

Performance-Based Seismic Evaluation of Single Pile and Pile Groups in Layered Soil Using Plaxis 3D

MOHAMMED ARSALAN SIDDIQUE¹, AND ANUSUDHA VISVANATHAN²

¹PG Scholar, Department of Civil Engineering, FET, JAIN (Deemed-to-be University),
Bengaluru-562112, Karnataka, India

*Corresponding author: muhammedarslansiddique@gmail.com

²Assistant Professor, Department of Civil Engineering, FET, JAIN (Deemed-to-be University),
Bengaluru-562112, Karnataka, India
anusudhavisvanathan@gmail.com

Abstract

This study investigates the seismic response of pile foundations in layered soil using numerical analysis in PLAXIS 3D. The first objective involves modelling a single pile under dynamic loading to evaluate the variation of bending moment along its length and to identify the critical location of maximum bending moment. The results indicate that the maximum bending moment occurs near the interface of different soil layers due to stiffness variation and soil pile interaction.

The second objective focuses on a parametric study to assess the influence of soil stiffness, damping ratio, earthquake duration, and water table level on pile response. The findings show that soil stiffness significantly affects both bending moment and lateral displacement, while damping ratio has limited influence on bending behaviour. Earthquake duration affects the cumulative response of the pile, and variations in water table level cause moderate changes due to their effect on effective stress conditions.

The third objective compares the behaviour of a single pile with a 2×2 pile group under seismic loading. The results show that pile groups develop higher bending moments due to interaction effects but exhibit lower lateral displacement, indicating improved stiffness and stability.

Overall, the study highlights the importance of soil properties and group effects in the seismic design of pile foundations.

Keywords- Pile foundation, Soil pile interaction, Seismic loading, Bending moment, Lateral displacement, Soil stiffness, Pile group, Finite element analysis (FEA).

Introduction

A foundation is the lowest part of a structure that safely transfers the loads from the superstructure to the underlying soil or rock. It ensures stability, limits settlement, and prevents structural failure. Foundations play a crucial role in maintaining the overall safety and serviceability of any building, bridge, tower, or industrial facility. Foundations are broadly classified into Shallow and Deep categories depending on depth and load transfer mechanism. Common types are: Isolated Footings, Combined Footings, Strip Footings and Raft/Mat Foundations.

Deep foundations -transfer loads to deeper stronger soil strata when the near-surface soils are weak or compressible. It's used when the topsoil is weak, large loads from high-rise buildings or bridges, Coastal or riverbank structures and Seismic zones with liquefiable soils. Common types are: Pile Foundations, Pier Foundations and Caissons or Wells.

Pile Foundation consists of long, slender structural members made of concrete, steel, or timber, installed into the ground to transfer loads to deeper, more competent soil layers.

Types of Piles Based on Load Transfer: End-Bearing Piles it transfers loads to a hard stratum (dense sand/rock), Friction Piles it transfers loads through skin friction along the length and Combined (Friction and End Bearing) Piles the most common in layered soil profiles. Functions of Pile Foundations it helps in transferring vertical loads through skin friction and end bearing. It resists lateral loads and provide stability during earthquakes or wind. Minimize settlement. Improve load distribution in weak soil conditions. Prevent uplift in structures exposed to wind or water pressure.

Single Pile Foundation is a long, slender structural element made of concrete, steel, or timber, installed vertically (or sometimes batter) into the ground to transfer loads from a superstructure to deeper, more competent soil strata. Piles are essential when surface soils are too weak or compressible to support loads safely.

Pile Group is a set of multiple piles arranged in a specific geometric configuration (square, rectangular, circular, or triangular) and connected at the top with a pile cap. Pile groups are used when single pile cannot carry the required load, the structure is large (bridges, towers, high-rise buildings, tanks) and larger stiffness and stability are required against lateral or seismic forces.

Pile Group Behaviour in Layered Soil

In layered soils (soft clay over dense sand, loose sand over stiff clay): Soil stiffness changes with depth, the sudden increase in bending moment occurs at layer interfaces, liquefiable layers increase seismic-induced lateral movement and piles may undergo excessive curvature near the soft to stiff transition.

