SIMULATION OF EXCESS PORE PRESSURE AND VERTICAL SETTLEMENT OF SOIL UNDER CYCLIC LOADING USING ABAQUS

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In

Soil Mechanics and Foundation Engineering

By

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

This is to declare that I, **Kalyan Prasad Mahato**, student of Geotechnical Engineering Division of the Department of Civil Engineering, class roll no. **002210402002**, have prepared this thesis entitled **"SIMULATION OF EXCESS PORE PRESSURE AND VERTICAL SETTLEMENT OF SOIL UNDER CYCLIC LOADING USING ABAQUS"**under the supervision of **Prof. Ramendu Bikas Sahu**. This manuscript is original and not directly plagiarized in any sense. However, the Literature studied for the preparation of this report has been cited wherever required and also presented in the list of references.

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CERTIFICATE

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The forgoing thesis titled **"SIMULATION OF EXCESS PORE PRESSURE AND VERTICAL SETTLEMENT OF SOIL UNDER CYCLIC LOADING USING ABAQUS"** is hereby approved as a creditworthy study of an engineering subject conducted and presented satisfactorily to warrant its acceptance as a precondition to the degree for which it was submitted. It is understood that the undersigned does not automatically support or accept any argument made, opinion expressed, or inference drawn in it by this approval, but only approves the thesis for the reason it was submitted.

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NOTATIONS AND ABBREVIATIONS

C_1, c_2, C_3= Soil parameters.

C_c= Compression index.

C_s= Swelling index.

d= Sensitivity of pore water pressure.

d_{50}= Mean grain size diameter.

D_r= Relative Density in percentage.

e_o= Void ratio.

f(e)= Void ratio function.

K= Permeability.

κ= Represent elastic behaviour of soil.

P_a= Atmospheric pressure.

P_i= Initial effective stress.

P_{N-1}= Mean effective stress at the end of (N-1)th cycles.

ΔU_N^*= Residual pore pressure ratio at Nth cycle.

W_L= Liquid limit.

ρ = Density of soil.

γ_w= Specific unit weight of water.

ν= Poisson's ratio.

ϕ' = Internal friction angle.

WYS= Wet Yield Surface.

FSR= Flow stress ratio.

ABSTRACT

The generation of excess pore pressure and resulting settlement in clay soils subjected to cyclic loading is a critical factor influencing the stability and serviceability of foundations in civil engineering projects. This study investigates the mechanisms of pore pressure accumulation and deformation in clay soils when exposed to repeated loading, such as that from traffic or wave action, focusing on the soil's stress-strain response and long-term settlement characteristics.

The research employs a series of laboratory cyclic loading tests on undisturbed and remolded clay samples to simulate real-world loading conditions. Parameters such as loading frequency, amplitude, and duration are systematically varied to assess their impact on pore pressure buildup and soil displacement. Data is analyzed to determine the relationship between excess pore pressure and factors like soil plasticity, water content, and initial stress state.

Findings indicate that cyclic loading leads to a progressive accumulation of pore pressure, which reduces the effective stress in the soil, resulting in softening and increased settlement. The rate and extent of settlement are found to depend strongly on the cyclic loading characteristics and the soil’s intrinsic properties, with higher frequency and amplitude leading to greater settlement. The results provide a framework for predicting soil behavior under cyclic loads, aiding in the design of more resilient foundations in soft clay soils.

This thesis contributes to the understanding of soil-structure interaction under cyclic loading and offers practical recommendations for engineers in predicting and mitigating settlement in clayey soils, improving the long-term stability and performance of infrastructure.

INTRODUCTION

1.1 GENERAL

Excess pore water pressure generation in a subgrade soil layer is identified as one of the key parameters affecting the behavior and long-term performance of any sub-structure (railway or pavement) subjected to cyclic traffic loading. By understanding the mechanisms behind excess pore water pressure generation, engineers and designers can develop improved design practices that take these effects into account and help to prevent or mitigate its potential impacts. It should be noted that when a saturated subgrade is subjected to cyclic loading, excess pore water pressure accumulation can be generated with time, and eventually, it could lead to migration of particles into the overlying granular layers. The migration of subgrade soil to the upper layers would lead to clogging of pores in the contaminated coarse aggregate layers and a reduction in the drainage capacity of the upper layers. This condition would lead build-up of excess pore water pressure when a saturated subgrade is subjected to cyclic loading. The build-up of excess pore water pressure under cyclic traffic loadings seem to be similar to the rapidly increasing excess pore water pressure initiated during an earthquake. As the drainage capability is decreased under continuous cyclic loading, excess pore water pressure does not have enough time to dissipate and eventually leading the build-up of excess pore water pressure.

In an element of soil, depending on the boundary conditions, a cyclic loading can lead to an accumulation of residual strains and/or changes in the average effective stress. Closed stress loops result in not perfectly closed strain loops or vice versa. A simultaneous accumulation of stress and strain is also possible. The accumulation of strain leads to residual deformations, e.g. settlements of shallow foundations or tilting of laterally loaded piles. The magnitude of these permanent deformations depends on the loading (average load, load amplitude) and the type and current state (void ratio, cyclic preloading)of the subsoil. Even small amplitudes can significantly contribute if the number of cycles is high.

1.2 EXCESS PORE PRESSURE

The generation of excess pore pressure in clay soils under various loading conditions is a critical issue in geotechnical engineering, as it directly influences soil stability, strength, and potential for settlement. Excess pore pressure occurs when external loads exceed the ability of soils to drain and dissipate water pressure, resulting in reduced effective stress and potentially leading to soil failure. In practical terms, accurately predicting and managing excess pore pressure is essential for the safe and efficient design of foundations, retaining structures, and other load-bearing systems on clay-rich soils.

With advances in computational modeling, simulation tools like Abaqus have become invaluable for analyzing complex soil behaviors under various loading scenarios. Abaqus, a powerful finite element analysis (FEA) software, enables the detailed simulation of soil response under mechanical and hydraulic loads. It allows engineers to predict the behavior of clay soils by accounting for factors such as soil composition, initial stress states, drainage conditions, and load cycles. By implementing constitutive models tailored to clay behavior, such as the Modified Cam-Clay model, Abaqus provides insights into the development and distribution of excess pore pressures over time.

This thesis aims to develop a computational approach for calculating excess pore pressure generation in clay soils using Abaqus software. The study investigates the impact of key parameters including cyclic loading patterns, soil permeability, and consolidation characteristics on pore pressure buildup. The research process involves validating the Abaqus model against laboratory test results and then applying it to a range of hypothetical and real-world scenarios.

The outcomes of this research will provide a reliable and efficient tool for predicting excess pore pressure in clay soils, offering practical implications for foundation and infrastructure design on soft clay deposits. Additionally, the study will contribute to the body of knowledge in computational geomechanics, demonstrating how simulation can supplement traditional testing methods, reduce project risk, and enhance the safety and durability of civil engineering structures.

1.3 SETTLEMENT

The settlement of clay soils under cyclic loading is a key concern in geotechnical engineering, especially for structures such as roadways, railways, offshore foundations, and buildings subject to repetitive loads. Cyclic loading, from sources like traffic, machinery, waves, and seismic activity, can induce settlement over time, impacting the structural integrity and serviceability of foundations resting on clay soils. Clay soils, due to their low permeability and high compressibility, are particularly susceptible to deformation and long-term settlement under these conditions. The accurate prediction of settlement in clay soils under cyclic loading is therefore essential for the safe and economical design of infrastructure.

