raft suffered a slightly higher displacement than other foundations, and coarse particles exhibited more structural displacement on the pile raft than fine particles on the pile raft

Figure 51c reveals that during the Kashmir earthquake, a 2-meter engineered fill with loose soil containing fine particles at a depth of 13 meters experienced more pronounced effects on the pile with an extended raft in the X direction. Furthermore, Figure 51d illustrates that coarse particles had the maximum impact on the pile with an extended raft but underwent less displacement than fine particles. This implies that the earthquake applied a greater dynamic pressure on these two foundations. Structures supported by pile with extended raft foundations encountered greater structural displacement in the fine particle soil, measuring 0.3896 meters. Additionally, it observed a maximum displacement of 0.3378 meters in coarse particle soil in the X direction under the influence of the Kashmir earthquake. In conclusion, the pile with an extended raft suffered a slightly higher displacement than other foundations, and fine particles exhibited more structural displacement than coarse particles on it.

Figure 451e and Figure 51f shows that natural soil experiences a lesser amount of displacement compared to all other soil types. Both pile with extended raft and extended raft exhibit a displacement of 0.2837 meters in both soil profiles, while pile raft and raft foundation demonstrate the same displacement value of 0.14 meters in the X direction under the Kashmir earthquake. However, the graphs indicate identical displacement patterns, suggesting that the Kashmir earthquake has a similar impact on natural soil with the GWT and natural soil without GWT. Although the graphs clearly show that the pile doesn't significantly affect structural displacement, the absence of accuracy in the results is evident. In conclusion, the graphs indicate that pile with extended raft experiences the maximum structural displacement under the Kashmir earthquake in the X direction.

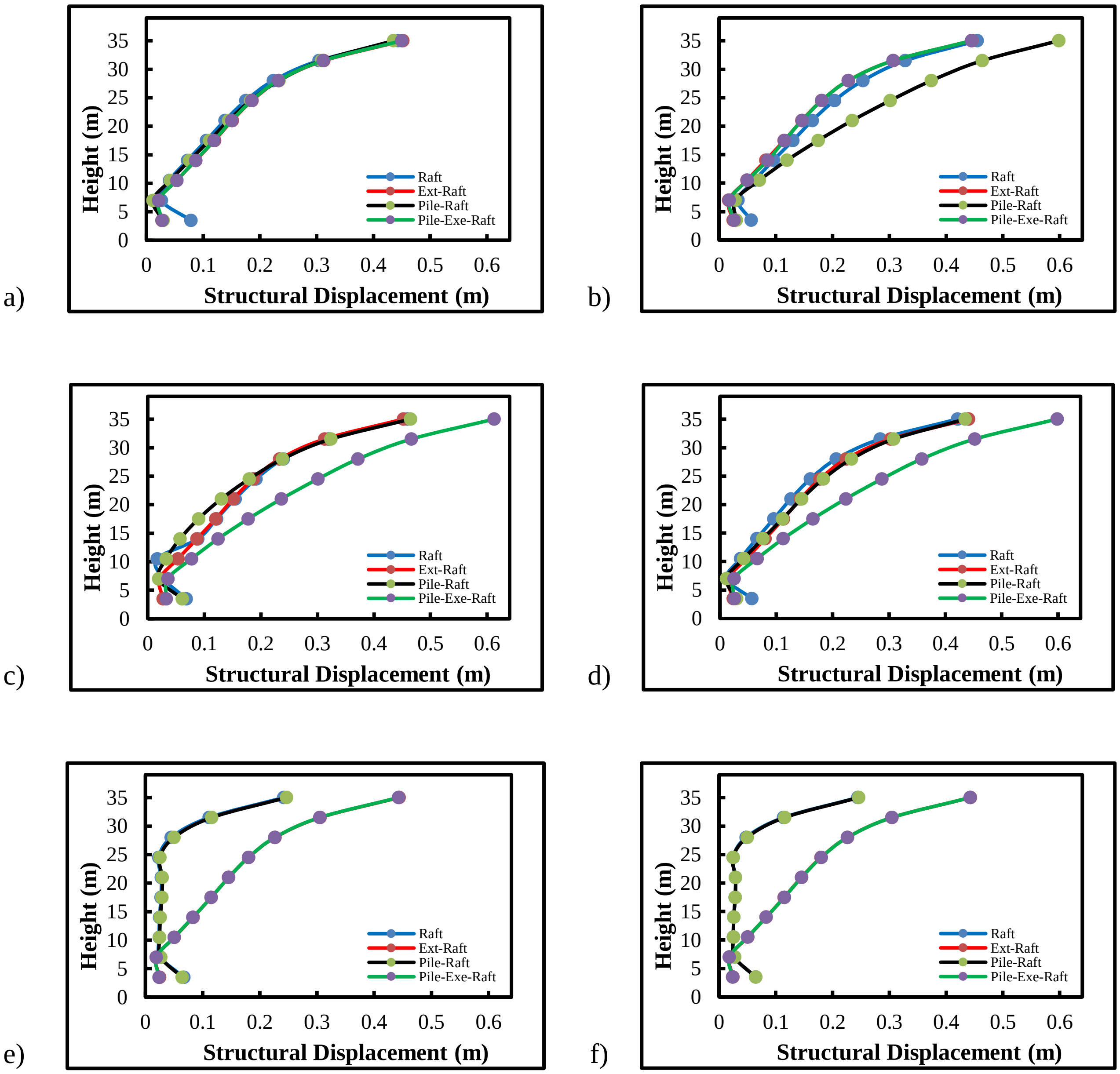


Figure 52: Structural displacement under Kashmir earthquake in Y direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Kashmir earthquake, Figure 52a shows that loose soil with fine particles at a depth of 15 meters experienced slightly more pronounced effects on both the extended raft and pile raft under Kashmir earthquake in the Y direction. Additionally, Figure 52b reveals that coarse particles had an equivalent impact on these two foundations and underwent more displacement compared to fine particles. Structures supported by pile raft foundations encountered greater structural displacement in the fine particle soil, measuring 0.455 meters within the pile raft. Furthermore, the pile raft experienced a maximum displacement of 0.5986 meters in coarse particle soil. In summary, the extended raft suffered a slightly higher displacement than other foundations, and coarse particles resulted in more structural displacement on the pile raft than fine particles on the pile raft

Figure 52c shows that during the Kashmir earthquake, a 2-meter engineered fill with loose soil containing fine particles at a depth of 13 meters experienced more pronounced effects on the pile with an extended raft in the Y direction. Moreover, Figure 52d demonstrates that coarse particles also had the maximum impact on the pile with an extended raft but underwent less displacement compared to fine particles. This suggests that the earthquake applied a greater dynamic pressure on these pile with extended foundations. Structures supported by pile with extended raft and extended raft encountered greater structural displacement in the fine particle soil, measuring 0.6124 meters. Additionally, a maximum displacement of 0.4412 meters was observed in coarse particle soil in the Y direction under the influence of the Kashmir earthquake. In summary, the pile with an extended raft suffered a slightly higher displacement than other foundations, and fine particles exhibited more structural displacement than coarse particles on it.

Figure 52e and Figure 52f illustrate that natural soil experiences less displacement compared to other soil types. Both the pile with extended raft and extended raft exhibits a displacement of 0.4425 meters in both soil profiles, while the pile raft and raft foundation demonstrate the same displacement value of 0.2417 meters in the Y direction under the Kashmir earthquake. While the graphs make it evident that the pile has a minimal impact on structural displacement, the lack of precision in the results is apparent. In summary, the graphs indicate that the pile with extended raft experiences the maximum structural displacement in the Y direction under the Kashmir earthquake. Additionally, the results reveal that the Kashmir earthquake exerts more pressure and induces greater structural displacement in the Y direction.

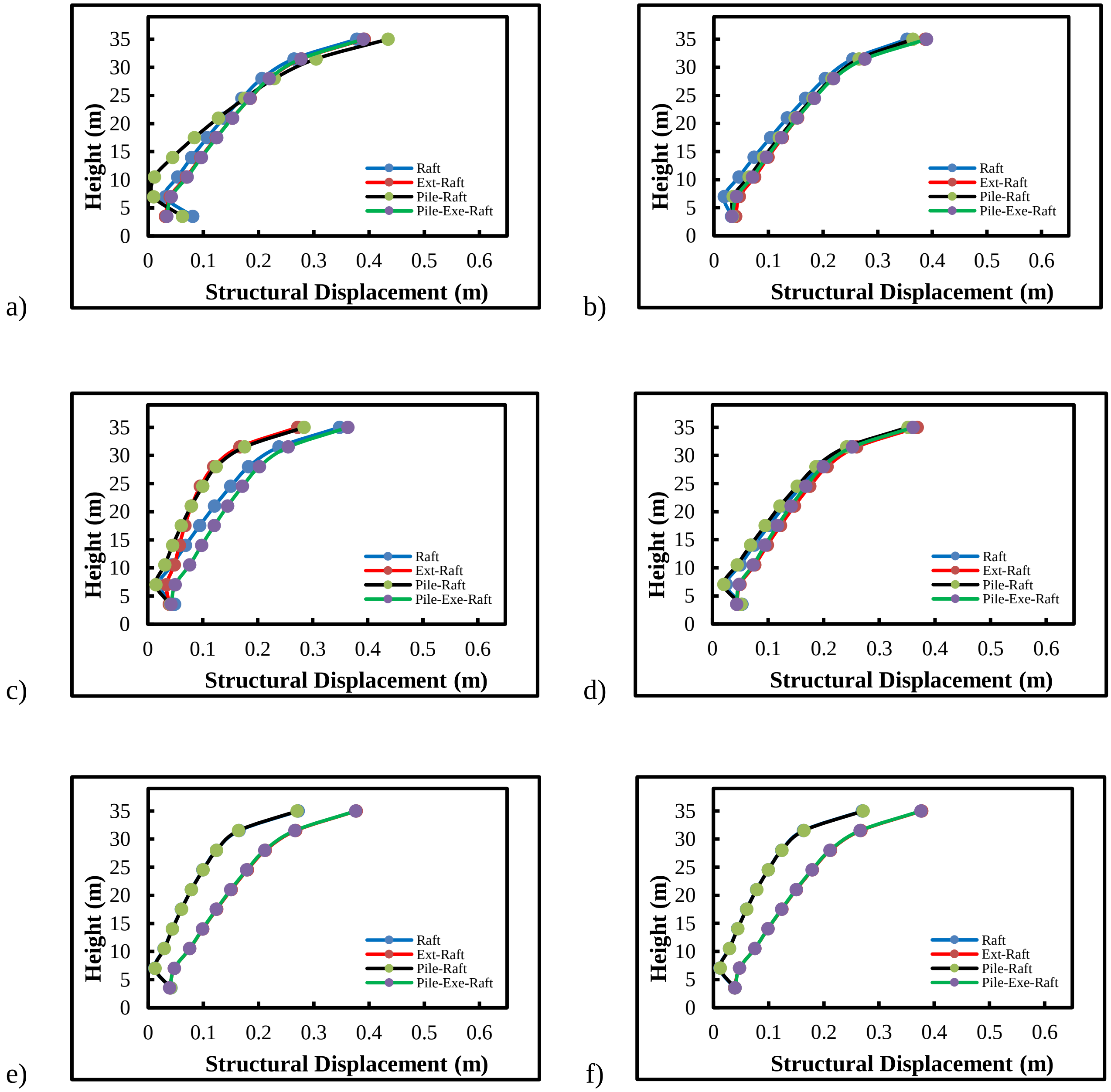


Figure 53: Structural displacement under Mirpur earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 53a shows that during the Mirpur earthquake, loose soil with fine particles at a depth of 15 meters had a slightly more pronounced impact on the pile raft in the X direction. In Figure 53b, coarse particles had an equal impact on all foundations, but the pile foundation experienced less displacement. Structures supported by pile raft foundations encountered greater structural displacement in the fine particle soil, measuring 0.4344 meters. Additionally, the pile with extended raft experienced a maximum displacement of 0.3896 meters in coarse particle soil. In summary, the pile raft suffered a slightly higher displacement in fine particles, and coarse particles improved the pile foundation, exhibiting less structural displacement than fine particles under the Mirpur earthquake in the X direction.

Figure 53c reveals that during the Mirpur earthquake, a 2-meter engineered fill with loose soil containing fine particles at a depth of 13 meters experienced more pronounced effects on the pile with an extended raft in the X direction. Additionally, Figure 53d indicates that coarse particles had the maximum impact on the extended raft but underwent more displacement than fine particles on other foundations. The analysis of coarse particles indicates that the earthquake applied greater dynamic pressure on pile with extended foundations. Structures supported by pile with extended raft foundations encountered greater structural displacement in the fine particle soil, measuring 0.3636 meters. Furthermore, the extended raft observed a maximum displacement of 0.3678 meters in coarse particle soil in the X direction under the influence of the Mirpur earthquake. To sum up, the pile with an extended raft suffered a slightly higher displacement than other foundations, and coarse particles exhibited more structural displacement than fine particles on it

Figure 53e and Figure 53f shows that natural soil experiences a lesser amount of displacement compared to all other soil types. Both pile with extended raft and extended raft exhibit a displacement of 0.3765 meters in both soil profiles, while pile raft and raft foundation demonstrate the same displacement value of 0.27 meters in the X direction under the Mirpur earthquake. However, the graphs indicate identical displacement patterns, suggesting that the Mirpur earthquake has a similar impact on natural soil with the GWT and natural soil without GWT. Although the graphs clearly show that the pile doesn't significantly affect structural displacement, the absence of accuracy in the results is evident. In conclusion, the graphs indicate that pile with extended raft experiences the maximum structural displacement under the Mirpur earthquake in the X direction.

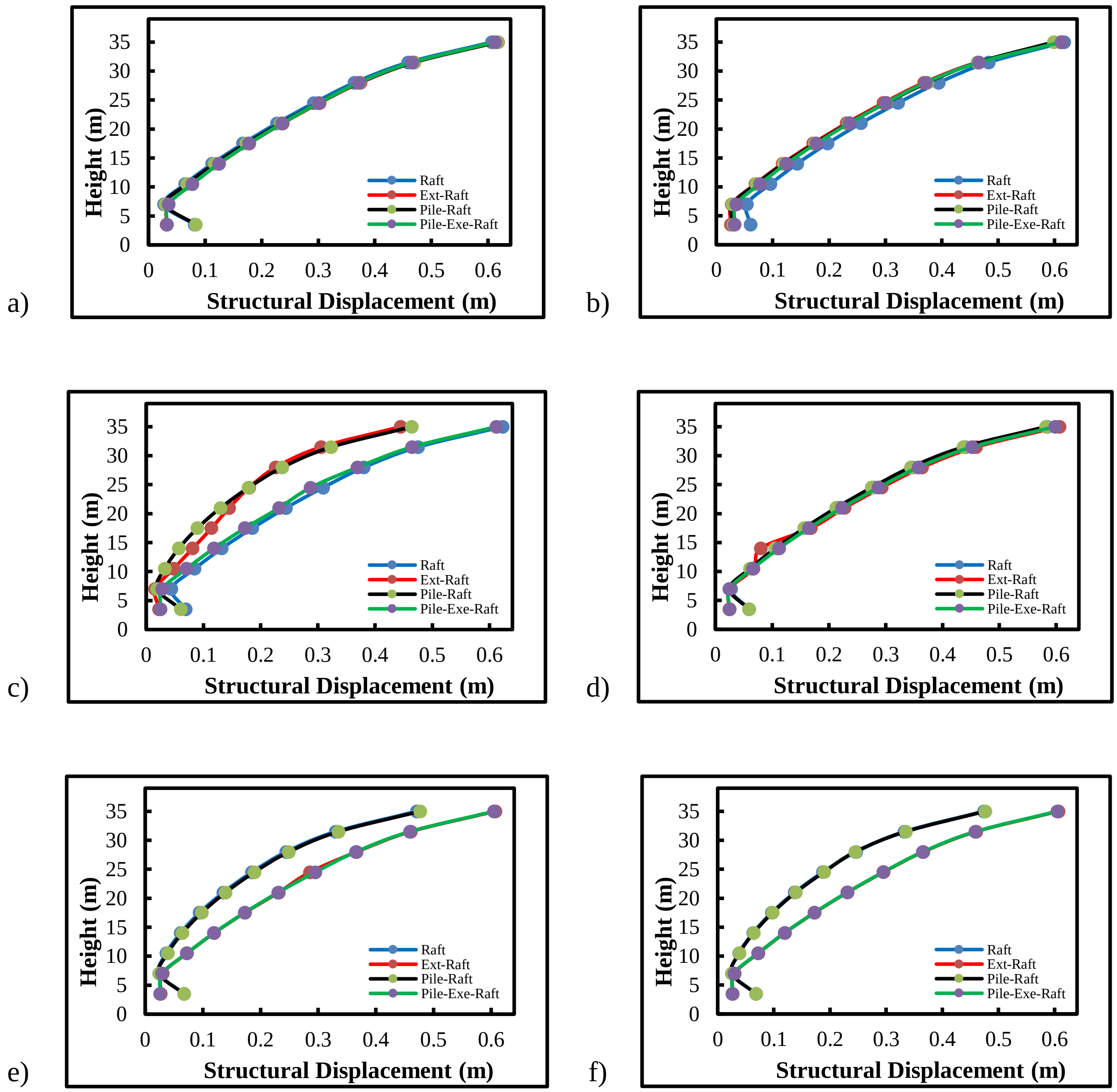


Figure 54: Structural displacement under Mirpur earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 54a shows that during the Mirpur earthquake, loose soil with fine particles at a depth of 15 meters had a slightly more pronounced impact on the extended raft in the Y direction. Additionally, Figure 54b indicates that coarse particles had an equal impact on all foundations, but the pile foundation experienced more displacement than other foundations. Structures supported by extended raft foundations encountered greater structural displacement in the fine particle soil, measuring 0.6174 meters. Furthermore, the pile with extended raft experienced a maximum displacement of 0.6124 meters in coarse particle soil. In summary, the expansion in the raft suffered a slightly higher displacement in both fine and coarse particles, but the structural displacement is almost the same in both types of particles under the Mirpur earthquake in the Y direction.

