# Performance-Based Seismic Evaluation of Single Pile and Pile Groups in Layered Soil using PLAXIS 3D

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*Abstract* — The seismic design of deep foundations requires accurate prediction of structural damage using the Performance-Based Seismic Design (PBSD) framework, which focuses on evaluating Engineering Demand Parameters (EDPs) such as Maximum Bending Moment (M(max)) and Peak Curvature (M(max)). This study conducts a comprehensive numerical investigation into the dynamic response of single piles and various pile group configurations (e.g., 2 x 2, 3 x 3) embedded in layered soil under seismic loading. The methodology utilizes the 3D Finite Element Method (FEM) via PLAXIS 3D to perform Time History Dynamic Analysis (THDA) with non-linear constitutive models, which is essential for accurately simulating complex Soil-Pile-Structure Interaction (SPSI) and the effects of dynamic pore water pressure generation in liquefiable strata. Review of existing literature confirms that while pile groups introduce significant Pile Group Interaction (PGI) leading to amplified internal forces (up to 192% in shear) compared to single piles, they can simultaneously lead to reduced vertical settlement. The foundation's performance is highly sensitive to variations in soil stiffness, damping ratio, and the specific characteristics of the earthquake record (duration, intensity, spectral content). Addressing a critical research gap, this project establishes an integrated parametric framework to simultaneously evaluate the combined influence of these variables across different pile group sizes. The results provide essential quantitative data to inform reliable performance-based design and vulnerability assessment for deep foundations in complex, seismically active geotechnical environments.

***Keywords:*** Performance-Based Design (PBSD), PLAXIS 3D, Pile Group Interaction (PGI), Layered Soil, Seismic Response, Maximum Bending Moment (M(max)) Non-Linear Analysis

## I. INTRODUCTION

### A. *Foundation Systems*

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.

#### 1) *Importance of Foundations*

- Distribute loads safely to the ground
- Reduce excessive settlement
- Provide stability against overturning and sliding
- Prevent structural damage during environmental actions (wind, flood, earthquake)

#### 2) *Loads Acting on Foundations*

Foundations must resist:

- Vertical loads (dead load, live load)
- Horizontal/lateral loads (wind, earthquake, earth pressure)
- Uplift forces
- Moments from structural actions

### B. *Types of foundations*

Foundations are broadly classified into Shallow and Deep categories depending on depth and load transfer mechanism.

#### 1) *Shallow Foundations*

Shallow foundations transfer loads at a relatively small depth, typically less than the width of the foundation.

Common types are:

Soil near the surface is strong enough to carry the load, and settlements are within permissible limits.

- Isolated Footings
- Combined Footings
- Strip Footings
- Raft/Mat Foundations

### C. *Deep Foundations*

Deep foundations transfer loads to deeper, stronger soil strata when the near-surface soils are weak or compressible.

It's used when the: -

- The topsoil is weak
- Large loads from high-rise buildings or bridges
- Coastal or riverbank structures
- Seismic zones with liquefiable soils

Common types are:

- Pile Foundations
- Pier Foundations
- Caissons / Wells

Among these, pile foundations are the most widely used deep foundation system

### D. *Pile Foundations*

A 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.

#### 1) *Functions of Pile Foundations*

- Transfer vertical loads through skin friction and end bearing
- Resist 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

#### 2) *Types of Piles Based on Load Transfer*

- End-Bearing Piles- Transfer loads to a hard stratum (dense sand/rock).
- Friction Piles- Transfer loads through skin friction along the length.

- Combined (Friction + End Bearing) Piles- Most common in layered soil profiles.

*3) Types of Piles Based on Material*

- Concrete piles (cast-in-situ or precast)
- Steel piles
- Timber piles
- Composite piles

*4) Types of Piles Based on Installation*

- Driven piles
- Bored piles
- Screw piles
- Vibro-driven piles

### *E. Single Pile Foundations*

A single pile 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.

*1) Characteristics of a Single Pile*

- Acts as a vertical cantilever in soil when subjected to lateral loads.
- Load is transferred through skin resistance and end resistance.
- Behavior depends on:
  - Soil type
  - Pile material and diameter
  - Length-to-diameter ratio (slenderness)
  - Groundwater conditions

*2) Purpose of Single Pile*

- Transfer vertical loads (dead, live, uplift).
- Resist lateral loads (wind, earthquake, wave forces).
- Improve foundation stability in weak surface soils.
- Bypass problematic soil (loose sand, soft clay, organic deposits).

*3) Behavior of Single Pile Under Loads*

- Under vertical loads, the pile carries:
  - Skin friction along its shaft.
  - End bearing resistance at the tip.
- Under lateral loads, the pile behaves like a vertical beam on an elastic foundation, resulting in bending, shear, and deflection.
- In seismic conditions, piles experience inertia loads from the structure and kinematic loads from soil movement.
- Maximum moment occurs near the pile head or at soil layer interfaces.