Traditionally, the evaluation of soil settlement has relied heavily on empirical methods and laboratory testing, which can be time-consuming, expensive, and limited in their applicability to complex loading conditions. However, advancements in computational modeling, specifically through finite element analysis software like Abaqus, provide an efficient and versatile approach to studying the settlement behavior of clay soils under cyclic loading. Abaqus allows for the simulation of complex soil behaviors, enabling engineers to model the effects of cyclic loading on clay settlement accurately and to account for variations in soil properties, loading conditions, and environmental factors.

This thesis explores the settlement of clay soils due to cyclic loading using Abaqus software, aiming to develop a reliable model that can predict settlement behavior under a range of cyclic loading scenarios. The study's primary objectives are to validate the simulation results against existing empirical data, assess how cyclic loading parameters (such as frequency, amplitude, and duration) affect settlement, and evaluate the influence of different soil properties on deformation.

Through this research, it is aimed to provide engineers and researchers with a deeper understanding of the settlement mechanisms in clay soils under cyclic loading and offer a framework for using Abaqus in practical geotechnical design applications. By establishing simulation guidelines, this thesis seeks to contribute to safer, more resilient foundation designs and enhance the ability of engineers to predict and mitigate settlement risks in clayey soils subjected to repetitive loading.

LITERATURE REVIEWS

2.1 INTRODUCTION

In this section, a compilation of past research studies focusing on response of clay under cyclic loading is presented. Additionally, this review work includes studies on generation of excess pore pressure and settlement due to cyclic loading.

2.2 LITERATURE REVIEWS

2.2.1 PORE PRESSURE

Wang et al.(1989). Perform non-uniform cyclic triaxial tests on Monterey sand to determine the pore pressure development during non-uniform cyclic loading. Two series of tests are performed in which the number and magnitude of stress cycles are unchanged but the order in which the cycles are applied varies. Prediction of pore pressure accumulation, both deterministic and stochastic, due to non-uniform loading are typically based upon Miner's cumulative damage method. According to cumulative damage theories, the accumulated pore pressure is not affected by the sequence of the loading pulses. The results of nine non-uniform cyclic triaxial tests performed upon specimens of Monterey sand at a relative density of 54% are presented to illustrate the development of the model. This model is a modification of a model developed by Seed, Martin and Lysmer (1976) based upon normalized pore pressure generation curves. The effects of both stress ratio increase and stiffness deterioration are implicitly accounted for in this improved model. A recently developed computer-controlled electro-pneumatic cyclic loading system was used in this study. The system has four major elements: (1) a mini-computer with a programmable clock and analog to digital *(A/D)* and digital to analog *(D/A)* converters, (2) an electronic/pressure transducer with relay, (3) a double-acting piston, and (4) two volume boosters. A series of additional non-uniform loading tests were conducted to evaluate the applicability of the proposed stress-dependent pore pressure generation model.

Experimental results from uniform and non-uniform· cyclic triaxial loading tests show that the stress-ratio dependence of pore pressure generation must be considered in order to accurately predict pore pressure development during non-uniform cyclic loading. The test results demonstrate that pore pressure generation during non-uniform cyclic loading is a function of both the magnitude and the order of the applied stress cycles. Use of a single average pore pressure generation curve to predict pore pressure generation in these non-uniform tests is likely to result in underestimation of the magnitude of pore pressure generation. By introducing a set of stress-ratio dependent pore pressure generation curves, the results of uniform cyclic tests are shown to accurately predict the end-of-sequence residual pore pressure as well as the pore pressure generation path during non-uniform cyclic loading tests. End of cycle pore pressure generation curves resulted in better agreement between observed and predicted results than the peak pore pressure generation curves. The primary deficiency in this method is that it may underestimate the influence of stress cycles below the threshold level that causes liquefaction in uniform cyclic tests.

Polito et al (2008). It discusses the applicability of two simple models for predicting pore water pressure generation in nonplastic sand and silty soil during cyclic loading. The first model was developed by Seed et al. in the 1970s and relates the pore pressure generated to the cycle ratio, which is the ratio of the number of applied cycles of loading to the number of cycles required to cause liquefaction. The second model is the Green-Mitchell-Polito model proposed by Green et al. in 2000, which relates pore pressure generation to the energy dissipated within the soil. The data from the 145 cyclic triaxial tests used to evaluate the proposed models were culled from nearly 300 cyclic triaxial tests (Polito 1999; Polito and Martin 2001). The specimens tested in the study were comprised of one of two base sands, mixed with various amounts of nonplastic silt. Eight combinations of sand and silt were created using each of the two sands, with silt contents varying from 4–75% by weight. Polito and Martin (2001) have shown that the liquefaction of sands and nonplastic silts is more a function of relative density than of void ratio.

While several models have been developed and calibrated for predicting excess pore pressures in clean sands, little work has been done in this area for nonplastic, silty soils. Two models (i.e., Seed et al. and GMP models) were evaluated for predicting residual excess pore pressure generation in nonplastic, silty soils and both were found to be effective means of making such analyses, with the GMP model only being applicable for soils having a $Dr \leq 85\%$. Using data from approximately 150 cyclic triaxial tests covering a wide range of nonplastic silt contents and densities, the writers applied nonlinear mixed effect regression techniques to develop correlations for estimating the parameters required to calibrate the models. The results show that the trends in both α and PEC calibration parameters for the Seed et al. and Green et al. pore pressure generation models, respectively, differ significantly for soils containing less than and greater than 35% fines, consistent with the limiting fines content concept.

Rambha Devi, Sahu and Mukherjee (2014), Stress controlled cyclic triaxial tests were performed under different cyclic stress ratios (CSRs) and confining stress of 100 kPa on normally consolidated locally available clay and organic clay with 15% (RO1) and 26% (RO2) organic contents to study the axial strain and pore pressure response. The test result get that Normalized undrained cohesion of organic clay is higher than that of inorganic clay. The effective angle of internal friction is found to be 26.5° in inorganic clay and 33.8° and 34.7° in RO1 and RO2 respectively. The axial strain developed under cyclic loading is higher in inorganic clay than that in organic clay. A strain of 2–2.5% may be taken as the failure strain upto which the strain increases steadily even at high CSRs for both inorganic clay and organic clay. Thereafter the rate of increase in strain becomes high ultimately reaching very high values. Both the axial strain and pore pressure are affected by the rate of cyclic loading with higher rate of loading showing lesser response in both inorganic and organic clay at initial cycles. The final axial strain is lesser at lower frequencies for both inorganic and organic clay but the difference is not significant. The final pore pressure ratio is not significantly affected by the rate of cyclic loading. An increase in post-cyclic strength is observed in both inorganic and organic clay. The increase in post-cyclic strength is higher in organic clay.