In Figure 54c, it's evident that during the Mirpur earthquake, a 2-meter engineered fill with loose soil containing fine particles at a depth of 13 meters experienced more pronounced effects on the raft in the Y direction. Moreover, Figure 54d indicates that coarse particles had the maximum impact on the extended raft but underwent more displacement than fine particles on both pile raft and extended foundations. The analysis of coarse particles suggests that the earthquake applied greater dynamic pressure on extended foundations. Structures supported by raft foundations encountered greater structural displacement in the fine particle soil, measuring 0.6230 meters. Additionally, the extended raft observed a maximum displacement of 0.6059 meters in coarse particle soil in the Y direction under the influence of the Mirpur earthquake. In summary, the pile with raft suffered a slightly higher displacement than other foundations, and coarse particles exhibited more structural displacement than fine particles on it.

In Figure 54e and Figure 54f, it is evident that natural soil undergoes less displacement compared to other soil types. Both pile with extended raft and extended raft exhibit a displacement of 0.6050 meters in both soil profiles, while pile raft and raft foundation show the same displacement value of 0.4750 meters in the Y direction under the Mirpur earthquake. However, the graphs reveal similar displacement patterns, suggesting that the Mirpur earthquake has a comparable impact on natural soil with the GWT and natural soil without GWT. To summarize, the graphs demonstrate that the pile with extended raft experiences the maximum structural displacement under the Mirpur earthquake in the Y direction

4.5.2 Story Drift Curves

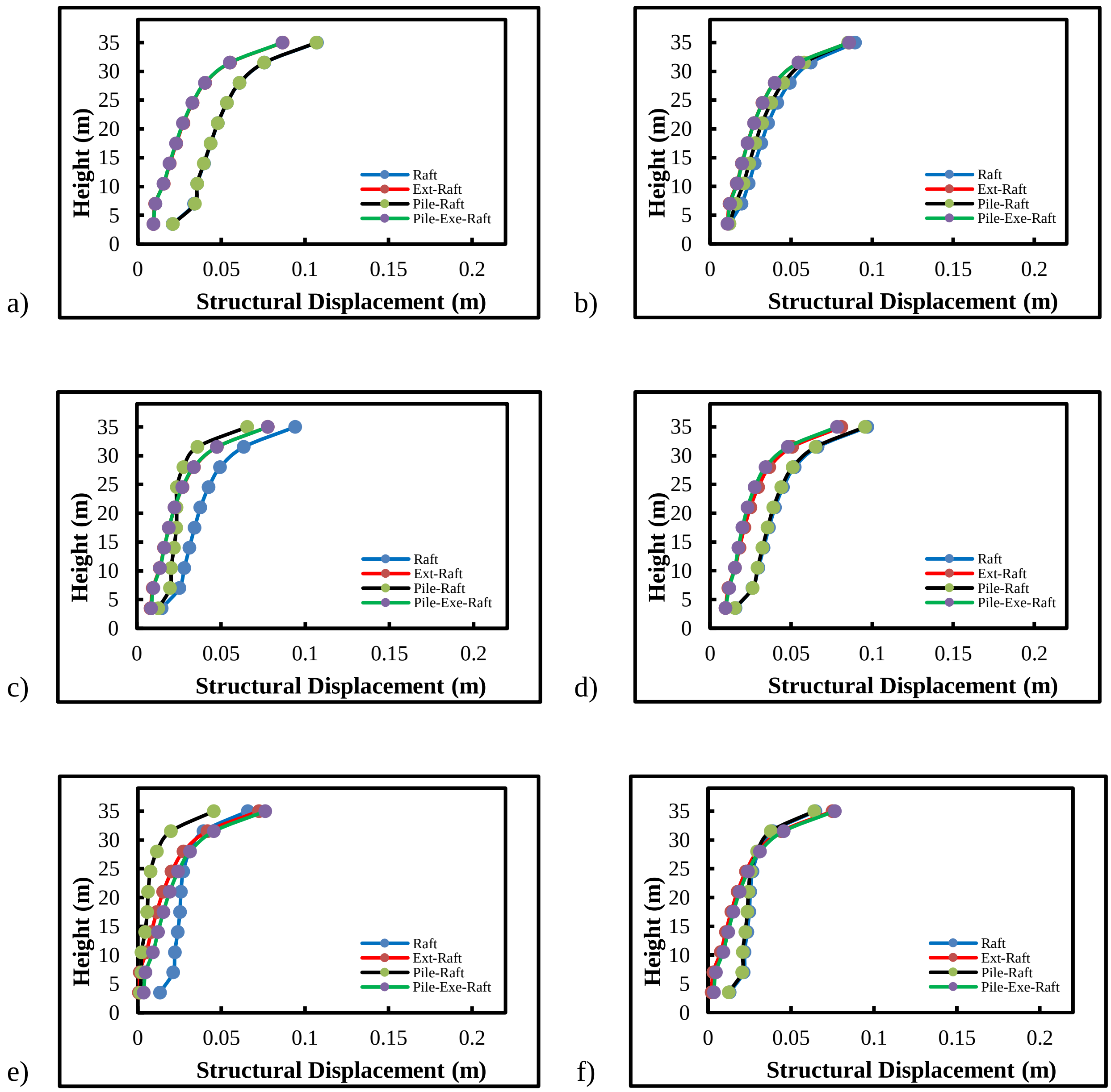


Figure 55: Story drift under Kashmir earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 55a illustrates that, during the Kashmir earthquake, loose soil with fine particles at a depth of 15 meters experienced more significant effects on the raft foundation. Raft foundations encountered 0.107 meters of story drift in the X direction. However, Figure 55b shows that the raft foundation experienced 0.089 meters of story drift in the coarse particles. This data indicates that these raft foundations exhibited the worst behavior regarding story drift. Furthermore, the story drift in pile foundations with extended rafts and extended rafts alone is the same and yields convenient results. This implies that the addition of an extended raft did not have a significant impact on story drift behavior. However, it's important to note that pile foundations did not seem to affect story drift behavior during the earthquake.

Figure 55c shows that a 2-meter layer of engineered fill on top of 13 meters of loose soil with fine particles experienced more pronounced effects in the raft foundation. Both pile raft and raft foundations encountered 0.094 meters of story drift in the X direction. However, according to Figure 55d, the raft foundation also exhibited 0.0971 meters of story drift in the coarse particles. This data suggests that these raft foundations displayed the most unfavorable behavior concerning story drift. Moreover, the story drift in pile foundations with extended rafts and extended rafts alone has a minor difference. This suggests that the addition of an extended raft did not significantly impact story drift behavior. However, it's crucial to note that pile foundations did not appear to influence story drift behavior during the earthquake

Figures 55e and 55f shows that natural soil with a GWT and it experienced more pronounced effects in the pile with extended raft foundation. It underwent 0.0763 meters of story drift in the X direction; however, Figure 55f reveals that the pile raft foundation was most affected by GWT. This data suggests that these pile with extended raft foundations displayed the most unfavorable behavior concerning story drift. In summary, based on Figure 55, it can be concluded that soil with fine particles exhibits more story drift in raft foundations, and a 2-meter engineered fill can mitigate the story displacement in fine soil but is less effective in coarse soil. The results also indicate that GWT does not significantly affect foundations, except for pile raft, where it notably increases story drift in the X direction under Kashmir earthquake conditions

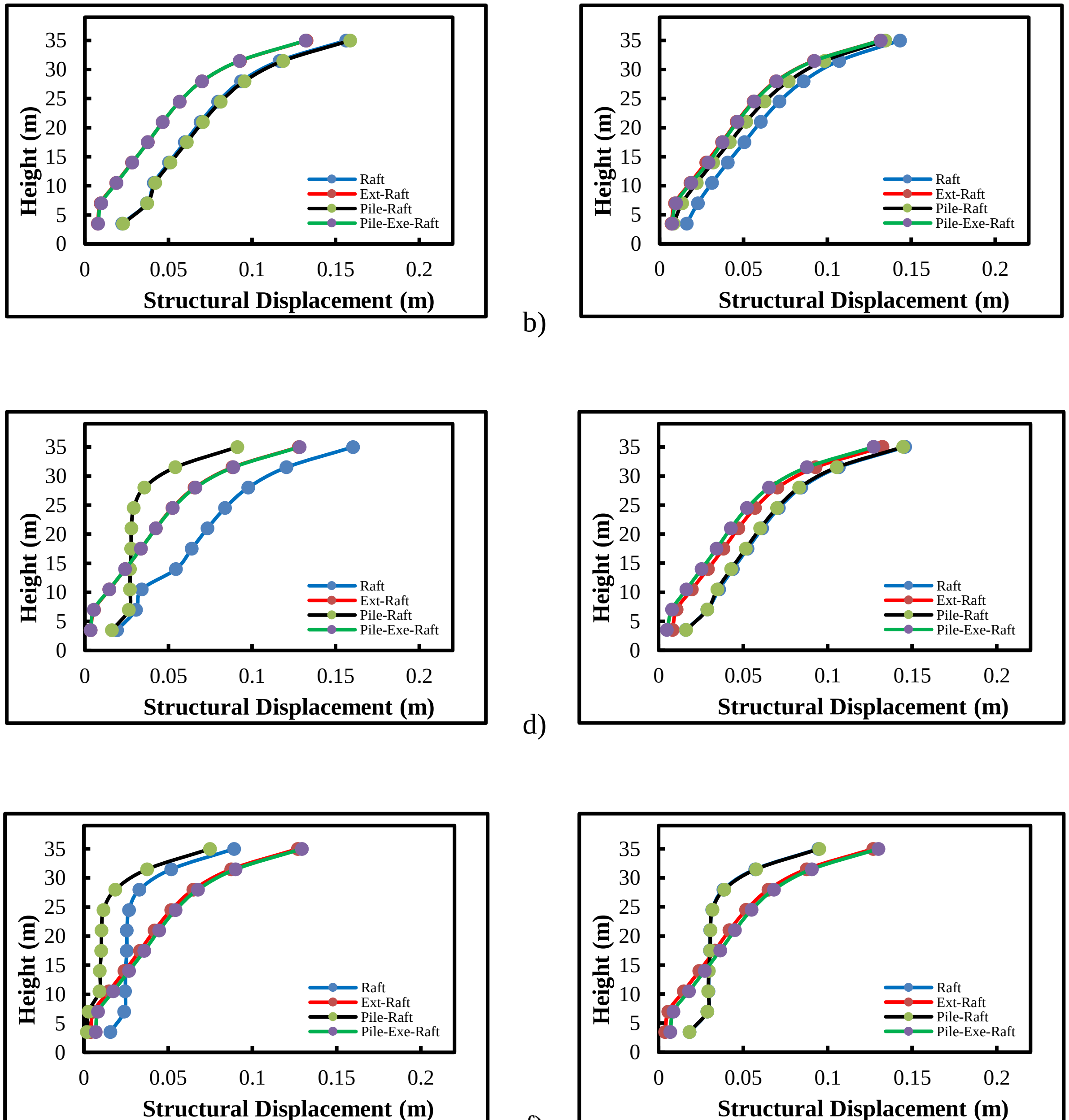


Figure 56: Story drift under Kashmir earthquake in Y direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 56a shows that, under the Kashmir earthquake, loose soil containing fine particles at a depth of 15 meters showed more pronounced effects on both pile raft and raft foundations. Both foundations experienced 0.158 meters of story drift in the Y direction. In contrast, Figure 56b indicates that the raft foundation demonstrated 0.143 meters of story drift in the coarse particles. This data suggests that these raft foundations displayed the most unfavorable behavior in terms of story drift. Additionally, the story drift in pile foundations with extended rafts and extended rafts alone is identical and provides convenient results. This suggests that the introduction of an extended raft did not significantly influence story drift behavior. It's noteworthy, however, that pile foundations did not appear to impact story drift behavior during the earthquake.

Figure 56c reveals that a 2-meter layer of engineered fill atop 13 meters of loose soil with fine particles had more pronounced effects on the raft foundation. Both pile raft and raft foundations experienced 0.160 meters of story drift in the Y direction. However, as shown in Figure 56d, the raft foundation also demonstrated 0.145 meters of story drift in the coarse particles. This data implies that these raft foundations exhibited the least favorable behavior regarding story drift. Additionally, the story drift in pile foundations with extended rafts and extended rafts alone exhibits a minor distinction. This suggests that the inclusion of an extended raft did not significantly alter story drift behavior. However, it's essential to note that pile foundations did not seem to impact story drift behavior during the earthquake.

Figures 56e and 56f illustrate that natural soil with a GWT experienced more prominent effects in the pile with an extended raft foundation. It registered 0.13 meters of story drift in the Y direction; however, Figure 38f highlights that the pile raft foundation was most impacted by GWT. This data implies that these pile with extended raft foundations exhibited the most unfavorable behavior regarding story drift. In summary, drawing from Figure 56, it can be inferred that soil with fine particles tends to show more story drift in raft foundations. A 2-meter engineered fill can alleviate story displacement in fine soil but proves less effective in coarse soil. Additionally, the results suggest that GWT does not significantly affect foundations, except for pile raft, where it notably increases story drift in the X direction under Kashmir earthquake conditions. Furthermore, the Kashmir earthquake exhibits similar behavior in both the X and Y components but demonstrates greater intensity in the Y direction.

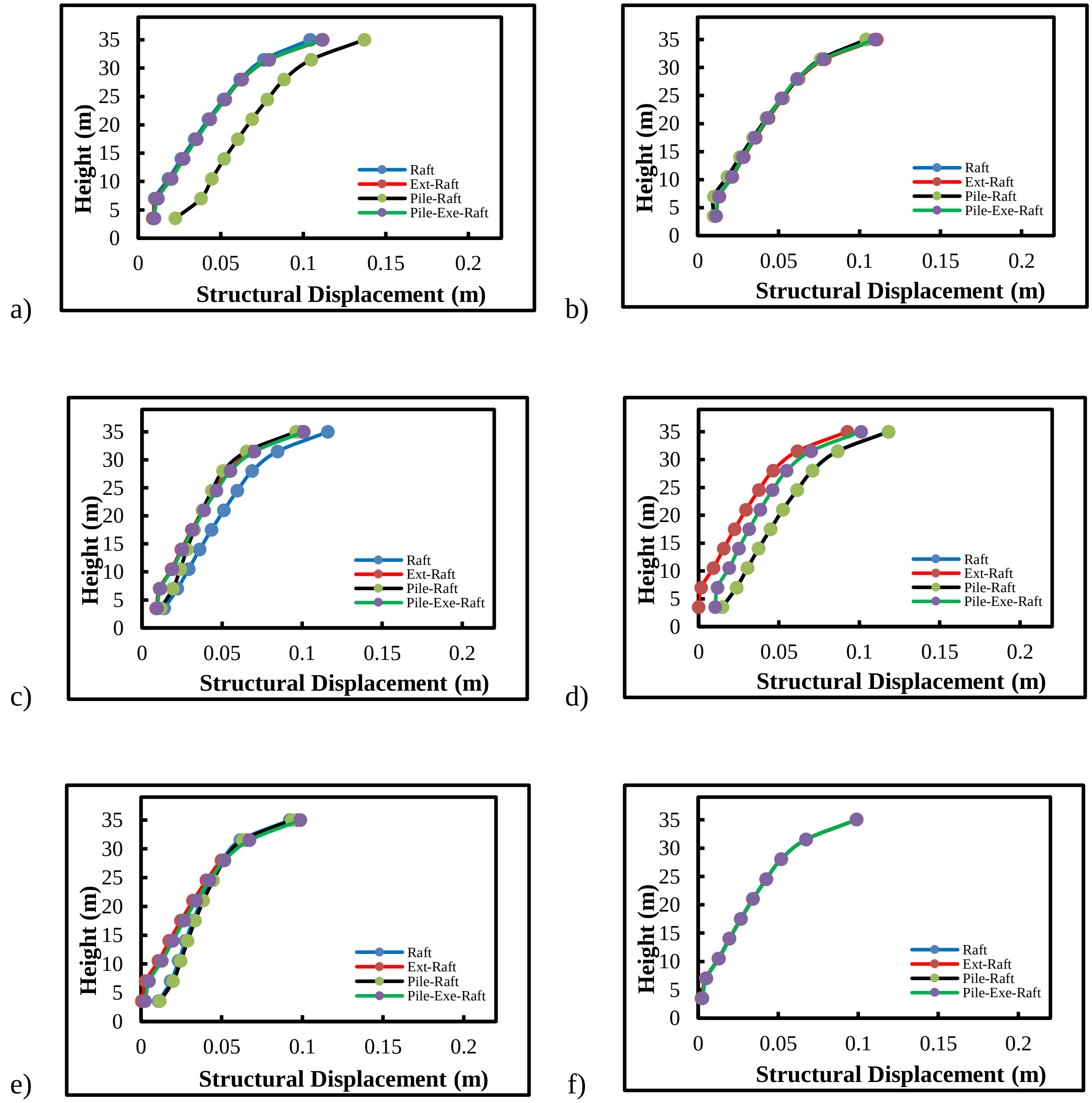


Figure 57: Story drift under Mirpur earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 57a reveals that, during the Mirpur earthquake, loose soil with fine particles at a depth of 15 meters had more pronounced effects on pile raft foundations. These foundations experienced 0.137 meters of story drift in the X direction. Conversely, as shown in Figure 57b, the extended raft foundation displayed a maximum story drift of 0.11 meters in the coarse particles. This data implies that both pile raft and extended raft foundations exhibited the least favorable behavior in terms of story drift. Moreover, the story drift in pile foundations is influenced by various soil particles, while the rest of the foundation types exhibit similar behavior in both soils. This suggests that the introduction of an extended raft did not significantly alter story drift behavior. However, it's noteworthy that pile foundations appear to impact story drift behavior during the earthquake.