Layered Soil -Soil found at any site is usually not uniform with depth. Instead it consists of different layers, and each layer has its own physical and mechanical properties. These layers are formed over a long period of time due to natural geological processes. When designing foundations, especially deep foundations like piles, it becomes important to understand how each layer behaves, since the loads from the structure are transferred through these layers to deeper soil. Layered soil profiles can be classified based on the arrangement and stiffness of soil layers, which significantly influence pile behaviour. In cases of soft soil over stiff soil, commonly found in coastal areas, increased pile bending occurs at the stiffness interface along with higher settlements in the soft layer. Conversely, stiff soil over soft soil restricts surface movement but leads to differential settlement and bending due to the compressibility of the underlying soft layer. Alternating sand-clay layers, often seen in riverbeds, exhibit complex nonlinear behaviour during seismic loading and may undergo partial liquefaction. A liquefiable sand layer sandwiched between stiff layers is particularly critical, as it can lose lateral support during earthquakes, causing severe pile bending at the interface. Additionally, fill over natural soil presents unpredictable behaviour in the upper layer, while the underlying natural soil governs the overall response.

PLAXIS 3D is a numerical software used in geotechnical engineering to study problems related to soil behaviour, deformation, and stability. It is based on the finite element method. Engineers use this software to model and analyse different types of structures such as foundations, tunnels, embankments, retaining walls, and offshore systems. It is also widely used for seismic analysis because it can handle complex conditions like 3D geometry, nonlinear soil behaviour, and dynamic loading. PLAXIS 3D is widely used in the seismic analysis of pile foundations to evaluate their behaviour under dynamic loading conditions. It facilitates the analysis of lateral response in single piles by estimating parameters such as displacement, bending moment, shear forces, and potential plastic hinge formation. For pile groups, it helps in understanding interaction effects, reduction in lateral stiffness, and load redistribution among piles during earthquake loading. The software also captures both kinematic interactions, caused by soil movement, and inertial interaction due to superstructure forces. Additionally, PLAXIS 3D is effective in assessing liquefaction-induced responses, including excess pore pressure generation, loss of lateral support, and resulting settlement or down drag effects. It further supports performance-based seismic design (PBSD) by enabling evaluation under different earthquake levels such as Service Level Earthquake (SLE), Design Basis Earthquake (DBE), and Maximum Considered Earthquake (MCE), allowing engineers to assess damage states, serviceability limits, and collapse prevention criteria.

Methodology

3D soil domain was created with dimensions: Length (X) = 20 m, Width (Y) = 20 m, Depth (Z) = -20 m
The soil profile consists of three layers:

Layer 1 depth 0m to -5m Clay soil, Layer 2 depth -5m to -15m Sand soil and Layer 3 depth -15m to -20m Dense Sand Soil type.

Soil Properties Clay (Layer 1) $\gamma_{unsat} = 17 \text{ kN/m}^3$, $\gamma_{sat} = 19 \text{ kN/m}^3$, $E = 10,000 \text{ kN/m}^2$, $\nu = 0.45$, $c = 20 \text{ kN/m}^2$, $\phi = 0^\circ$ and $\psi = 0^\circ$

Sand (Layer 2) $\gamma_{unsat} = 18 \text{ kN/m}^3$, $\gamma_{sat} = 20 \text{ kN/m}^3$, $E = 25,000 \text{ kN/m}^2$, $\nu = 0.35$, $c = 10 \text{ kN/m}^2$, $\phi = 25^\circ$ and $\psi = 2^\circ$

Dense Sand (Layer 3) $\gamma_{unsat} = 19 \text{ kN/m}^3$, $\gamma_{sat} = 21 \text{ kN/m}^3$, $E = 50,000 \text{ kN/m}^2$, $\nu = 0.30$, $c = 0$, $\phi = 35^\circ$ and $\psi = 5^\circ$

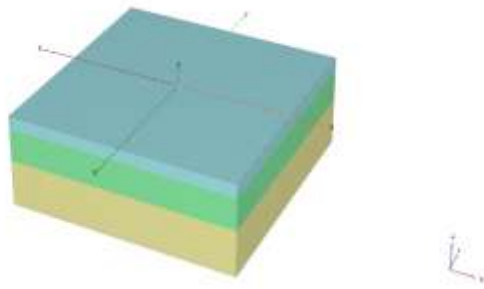


Figure- 2.1 Soil Layers

Pile Modeling

Single Pile-Type: Embedded beam row

Length: 18 m, Diameter: 0.6 m

Position: (0,0,0) to (0,0, -18)

pile properties:

Material: Concrete, unit weight = 25 kN/m³ and Elastic modulus = 30×10^6 kN/m²

Interface Properties: Skin resistance: 80–120 kN/m and Base resistance: 1500 kN

Load Application: Static load: $F_z = -500$ kN and Dynamic load: Earthquake input via load multiplier: Bhuj earthquake record.

i. Soil Stiffness- Cases considered: 0.5E, 1E and 2E. Change: Modify E in all layers.

ii. Damping Ratio- Cases Considered: $\beta=0.01$, $\beta=0.02$ and $\beta=0.05$. Change: Rayleigh damping parameter.

iii. Earthquake Duration- Cases Considered: Time Interval: - 30 sec, 40 sec and 60 sec. Change: Dynamic time interval

iv. Water Table Level- Cases Considered: Head- 0m and -5m. Change: Groundwater head in borehole.

v. 2×2 Pile Group piles arranged in square pattern Spacing =3D (1.8 m). Pile cap: 3 m × 3 m × 0.5 m

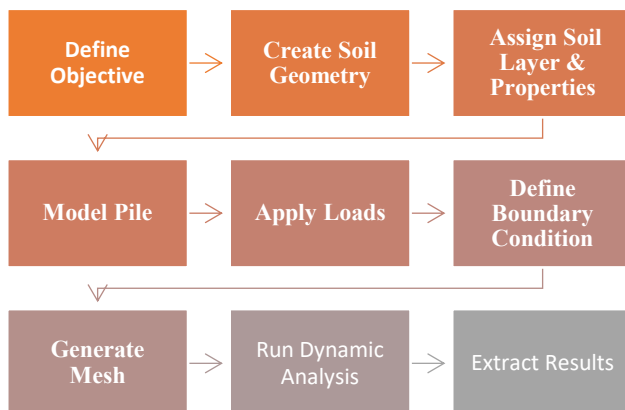


Figure-2.2 Methodology flow chart

Results and Discussion

Single Pile

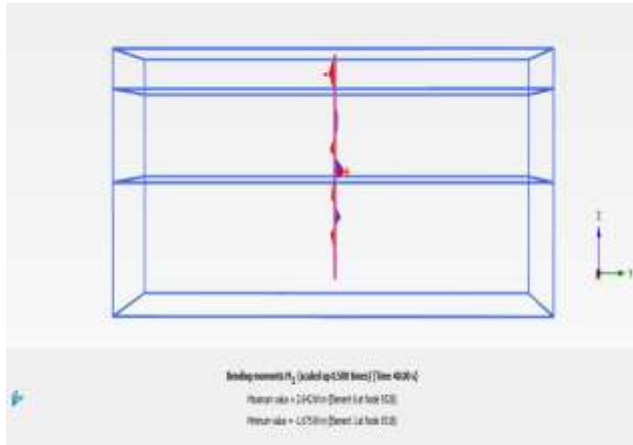


Figure-3.1 Bending Moment M_2

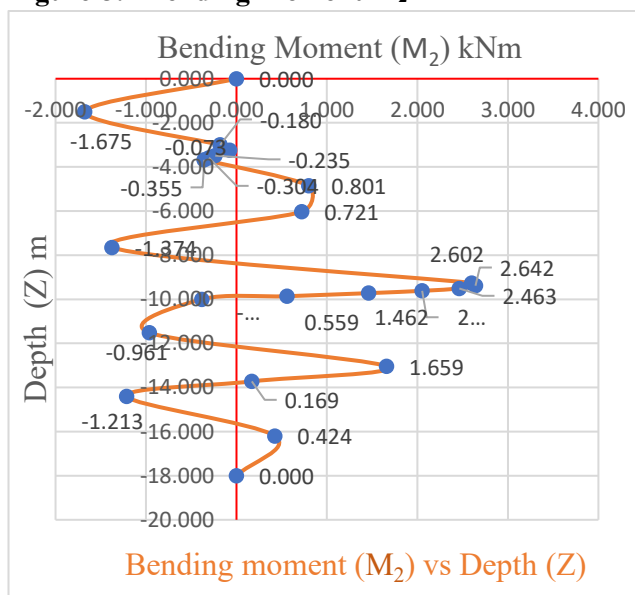


Figure- 3.2 Bending moment (M_2) vs Depth (Z)

Bending moment (M_2) shows a non-uniform distribution along pile depth due to layered soil behavior. Maximum positive bending moment +2.642 kNm occurs at -9 m to -10 m depth (sand to dense sand transition zone). Maximum negative bending moment -1.675 kNm is observed near -2 m depth in clay layer. Change from negative to positive BM along depth shows curvature due to soil resistance variation. In deeper region bending moment reduces towards zero due to strong support from dense sand. Maximum lateral displacement (U_x) is very small, indicating stable soil pile interaction.