Konstadinou and Georgiannou (2014) The standout pore pressure prediction model, presented by Ishibashi et al. (1977) was established as one of the most commonly used models obtained an equation that predicts the values for the rise in incremental pore pressure as a function of the stress history, the number of cycles and the applied shear stress. The following relationship proposed to describe the pattern of incremental excess pore water pressure generation with cycles up to initial liquefaction.

$$\Delta U_N^* = (1 - U_{N-1}^*)(\frac{\tau_{\theta z}}{P_{N-1}})^n f(e)^d (\frac{P_i}{P_a})^c \times [\frac{C_1}{(N^{c_2} + C_3 N)} + C_4 C_1]$$

The finer sands have highest liquefaction potential or least resistance to liquefaction.

Following is the final expression for the accumulation of pore water pressure with shear work.

$$\frac{U}{P_i'} = [1.68(d_{50})^{-0.146}][10^{-2(D_r-0.7)}\frac{W}{P_i'}]^{0.6}$$

Two independent prediction methods for the generation of excess pore water pressure during torsional cyclic loading have been presented. The first expresses the variation in pore water pressure with the number of loading cycles. Based on the methodology proposed by Ishibashi et al. (1977), a modified expression is developed which includes stress intensity, cycle number, density and a dependent mean effective stress level and requires only one material dependent parameter. The proposed equation is able to simulate the generation of excess pore water pressure with loading cycles up to the stage of initial liquefaction. Second method to derive an expression of excess pore water pressure generated during cyclic loading as a function of the amount of energy dissipated within the specimen.

Kumar et al. (2014) reported a study on the determination of shear modulus and damping ratio of Brahmaputra sand under varying confining pressures, loading frequencies and shear strain levels using strain controlled undrained Cyclic Triaxial test records. This paper presents the experimental investigation of influence of confining pressure, loading frequency and shear strain level on dynamic properties of Brahmaputra sand. The test material been classified as poorly graded sand (SP). Specific gravity has been found to be 2.7, and the maximum and minimum dry densities are obtained as 16.841 kN/m3 and 13.849 kN/m3 respectively. The average friction angle (φ) shown in Table 1, has been determined from direct shear tests and simple triaxial tests at relative density 60%.Strain-controlled cyclic triaxial tests have been carried out on reconstituted cylindrical specimen (70 mm diameter and 135 mm height). To comprehend the strain dependent dynamic behavior of Brahmaputra sand, a series of strain controlled undrained tests have been conducted on isotropically consolidated reconstituted samples at relative density 60% and at peak axial strain 0.01% - 3% subjected to varying confining pressures (50 kPa, 100 kPa and 150 kPa) and loading frequencies (0.1 Hz, 0.5 Hz, 1Hz, 2 Hz, 3Hz and 4 Hz).Based on 40 cycles of applied axial strain represents the exponential decay of deviator stress with the increasing number of cycles (N) due to deformation of soil structure; while, the increase in pore pressure generation.

Kumar et al. (2017) conducted strain-controlled cyclic triaxial tests for a peak shear strain range of 0.015–4.5% at 1 Hz loading frequency on test specimens prepared at different relative density

(30–90%) and confining stress (50–150 kPa).It was reported that the response of soils at high strain levels (> 0.01%) is substantially different than that at low strain levels (<0.001%), primarily due to the nonlinear stress-strain behaviour and damping characteristics at higher strains. Brahmaputra river sand was chosen for the purpose, and strain-controlled Cyclic Triaxial(CT) tests were performed at 1 Hz loading frequency for a peak shear strain range of 0.015–4.5%, on the reconstituted specimens prepared at different RD (30–90%) and consolidated under different σ′c(50–150 kPa). Shear modulus (G) of BS soil is observed to be significantly affected by the variations in σ′c and RD. However, the scatter of the estimate becomes lower when expressed in terms of the modulus reduction (G/Gmax) curve. In comparison to the classical curves, G/Gmax curve of BS specimens depicted lower range of modulus ratio; however, the trend was well-matching with those reported for Indian soils.

Khasawneh et al. (2017) presented a three-dimensional elastoplastic soil constitutive model designed to simulate the behavior of granular soils under low-frequency cyclic loads. This model, developed for Integral Abutment Bridges (IABs), is capable of handling cyclic loading with a piecewise linear approach and a hyperbolic stress-strain relationship. The model uses the Drucker-Prager (D-P) yield criterion with an unassociated flow rule to predict plastic strain in soils. It incorporates a novel algorithm that adapts upon load reversals, controlling stiffness using the Masing rules. It enhanced from prior models to include three-dimensional capabilities, adaptations to plane strain, and realistic soil behavior during cyclic reloading. Implemented in ABAQUS, the model was tested against physical and laboratory experiments (e.g., cyclic triaxial and direct simple shear tests) to verify accuracy. The model accurately captures granular soil behavior under IAB-specific loading conditions and performs well in predicting soil response across scales. Its design maintains minimal required parameters while enabling application in structural simulations of soil-structure interaction (SSI) under cyclic load. This work demonstrates the utility of simplified models in practical engineering, particularly in scenarios involving frequent low-strain cyclic loading, such as seasonal temperature changes affecting bridge structures.

Gluchowski et al. (2019) focussed on understanding the behavior of cohesive soils under cyclic triaxial loading in undrained conditions. He investigates the effect of undrained cyclic loading on cohesive soils, particularly focusing on the pore pressure generation and plastic strain accumulation in isotropic and anisotropic consolidation conditions. Highlight the importance of consolidation conditions in influencing soil response under cyclic loading, relevant to infrastructure exposed to repetitive loads, such as foundations and road bases. Soil samples were tested under both isotropic and anisotropic (K0) consolidation conditions using a cyclic triaxial apparatus. These tests analyzed the changes in excess pore water pressure and plastic strain as the soils underwent cyclic loading with various deviator stress levels and consolidation pressures. The development of excess pore pressure is highly dependent on consolidation type and stress levels. Anisotropic consolidation conditions led to higher pore pressure and plastic strain accumulation compared to isotropic consolidation. The soil's behavior showed significant variation in terms of pore pressure increase and strain accumulation, with anisotropically consolidated samples demonstrating a more rapid rise in pore pressure and strain accumulation during initial cycles. Tests indicated a relationship between initial void ratio, stress amplitude, and pore pressure generation, which affects long-term stability under cyclic loading. These findings are particularly applicable to geotechnical engineering, where understanding cyclic behavior in cohesive soils can enhance the design and durability of structures subject to repetitive loading, such as roads and embankments. This study offers insights into the dynamic soil response crucial for improving construction practices and optimizing load-bearing design in cohesive soil environments.

Tan Manh Do et al. (2023) focussed on understanding the excess pore water pressure (PWP) generation in fine granular materials, specifically railway sand and tailings, under cyclic loading conditions. The research investigates PWP generation in subgrade materials subjected to cyclic loading, which is critical for designing and maintaining sub-structures in pavements and railways. This study used undrained cyclic triaxial tests to examine PWP behavior in railway sand and tailings at varying densities and stress conditions. The study shows that excess PWP accumulates over time under cyclic loading. This accumulation significantly depends on cyclic stress ratios (CSR), density conditions, and material types. For low CSR values, PWP increased gradually, while high CSR values led to rapid PWP increases, reaching failure states after several cycles. Samples with higher relative compaction displayed better resistance to cyclic loading, resulting in slower PWP buildup compared to less compacted samples. This finding emphasizes the role of density in controlling stability under repeated loading. Railway sand samples demonstrated a higher resistance to cyclic loads than tailings, which may be due to the coarser grain size and shape of sand particles compared to the finer, more rounded tailings particles. A key discovery is the proportional relationship between PWP and cyclic axial strain, with distinct zones that characterize PWP response stages:

Stable Zone (≤0.2% strain): PWP ratios are low, indicating stability.