Figure 57c shows that a 2-meter layer of engineered fill on top of 13 meters of loose soil with fine particles had more pronounced effects on the raft foundation, with 0.116 meters of story drift in the X direction. However, as depicted in Figure 57d, the raft foundation also exhibited 0.118 meters of story drift in the coarse particles. This data implies that these raft foundations displayed the least favorable behavior concerning story drift. Additionally, Extended raft foundations had the most pronounced effects in both soils. This result also suggests that, upon comparing Figures 4.40, a 2-meter layer of engineered fill improved the structural behavior in fine soil but did not show the same improvement in coarse soil.

Figures 57e and 57f demonstrate that natural soil with a GWT had more pronounced effects on the pile with an extended raft foundation. It recorded 0.098 meters of story drift in the X direction; however, Figure 38f highlights that the pile with an extended raft foundation was most affected by GWT. This data implies that these foundations exhibited the most unfavorable behavior concerning story drift. In summary, based on Figure 4.44, it can be concluded that soil with fine particles tends to exhibit more story drift in pile raft foundations. A 2-meter engineered fill can mitigate story displacement in fine soil but proves less effective in coarse soil. Additionally, the results suggest that GWT does not significantly affect foundations, except for the pile with an extended raft, where it notably increases story drift in the X direction under the Mirpur earthquake.

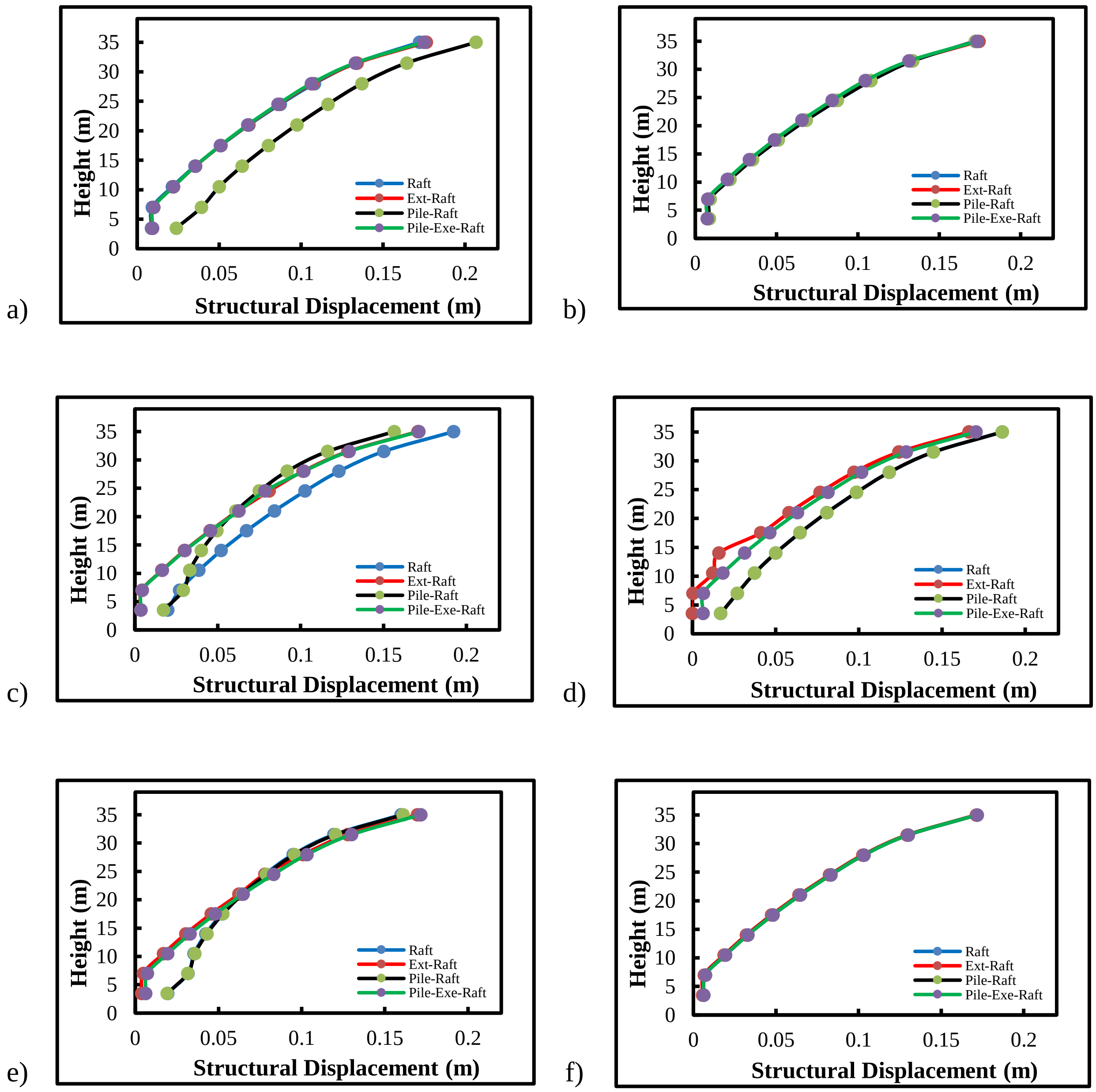


Figure 58: Story drift under Mirpur earthquake in Y direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle, d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

Figure 58a indicates that, amid the Mirpur earthquake, loose soil with fine particles at a depth of 15 meters had more pronounced effects on pile raft foundations. These foundations recorded 0.206 meters of story drift in the Y direction. In contrast, as depicted in Figure 58b, the extended raft foundation displayed a maximum story drift of 0.175 meters in the coarse particles. This data suggests that both pile raft and extended raft foundations exhibited the least favorable behavior in terms of story drift. Furthermore, the story drift in pile foundations is influenced by various soil particles, while the remaining foundation types exhibit similar behavior in both soils. This implies that the introduction of an extended raft did not significantly alter story drift behavior. However, it's noteworthy that pile foundations seem to impact story drift behavior during the earthquake.

Figure 58c reveals that a 2-meter layer of engineered fill on top of 13 meters of loose soil with fine particles had more pronounced effects on the raft foundation, resulting in 0.192 meters of story drift in the Y direction. However, as shown in Figure 58d, the raft foundation also displayed 0.186 meters of story drift in the coarse particles. This data implies that these raft foundations exhibited the least favorable behavior concerning story drift. Additionally, Extended raft foundations had the most pronounced effects in both soils. This result also suggests that, upon comparing Figures 4.41, a 2-meter layer of engineered fill improved the structural behavior in fine soil but did not show the same improvement in coarse soil.

Figures 58e and 58f illustrate that natural soil with a GWT had a more pronounced impact on the pile with an extended raft foundation, resulting in a recorded 0.172 meters of story drift in the Y direction. However, Figure 4.45f emphasizes that the pile with an extended raft foundation was most influenced by GWT. This data suggests that these foundations displayed the most unfavorable behavior concerning story drift. In summary, drawing from Figure , it can be concluded that soil with fine particles tends to experience more story drift in pile raft foundations. A 2-meter layer of engineered fill can alleviate story displacement in fine soil but proves less effective in coarse soil. Additionally, the results suggest that GWT does not significantly affect foundations, except for the pile with an extended raft, where it notably increases story drift in the Y direction under the Mirpur earthquake. Furthermore, similar to the Kashmir earthquake, the Mirpur earthquake also demonstrates comparable behavior in both the X and Y components but exhibits greater intensity in the Y direction.

4.6 Discussion

On the bases of results, it is clear that the use of a pile foundation system with an extended raft emerges as the most efficient (almost half of raft foundation) choice when dealing with non-liquefiable soil subjected to static and dynamic loading conditions. This combination offers superior resistance to differential settlement, a critical factor in maintaining the structural integrity of buildings. Furthermore, the extended raft provides a larger surface area for distributing the heavy loads of structures, which is crucial for stability. It's worth noting that soil composed of coarse particles exhibits excellent behavior in this context, offering stable support. Conversely, soils with fine particles are deemed less effective in settlement analysis due to their propensity to compress and settle more easily. On the other hand, an engineered fill soil overlay is highly commendable for addressing liquefaction and settlement concerns, and it enhances the soil's bearing capacity to accommodate substantial structures. However, it should be noted that such soil may have a lower capacity to absorb loads when compared to loosen soil with coarse particles, making the selection of foundation systems a matter of careful consideration and site-specific analysis. The reason behind the effective behavior of coarse particles is their stiffness factor. Coarse particle soil has a stiffness factor of 60,000 KN/m^2, which is higher than that of fine particles (15,000 KN/m^2) and engineered fill soil (20,000 KN/m^2). Consequently, it performs better compared to fine soil and engineered fill soil.

The findings from liquefaction analysis conducted under static loading conditions, revealing consistent behavior between liquefiable and non-liquefiable soils, serve as compelling evidence that liquefaction indeed occurred under dynamic loading conditions. This underscores the critical influence of dynamic forces on soil behavior. In response to such seismic challenges, a pile raft foundation system emerges as the more suitable choice for liquefiable soils and it suffered only 40mm of liquefaction during the Kashmir earthquake and 50mm during the Mirpur earthquake, while other foundations experienced approximately 80mm of liquefaction, primarily due to its capacity to effectively reduce settlement rates. Soils enriched with engineered fill material and coarse particles as input parameters demonstrate remarkable efficiency and stability, displaying consistent performance under both dynamic and static loading scenarios. In contrast, soils comprising predominantly fine particles exhibit poor results when subjected to dynamic loading, emphasizing the significance of soil composition and the imperative need for robust foundation selection in regions prone to seismic activities.

The analysis of superstructure behavior in various foundation types provides valuable insights. In non-liquefiable soil, both pile with extended raft and raft foundations demonstrate relatively similar and effective performance. However, when dealing with liquefiable soil conditions, pile-raft and raft foundations emerge as more preferable options, with comparable results in terms of structural damage. Interestingly, the data does not exhibit a discernible pattern, particularly in the context of story drift and displacement, suggesting that the presence of piles does not significantly impact the superstructure's behavior. The superstructure's symmetric nature also plays a role, as the results indicate that it is more influenced in the Y direction, as evidenced by dominant displacement and story drift values in that direction. Additionally, it's worth noting that some graphs indicate limited dynamic effects of earthquakes on the superstructure, leading to less efficient results in the assessment of structural damage. These findings underscore the complex interplay between soil conditions, foundation types, and structural responses in seismic events, emphasizing the need for comprehensive analysis and design considerations.

Urban growth is the primary reason for the expansion of built-up areas for accommodation and commercial purposes, compelling engineers to develop barren land for construction. However, proper preparation of this land for construction is essential. According to a rough estimation by Shah et al. (2021), over 80% of the once-barren land in Islamabad city has been converted to construction since 1979. The process often involves the cut and fill method to level the barren land, making it suitable for construction. Soil that has been cut undergoes proper consolidation and compaction, whereas fill soil often lacks these processes due to the time-intensive nature of proper compaction and consolidation. As a result, fill soil commonly experiences settlement problems. The presented study addresses such conditions and proposes the use of a pile with an extended raft as a more sustainable approach to mitigate settlement in fill soil. However, the study also emphasizes the necessity of designing foundations after a thorough investigation of soil conditions, particularly concerning liquefaction. The study suggests that an extended raft is less effective for combating liquefaction, hence foundation design must include proper soil investigation to address this issue. For areas prone to liquefaction, the study recommends a pile-raft approach, where factors such as the length, number, diameter, and location of piles become significantly important.

Moreover, when settlement is a more dominant factor than liquefaction, the expansion in the raft should be prioritized. Therefore, an extended raft is suggested as a crucial element in the design to tackle settlement issues in fill soil conditions. Additionally, an amendment in the building regulations is proposed to mandate the provision of extended rafts by builders. Engineered fill soil, with an increased stiffness factor, enhances soil stability. Therefore, an engineered fill overlay could be a more efficient approach for loose soils.

4.7 Summary

In this study, we conducted a parametric investigation of settlement patterns for mid-rise buildings, considering various soil profiles. The analysis involved 24 different building models with varying foundations and soil combinations. It's essential to note that the behavior of all models varied significantly under different soil profiles and foundation types. A noteworthy innovation arising from this research was the extended-raft foundation, which yielded promising results. Specifically, it demonstrated an effective reduction in settlement. Nevertheless, it should be acknowledged that extended-raft foundations might exert increased pressure and loading, potentially resulting in water expulsion during liquefaction. Consequently, pile-raft foundations exhibited more effective behavior in resisting liquefaction. When dealing with non-liquefiable soil, pile foundations with extended raft structures proved particularly efficient at reducing settlement rates. Furthermore, the results suggested that soils with coarse particles displayed a robust resistance to settlement under both static and dynamic loading conditions. Additionally, areas with 2 meters of engineered fill soil exhibited a greater capacity to absorb static and dynamic loading. On the other hand, the superstructure did not yield satisfactory results, primarily due to the absence of a discernible pattern in the data. In most cases, both pile-raft and raft foundations exhibited similar behavior in terms of story drift and displacement. Similarly, pile foundations with extended raft structures and extended raft foundations displayed comparable results. Based on the results, it's evident that the superstructure comprises a symmetric building. It's also clear that the structure is more significantly affected in the Y direction as opposed to the X direction. This is due to the fact that the dominant values for structure displacement and story drift occur in the Y direction. It's worth noting that some graphs indicated that the dynamic effects of earthquakes did not significantly impact the superstructure, resulting in inefficient results for assessing structural damage.

CHAPTER 5

Summary and Future work

5.1 Summary

The study addresses the challenges arising from rapid global urbanization, focusing on the impact of cut and fill processes on soil stability and structural integrity. Utilizing PLAXIS 3D, the researchers created 24 models with various soil profiles and foundation strategies to conduct static and dynamic analyses. Results indicate that extending raft foundations proves effective and sustainable, reducing settlement by approximately 25% in fine particles and 50% in coarse particles. However, this method may increase pressure, potentially causing water expulsion during liquefaction. Pile-raft foundations emerged as more effective in liquefaction scenarios, experiencing minimal liquefaction (40mm during the Kashmir earthquake, 50mm during the Mirpur earthquake). Soils with coarse particles effectively resisted settlement under static and dynamic loading conditions. The analysis of superstructural behavior revealed an absence of a discernible pattern in story drift curves and displacement graphs, attributed to soil inefficiency in transmitting dynamic loads. Notably, both earthquakes exerted dominant forces in the Y direction. Importantly, the study identifies a gap in prior investigations, as there has been no exploration of settlement in structures on variable slopes with differing soil profiles. The primary objective is to offer an in-depth analysis and cost-effective solutions to mitigate structural settlement, providing valuable insights for urban development and construction practices amidst rapid global urbanization.