Overall, the results show that soil layering controls both bending moment and displacement, with critical stress occurring at layer zones.

Soil Stiffness

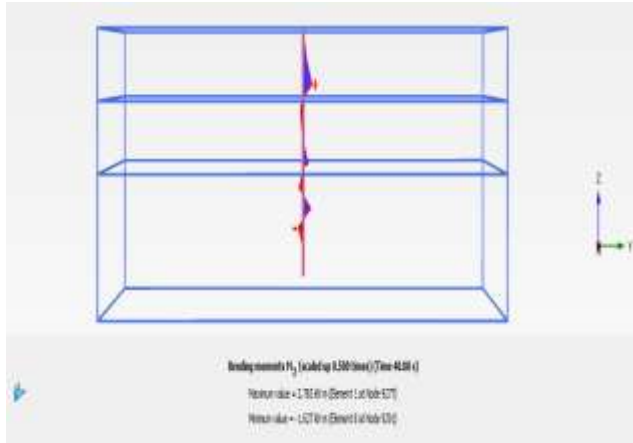


Figure-3.3 Case-1 Bending Moment M_2

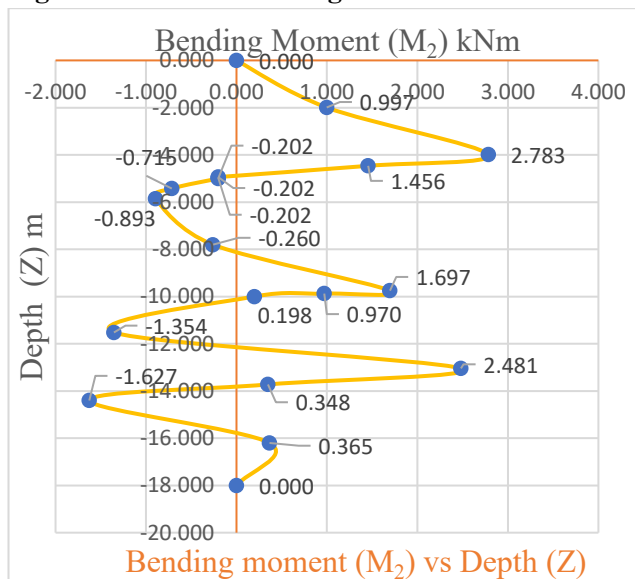


Figure- 3.4 case1- Bending moment (M_2) vs Depth (Z)

As soil stiffness increases, the pile shows reduced deformation tendency. Maximum bending moment varies with stiffness due to soil pile interaction. In softer soil (0.5E), bending moment is higher due to lower resistance. In stiffer soil (2E), soil provides more confinement, reducing pile bending. The displacement values obtained are very small and hence not considered significant for comparison. The maximum positive bending moment of about +2.783 kNm is observed at a depth between -4 m and -5 m.