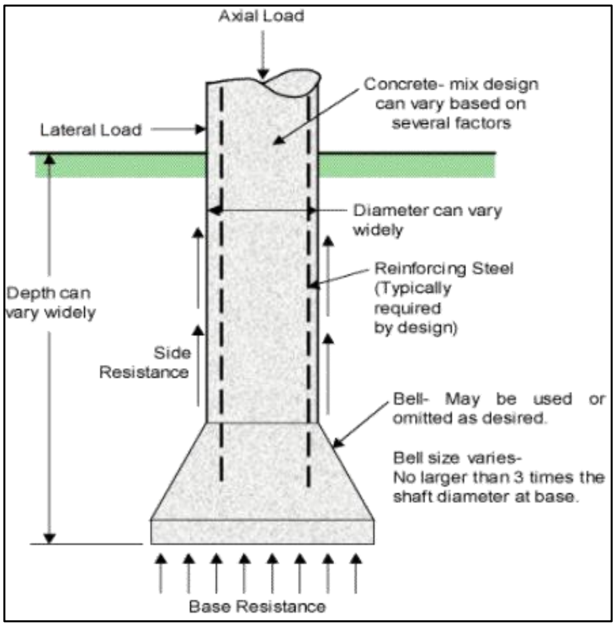

Fig. 1.1: Single Pile Foundation.

### *F. Pile groups*

A 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:

- A single pile cannot carry the required load.
- The structure is large (bridges, towers, high-rise buildings, tanks).
- Larger stiffness and stability are required against lateral or seismic forces.

A pile group behaves as a system rather than individual piles, due to the strong soil–pile–pile interaction.

*1) Components of a Pile Group*

- Individual Piles- Each pile carries a portion of the total axial, lateral, and moment loads.
- Pile Cap
  - A thick reinforced concrete slab.
  - Transfers load from the superstructure to all piles.
  - Ensures uniform load distribution and group behavior.
- Surrounding Soil
  - Plays a major role in load transfer.
  - Interaction between soil layers affects pile performance.

*2) Importance of Pile groups are:*

- Loads are too high for a single pile.
- A structure requires very low settlement.
- Building is in weak soil conditions.
- Lateral loads (wind, waves, seismic, earth pressure) are large.
- Redundancy is required for safety.

*3) Arrangement or Patterns of Pile Groups*

Pile groups can be arranged in many patterns depending on the load distribution and structural requirements:

- Square Pile Group - Most common: 2×2, 3×3, 4×4, 5×5
  Used for buildings, tanks, and heavy footings.

- Rectangular Group - Used for bridge abutments, retaining walls, and long footings.
- Circular Group - Used for tower foundations, offshore structures, chimneys.
- Triangular or Row Pile Group - Used where space is limited or loading is directional.

*4) Pile Group Behavior in Layered Soil*

In layered soils (soft clay over dense sand, loose sand over stiff clay):

- Soil stiffness changes with depth
- Sudden increase in bending moment occurs at layer interfaces
- Liquefiable layers increase seismic-induced lateral movement
- Piles may undergo excessive curvature near the soft-to-stiff transition

Pile groups are therefore more sensitive to layered soil profiles than single piles

*5) Seismic Behavior of Pile Groups*

During an earthquake, pile groups experience:

a) Inertial Loading
- Shaking of the superstructure transmits forces to pile cap → piles
- Front piles take high bending moment
- Overall stiffness contributes to global performance

b) Kinematic Loading
- Soil layers undergo deformation
- Stronger layers move differently than weaker layers
- Causes bending concentration at layer boundaries
- May cause failure even without any superstructure load

c) Liquefaction Effects

If loose sand liquefies:

- Lateral spreading pushes the pile group
- Group displacement increases drastically
- Downward drag forces increase (negative skin friction)
- Pile bending failure becomes critical

Pile groups are more susceptible to liquefaction-induced damage than single piles.

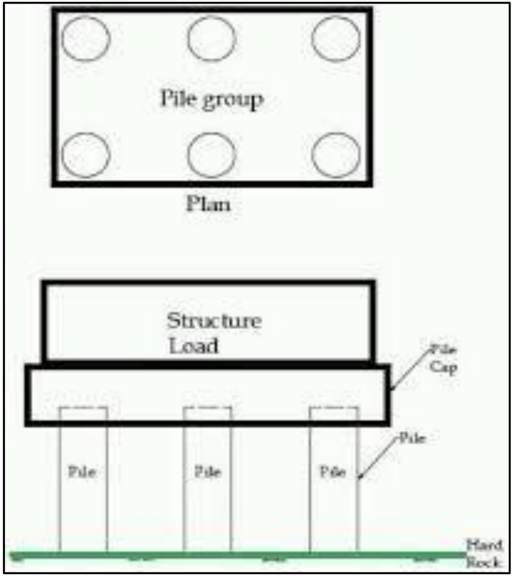

Fig. 1.2: Pile Group

Fig. 1.3: Pile Cap

*G. Seismic Evaluation of Pile Foundations*

Pile foundations are essential in areas where surface soils are weak, compressible, or susceptible to liquefaction. During earthquakes, pile foundations are subjected to complex interactions between the structure, soil layers, and dynamic ground motion. Evaluating their seismic performance is critical to avoid catastrophic failures in bridges, buildings, metro stations, offshore structures, and lifeline systems.