5.2 Future Work

The study focused on vertical symmetric structures, urging future research to include asymmetric buildings and different geographic zones for a more comprehensive understanding. It also suggests expanding analyses to various building types and heights and refining liquefaction assessments by considering different depths of the groundwater table and incorporating soil properties for more accuracy.

CHAPTER 6

Conclusions & Recommendations

6.1 Conclusions

The pile-raft foundations are usually considered to be rigid enough to guarantee the restraint against dynamic loading and Static loading however the soil bearing capacity also depends on soil type, input parameters, foundation width and foundation type.

also. On the basis of present study following conclusion can be drawn: -

1. Piles with extended rafts exhibit the most efficient settlement reduction rates, ranging from 25% to 70% under static load and 20% to 25% under dynamic loading. This reduction is relatively higher compared to all other foundations and is considered a key factor in non-liquefiable soil under both static and dynamic loading conditions. The combination of piles with extended rafts and extended rafts alone offers increased resistance against differential settlement, providing a larger area to transfer the heavy structural load.

2. Liquefaction analysis under static loading reveals similar behavior in liquefiable and non-liquefiable soils, signifying liquefaction under dynamic loading. The pile-raft system is recommended for liquefiable soil, showing minimal liquefaction (40mm for Kashmir earthquake, 50mm for Mirpur earthquake). Soils with engineered fill and coarse particles perform well under both dynamic and static loading, while fine particles yield poor results under dynamic loading.

3. Soil with coarse particles exhibits an effective reduction rate ranging from 0% to 70% under static load and 0% to 55% under dynamic load. However, soil with fine particles experiences a lower settlement reduction rate of 0% to 36% under static load and 0% to 30% under dynamic load. The results also reveal that an engineered fill overlay increases the bearing capacity of fine particle soil but does not yield efficient results when overlaid on soil with coarse particles.

4. The difference between pile with extended raft and extended raft under static load ranges from 0% to 5% and 0% to 15% under dynamic load in coarse soil. Extended raft absorbs

the maximum load on coarse particles, so only an extended raft may be sufficient where the soil contains coarse particles, making the foundation more economical and affordable structure to fulfill the 9th Sustainable Development Goal.

5. Superstructure behavior in pile with extended raft and raft is relatively same and consider to be more effective in non-liquefiable soil however pile-raft and raft foundation are more preferable in liquefiable soil and relatively have same result of structural damages. Based on the results, it is clear that the structure is more affected in the Y direction rather than the X direction because the structure's displacement and story drift have dominant values in the Y direction.
6. The superstructure's performance lacked consistency, as both pile-raft and raft foundations exhibited similar behavior in terms of story drift and displacement. The presence of piles did not significantly impact the symmetric building's behavior, and dynamic earthquake effects had limited impact, yielding inefficient structural damage assessments.

Urban growth drives the expansion of built-up areas, transforming barren land for construction. For settlements dominating over liquefaction, prioritizing raft expansion is suggested. In liquefaction-prone areas, a pile-raft approach is recommended, considering factors like pile length, number, diameter, and location. The study advocates for incorporating extended rafts in designs to address settlement issues in fill soil, proposing an amendment to building regulations for mandatory extended raft provision. Additionally, engineered fill with an increased stiffness factor is proposed for loose soils to enhance stability. An extended raft effectively bears the heaviest load on coarse particles, making it a cost-effective foundation where coarse soil prevails. Furthermore, a pile foundation with an extended raft, under extensive loading, provides resilience to the structure, and the extended raft has an effective settlement reduction rate on coarse particles. These are also considered economical and affordable compared to traditional pile foundations. Therefore, this approach is regarded as a sustainable option for structures, fulfilling the 9th Sustainable Development Goal, which emphasizes the development of resilient infrastructure with a focus on economic affordability.

6.2 Recommendations

The current study exclusively focused on vertical symmetric structures, limiting its scope to a specific type of building. To enhance the generality of our findings and understand their implications across a broader range of scenarios, it is imperative that future research includes

1. Asymmetric building types characterized by mass and plan irregularities, as well as different geographic zones. It's important to acknowledge that this study did not provide conclusive comparisons of settlement results using well-established methods.
2. The analysis was constrained to 10-story buildings. Expanding the scope to include settlement analysis across various types and heights of buildings holds the potential to unlock more comprehensive insights and advance our understanding of this field, ultimately contributing to improved construction and infrastructure practices.
3. To enhance the accuracy of liquefaction analysis results, this study positions the GWT at a depth of 6 meters. To further refine the analysis, consideration should be given to conducting assessments at various depths of the GWT. Additionally, the study does not currently account for the physical properties of the soil and the specific type of soil behavior concerning liquefaction. Therefore, incorporating a deeper understanding of these factors is essential for a more comprehensive liquefaction analysis.

REFERENCES

AbdelSalam, S. S., Sritharan, S., & Suleiman, M. T. (2011). LRFD resistance factors for design of driven H-piles in layered soils. *Journal of Bridge Engineering*, *16*(6), 739-748**.**

Alimohammadi, P., Kassim, K. A., Nazir, H., & Kharii, M. (2013). Influence of length to diameter ratio on the settlement of expanding pier due to radial consolidation in soft clay *Electronic Journal of Geotechnical Engineering*, *18*, 4217-4230.

Al-Taie, E. T., Al-Kalali, H. H., & Fattah, M. Y. (2019). Evaluation of settlement and bearing capacity of embankment on soft soil with reinforced geogrids. International Journal of Engineering Research & Technology (Ahmedabad), 8(6), 99-103.

Das, B., Advanced Soil Mechanics. Taylor & Francis, London & New York, 2008

Donald P Coduto. Geotechnical Engineering: Principles and Practices

Gündüz, B. (2008). Analysis of settlements of test embankments during 50 years-a comparison between field measurements and numerical analysis.

Hassan, A. M. (2019). studying the behaviour of deep excavation adjacent to old buildings using PLAXIS 3D. Journal of the Egyptian Society of Engineers, 58(1), 20-15.

Minnesota Department of Transportation, Pavement Design, 2007

Montgomery, J., & Karstunen, M. (2009). Modelling embankments with vertical drains–a comparison of numerical methods. Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4),

Özhan, H. O., Bayat, E. E., & Zanjani, E. Y. (2016). Dynamic Analysis of Buried Pipelines with Geogrid Reinforcement.

Saygili, G., Andresen, L., & Grimstad, G. Finite element analysis of the Saint Alban embankment failure with an anisotropic undrained strength model.

Abdoun, T., & Dobry, R. (2002). Evaluation of pile foundation response to lateral spreading. *Soil Dynamics and Earthquake Engineering*, *22*(9-12), 1051-1058.

Amornfa, K., Phienwej, N., & Kitpayuck, P. (2012). Current practice on foundation design of high-rise buildings in Bangkok, Thailand. Lowland technology international, 14(2, Dec), 70-83

Amornfa, K., Quang, H. T., & Tuan, T. V. (2022). 3D numerical analysis of piled raft foundation for Ho Chi Minh City subsoil conditions. *Geomechanics and Engineering*, *29*(2), 183-192.

Anastasopoulos, I. (2013). Structural damage of a 5-storey building: differential settlement due to construction of an adjacent building or because of construction defects. International Conference on Case Histories in Geotechnical Engineering, Chicago,

Ata, A., Badrawi, E., & Nabil, M. (2015). Numerical analysis of unconnected piled raft with cushion. *Ain Shams Engineering Journal*, *6*(2), 421-428.

Ayoubi, P., & Pak, A. (2017). Liquefaction-induced settlement of shallow foundations on two-layered subsoil strata. *Soil Dynamics and Earthquake Engineering*, *94*, 35-46.

Burland, J. B., Jamiolkowski, M. B., & Viggiani, C. (2009). Leaning Tower of Pisa: behaviour after stabilization operations. *ISSMGE International Journal of Geoengineering Case Histories*, *1*(3), 156-169.

Cho, J., Lee, J.-H., Jeong, S., & Lee, J. (2012). The settlement behavior of piled raft in clay soils. *Ocean Engineering*, *53*, 153-163.

Coduto, D. P. (2001). Foundation design. Pomona, California State Polytechnic University.

Cubrinovski, M., Bray, J. D., Taylor, M., Giorgini, S., Bradley, B., Wotherspoon, L., & Zupan, J. (2011). Soil liquefaction effects in the central business district during the February 2011 Christchurch earthquake. Seismological Research Letters, 82(6), 893-904.

Di Ludovico, M., Chiaradonna, A., Bilotta, E., Flora, A., & Prota, A. (2020). Empirical damage and liquefaction fragility curves from 2012 Emilia earthquake data. *Earthquake Spectra*, *36*(2), 507-536.

Dixit, J., Dewaikar, D., & Jangid, R. (2012). Assessment of liquefaction potential index for Mumbai city. *Natural Hazards and Earth System Sciences*, *12*(9), 2759-2768.

El-Garhy, B., Galil, A. A., Youssef, A.-F., & Raia, M. A. (2013). Behavior of raft on settlement reducing piles: Experimental model study. *Journal of Rock Mechanics and Geotechnical Engineering*, *5*(5), 389-399.

Fakhardin M. K., (2019). *Soil Settlement*, university of Kufa.

Gómez-Martínez, F., Millen, M. D., Costa, P. A., Romão, X., & da Fonseca, A. V. (2018). Potential relevance of differential settlements in earthquake-induced liquefaction damage assessment. 16th European Conference on Earthquake Engineering,

Guo, W., & Randolph, M. (1999). An efficient approach for settlement prediction of pile groups. *Geotechnique*, *49*(2), 161-179.

Hanash, A. A., Ahmed, M. D., & Said, A. I. (2019). Effect of Embedment Depth on Raft Foundation Settlement Under Seismic Load. IOP Conference Series: Materials Science and Engineering,

Henry, R. S., Lee, B.-Y., McGuigan, D., Finnegan, J., & Ashby, G. (2017). The 2016 Meinong Taiwan earthquake: learning from earthquakes report. Bulletin of the New Zealand Society for Earthquake Engineering, 50(3), 436-468.

Janalizadeh, A., & Zahmatkesh, A. (2015). Lateral response of pile foundations in liquefiable soils. *Journal of Rock Mechanics and Geotechnical Engineering*, *7*(5), 532-539.

Józefiak, K., Zbiciak, A., Maślakowski, M., & Piotrowski, T. (2015). Numerical modelling and bearing capacity analysis of pile foundation. Procedia Engineering, 111, 356-363.

Karamitros, D. K., Bouckovalas, G. D., & Chaloulos, Y. K. (2013). Seismic settlements of shallow foundations on liquefiable soil with a clay crust. Soil Dynamics and Earthquake Engineering, 46, 64-76.

Karamitros, D. K., Bouckovalas, G. D., Chaloulos, Y. K., & Andrianopoulos, K. I. (2013). Numerical analysis of liquefaction-induced bearing capacity degradation of shallow foundations on a two-layered soil profile. *Soil Dynamics and Earthquake Engineering*, *44*, 90-101.

Kashap, A. (2019). Bearing Capacity of Foundation Review Paper. Int. J. Eng. Res. Technol, 7(10), 62-66.

Katzenbach, R., Schmitt, A., & Turek, J. (2005). Assessing Settlement of High-Rise Structures by 3D Simulations. Computer-Aided Civil and Infrastructure Engineering, 20(3), 221-229.

Lambe, T. W., & Whitman, R. V. (1991). *Soil mechanics* (Vol. 10). John Wiley & Sons.

Kim, K. N., Lee, S.-H., Kim, K.-S., Chung, C.-K., Kim, M. M., & Lee, H. S. (2001). Optimal pile arrangement for minimizing differential settlements in piled raft foundations. *Computers and Geotechnics*, *28*(4), 235-253.

Labidul H. Barman, M. C., Gosh, J., Hossen, S. (2021). Comparison of cost and suitability of using raft and pile foundation for building.

Lee, J., Kim, Y., & Jeong, S. (2010). Three-dimensional analysis of bearing behavior of piled raft on soft clay. *Computers and Geotechnics*, *37*(1-2), 103-114.

Lin, L., Hanna, A., Sinha, A., & Tirca, L. (2017). High-rise building subjected to excessive settlement of its foundation: a case study. International Journal of Structural Integrity, 8(2), 210-221.

Luque, R., & Bray, J. D. (2020). Dynamic soil-structure interaction analyses of two important structures affected by liquefaction during the Canterbury earthquake sequence. *Soil Dynamics and Earthquake Engineering*, *133*, 106026.

Majik, R. K., & Savoikar, P. P. (2022). Ground modification techniques for deep soft soils sites in Goa region. Ground Improvement and Reinforced Soil Structures: Proceedings of Indian Geotechnical Conference 2020 Volume 2,

Millen, M., Rios, S., Quintero, J., & da Fonseca, A. V. (2020). Prediction of time of liquefaction using kinetic and strain energy. Soil Dynamics and Earthquake Engineering, 128,105898.

Millen, M., Viana da Fonseca, A., Quintero, J., Ferreira, C., Oztoprak, S., Oser, C., Bozbey, I., Aysal, N., Kosič, M., & Logar, J. (2021). Site classification using equivalent soil profiles for building- liquefaction interaction. Bulletin of Earthquake Engineering, 19, 3987-4012.

Mohamad, N., Razali, C., Hadi, A., Som, P., Eng, B., Rusli, M., & Mohamad, F. (2016). Challenges in construction over soft soil-case studies in Malaysia. IOP conference series: materials science and engineering,

Nguyen, D. D. C., Jo, S.-B., & Kim, D.-S. (2013). Design method of piled-raft foundations under vertical load considering interaction effects. *Computers and Geotechnics*, *47*, 16-27.

Okamura, M., Nelson, F., & Watanabe, S. (2019). Pre-shaking effects on volumetric strain and cyclic strength of sand and comparison to unsaturated soils. Soil Dynamics and Earthquake Engineering, 124, 307-316.

Özcebe, A. G., Giretti, D., Bozzoni, F., Fioravante, V., & Lai, C. G. (2021). Centrifuge and numerical modelling of earthquake-induced soil liquefaction under free-field conditions and by considering soil–structure interaction. *Bulletin of Earthquake Engineering*, *19*, 47-75.

Prabakar, J., Dendorkar, N., & Morchhale, R. (2004). Influence of fly ash on strength behavior of typical soils. *Construction and Building Materials*, *18*(4), 263-267.

Saygili, G., Andresen, L., & Grimstad, G. Finite element analysis of the Saint Alban embankment failure with an anisotropic undrained strength model.

Shahir, H., & Pak, A. (2010). Estimating liquefaction-induced settlement of shallow foundations by numerical approach. Computers and Geotechnics, 37(3), 267-279.

Shah, A., Ali, K., & Nizami, S. (2021). Spatio-temporal analysis of urban sprawl in Islamabad, Pakistan during 1979–2019, using remote sensing. GeoJournal, 1-14.

Shakeel, M., & Ng, C. W. (2018). Settlement and load transfer mechanism of a pile group adjacent to a deep excavation in soft clay. *Computers and Geotechnics, 96*, 55-72.

Shrestha, R., Tuladhar, A., & Zevenbergen, J. (2016). Exploring land governance in post disaster: a case of informal settlement. In: International Federation of Surveyors. Article of the month.

Small, J. C., & Liu, H. L. (2008). Time-settlement behaviour of piled raft foundations using infinite elements. *Computers and Geotechnics*, *35*(2), 187-195.

Su, L., Tang, L., Ling, X., Liu, C., & Zhang, X. (2016). Pile response to liquefaction-induced lateral spreading: a shake-table investigation. *Soil Dynamics and Earthquake Engineering*, *82*, 196-204.

Thiruvengadam, V., Wason, J., & Praseeda, K. Cost Modeling of Foundations of Reinforced Concrete Buildings Designed for Seismic Effects. 13th World Conference on Earthquake Engineering, Vancour, BC, Canada, Paper, Tsai, K., Hsiao, C. P., & Bruneau, M. (2000). Overview of building damages in 921 Chi-Chi earthquake. Earthquake Engineering and Engineering Seismology, 2(1), 93-108.

Uyanık, O. (2020). Soil liquefaction analysis based on soil and earthquake parameters. *Journal of Applied Geophysics*, *176*, 104004

Verdugo, R., & González, J. (2015). Liquefaction-induced ground damages during the 2010 Chile earthquake. *Soil Dynamics and Earthquake Engineering*, *79*, 280-295.

Wang, Y., Wang, Y., Kong, L., & Sun, Z. (2020). Post-liquefaction shearing behaviour of saturated gravelly soils: Experimental study and discrete element simulation. *Journal of Rock Mechanics and Geotechnical Engineering*, *12*(5), 1119-1130.

Yuan, Z., & Wang, L. (2009). Collapsibility and seismic settlement of loess. *Engineering Geology*, *105*(1-2), 119-123.