Metastable Zone (0.2–1% strain): Moderate to high PWP ratios emerge.

Unstable Zone (1–2.67% strain): PWP growth accelerates rapidly.

Failure Zone (>2.34% strain): Liquefaction or failure conditions occur.

These findings are useful for designing more resilient pavement and railway substructures by factoring in the effects of cyclic loading on PWP. Ensuring high relative compaction and monitoring CSR levels can potentially mitigate PWP buildup and enhance structural stability.

2.2.2 SETTLEMENT

Yildirim et al. (2006) provided a comprehensive experimental investigation into the behavior of normally consolidated soft clays under cyclic loading, with a particular focus on the effects of multiple cycles, stress ratios, and drainage periods on settlement and pore pressure dynamics. The experimental setup is thorough and replicates realistic cyclic load conditions. The authors employed stress-controlled two-way sinusoidal loading on clay samples, holding a fixed frequency of 0.1 Hz and applying drainage intervals between loading stages to observe pore pressure dissipation and its impact on settlements. The consistent use of multiple loading cycles with controlled stress levels provides a robust dataset for assessing cyclic shear and settlement behavior in clay. The first loading stage generates the highest pore pressures, resulting in substantial consolidation settlements. Subsequent loading cycles lead to reduced pore pressure and strain responses, indicating a form of strain hardening in the clay, which makes it more resistant to additional cyclic loading. Higher stress ratios and cycle numbers correlate with increased pore pressures and settlements, although the rate of settlement decreases with each cycle due to cumulative compaction effects.

Pecker (2008) aimed to consolidate knowledge of soil behavior during seismic events, examining field observations, laboratory findings, and theoretical models. By understanding how soils react under repeated cyclic stresses, particularly in earthquakes, this research becomes crucial for the seismic design of buildings and infrastructure, where site-specific responses vary depending on soil properties and seismic characteristics. Pecker notes that soft alluvial deposits generally amplify ground motion, especially at low frequencies, which has been consistently observed in major earthquakes like Loma Prieta (1989) and Kobe (1995). However, amplification varies, depending on factors such as earthquake magnitude, distance, and frequency content, as well as soil type and layering. Laboratory stress-strain tests reveal that soils exhibit hysteresis loops under cyclic loading, which reflect energy dissipation and strain hardening. The results demonstrate that soils exhibit stiffness degradation with increased shear strain and, in saturated conditions, can lead to pore pressure buildup, a precursor to liquefaction under intense shaking. The document introduces threshold strain levels—small strains where behavior remains nearly elastic, and larger strains where non-linear and irreversible deformations occur. This distinction is critical, as small to moderate strains may be modeled with simpler linear approximations, whereas higher strains demand complex modeling to capture soil weakening and liquefaction potential. Pecker emphasizes the importance of the equivalent linear viscoelastic model for engineering applications, as it balances simplicity and accuracy for typical design needs. However, he cautions that its limitations become evident when dealing with high-strain responses, where it fails to account for irrecoverable strains and settlements. For such cases, elastoplastic models, while computationally intensive, are more reliable.

Fattah et al. (2017) investigated the behavior of dry sand under cyclic loading applied to shallow footings, with a focus on loading rate, depth of embedment, and sand density. The study uses 63 model tests on dry sand with varied parameters: three sand densities (loose, medium and dense), two footing shapes (square and circular), three embedment depths, and three loading rates. A specially designed testing apparatus allowed for precise control of monotonic and cyclic loading. This experimental setup provides valuable insights by simulating real-world cyclic loading conditions in a controlled environment. Increased depth of embedment generally reduced settlement under cyclic loading, with greater depth correlating to increased bearing capacity. In loose sand, settlement increased with the loading rate, whereas, in dense sand, settlement decreased. The latter result is attributed to dense sand particles not having enough time to rearrange under faster loading, resulting in lower settlement than under slower loading rates. Higher cyclic loads led to increased settlement, but after several cycles, the rate of settlement decrease stabilized or failure occurred due to excessive deformation. The overall effect of sand density on cyclic settlement was minor due to the uniformity in particle size, which limited densification during loading. This study offers valuable insights into cyclic loading behavior on dry sandy foundations, emphasizing practical applications in foundation design where cyclic loading is prevalent. It demonstrates that appropriate design adjustments based on loading rates, embedment depths, and soil density can effectively manage settlement risks.

Lemnitzer et al. (2020) examined the settlement behavior of organic soils, specifically peat, under cyclic loading. The study involved centrifuge testing of three levee models on peat foundations, using scaled ground motions and real earthquake records (e.g., Loma Prieta and Kobe earthquakes). The models were equipped with various sensors, including pore pressure transducers and accelerometers, to track levee response during and after shaking. Postcyclic settlements were measured and compared to predictions from a one-dimensional nonlinear consolidation model, iConsol.js, which integrates both primary consolidation and secondary compression. The study confirmed that cyclic loading accelerates settlement rates in peat due to the combination of increased pore pressure and an accelerated rate of secondary compression. This rate increase is attributed to changes in the soil's internal structure due to cyclic strain, which resets secondary compression behavior. Secondary compression contributed significantly to overall settlement, especially in post-earthquake conditions. Ignoring the secondary compression reset resulted in significant under predictions of observed settlements. The onset of accelerated secondary compression occurred once shear strains exceeded a threshold (about 0.1% for low-organic peat and 0.7% for high-organic peat), indicating that the rate of settlement post-cyclic loading depends on strain magnitude and peat's organic content. This research underscores the need to incorporate secondary compression reset in settlement predictions for structures on organic soils subject to cyclic loading. Such considerations can improve resilience by enabling more accurate predictions of post-seismic settlements in infrastructure on peat. Lemnitzer et al. provide valuable insights into peat settlement behavior under cyclic loading, with a practical model for predicting post-seismic settlement rates. This research offers significant contributions for seismic design in organic soil regions, supporting safer infrastructure on highly compressible foundations.

Toyota et al. (2021) investigated the cyclic-load-induced settlement in cohesive soils, specifically focusing on the effects of combined vertical, horizontal, and shear stresses. The study employed a hollow-cylindrical torsional shear apparatus to simulate cyclic loading conditions, applying controlled vertical, horizontal, and shear stresses to a reconstituted cohesive soil sample. This experimental setup allowed the authors to replicate actual traffic load conditions closely. Key parameters included loading frequency, stress amplitude, stress ratio, and over consolidation ratio (OCR). Various stress combinations were used to assess their impact on settlement behavior, allowing for a nuanced analysis of each component's effect on vertical strain and pore water pressure. The inclusion of horizontal and shear stresses, along with vertical stress, significantly impacted settlement rates. Cyclic loading conditions with combined stresses led to greater residual vertical strain than vertical stress alone, particularly under high OCR. Two types of deformation emerged under cyclic loading: incremental collapse (leading to failure) and plastic creep (stable, continual settlement at a dampened rate per cycle). The results indicate that higher loading frequencies tend to reduce deformation rates, but plastic creep still accumulates with repeated cycles. The study found that increasing the OCR is effective in reducing cyclic-induced settlement, as it increases soil stiffness and reduces pore pressure accumulation. An OCR of around 2 was particularly effective in mitigating collapse. The results suggest that considering multi-directional stresses in cyclic loading predictions can improve design accuracy for cohesive soils under traffic loads. Additionally, implementing higher OCRs can be a viable approach to minimize long-term settlement for infrastructure on cohesive soils. It presents a robust experimental framework for understanding cyclic-load-induced settlement in cohesive soils. Their findings underscore the significance of accounting for multi-directional stresses and suggest practical adjustments for managing settlement in cohesive soil foundations. This work provides essential data for engineers working on the design and maintenance of roads, railways, and other cyclically loaded structures on cohesive soils.