*1) Seismic Loads Acting on Pile Foundations*

During an earthquake, piles experience two distinct types of loads:

a) Inertial Interaction (Superstructure Response)
- Mass of the building generates inertial forces.
- Those forces are transferred to the pile cap.
- Pile cap transfers these forces to the piles.
- Piles bend and undergo shear forces along their length.

Key characteristics:

- Leading pile (toward direction of shaking) receives maximum bending moment.
- In structures with heavy superstructures (bridges, shear walls), inertial loads dominate.
- Results in pile head rotation and large deflection near the ground surface.

b) Kinematic Interaction (Soil Deformation)
- Soil moves differently at different depths.
- The pile is "dragged" by this soil movement.
- Even if the structure has no mass, piles experience bending due to soil movement.

Key characteristics:

- Bending is highest at layer interfaces, where stiffness changes abruptly.
- Kinematic loads become dominant for:
  - Deep piles
  - Soft–stiff layered soils
  - Liquefiable layers

- Flexible superstructures

### *2) Soil Behavior During Earthquakes*

Soil does not behave linearly under earthquake loading. Key phenomena include:

a) Nonlinear Stress–Strain Behavior
- Soils soften under cyclic loading.
- Shear modulus decreases.
- Damping increases.

This affects lateral pile resistance (p-y curves).

b) Liquefaction in Sandy Soils

Loose, saturated sands may lose strength during shaking, effects on piles:
- Reduction in lateral soil resistance
- Lateral spreading (ground movement towards free face)
- Negative skin friction (drag down forces)
- Potential bending failure
- Excess pore pressure buildup reduces soil stiffness drastically.

Liquefaction is one of the most dangerous conditions for pile foundations.

c) Stiffness Contrast Between Layers

In layered soils:
- Soft clay over stiff sand → bending concentrates at interface.
- Stiff layer over soft clay → pile experiences sudden curvature changes.
- Sudden stiffness changes lead to stress concentration zones.

### *3) Importance of Seismic Evaluation of Pile Foundations*

Seismic evaluation is crucial because:
- A large number of structures depend on piles.
- Most critical infrastructure (bridges, metro lines, ports) lies in seismic zones.
- Earthquakes cause ground deformation not predicted in static design.
- Layered soils amplify shaking and change pile behaviour.
- Liquefaction-induced failures have caused major collapses historically.
- Ensures safety, durability, and functionality of structures.

## *H. Layered soil*

Soil at any natural site is rarely uniform throughout its depth. Instead, it is composed of multiple layers, each having distinct physical, mechanical, and hydraulic properties. These layers are formed due to geological processes over thousands or millions of years. When designing foundations—especially deep foundations like piles it is essential to understand the behavior of each soil layer because structural loads are transferred through these layers to deeper strata.

Understanding layered soil profiles is critical for geotechnical analysis, especially under lateral and seismic loading, as stiffness contrasts strongly influence soil–structure interaction.

Layered soil refers to a soil profile composed of two or more soil strata stacked vertically, each differing in:
- Density
- Stiffness
- Strength
- Compressibility
- Permeability
- Grain size
- Plasticity

These variations result from depositional, environmental, and geological processes.

Example: A typical layered profile might be:
- 1–3 m: Loose sand
- 3–10 m: Soft clay
- 10–18 m: Medium-dense sand
- Below 18 m: Stiff clay or rock

Each layer behaves differently under load.

### *1) Formation of Layered Soil*

- Alluvial Deposits - Deposited by rivers → alternate layers of sand, silt, clay.
- Marine Deposits - Fine-grained soils laid in marine environment → soft clays with high compressibility.
- Aeolian Deposits - Wind-blown → loose sands or silty layers.
- Colluvial Deposits - Gravity-deposited soils on slopes → mixed layers.
- Weathered Rock Layers – Top layer: Completely weathered soil. Below: Moderately weathered. Deep: Fresh rock.
- Man-Made (Fill) Layers - Filled land → heterogeneous layers of various materials.