Damping Ratio

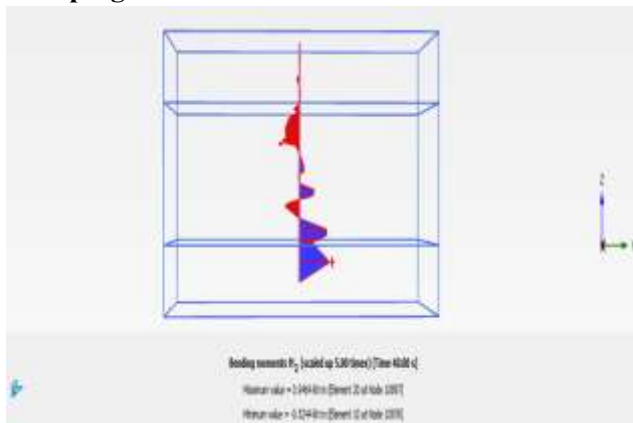


Figure-3.5 Case-3 Bending Moment M_2

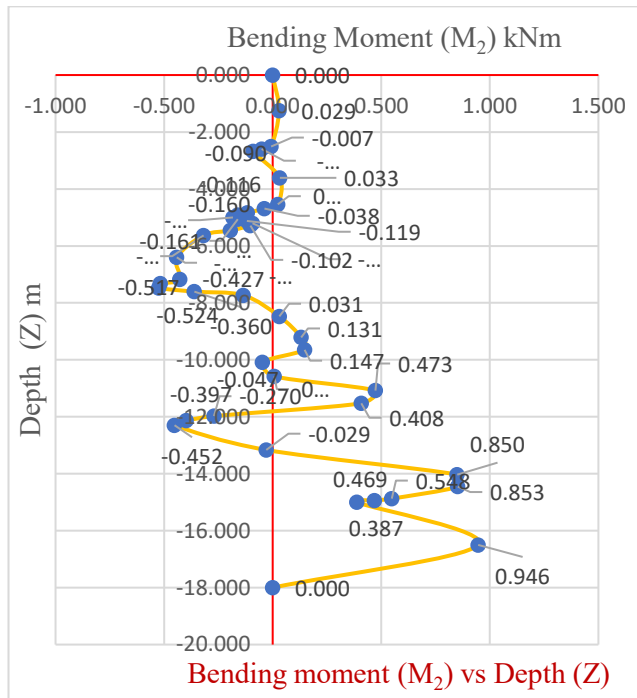


Figure- 3.6 Damping Ratio Bending moment (M_2) vs Depth (Z)

Variation in damping ratio from 1% to 5% shows negligible change in bending moment. The maximum bending moment is about +0.946 kNm at deeper depths (around -16 m to -18 m), while the minimum is about -0.524 kNm near mid-depth. Lateral displacement shows very minor variation. This indicates that the system response is not highly sensitive to damping. Soil pile system is stiffness dominated rather than damping controlled. Damping effect becomes significant only under high vibration levels.

Earthquake Duration

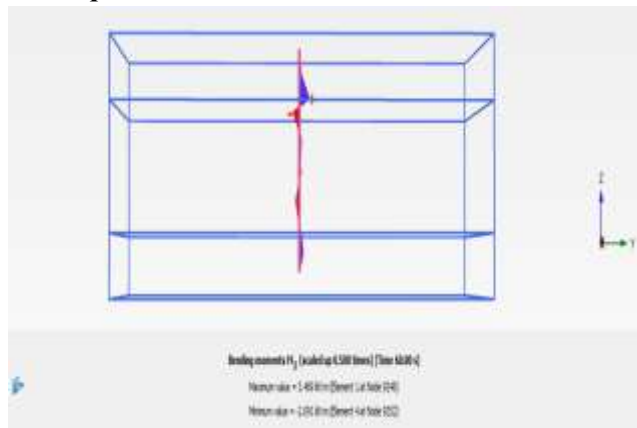


Figure-3.7 Case-2 Bending Moment M_2

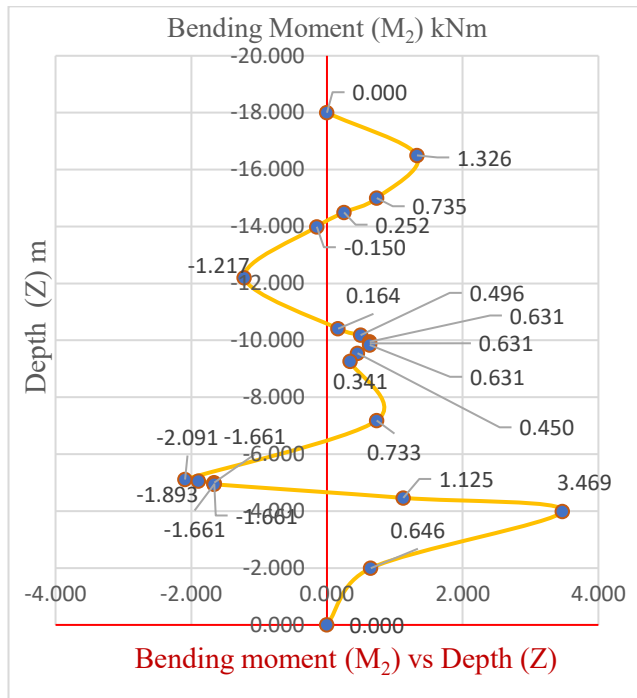


Figure- 3.7 Earthquake Duration Bending moment (M_2) vs Depth (Z)

Increase in earthquake duration leads to higher bending moment in the pile. For 60 sec duration, maximum bending moment is significantly higher than 30 sec. The maximum positive bending moment of about +3.469 kNm occurs at a shallow depth of around -4 m, which is within the upper soil layer. This is due to longer exposure to cyclic loading. Lateral displacement shows slight variation due to dynamic response characteristics. Duration plays a key role in energy transfer to the pile system. This demonstrates that longer earthquake duration results in greater accumulation of stresses in the pile.