Bowen Kong et al. (2022), examines the fractal characteristics of soft soil under cyclic loading, using Scanning Electron Microscopy (SEM) to investigate the impact of cyclic loading on soil's microstructure and fractal properties. The research involved SEM analysis to capture soil microstructure at different consolidation pressures, dynamic stress ratios, and over consolidation ratios. Soft soil samples were subjected to cyclic loading, followed by microstructural analysis to extract fractal dimensions, probability entropy, and cumulative strain parameters. The study used fractal dimension as a descriptor of the microstructure and developed a cumulative plastic strain model based on microstructural parameters. Fractal dimension values decreased with increasing consolidation confining pressure, dynamic stress ratio, and over consolidation ratio, indicating a more orderly pore structure under higher loads. This structure regularization suggests a hardening response under cyclic loading. Increased stress conditions led to faster strain accumulation initially, which then stabilized, indicating progressive soil compaction. High over consolidation ratios reduced cumulative strain, as soils with higher OCRs exhibited greater resistance to deformation. They present an innovative approach to modeling soil deformation by linking fractal characteristics to cyclic load-induced strain, advancing understanding of soft soil behavior under repeated loads. This research offers practical insights for predicting soil settlement, potentially improving the resilience of structures on soft soil foundations.

Bolang Zhang et al. (2023), represents an important development in understanding the deformation and settlement of subgrade soils under cyclic loading, with specific focus on intermittent cyclic loading conditions. Cyclic loading of soils, especially in subgrade layers of infrastructure like railways and highways, can induce excess pore pressure, cumulative plastic strain, and progressive settlement, all of which threaten structural integrity. Zhang et al. aim to provide a more realistic model for predicting soil behavior by incorporating the effects of intermittent cyclic loading, a more accurate representation of stresses from moving traffic and trains. They approach this issue by developing a constitutive deformation model that builds upon existing models of soil behavior under cyclic loading. Traditional models, such as the Kelvin model and various empirical models, have limitations in accurately predicting soil deformation under intermittent loading due to their assumption of continuous cyclic stress application. In contrast, Zhang et al. introduce a **fractional generalized Kelvin model** modified with an Abel dashpot component, which enables modeling of nonlinear creep behavior in soil. The model effectively captures the development patterns of cumulative plastic strain under different cyclic loading regimes. It distinguishes between stable, critical, and failure patterns of strain development, enabling more accurate prediction of soil failure under different stress amplitudes and frequencies. Introducing intermittent loading phases allows for partial dissipation of pore water pressure, which promotes reconsolidation of soil particles. This is particularly beneficial for high-moisture soils, as it enhances the soil's resistance to deformation by increasing particle contact and structure stabilization, effectively reducing cumulative plastic strain over time. When compared with traditional empirical models, Zhang's model provides a more accurate fit for both stable and failure curves in cumulative strain. The fractional generalized Kelvin model shows adaptability across different soil types and loading conditions, providing a practical advantage over conventional models with fixed parameters that may not generalize well across varying conditions.

T. Wichtmann et al. (2023), investigates soil behavior under cyclic loading, focusing on experiments, constitutive modeling, and numerical applications. This study is particularly relevant for understanding how soils respond to high and low cyclic loads conditions often encountered in foundations, offshore structures, and transportation systems. They highlight that soil type (fine vs. coarse-grained) and cyclic load characteristics (e.g., number of cycles, strain amplitude, loading frequency) significantly influence the soil's cumulative response. Fine-grained soils, like clay, demonstrate strain accumulation and pore pressure buildup under undrained conditions, leading to progressive settlement and potential liquefaction. For coarse-grained soils like sand, factors such as initial density, grain size, and particle shape affect deformation under cyclic loading. The study finds that cyclic loading can reduce effective stress and shear strength, posing stability risks for structures if pore pressure approaches total stress. The authors performed extensive cyclic triaxial tests under various drained and undrained conditions to evaluate soil behavior. By employing different sample preparation techniques and geometries, they analyzed stress-strain relationships under isotropic and anisotropic conditions. The study developed a constitutive model using hypoplasticity with intergranular strain and the Sanisand model to simulate cyclic loading conditions. This model calibration utilized experimental data from sand and clay samples, with comparisons to the empirical results showing strong predictive performance.

2.3 SUMMARY

The studies emphasize that accurate prediction of soil response under cyclic loading is complex and requires detailed consideration of soil type, loading characteristics, and consolidation conditions. Recent advances in constitutive modeling provide enhanced tools for simulating cyclic behavior, which is critical for designing resilient geotechnical structures exposed to repetitive loads.

NUMERICAL MODELING AND METHODOLOGY

3.1 FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is a widely used computational technique for solving various intricate engineering problems. It involves dividing a structure or system into interconnected elements, which represent the behavior of the actual object. Through the utilization of mathematical models, such as governing physical laws or material properties, FEA solves a system of equations to simulate and predict the system's behavior under different boundary conditions. By discretizing the problem domain, FEA can ascertain stresses, strains, displacements, and other relevant parameters. This method enables engineers and scientists to assess the performance, strength, and durability of structures, components, and materials. FEA finds extensive application in mechanical, civil, aerospace, and automotive engineering, aiding in design optimization, virtual prototyping, and gaining insights into complex phenomena.

3.2 ABAQUS

Abaqus/CAE is a complete Abaqus environment that provides a simple, consistent interface for creating, submitting, monitoring, and evaluating results from Abaqus/Standard and Abaqus/Explicit simulations. Abaqus/CAE is divided into modules, where each module defines a logical aspect of the modeling process; for example, defining the geometry, defining material properties, and generating a mesh. As we can move from module to module and build the model from which Abaqus/CAE generates an input file that we submit to the Abaqus/Standard or Abaqus/Explicit analysis product. The analysis product performs the analysis, sends information to Abaqus/CAE to allow us to monitor the progress of the job, and generates an output database. Finally, we can use the Visualization module of Abaqus/CAE to read the output database and view the results of our analysis.

3.3 METHODOLOGY

To model a triaxial test using Abaqus, a finite element analysis (FEA) software, there are several steps involved that ensure accurate simulation of the physical behavior of the material under triaxial conditions. Here's a breakdown of the methodology for modeling a triaxial test in Abaqus.

1. Defining the Geometry

Create the Specimen Geometry: Start by modeling the geometry of the sample, which is typically a cylindrical shape to mimic the real triaxial test. The dimensions should match the actual specimen dimensions.