### *2) Classification of Layered Soil Profiles*

Layered soil can be categorized based on how layers are arranged:

a) Soft Soil Over Stiff Soil

Example: Soft clay → Stiff clay
- Common in coastal and marine areas
- Pile bending increases at stiffness boundary
- Large settlements near soft layer

b) Stiff Soil Over Soft Soil

Example: Dense sand → Soft clay
- Upper stiff layer restricts movement
- Lower soft layer settles more
- Causes differential settlement and bending in piles

c) Sand–Clay Alternating Layers
- Very common in riverbeds
- Nonlinear behavior during earthquakes
- Potential for partial liquefaction

d) Liquefiable Sand Layer Between Stiff Layers
- Most dangerous for pile foundations
- Liquefaction → complete loss of lateral support
- Severe bending at liquefied layer boundary

e) Fill Over Natural Soil
- Upper fill layer is unpredictable
- Underlying natural soil controls ultimate behavior

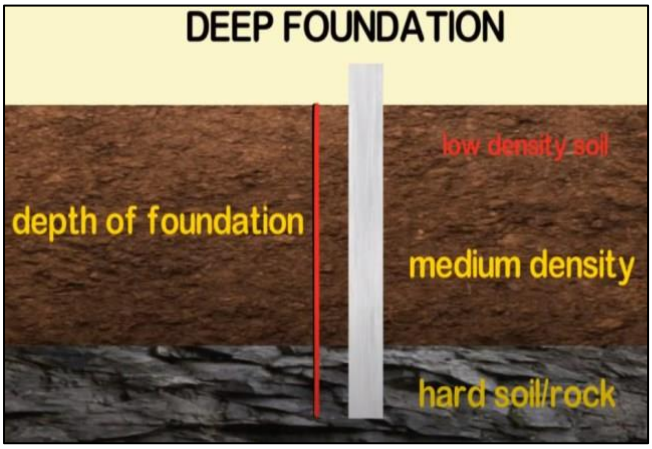

Fig. 1.4: Different types of Soil density.

Fig. 1.5: Different types of Soil Layers.

## *I. PLAXIS 3D*

PLAXIS 3D is a finite element–based numerical simulation software specifically developed for the analysis of deformation, stability, and soil–structure interaction (SSI) problems in geotechnical engineering. It is widely used for advanced modelling of foundations, excavations, tunnels, embankments, retaining structures, offshore foundations, and seismic problems. Because of its capability to capture complex 3D geometry, nonlinear soil behavior, and dynamic loading, PLAXIS 3D has become one of the most reliable tools for seismic analysis of pile foundations.

### *1) PLAXIS 3D Is Important for Pile Foundation Analysis*

Traditional analytical methods often assume:

- 2D idealization
- Linear elasticity
- Constant soil stiffness
- Simplified p–y curves

These assumptions cannot capture:

- Bending moment distribution along pile length
- Soil–pile–pile interaction in pile groups
- Cyclic degradation during earthquakes
- Effects of layered soil
- Kinematic vs inertial interaction

PLAXIS 3D overcomes these limitations by offering:

- Full 3D geometry of piles, pile caps, soil layers
- Embedded pile elements that calculate skin friction + end bearing automatically
- Nonlinear dynamic material models (e.g., HS, HS-small, PM4Sand)
- Earthquake time-history input
- Excess pore pressure generation
- Group interaction factors

Thus, it gives a more accurate representation of the real seismic behaviour of piles.

### *2) 3D Finite Element Modelling*

PLAXIS 3D uses tetrahedral and hexahedral elements to model:

- Soil
- Rock
- Structural elements
- Interfaces

It can simulate real-world geometry including non-uniform soil profiles, sloping ground, irregular pile arrangements, and multi-layered deposits.

### *3) Advanced Soil Constitutive Models*

PLAXIS 3D includes several constitutive models such as:

a) Mohr–Coulomb Model (MC): Basic elastic–plastic model used for simple cases.

b) Hardening Soil Model (HS): More realistic stress-dependent stiffness; suitable for sand, clay, silt.

c) Hardening Soil Model with Small-Strain Stiffness (HSsmall): Captures stiffness at small strains; critical for seismic analysis.

d) Soft Soil and Soft Soil Creep Models: Used for soft clays, peat, and highly compressible materials.

e) PM4Sand / PM4Silt (User-defined soil models): Liquefaction-capable dynamic models for saturated granular soils.

These models allow the simulation of soil behavior during:

- Cyclic loading
- Stiffness degradation
- Excess pore pressure generation
- Liquefaction

### *4) Structural Elements*

PLAXIS 3D provides specialized elements for geotechnical structures:

a) Embedded Beam Elements (for Piles)

Simulates:

- Axial resistance
- Lateral resistance
- Skin friction
- End bearing

Very useful for single piles and pile groups.

b) Volume Pile Elements

- For detailed modelling of large-diameter or rigid piles.

c) Plate, Beam, and Interface Elements

- Used for pile caps, rafts, retaining walls, offshore structures.

### *5) Dynamic (Seismic) Analysis Module*

PLAXIS 3D supports:

- Time-history analysis
- Input of earthquake acceleration records

- Frequency-dependent damping
- Rayleigh damping
- Absorbing (viscous) boundaries

Simulation of liquefaction

This makes it ideal for seismic evaluation of pile foundations.