Zeng, C.-F., Zheng, G., Zhou, X.-F., Xue, X.-L., & Zhou, H.-Z. (2019). Behaviours of wall and soil during pre-excavation dewatering under different foundation pit widths. *Computers and Geotechnics*, *115*, 103169

APPENDIX

Appendix A

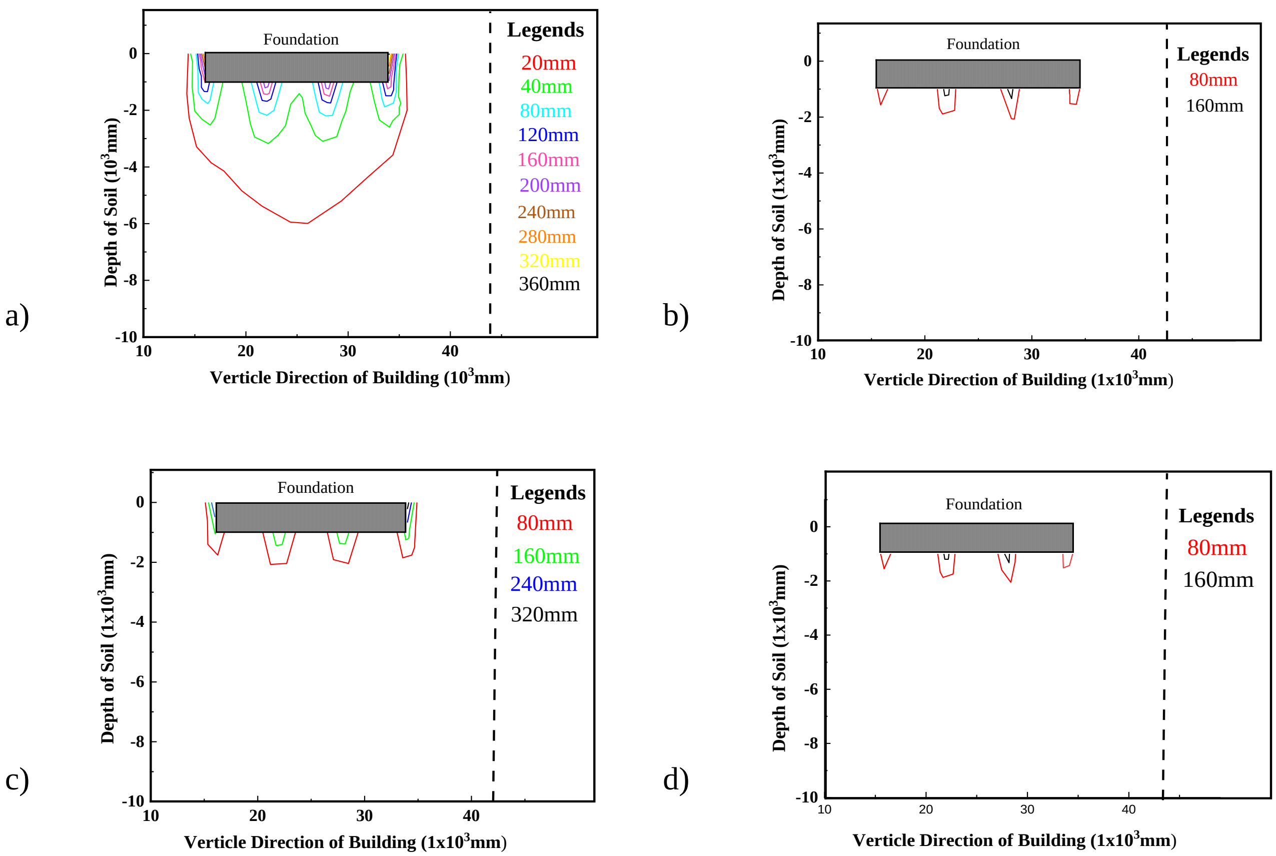


Figure A-1: Static Settlement on edge columns in 15m loose soil with fine particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft

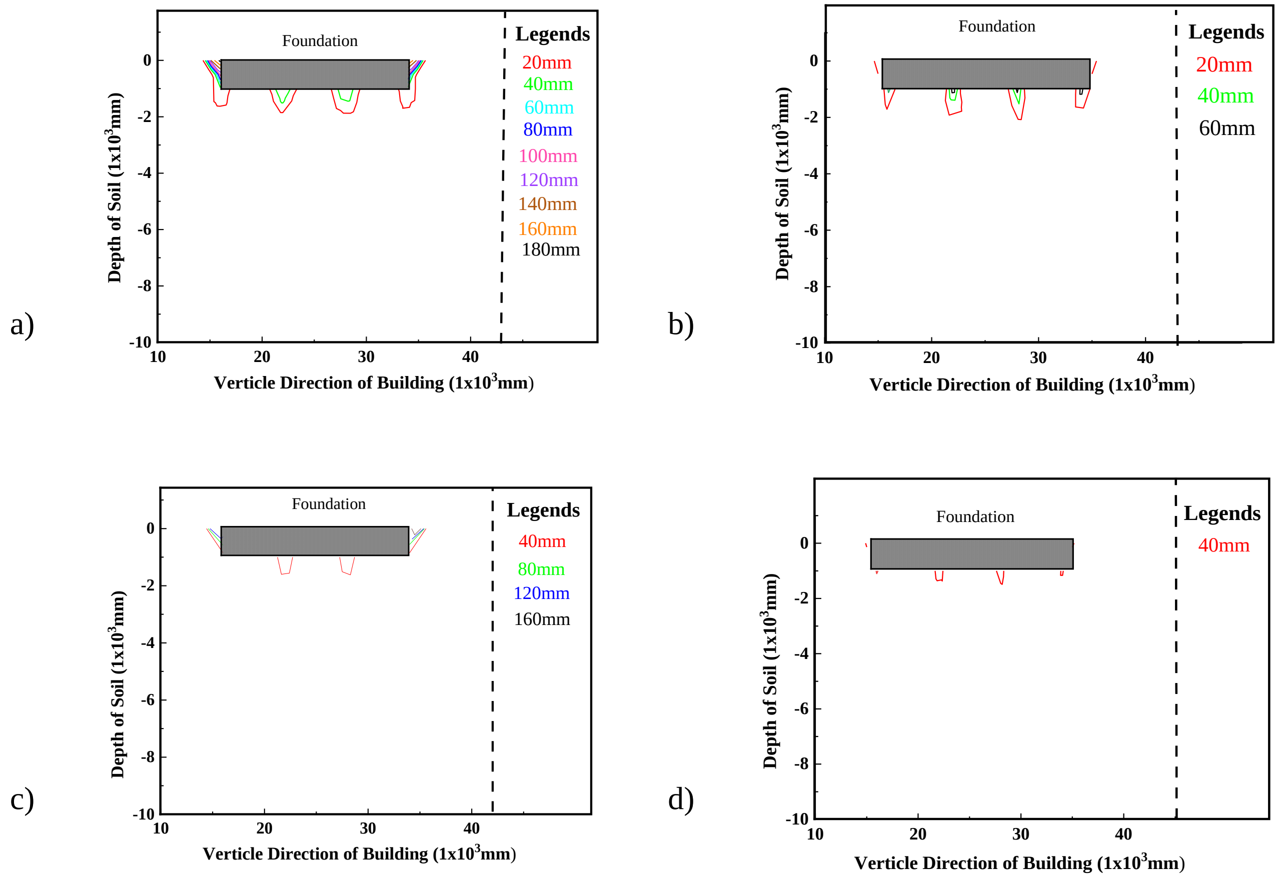
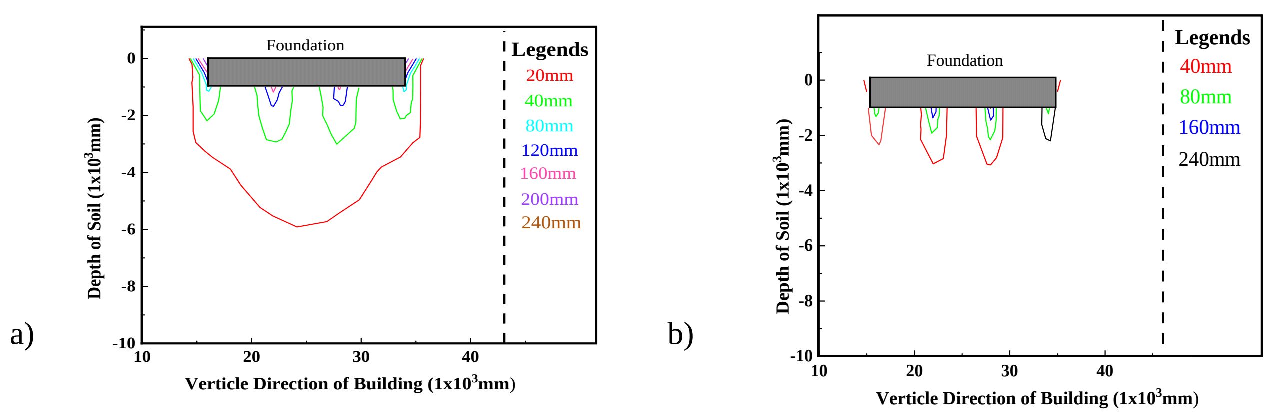


Figure A-2: Static Settlement on edge columns in 15m loose soil with course particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft



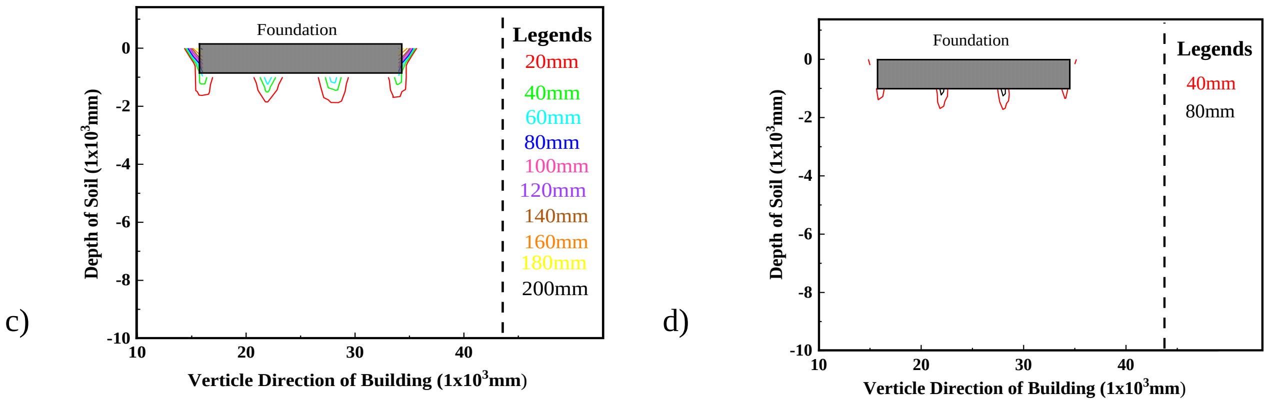


Figure A-3: Static Settlement on edge columns in 2m Engineered fill 13m loose soil with fine particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft

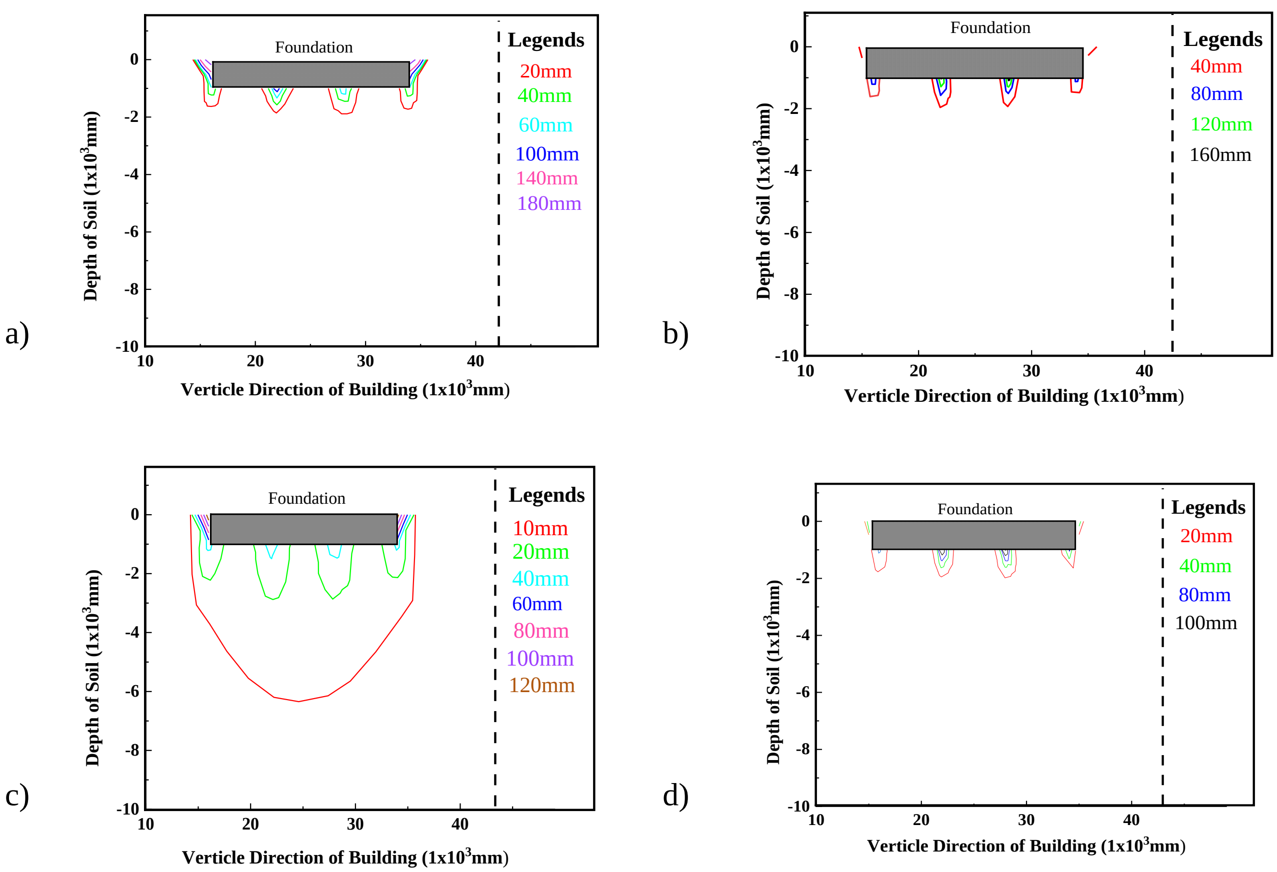


Figure A-4: Static Settlement on edge columns in 2m Engineered fill 13m loose soil with course particles; a) raft, b) extended raft, c) rile-raft, d) pile with extended raft

Appendix B

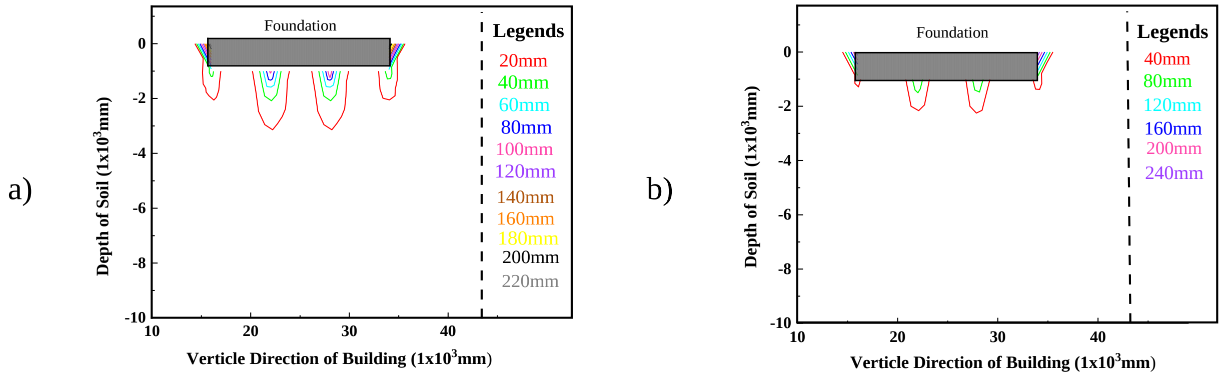


Figure B-1: Dynamic settlement on edge column in 15m loose soil with course particles raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