Water Table Level

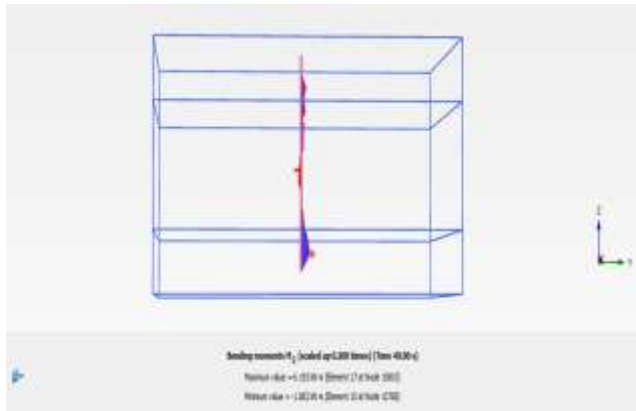


Figure-3.8 Case-2 Bending Moment M_2

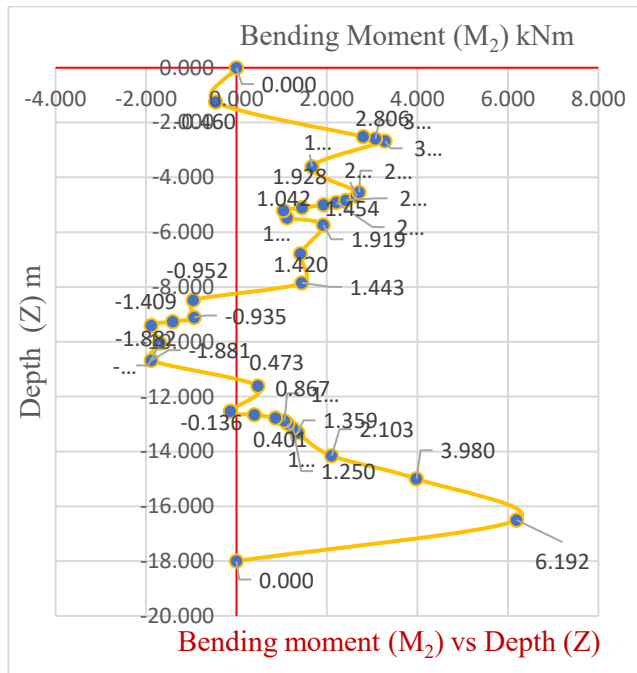


Figure-3.9 Water table level Bending moment (M_2) vs Depth (Z)

Two cases analyzed: Water table at 0 m and lowered to -5 m. Maximum bending moment increased from 0.845 kNm (0 m) to 6.192 kNm (-5 m). Minimum bending moment also increased in magnitude from -0.768 kNm to -1.882 kNm. Lateral displacement (U_x) decreased from 0.9828×10^{-6} m to 0.4319×10^{-6} m when water table was lowered. Lowering water table increases effective stress, making soil stiffer. Stiffer soil reduces deformation but transfers more load to the pile, causing higher bending moments. Overall, water table level significantly affects pile response.