Earthquake motion can be applied:

- At the base
- At side boundaries
- As shear waves
- As both horizontal + vertical input

### *6) Meshing and Solver Efficiency*

PLAXIS includes:

- Fully automatic mesh generation
- Local refinements around piles and critical boundaries
- Fast solvers for large models
- Dynamic timestep optimization

This reduces simulation time while maintaining accuracy.

### *7) Application of PLAXIS 3D in Seismic Analysis of Pile Foundations*

PLAXIS 3D is widely used for:

a) Seismic lateral response of single piles
   - Lateral displacement
   - Bending moment
   - Shear forces
   - Plastic hinge formation

b) Pile group behavior under earthquake loading
   - Group interaction effects
   - Reduction in lateral stiffness
   - Load redistribution among piles

c) Kinematic and inertial interaction
   - Soil movement causes kinematic loads
   - Superstructure inertia causes additional loads

d) Liquefaction-induced pile response
   - Excess pore pressure ratio
   - Loss of lateral support
   - Down-drag and settlement

e) Performance-Based Seismic Design (PBSD)

PLAXIS enables evaluation at:

- Service Level Earthquake (SLE)
- Design Basis Earthquake (DBE)
- Maximum Considered Earthquake (MCE)

It becomes possible to assess:

- Damage levels
- Serviceability
- Collapse prevention

## II. LITERATURE REVIEW

1) Kramer, S. L., Valdez, C., (2014): - A broad PEER-style performance-based framework for pile groups. They combine probabilistic seismic hazard, structural response, and geotechnical models to develop load/resistance and demand/capacity factors. Analytical/numerical work uses equivalent-linear or simplified site models for the hazard stage then applies a 3-D soil–pile group model (OpenSees) for response; extensive parametric and statistical analyses are included.
   Key findings: (i) PBSD for pile foundations is feasible but complex because pile response involves multiple interdependent load & response components; (ii) OpenSees (discrete p-y, t-z, Q-z elements) can effectively represent pile group response when validated; (iii) lack of full-scale seismic data is a major limitation for calibrating probabilistic design factors; (iv) design and demand factors are sensitive to structural characteristics, soil type, ground motion set, and modelling uncertainty. They offer a modular two-stage approach (predict loads from ground motion → predict foundation response) and propose procedures for computing design/demand factors.
2) Jawad, A. S. & Albusoda, B. S. (2024): - 3-D PLAXIS dynamic finite-element analyses of pile/raft systems in layered profiles. They use a nonlinear constitutive model (hypoplastic model) to simulate both dry and saturated loose sands under recorded earthquake motions, and they validated PLAXIS results against experimental/numerical references.
   Key findings: site profile, pile diameter and length, and the characteristics of the input ground motion strongly control dynamic response. Increasing pile length (larger L/D) significantly reduced peak acceleration transmitted to the raft (reported up to ~40% reduction for some records). Both saturated and dry cases were examined and show the influence of pore-pressure evolution and geometry on dynamic response.
3) Dewi, S. & Gouw, T. L. (2011): - PLAXIS 3D Foundation parametric study of lateral capacity of pile groups. They varied pile spacing, number of piles in the group, and soil stiffness modulus. The study used finite-difference computations for single-pile capacity (to provide the single-pile baseline) and PLAXIS 3D for group behavior.
   Key findings: (i) group lateral capacity < sum of single pile capacities; hence the *efficiency (reduction) factor* is needed; (ii) efficiency decreases as number of piles increases (they reported values down to ~0.20 for dense groups); (iii) soil stiffness has a strong positive effect on group efficiency (higher stiffness → higher efficiency); (iv) spacing increases efficiency (wider spacing → higher effective capacity). Study scope excluded pile cap effects and limited spacing/diameter ranges; authors list further parametric cases as future work.
4) Sawamura, Y. et al. (2021): - Confirmed the effectiveness of a composite foundation (pile foundation with ground improvement under the footing) in enhancing seismic performance in liquefiable ground through centrifuge model tests and finite element analysis.
5) Quoc, L.B. (2025): - Evaluated the seismic behavior of single piles and pile groups in soft soil using PLAXIS 3D simulation. A key finding was that internal forces (shear force and bending moment) increase much more significantly in a pile group compared to a single pile under seismic loading.
6) Bradley, B.A. et al. (2018): - Investigated the correlation between Engineering Demand Parameters (EDPs) and various Intensity Measures (IMs) as part of a

performance-based earthquake engineering framework for pile foundations in non-liquefiable soils.

7) Ismael, M.A. & Ahmed, B.A. (2023): - Focused on the stability of a collective pile subjected to seismic loads in dry soils with sloping layers using PLAXIS 3D. The study observed that settlement ratios increased with higher seismic intensity.