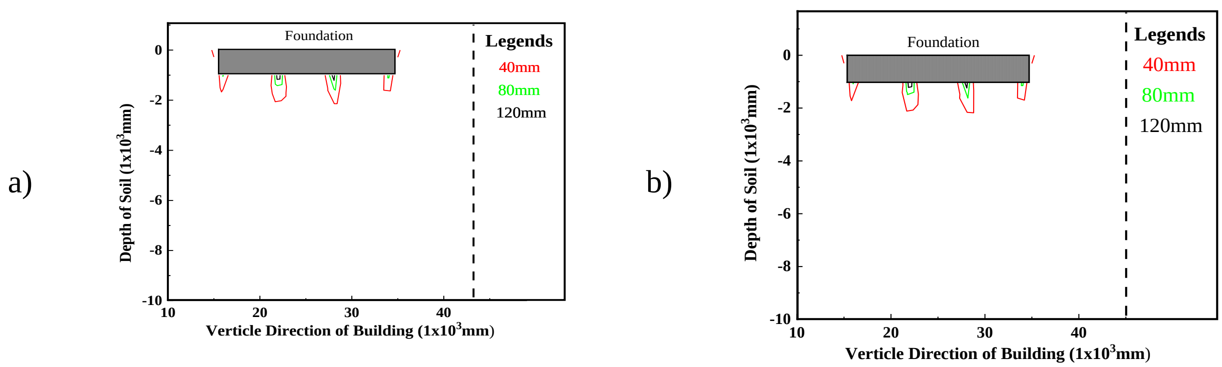


Figure B-2: Dynamic settlement on edge column in 15m loose soil with course particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

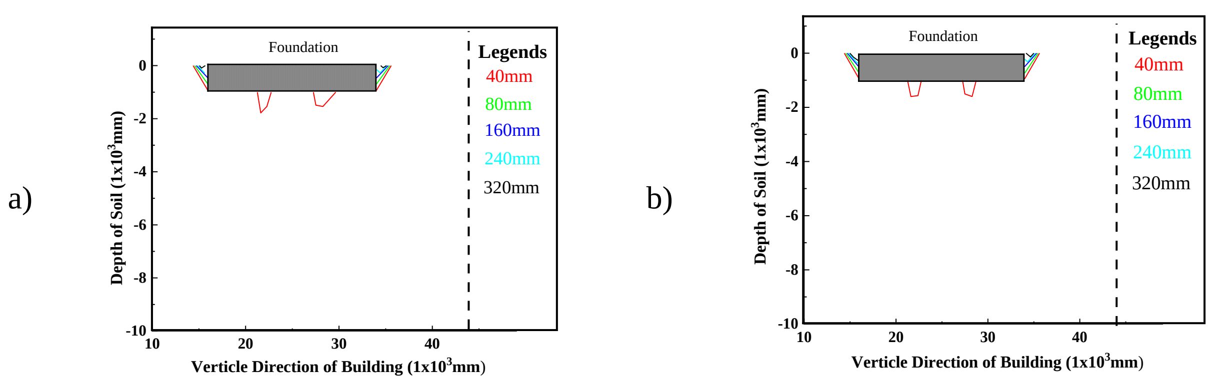


Figure B-3: Dynamic settlement on edge column in 15m loose soil with course particles under pile-raft foundation; a). Kashmir earthquake, b). Mirpur earthquake

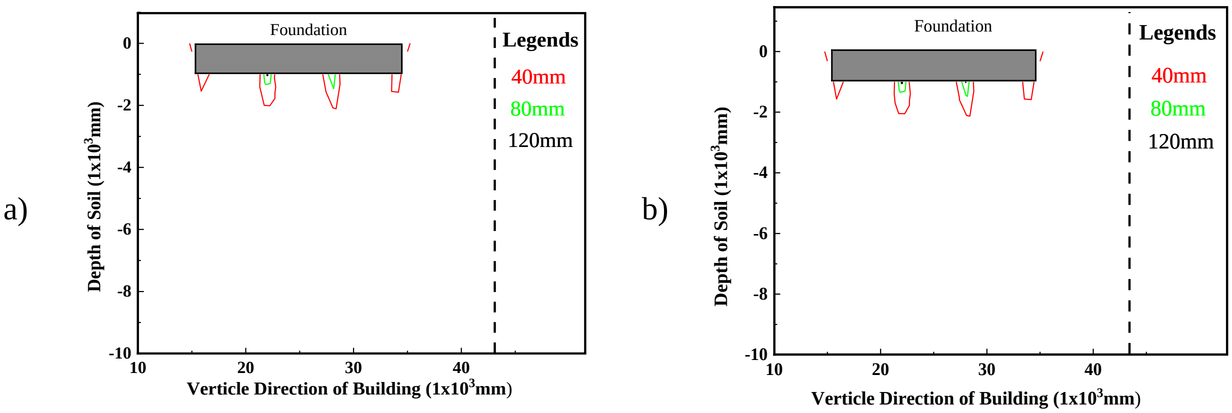


Figure B-4: Dynamic settlement on edge column in 15m loose soil with fine particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

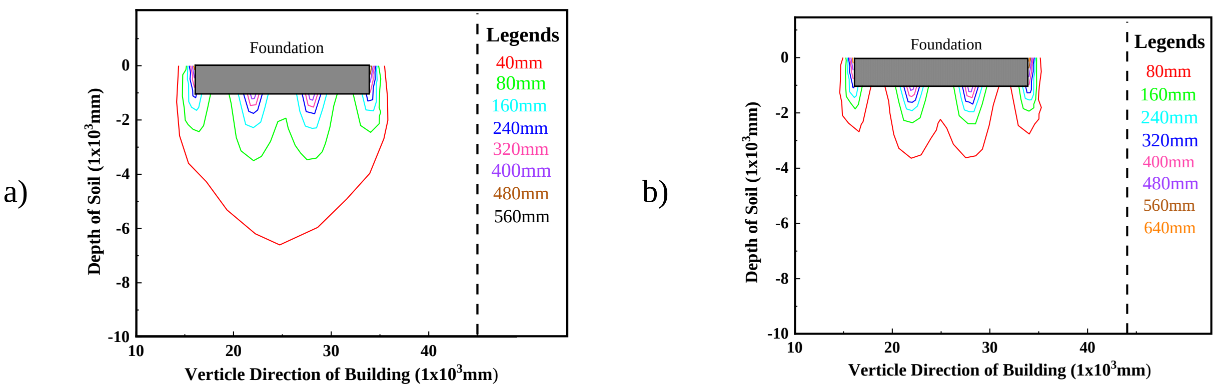


Figure B-5: Dynamic settlement on edge column in 15m loose soil with fine particles raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

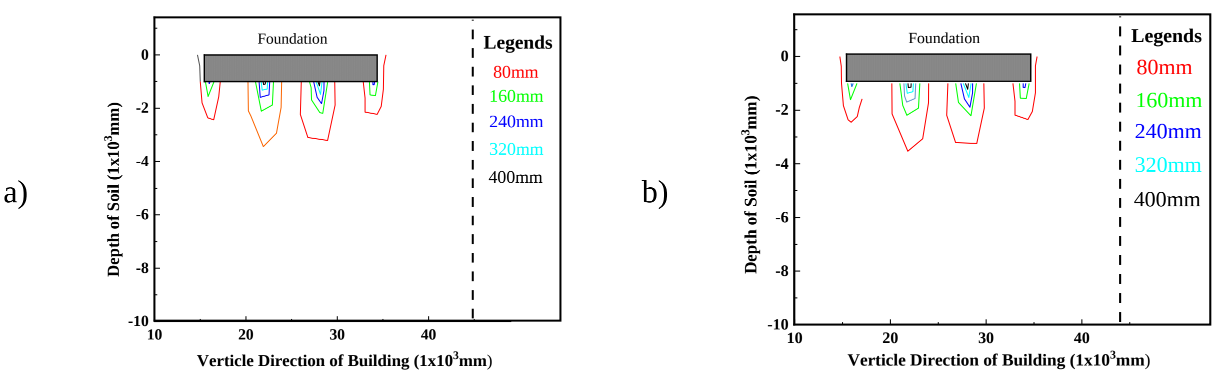
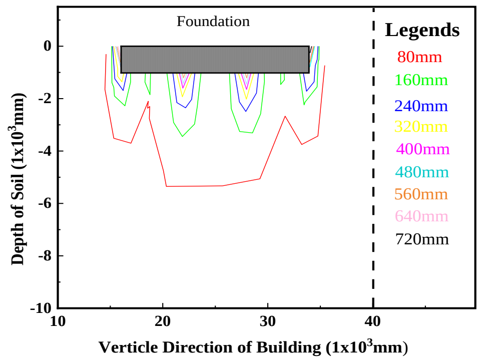


Figure B-6: Dynamic settlement on edge column in 15m loose soil with fine particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a)



b)

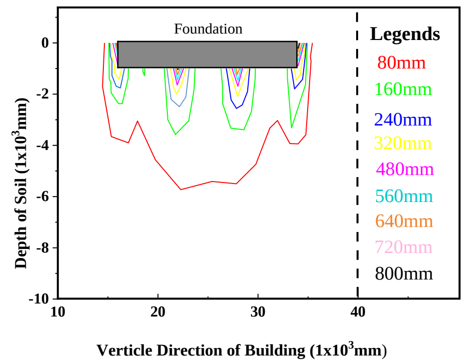
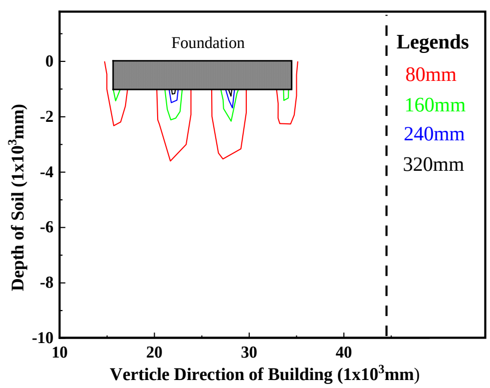


Figure B-7: Dynamic settlement on edge column in 15m loose soil with fine particles under pile-raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a)



b)

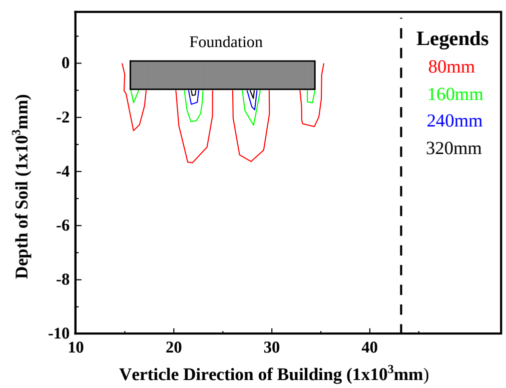
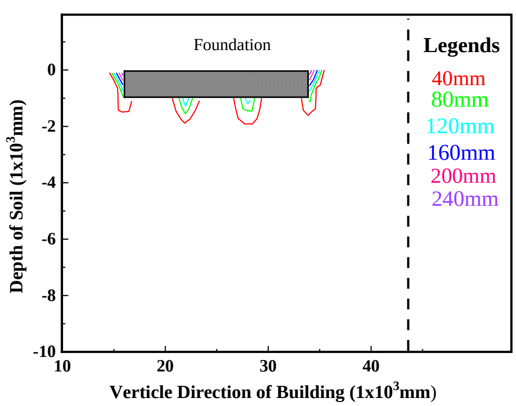


Figure B-8: Dynamic settlement on edge column in 15m loose soil with fine particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a)



b)

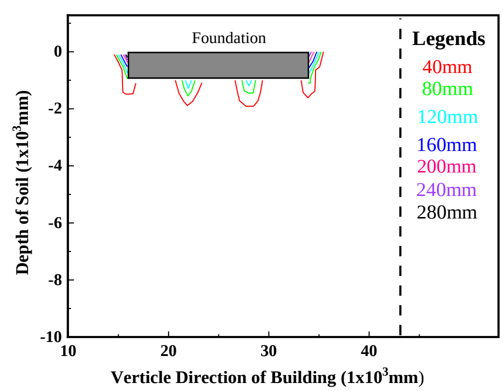


Figure B-9: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with course particles under raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

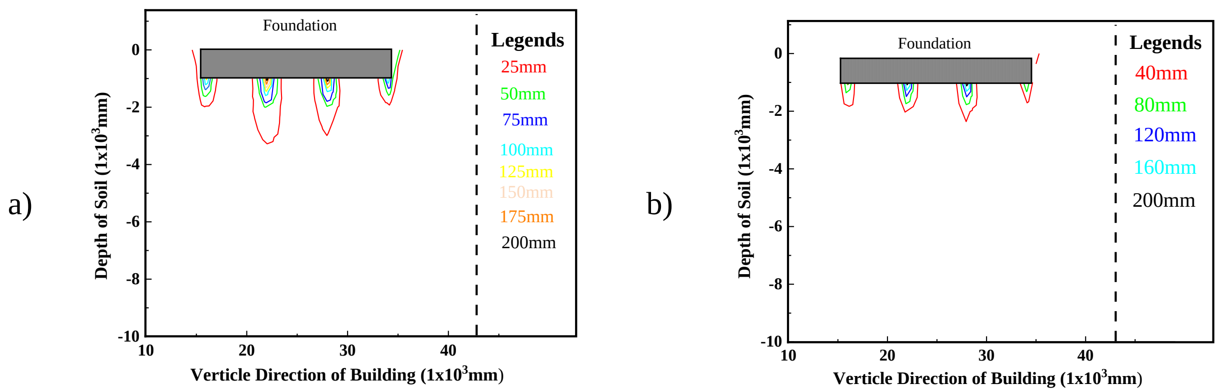


Figure B-10: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with course particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

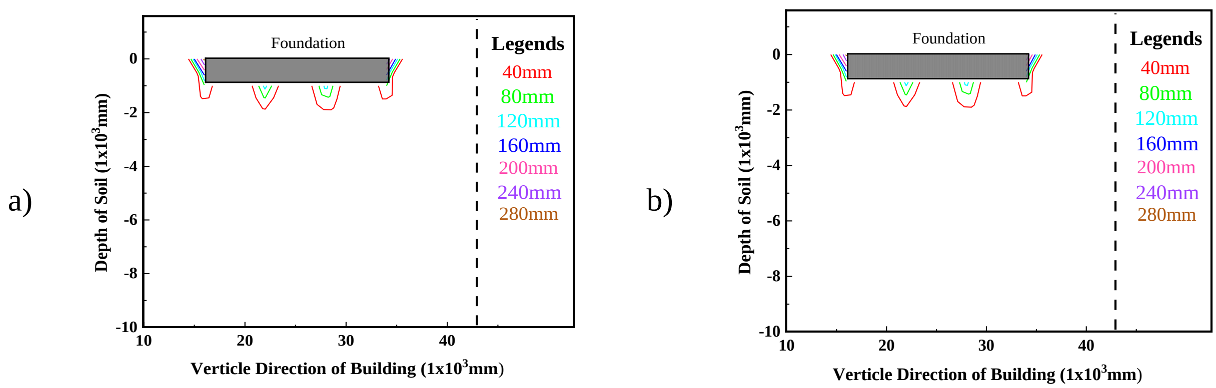


Figure B-11: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with course particles under pile-raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

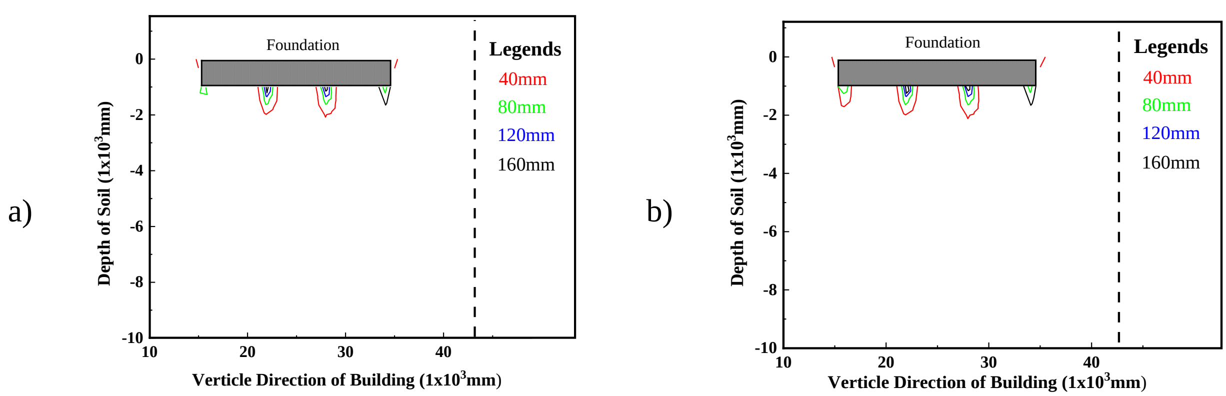
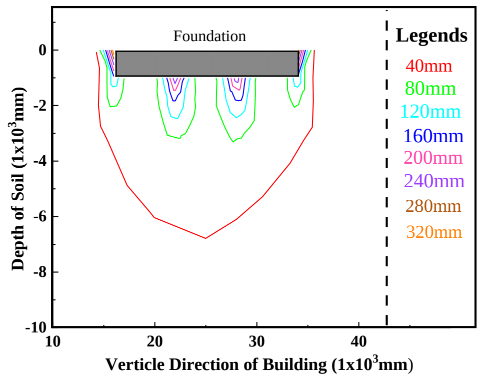


Figure B-12: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with course particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a)



b)