Container Geometry (if applicable): If the model includes a confining pressure (as in a true triaxial test), model the container or confinement setup.

Symmetry Considerations: Use symmetry if applicable (e.g., axisymmetric conditions) to reduce computational effort. This typically involves using a 2D axisymmetric model instead of a 3D model.

2. Material Definition

Choose the Material Model: Define the material properties based on the type of material being tested (e.g., soil, rock, concrete). Common models include:

Elastic: For linear elastic behavior.

Mohr-Coulomb: For soils or rocks, capturing cohesion and friction.

Drucker-Prager: For materials that experience shear softening.

Modified Cam-Clay: Often it is used for soft clays.

Define Material Properties: Input parameters like Young's modulus, Poisson's ratio, density, and plastic parameters (e.g., cohesion, friction angle, dilation angle).

3. Meshing the Model

Ensure the mesh is adequately refined, especially in regions where large strain gradients are expected.

Mesh the Geometry: Choose an appropriate element type. In a triaxial test, use:

CAX4R: For 2D axisymmetric cases, a 4-node quadrilateral with reduced integration.

C3D8R: For 3D cases, an 8-node hexahedral element with reduced integration.

Mesh Density: Use finer meshing in areas where stress gradients are high (e.g., near boundaries) and coarser in regions with less deformation. Ensure that the mesh is sufficiently refined to capture the specimen's deformation behavior accurately.

4. Boundary Conditions and Loading

Boundary Conditions: Apply symmetry boundary conditions if using a 2D axisymmetric model. Fix the bottom of the specimen to simulate the loading platen's effect. Allow lateral boundaries to simulate realistic constraints (typically by allowing displacements perpendicular to the loading direction while restraining other movements).Consider incorporating pore pressure if modeling a drained or undrained triaxial test for soils.

Loading:

Confining Pressure: Apply a uniform pressure to the specimen's lateral surface to simulate confining pressure.

Axial Load: Apply the axial load or displacement at the top of the specimen. This can be displacement-controlled or load-controlled, depending on the test type.

5. Interaction Properties (Optional)

Define any interaction between parts if the model includes multiple components (like loading platens). Specify friction properties if the interaction between the loading surfaces and the sample is crucial.

6. Step Definition

Create analysis steps to simulate the different stages of loading.

Initial Step: Often includes only boundary conditions without loads.

Confining Pressure Step: A static general step to apply the lateral pressure.

Axial Loading Step: Another static general step (or dynamic if required) for applying the axial load or displacement.

Use nonlinear material properties if the material exhibits plastic or damage behavior.

7. Assign Loads and Boundary Conditions to Steps

Assign the defined loads and boundary conditions to the appropriate steps. Ensure that the loading is applied gradually to avoid numerical instability (use smooth ramping if needed).

8. Defining the Output Requests

Field Outputs: Select the variables you want to monitor during the simulation (e.g., stresses, strains, displacement and pore pressure if applicable).

History Outputs: Record data at specific points, such as the axial stress-strain response, to understand the material behavior.

9. Running the Simulation

Run the analysis using Abaqus/Standard for static and quasi-static problems. For dynamic problems, use Abaqus/Explicit. Monitor the convergence criteria and ensure there are no excessive errors during the simulation.

10. Post-Processing

Review Results: Use Abaqus/CAE (the GUI) to visualize the deformed shape, stress distributions, and any localized failure zones.

Stress-Strain Curves: Extract the data from output files to plot stress-strain curves, which are key indicators of the material's mechanical properties.

Check for Failure Mechanisms: Study the failure pattern (e.g., shear bands) to ensure it aligns with experimental results.

11. Validation and Calibration (if necessary)

Compare the simulation results with experimental data to validate the model. Adjust material parameters or model configurations if necessary to achieve a better match with physical test data.

By following these steps, we can effectively simulate a triaxial test using Abaqus to gain insights into the material's behavior under different stress states.

3.4 USE OF ABAQUS/CAE FOR THE PRESENT STUDY:

To simulate the model in Abaqus/CAE it required the essential input data like geometrical dimensions of the model, material properties of clay, types of loading, etc. In this study I use the clay soil with low permeability. For numerical modeling, the finite element analysis software Abaqus 6.14 has been used. The process follows a sequential order of creation of part, material properties, meshing, cyclic loading with adequate boundary condition, creation of and finished with adequate data output.

Material Model and Properties

For this analysis I have used the Cam Clay Model with following two types of clay material properties, one with **15%** organic compound (Clay-1) and another one with **26%** organic compound (Clay-2).

Table 3.1 Cam Clay Model general and elastic properties of Clay-1.

General				Elasticity	
ρ (kg/m^2)	k (m/Sec)	γ_w (KN/m^3)	e_o	κ	ν
1900	1e-6 to 1e-10	9.81	0.889	0.026	0.28

Table 3.2 Cam Clay Model plastic properties of Clay-1.

Plasticity				
λ	M	$\frac{P_0'}{2}$ (kPa)	WYS	FSR
0.174	1.29	25 to 100	1	1

The parameter κ defines the elastic behavior of the soil in the Cam Clay Model and it is related to the swelling index through the equation κ= Cs/2.3. The parameter λ is related to the compression index through λ= C_c/2.3.

For Clay-1, C_s= 0.06 and C_c= 0.4.

Internal angle of friction, $\phi' = 34.2°$.

Table 3.3 Cam Clay Model general and elastic properties of Clay-2.

General				Elasticity	
ρ (kg/m^2)	k (m/Sec)	γ_w (KN/m^3)	e_o	κ	ν
1500	1e-6 to 1e-10	9.81	1.2848	0.026	0.28

Table 3.4 Cam Clay Model plastic properties of Clay-2.

Plasticity				
λ	M	$\frac{P_0'}{2}$ (kPa)	WYS	FSR
0.250	1.43	25 to 100	1	1

For Clay-2, C_s= 0.06 and C_c= 0.576.

As given Liquid Limit W_L= 74% so as we know C_c= 0.009(W_L-10) for NC clay.

Internal angle of friction, $\phi' = 35.3°$.

The Cam Clay strength parameter M is related to the internal friction angle of the soil, ϕ', as follows:

$$M = \frac{6 \sin \emptyset'}{3 - \sin \emptyset'}$$

A 3D cylindrical model of 75 mm diameter and 150 mm height is prepared to calculate the excess pore pressure same as taken by **Rambha Devi et al. (2014)** for their experimental result and a 2D model of 3.6 m width and 7.2 m height is prepared to calculate the settlement with the above mentioned soil properties.