### *A. Research Gap Identification*

- Scope Extension of Performance-Based Analysis: Bradley, B.A. et al.'s investigation into performance-based seismic response was specifically focused on non-liquefiable soils, suggesting a need to fully apply and validate similar performance-based frameworks for foundations in liquefiable ground.
- Insufficient parametric coverage for dense or industrial-scale groups and pile-cap effects: Dewi & Gouw show spacing, group size and stiffness effects but intentionally omit pile cap effects and some spacing ranges; they recommend expanded parametric ranges (2D, 3D, 7D, 8D spacing, different pile sizes, cap effects, etc.). Your study can contribute by including cap flexibility and intermediate/denser spacing in layered soils.
- Pile Group Response in Sloping Saturated Soils: The work by Ismael, M.A. & Ahmed, B.A. focused on pile group response in dry soils with sloping layers. Further work is necessary to fully model the complex interaction and stability in saturated (potentially liquefiable) sloping layered soils under seismic loading.

## III. OBJECTIVES AND METHODOLOGY

### *A. Objectives*

- To model a single pile in layered soil and evaluate its seismic response using PLAXIS 3D.
- To determine the location of maximum bending moment along the pile length.
- To analyze sensitivity of pile response to changes in: Soil stiffness, Damping ratio, Earthquake duration, Water table level.
- To compare single pile vs 2×2 vs 3×3 pile groups under seismic loading.

### *B. Methodology*

All dynamic analyses use time-history (transient) analysis in PLAXIS 3D. Use a two-stage modelling strategy: initial geostatic + staged construction (static) → dynamic time history stage.

#### *1) Baseline model: single pile in layered soil*

a) Decide scope and gather inputs
   1) Select representative soil profiles (at least two different profiles recommended; you can start with one). Example profiles:
      - Profile 1 — Soft clay (0–8 m) over dense sand (8–30 m).
      - Profile 2 — Loose saturated sand (6–12 m) susceptible to liquefaction, overlain by silt.
   2) Pile geometry (choose and keep constant across models):
      - Diameter D = 0.6 m, Length L = 20 m (example; adjust as needed).
      - Concrete: E = 25 GPa, ν = 0.2, density = 24 $kN/m^3$.
   3) Pile cap: plate element, thickness = 0.6 m, or rigid cap modelling option for one case and semi-rigid in another.
   4) Groundwater table: initial baseline at mid depth (e.g., 10 m below ground surface).
   5) Earthquake records: collect 2–3 accelerograms (e.g., El-Centro, Kobe, and one site-specific or synthetic). Scale to three target PGA levels corresponding to SLE/DBE/MCE (examples: 0.1g, 0.25g, 0.4g — adapt to local hazard).

Keep a log file with all input files, parameter choices and reasons (this is important for reproducibility).

#### *2) PLAXIS 3D: domain & geometry setup*

- Create new PLAXIS 3D project and set units (KN, m, s).
- Create soil volumes: draw horizontal layers for the depth required (extend domain horizontally at least 4–5 × pile length from the pile center in each horizontal direction — e.g., for L = 20 m, lateral extent ≥ 80–100 m). Depth of model base should be at least pile tip depth + 5–10 m.
- Define materials for each layer (see Material Models below).
- Add groundwater / phreatic line and check pore pressure initialization method.

#### *3) Material models & parameterization*

a) Constitutive model choice (baseline):
   - For clays/silts: Hardening Soil with Small-strain stiffness (HS-Small).
   - For non-liquefiable sands: Hardening Soil (HS) or HS-Small.
   - If you plan liquefaction cases: for those sand layers use PM4Sand (or UBC3D-PLM) in the dynamic stage (see two-stage notes).

b) Typical parameter examples (start values — replace with site or literature values):
   - Clay: $\gamma = 18\ KN/m^3$, E50ref = 8 MPa, Eurref = 80 MPa, ν = 0.2, c = 20 kPa, φ = 25°.
   - Dense sand: $\gamma = 19\ KN/m^3$, φ = 36°, Dr = 70%, G0 ≈ 40–60 MPa (set via Eurref or G0), E50ref = 40 MPa, ν = 0.3.
   - PM4Sand: use benchmark calibration values if site data not available (document source).

c) Interfaces:
   - For pile–soil interface uses an interface element with shear strength reduction factor R_inter ≈ 0.6–0.9 (typical). Set normal stiffness high enough (e.g., K_n = 10–100 × E_pile / D).

d) Pile / structural properties:
   - For embedded beam piles: diameter, axial stiffness EA, flexural stiffness EI ($EI = E_{pile} \times I$ wish $I = \pi D^4/64$), mass per unit length.
   - For pile cap: plate element with specified thickness and material.

#### *4) Mesh & boundaries*

a) Meshing:
   - Use PLAXIS automatic mesh generator.
   - Apply local mesh refinement around the pile: element size around pile ~ D/3 to D/5 for accurate moment curvature. Coarser mesh far away.

b) Boundary conditions:

- Lateral boundaries: free-field or viscous/absorbing boundaries.
- Base: fixed in vertical and horizontal (or use compliant base with absorbing conditions if preferred).

c) Check element quality and refine if high aspect ratios exist.