Pile Group

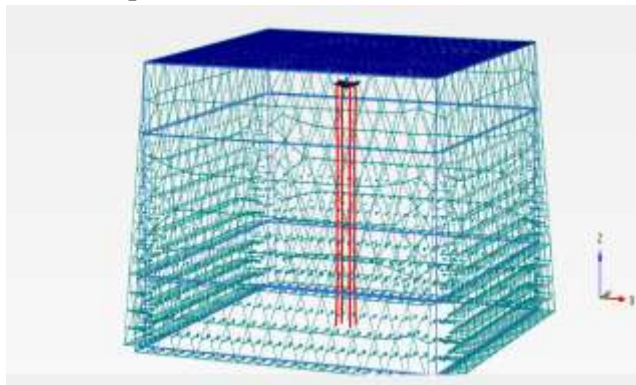


Figure-3.10 2X2 Pile Group Output

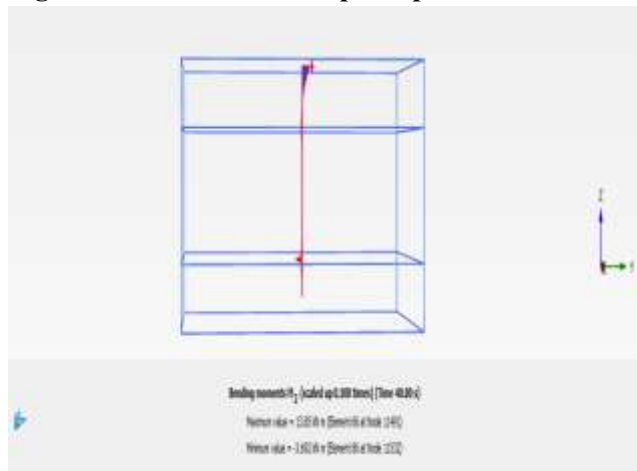


Figure-3.11 Pile-4 Bending Moment M_2

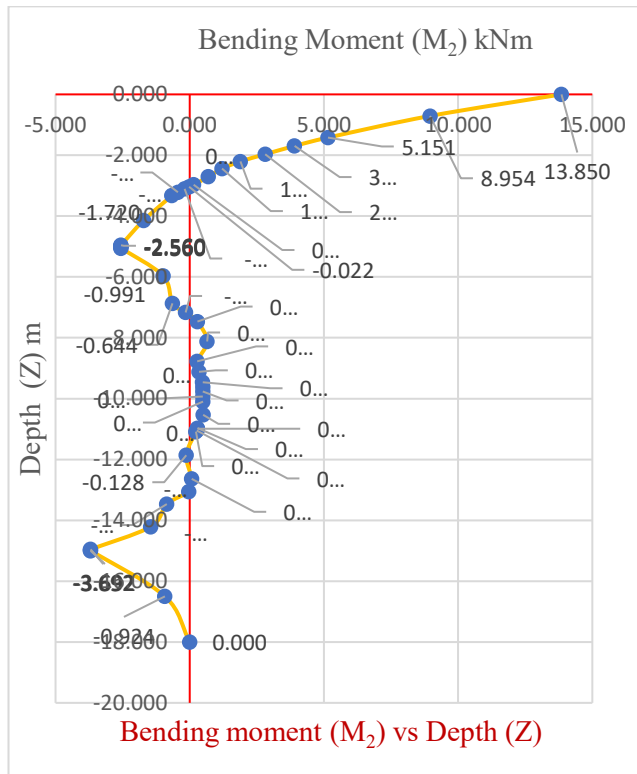


Figure-3.12 Pile-4 Bending moment (M_2) vs Depth (Z)

Maximum bending moment = +13.85 kNm at pile head (0 to -2 m). Minimum bending moment = -3.692 kNm at -14 m to -16 m depth. Bending moment is highly non-linear and fluctuating along depth. Peak moment at top due to pile cap restraint and group interaction. Mid-depth (-6 m to -12 m) shows moment reversal and redistribution. Overall behavior is stiffer system leads to high internal forces, low deformation.