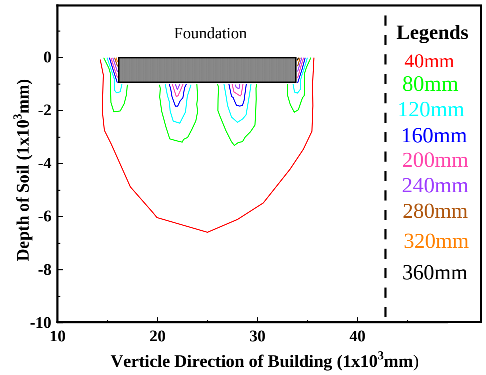
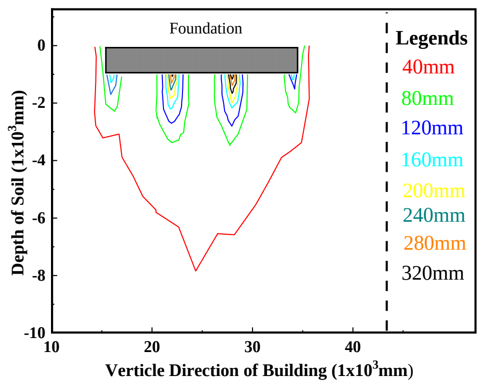


Figure B-13: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with fine particles under raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a)



b)

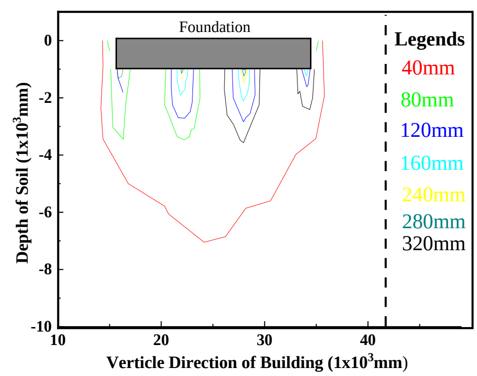
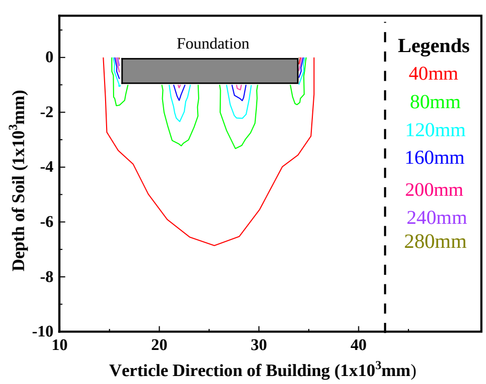


Figure B-14: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with fine particles under extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

a)



b)

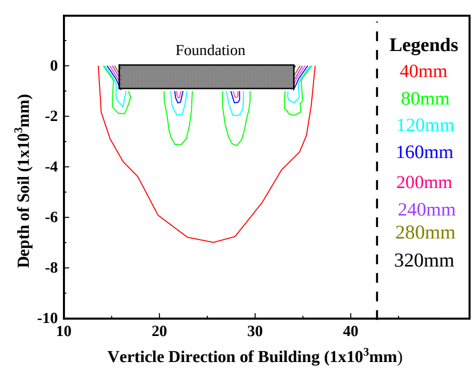


Figure B-15: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with fine particles under pile-raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

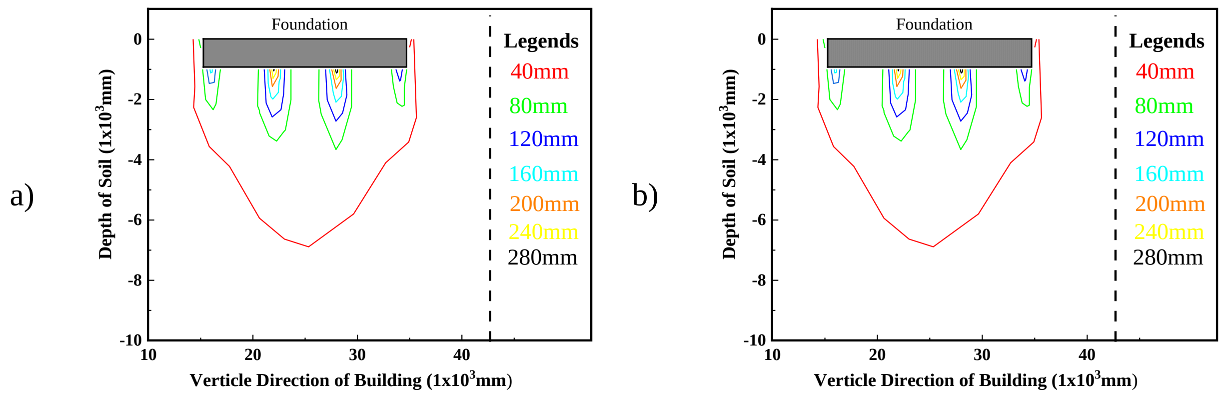


Figure B-16: Dynamic settlement on edge column in 2m Engineered fill 13m loose soil with fine particles under pile with extended raft foundation; a) Kashmir earthquake, b) Mirpur earthquake

Appendix C

a) b)

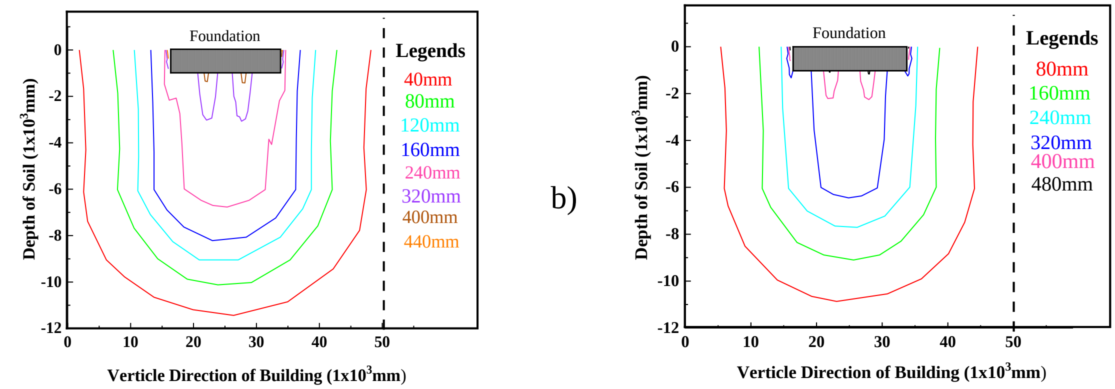


Figure C-1: Dynamic settlement on edge column in raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable

a) b)

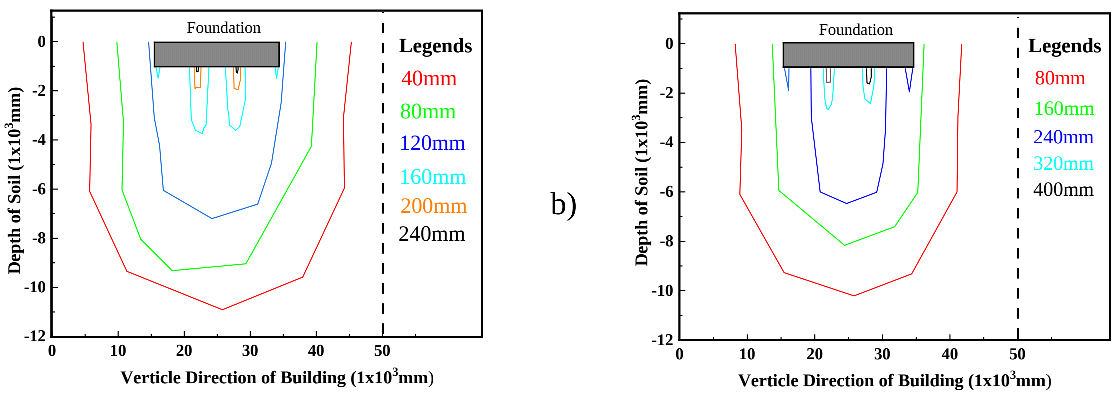


Figure C-2: Dynamic settlement on edge column in pile-raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

a) b)

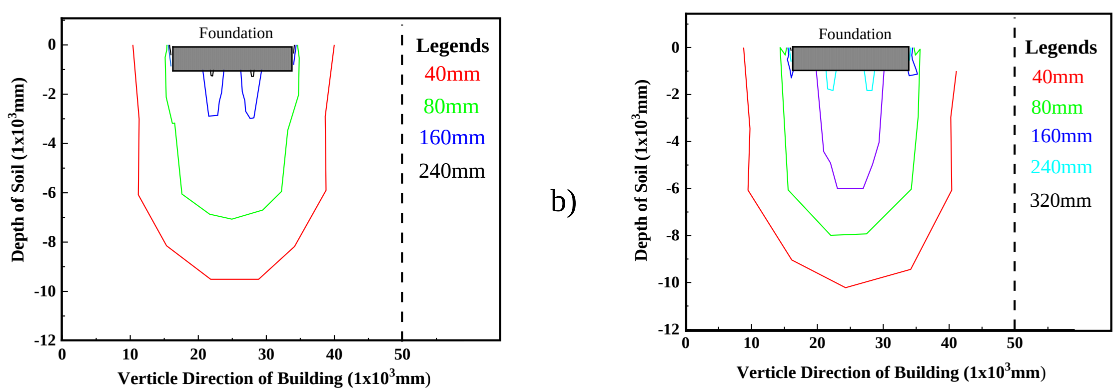


Figure C-3: Dynamic settlement on edge column in pile-raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

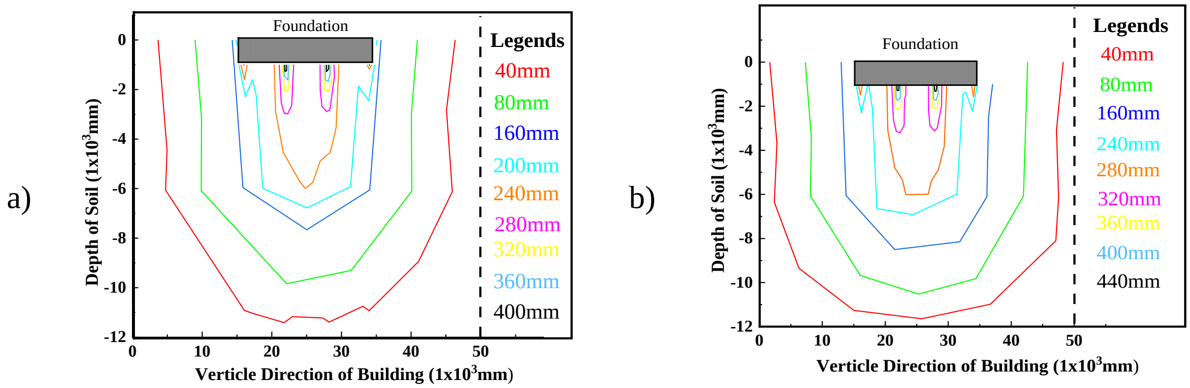


Figure C-4: Dynamic settlement on edge column in pile with extended raft foundation under Kashmir earthquake; a) non-liquefiable soil, b) liquefiable soil

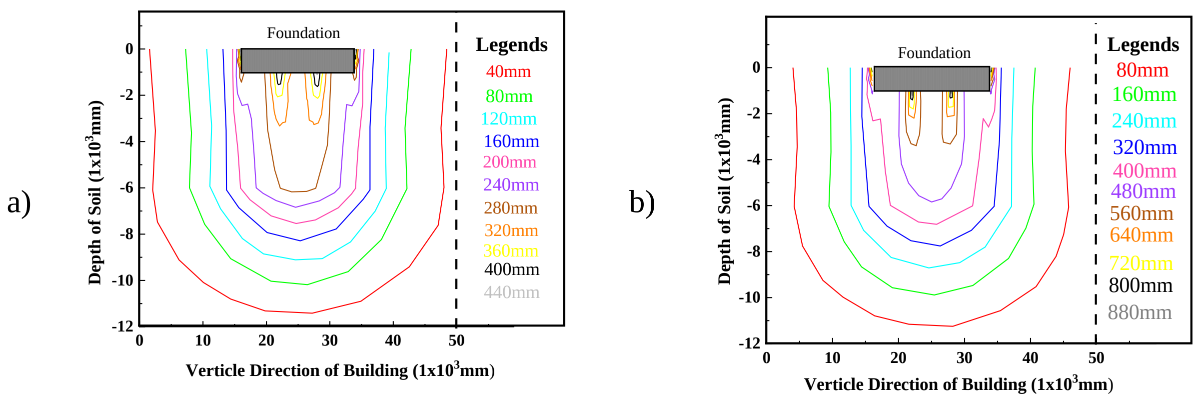


Figure C-5: Dynamic settlement on edge column in raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable

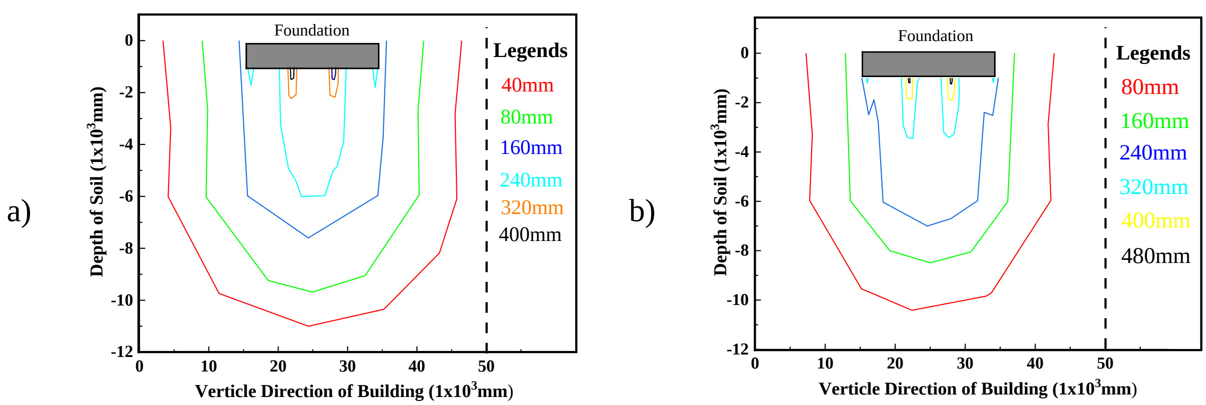


Figure C-6: Dynamic settlement on edge column in pile-raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable soil

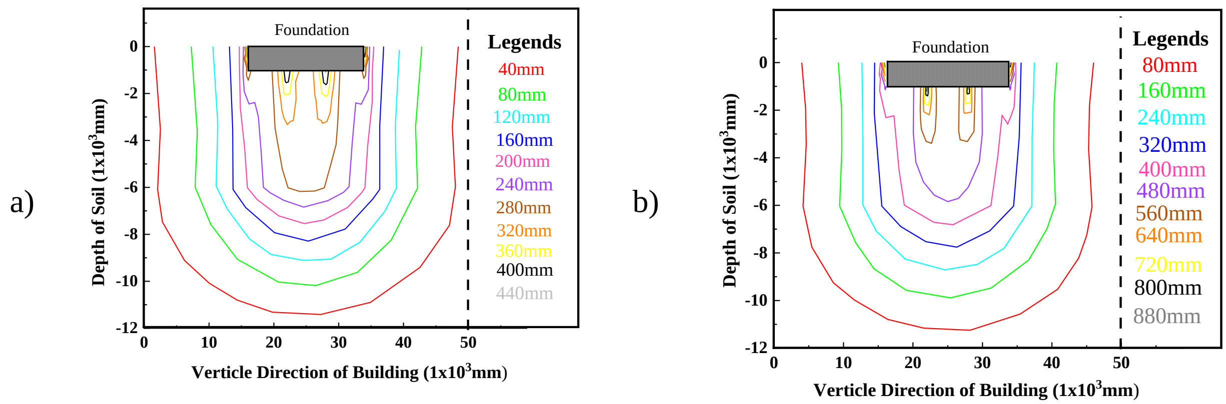


Figure C-7: Dynamic settlement on edge column in pile-raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable soil