*5) Initial stress & staged construction*

1) Geostatic: run initial geostatic to establish in-situ K0 (use Jaky K0 or measured).
2) Staged construction:
   - Add the pile using the embedded beam or volume pile approach. For bored piles, you can create the pile volume and assign pile material; for embedded beams, add embedded pile element and assign pile sections.
   - Add pile cap (plate) and superstructure mass or inertia if needed (for inertial interaction).
3) Check static pushover (optional) — apply lateral static load to test pile behavior and sanity check p-y response.

*6) Dynamic (time-history) analysis setup*

a) Define dynamic settings:

- Time step Δt: choose small enough to capture record frequencies. A common starting point: Δt = 0.002–0.005 s. For high-frequency content choose smaller dt.
- Damping: Rayleigh damping using α and β. Determine α/β by specifying target damping (ζ) at two frequencies (e.g., fundamental soil/pile frequency and first structural frequency). Typical modal damping: 2–5% (sensitivity will be studied).

b) Ground motion input:

- Import horizontal acceleration time series (ACC).
- Scale to SLE/DBE/MCE PGA levels. Apply at base (or use free-field boundaries).
- If available run bi-directional components in separate runs or combined for advanced study.

c) Absorbing boundaries: ensure lateral boundaries are absorbing to avoid spurious reflections.

*7) Run & check*

1) Run dynamic analysis for each earthquake/scenario.
2) Check results for numerical stability:
   - No sudden, non-physical values of displacement or pore pressure.
   - Time step small enough (no oscillations).
3) If problems arise, reduce time step, refine mesh, or adjust damping.

*8) Postprocessing — find maximum bending moment location*

1) Extract bending moment envelope along pile length:
   - In PLAXIS, query beam/embedded element bending moment; plot maximum absolute moment vs depth.
2) Identify depth(s) with peak moment — typically near ground surface and at stiffness interfaces.
3) Save time histories of pile head displacement, rotation, and moment at critical sections.
4) Export results (CSV) for plotting in Excel and for report figures.

### *C. Sensitivity analyses*

*1) Strategy & experimental matrix*

Use an OFAT (one-factor-at-a-time) approach first, then limited combinations for interactions.

Suggested baseline: the validated single pile model from Part A.

Sensitivity levels (example):

- Soil stiffness: 0.7× E50ref (softer), 1.0× baseline, 1.3× E50ref (stiffer).
- Damping ratio (Rayleigh target): low 1%, baseline 3%, high 6%.
- Earthquake duration: short (≈ 20 s), baseline (≈ 50 s), long (≈ 120 s). Use different records or extend using real long records (avoid naive looping unless validated).
- Water table level: deep (below pile tip), baseline (mid depth), shallow (near surface).

Total runs example: baseline + (2 soil stiffness) + (2 damping) + (2 duration) + (2 water table) = 9 sensitivity runs + baseline = 10 runs. Add 3–6 combined parameter runs for interactions → ~15 runs.

*2) How to implement each parameter change in PLAXIS*

a) Soil stiffness:

- Edit material properties: change E50ref, Eurref, and/or G0 (for PM4Sand).
- Re-run geostatic + staged construction to update initial stresses (important).

b) Damping ratio:

- Modify dynamic settings → Rayleigh damping coefficients or directly change modal damping targets.
- If using PM4Sand/hysteretic models, note that material damping is implicit; still use small Rayleigh as supplemental damping.
- Important: do not arbitrarily set very high α/β — document choices.

c) Earthquake duration:

- Use different ACC files for different durations, or choose records with different durations.
- Scaling: ensure PGA target is same for SLE/DBE/MCE across durations if you want to isolate duration effect.

d) Water table:

- Change phreatic surface location in Groundwater options.
- If water table change affects initial pore pressure state, re-run geostatic and drainage analysis to equilibrium.

*3) Outputs to extract for each run*

- Max bending moment envelope vs depth (absolute max).
- Max pile head displacement (peak & residual).
- Max shear & axial force.
- Time history of excess pore pressure (ru) at critical nodes for liquefaction scenarios.
- For groups (later section): cap rotation, tilt, settlement.

*4) Presentation & sensitivity quantification*

- Tornado plots: percent change in peak moment/head displacement vs baseline for each parameter.
- Overlay envelopes: show moment vs depth for baseline and sensitivity cases.
- Tables: numeric summaries (peak moment, depth of peak, peak head displacement, residual).
- Ranking: rank parameters by magnitude of influence on each response metric.