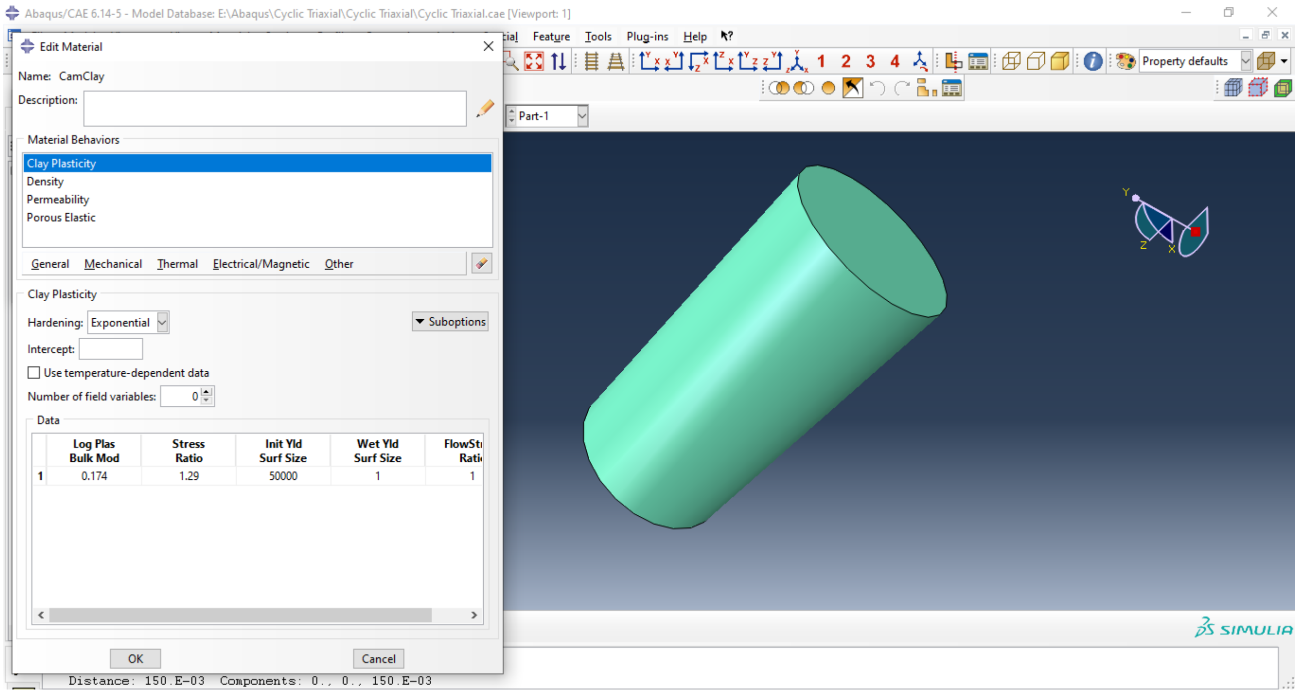

Fig. 3.1 cylindrical model for Cyclic Triaxial Test.

Step module

The Step module in Abaqus defines and manages the sequence of analysis steps in a simulation, controlling the time increment and loading application throughout the analysis. In Abaqus, analyses are divided into steps, where each step represents a phase of the simulation with specific loadings, boundary conditions, and solver controls. This module is essential for simulations with varying loads, such as cyclic loading in a triaxial test, as it allows different conditions to be set for each part of the analysis.

Initial Step: This is the default, automatically created first step in all Abaqus analyses. It's where initial conditions, such as boundary conditions and predefined fields (e.g., temperature or stress state), are applied.

Analysis Steps:

- Abaqus offers various types of steps depending on the analysis requirements, including *Static*, *Dynamic*, and *Frequency* steps, each suited for different kinds of simulations:

Static, General: For static loading conditions.

Dynamic, Implicit/Explicit: For simulations with dynamic loading.

Visco: For capturing time-dependent behaviors, such as viscoelasticity or creep.

Each step can have unique properties, such as load amplitude, time increment control, and output frequency, allowing complex loading conditions to be modeled over time.

For cyclic loading, such as in a triaxial test, a *Dynamic, Implicit* step or *Static, General* step with cyclic loading amplitude can be used. Here in this study I have used **Static General Step** with cyclic strain rate amplitude.

Increment Control

Abaqus requires defining increments, which control the time progression within each step. For this study I have used the **Automatic Increment Control** system.

Load module

In a cyclic triaxial test simulation, the Load module is essential for applying cyclic loading and confinement.

For a triaxial test, a confining pressure simulates the surrounding stress on the specimen's lateral surface. In this study I have used **50 kPa**, **100 kPa and 200 kPa** confining pressure.

For cyclic axial loading, apply a sinusoidal load or displacement on the top surface of the specimen. Here in this study I used **Triangular Tabular Cyclic Displacement** with a stain rate of **0.1mm/sec.** Also the frequency of loading is **0.1 Hz**.

Boundary Condition

In this study I have used fixed boundary condition from bottom and make it free from top to apply vertical cyclic strain along the vertical axis.

Mesh Module

Meshing is a critical step in any Abaqus simulation, especially under cyclic loading, as it affects the accuracy, stability, and efficiency of the results. Cyclic loading often requires high precision to capture stress concentrations, fatigue effects, and potential areas of failure, so mesh quality and density become particularly important.

For a full 3D model, use elements like C3D8R (8-node linear brick, reduced integration).

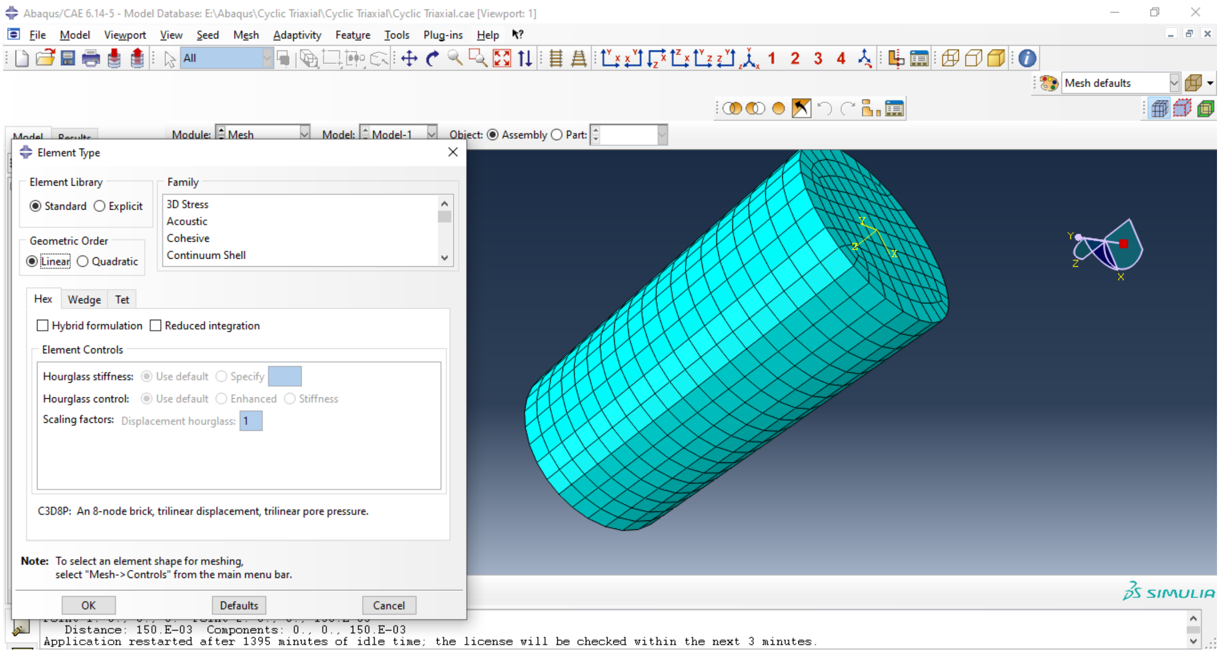

Fig. 3.2 Types of meshing used in the Cyclic Triaxial Test Model.