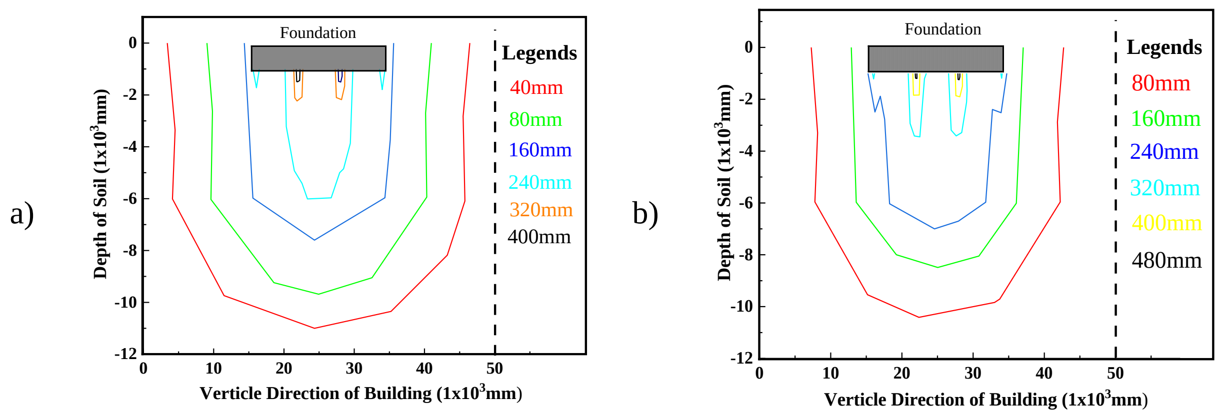


Figure C-8: Dynamic settlement on edge column in pile with extended raft foundation under Mirpur earthquake; a) non-liquefiable soil, b) liquefiable soil

Appendix D

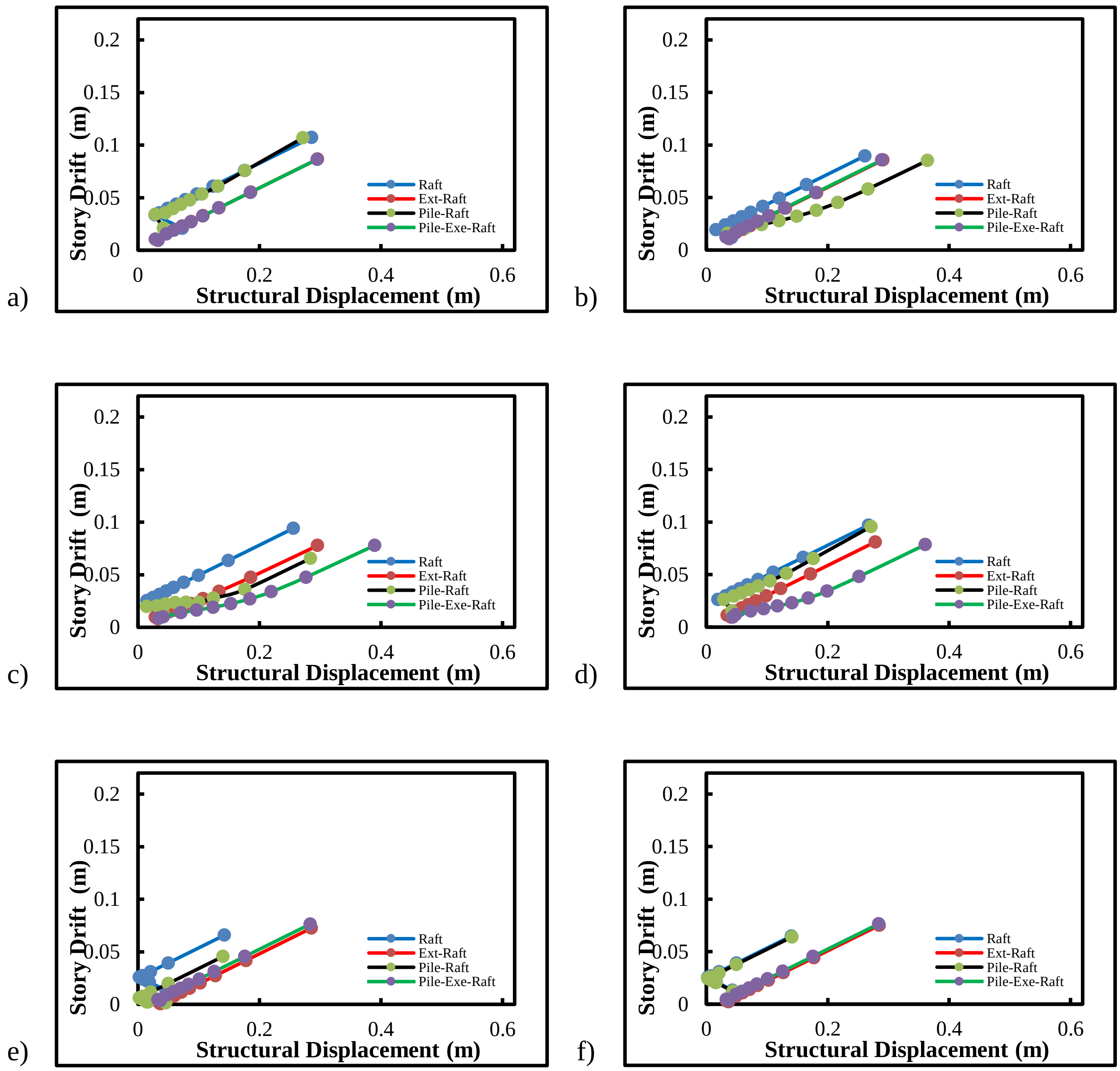


Figure D-1: Story drift vs structural displacement under Kashmir earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle,d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

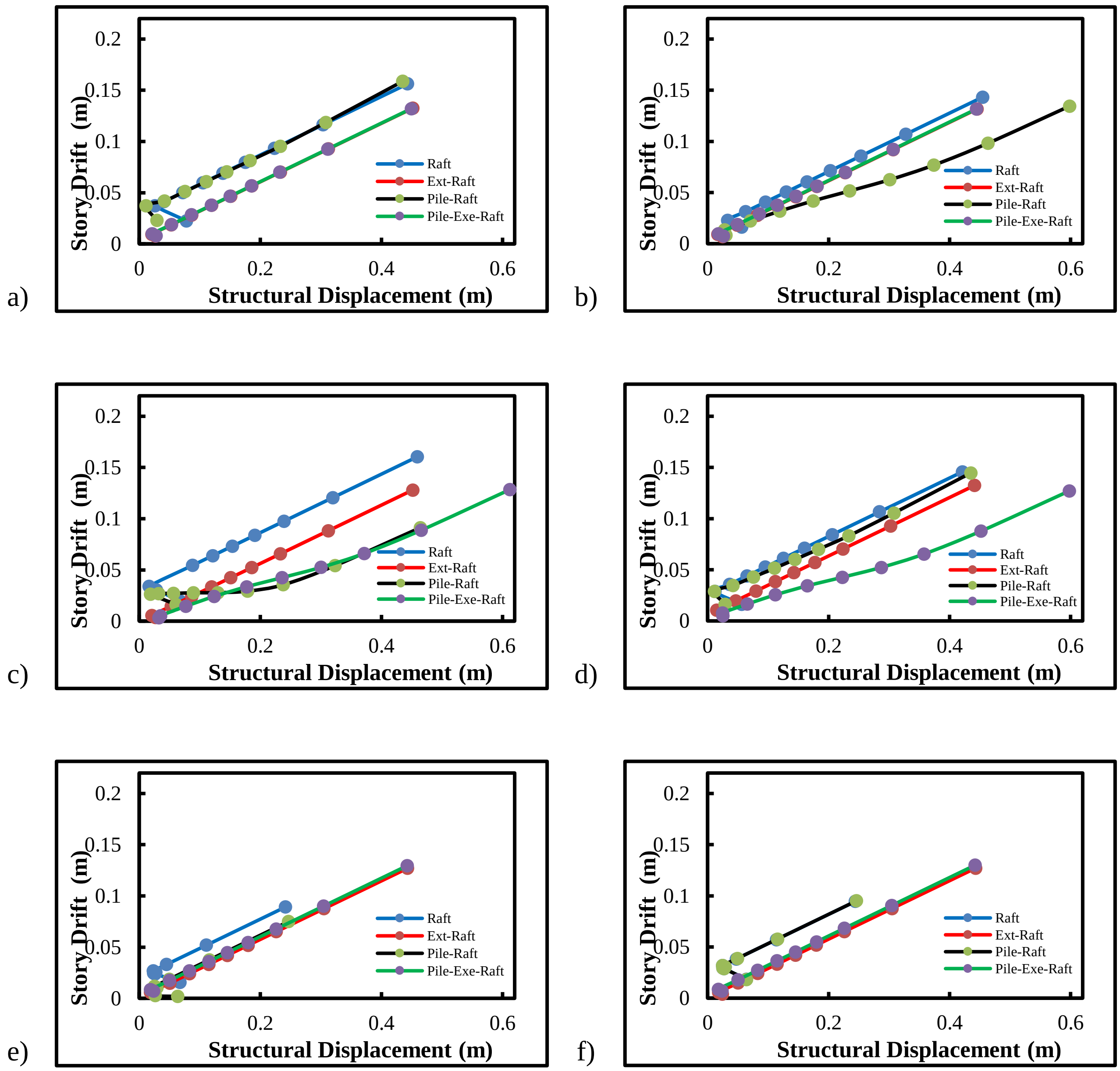


Figure D-2: Story drift vs structural displacement under Kashmir earthquake in Y direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle,d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

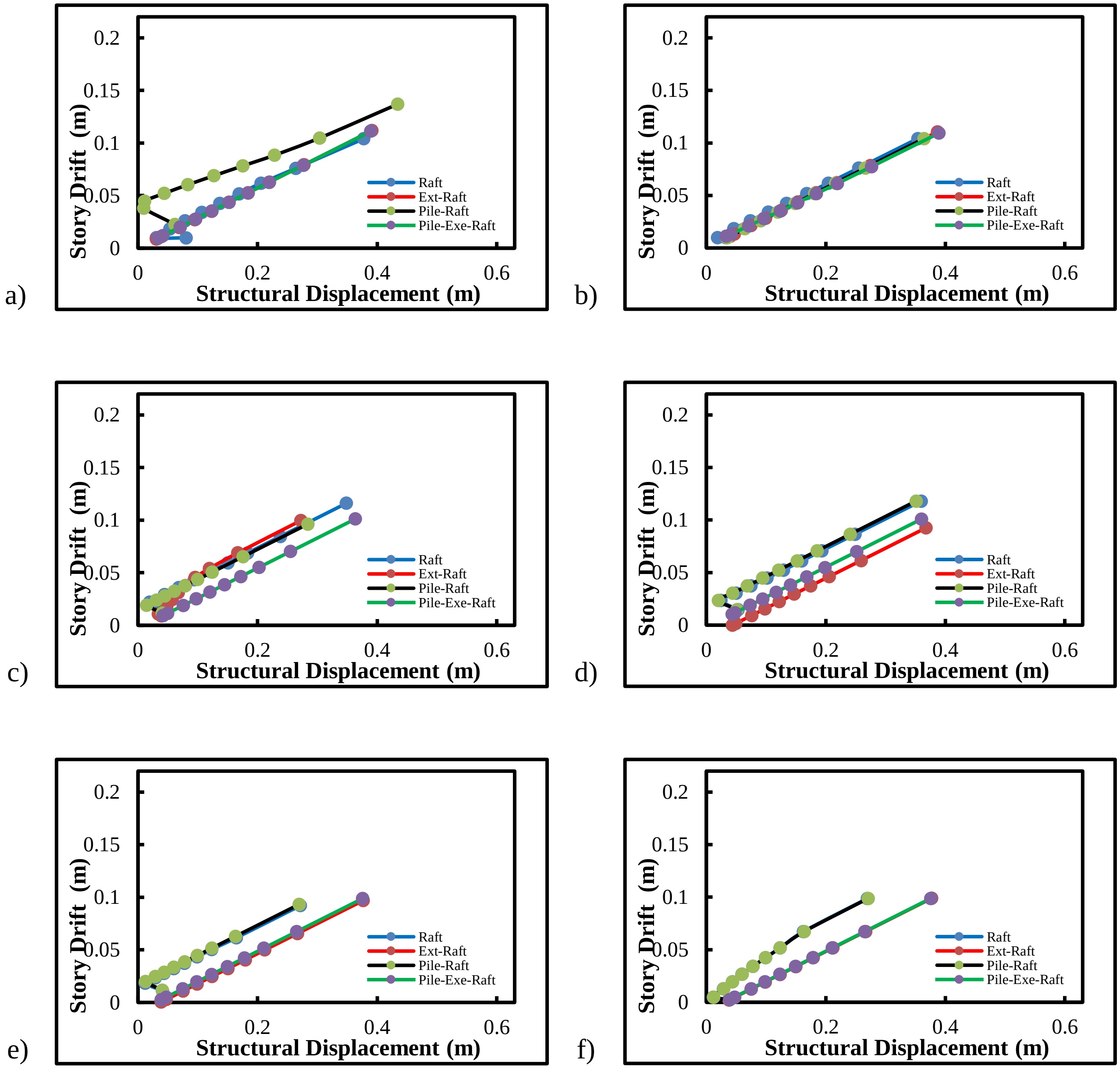


Figure D-3: Story drift vs structural displacement under Mirpur earthquake in X direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle,d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil

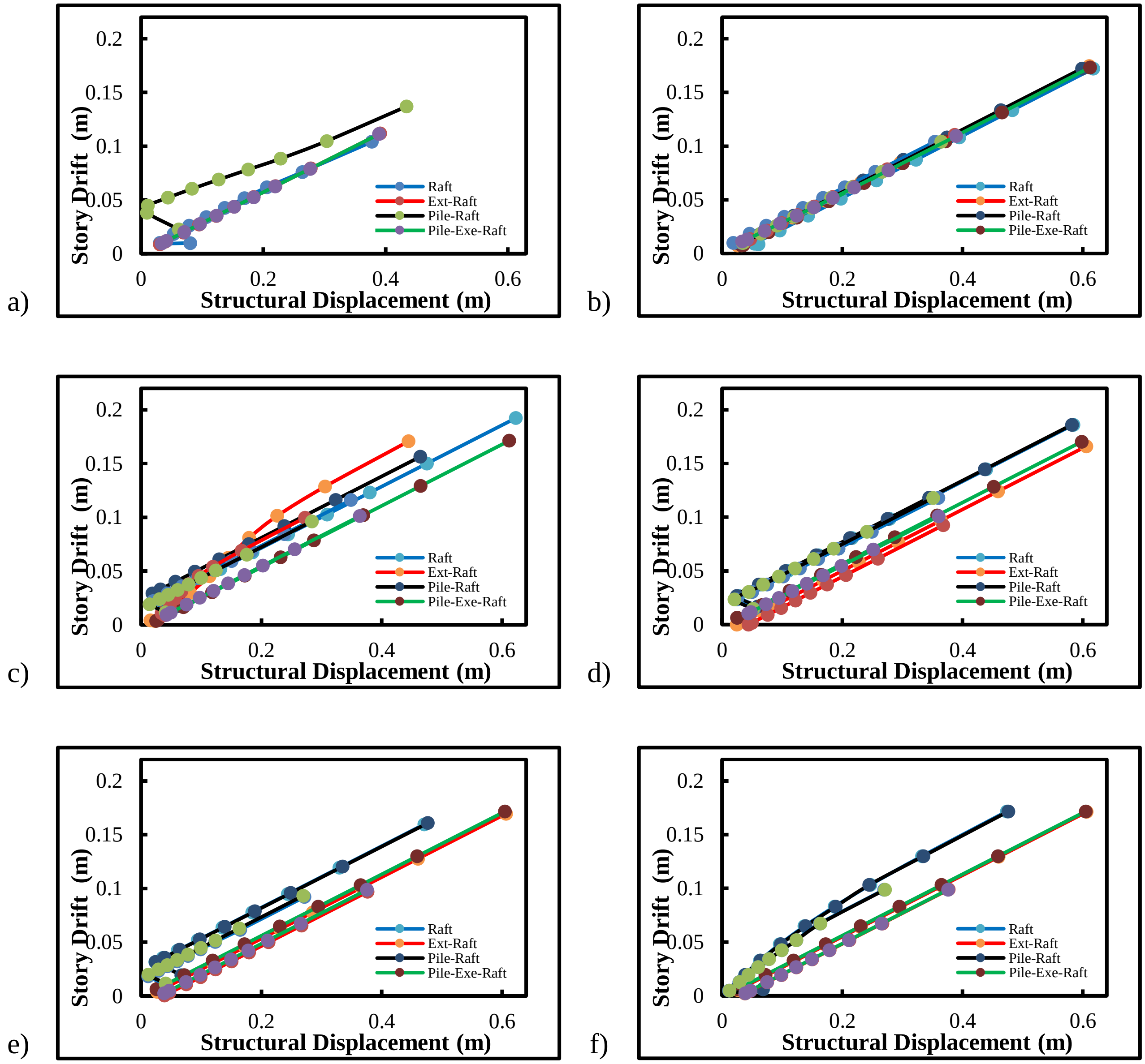


Figure D-4: Story drift vs structural displacement under Mirpur earthquake in Y direction; a) 15m Loos fill with fine particle, b) 15m Loos fill with course particle, c) 2m Engineered fill with 13m fine particle,d) 2m Engineered fill with 13m course particle, e) Natural soil with GWT, f) Natural soil