*5) Pile groups: 2×2 and 3×3*

a) Geometry & group definitions

1) Group layouts:
    - 2×2 square: 4 piles in square layout.
    - 3×3 square: 9 piles.
2) Spacing: choose typical spacings 3D, 4D, 5D (where D is pile diameter). For D = 0.6 m, these are 1.8 m, 2.4 m, 3.0 m.
3) Pile cap: model both rigid cap (very stiff plate) and semi-rigid cap (use realistic RC stiffness). For the rigid cap, set plate thickness large and very high E; for semi-rigid use actual RC section.

b) Modeling differences vs single pile

1) Use the same domain and mesh, but refine mesh around the group centroid.
2) When using embedded beam piles, ensure correct connectivity so the cap transfers loads to each pile.
3) For groups, explicitly model the pile cap to capture group rigidity effects.

c) Runs to perform

1) Baseline group cases (for each spacing) under same earthquake inputs (SLE/DBE/MCE).
2) Sensitivity cases (same parameter variations as in Part B) — for practical time limits, run sensitivity only for the most influential parameters found in B (e.g., soil stiffness and water table).
3) If computation time allows, run combined scenarios (e.g., soft soil + shallow water table + long duration).

Suggested run count:

- Single pile baseline + 2 sensitivity levels per parameter ~10 runs (from Part B).
- 2×2 baseline + 3 spacings + 2 cap stiffness options = 6–8 runs.
- 3×3 baseline + same spacings & cap options = 6–8 runs.
- Sensitivity runs on group cases for 2–4 select parameter combos → ~8 runs.

Total workable thesis run count ≈ 30–40 dynamic analyses (adjust based on compute capacity).

d) Postprocessing & comparisons

1) Group efficiency (η) for lateral demand:
    - η = (max group lateral resistance) / (n × max single pile lateral resistance) (Or define demand-based efficiency as ratio of group demand per pile to single pile demand.)
2) Compare:
    - Peak moment per pile (leading pile vs rear pile) — show envelopes for representative piles (leading, middle, corner).
    - Peak head displacement per pile and cap drift/rotation.
    - Settlement & tilt of group vs single pile.
    - Residual displacement and group rotation — key for PBSD.
3) Visualization:
    - Contour plots of lateral displacement & ru (if liquefaction).
    - Moment envelopes for leading piles vs single pile.
    - Bar charts / normalized comparison tables.

Methodology flow chart

## IV. EXPECTED OUTCOME

### *A. EXPECTED OUTCOME*

1) Understanding of how single piles and pile groups behave during an earthquake
   we will clearly see how the pile bends, displaces, and takes loads when ground shaking occurs.
2) Identification of the critical depth where maximum bending moment occurs
   PLAXIS 3D will show the exact location along the pile where damage is most likely during an earthquake.
3) Comparison of seismic performance of single pile, 2x2 pile group, and 3x3 pile group
   we will be able to say which arrangement performs better or worse under the same earthquake.
4) Effect of changing soil stiffness, damping ratio, earthquake duration, and water table level
   The sensitivity study will show how each factor increases or decreases pile displacement and bending moment
5) Improved understanding of soil pile interaction in layered soil
   The results will help in understanding how soft layers, stiff layers, or groundwater influence pile performance.
6) Validation of PLAXIS 3D as a useful tool for seismic analysis of pile foundations
   The study will prove that PLAXIS can accurately model realistic dynamic behavior of soil and piles.

## REFERENCE

[1] Bradley, B. A., Cubrinovski, M., & Dhakal, R. P. (2008). Performance-based seismic response of pile foundations in non-liquefiable soils. Conference Paper, GSP 181.

[2] Dewi, S., & Gouw, T. L. (N.D.). Analysis on laterally loaded group piles by PLAXIS 3D Foundation. Journal of Applied Science and Engineering, 19(2).

[3] Ismael, M. A., & Ahmed, B. A. (2023). Numerical Simulation of Pile Group Response in Slope Layered

Soil under the Effect of Seismic Loading. Journal of Engineering, 29(12).

[4] Kramer, S. L., Valdez, C., Blanchette, B., & Baker, J. W. (2014). Performance-Based Design Factors for Pile Foundations. WSDOT Research Report WA-RD 827.1.

[5] Le Bao Quoc. (2025). An evaluation of single pile and pile group behavior under seismic loading in soft ground. Journal of Materials and Construction, 15(1).

[6] Jawad, A. S., & Albusoda, B. S. (2024). Numerical Evaluation of Pile Group Behavior Subject to Earthquake Loads. Journal of Engineering, 30(5).

[7] Sawamura, Y., Inagami, K., Nishihara, T., Kosaka, T., Hattorid, M., & Kimura, M. (2021). Seismic performance of group pile foundation with ground improvement during liquefaction. Soils and Foundations, 61(2021), 944-959.

[8] Yang, Y., Xin, G., Chen, Y., Stuedlein, A. W., & Wang, C. (2023). Seismic Performance of Drained Piles in Layered Soils. Materials, 16(17), 5868.

[9] Jeremic, B., & Yang, Z. (2010). *Advanced Numerical Modeling of Piles in Liquefiable Soils*. Computers & Geotechnics

[10] Patil, S., & Choudhury, D. (2019). *Seismic Analysis of Piles in Layered Soil: State of the Art Review*. Geotechnical Earthquake Engineering Journal.