Single Pile

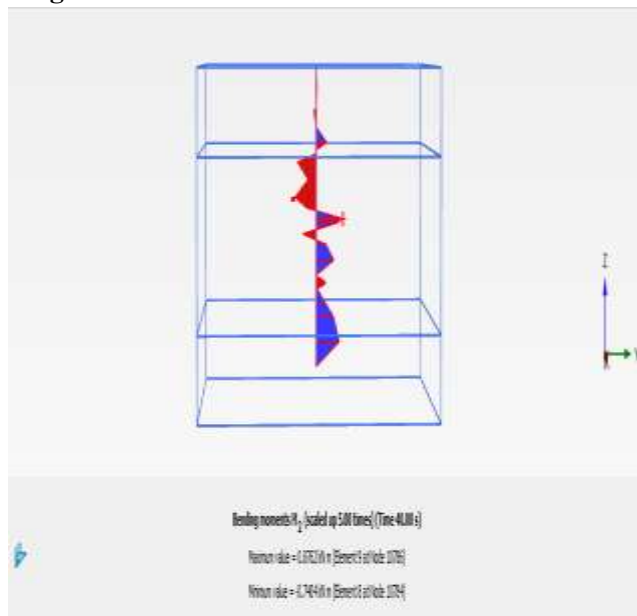


Figure-3.13 Single Pile Bending Moment M_2

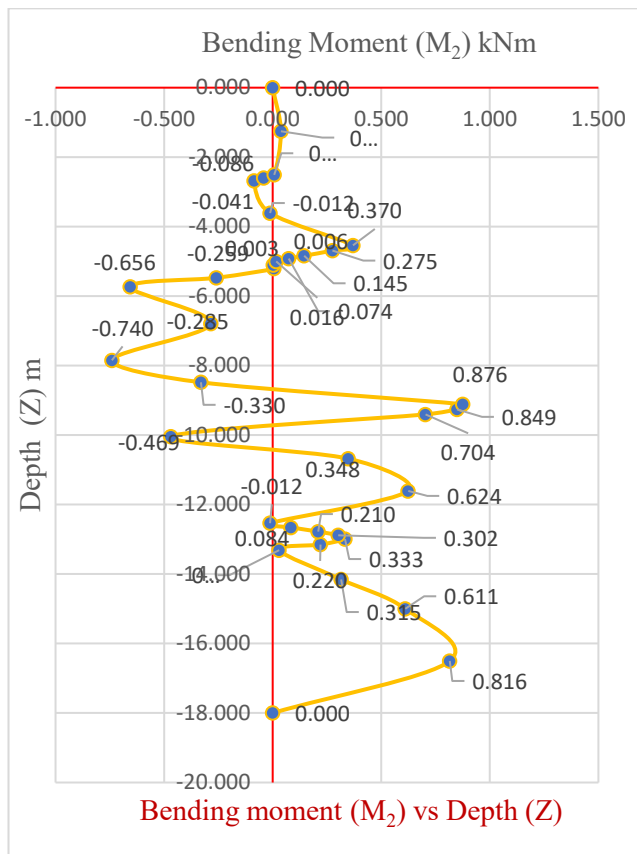


Figure-3.14 Single pile Bending moment (M_2) vs Depth (Z)

Maximum bending moment = +0.876 kNm at -9 m to -10 m depth. Minimum bending moment = -0.740 kNm at -6 m to -7 m depth. Bending moment varies smoothly along the pile length. Near ground surface the BM is 0 because free head behaviour. Maximum moment occurs at soil layer transition zone. Overall behaviour is flexible system leads to lower stress.

Comparison: Single Pile vs 2×2 Pile Group

- i. Maximum bending moment: Pile group = 13.85 kNm vs Single pile = 0.876 kNm.
- ii. Location of maximum BM: Pile group near pile head (0 to -2 m)
Single pile mid-depth (-9 m to -10 m).
- iii. Minimum bending moment: Pile group = -3.692 kNm vs Single pile = -0.740 kNm.
- iv. Pile group shows highly non-linear and fluctuating BM distribution.
Single pile shows smooth and gradual variation.
- v. Group effect and pile cap causes force concentration at pile head.
- vi. Single pile behavior depends on soil layer stiffness variation.
- vii. Displacement: Pile group displacement is very small (10^{-9} m). Single pile displacement is higher (10^{-6} m).
- viii. Pile group behaves as a stiffer system (less deformation, more force).
- ix. Pile group requires stronger design at pile head due to high BM.

Conclusion

The analysis of a single pile in layered soil shows that the bending moment varies along the depth due to changes in soil properties. The maximum bending moment of about +2.642 kNm occurs at -9 m to -10 m, while the minimum value of about -1.675 kNm is observed near -2 m in soft clay. This indicates that softer soil allows more deformation, while stiffer layers resist movement and create higher bending at certain depths.

From the sensitivity study, it is observed that soil stiffness and earthquake duration have major influence on pile response. Softer soil increases bending moment, while higher stiffness reduces deformation but increases force transfer. The damping ratio (1% to 5%) shows very little effect on results. Increasing earthquake duration increases bending moment up to 3.469 kNm due to repeated loading. Lowering the water table from 0 m to -5 m reduces displacement but increases bending moment up to 6.192 kNm due to increased soil stiffness.

The comparison between single pile and 2×2 pile group shows that the pile group experiences much higher bending moment (13.85 kNm) compared to single pile (0.876 kNm), with maximum value near the pile head due to pile cap and group interaction. At the same time, displacement is much lower in the pile group (10^{-9} m) compared to single pile (10^{-6} m), showing higher stiffness and stability. Overall, pile groups reduce movement but increase internal forces, so proper design is required under seismic loading.

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