Job module

Create a Job

Assign a job name and set up the job for a cyclic triaxial test model, linking it with the model and step definitions prepared earlier in the Step and Load modules. Choose appropriate options for the .inp file and set the job type (Standard for implicit cyclic analysis).Submit the job for analysis, selecting the number of processors if parallel processing is available to reduce computation time for large models. We can monitor the job during the process.

Visualization module

The Visualization module in Abaqus is designed for post-processing and interpreting simulation results. After an analysis completes, this module allows users to view and analyze data from the output database (.odb) file generated during the job. The Visualization module provides tools for exploring results like stress, strain, displacement, pore pressure, and other field outputs. It supports detailed inspection of the structural response, animations, contour plots, and custom report generation, making it crucial for validating and communicating findings from simulations.

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this study presents the results of the numerical simulation of excess pore pressure generation and settlement in organic clay soil subjected to cyclic loading, calculated using Abaqus software. The analysis focuses on the distribution and evolution of pore pressure, the deformation characteristics of the soil, and the cumulative settlement over time. Results are validated against experimental data to ensure model reliability, followed by a discussion of the implications for foundation design and soil stability in cyclic loading conditions. The simulation results show that excess pore pressure begins to accumulate rapidly in the initial loading cycles.

4.1.1 Excess Pore Pressure

This initial buildup is primarily influenced by the permeability of soil, loading frequency, and cyclic stress ratio. Pore pressure rises as the soil particles rearrange, reducing effective stress and causing progressive softening of the clay matrix. The results reveal that the pore pressure response is highly sensitive to loading amplitude, with higher amplitudes generating greater excess pore pressures.

Under repeated loading, the rate of pore pressure buildup slows down but remains positive, indicating continued accumulation with each cycle. The numerical results show that, as cyclic loading continues, a steady-state phase may be approached where pore pressure generation and dissipation stabilize. However, this steady-state is highly dependent on soil properties such as compressibility and initial void ratio. For low permeability soils, pore pressure tends to accumulate consistently, eventually reducing effective stress to critical levels that could lead to potential failure.

4.1.2 Settlement

The analysis shows a progressive increase in axial settlement with each loading cycle, indicating a cumulative deformation effect typical in clay soils under cyclic conditions. Settlement is initially high in the early cycles, corresponding to rapid pore pressure buildup, and then gradually levels off as the rate of pore pressure increase slows. This trend suggests that most settlement occurs in the initial phases of loading, while subsequent cycles contribute to a slower but continued deformation. The study highlights that the magnitude of settlement is significantly affected by the cyclic stress ratio, loading frequency, and initial soil conditions. Higher stress ratios and loading frequencies result in larger settlements due to accelerated pore pressure generation and increased soil strain. Additionally, settlement is more pronounced in soils with higher initial void ratios and lower confining pressures, as these conditions make the soil more susceptible to compaction under cyclic loading.

The simulation also reveals lateral deformation, with bulging occurring in the middle section of the soil sample, which is consistent with observed behavior in triaxial tests. This lateral deformation indicates shear strain accumulation due to cyclic loading, contributing to overall settlement and emphasizing the importance of capturing multi-directional strain effects in cyclic loading analyses. The lateral strain distribution helps in understanding the mechanisms of cyclic settlement, which could be crucial in designing soil layers or structures to withstand cyclic loads without significant lateral expansion.

4.2 PARAMETRIC STUDY AND IT'S EFFECT.

As stated earlier excess pore water pressure varies with several clay properties and cell pressure.

4.2.1 Variation with types of Clay.

As in this study I have used two types of clay with 15% and 26% organic compound. Soil with 15% organic content named as Clay-1 and Clay with 26% organic content named as Clay-2.

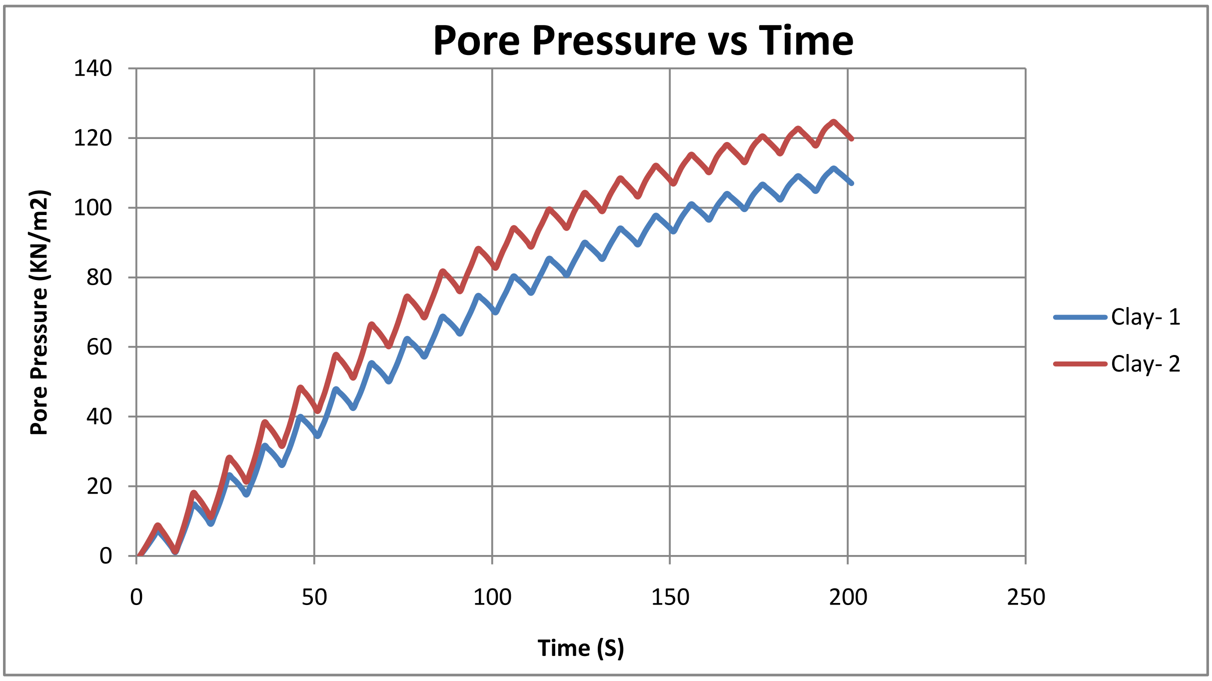

Fig. 4.1 Variation of Pore Pressure with Time for different soil.

As we can see in the above fig. 4.1 excess pore pressure varies with percentage of organic content in the clay soil. Higher the organic compound then higher the excess pore pressure generation at same number of cycle or same increment of time. As we know with increase in organic compound permeability of soil decreases due to this release of water during loading or applied strain is less that's why generation of excess pore pressure is higher with higher organic content.

4.2.2 Variation of excess pore pressure with change in cell pressure.

In this study I have used three different cell pressure of 50 kPa, 100 kPa and 200 kPa for both the soil Clay-1 and Clay-2.

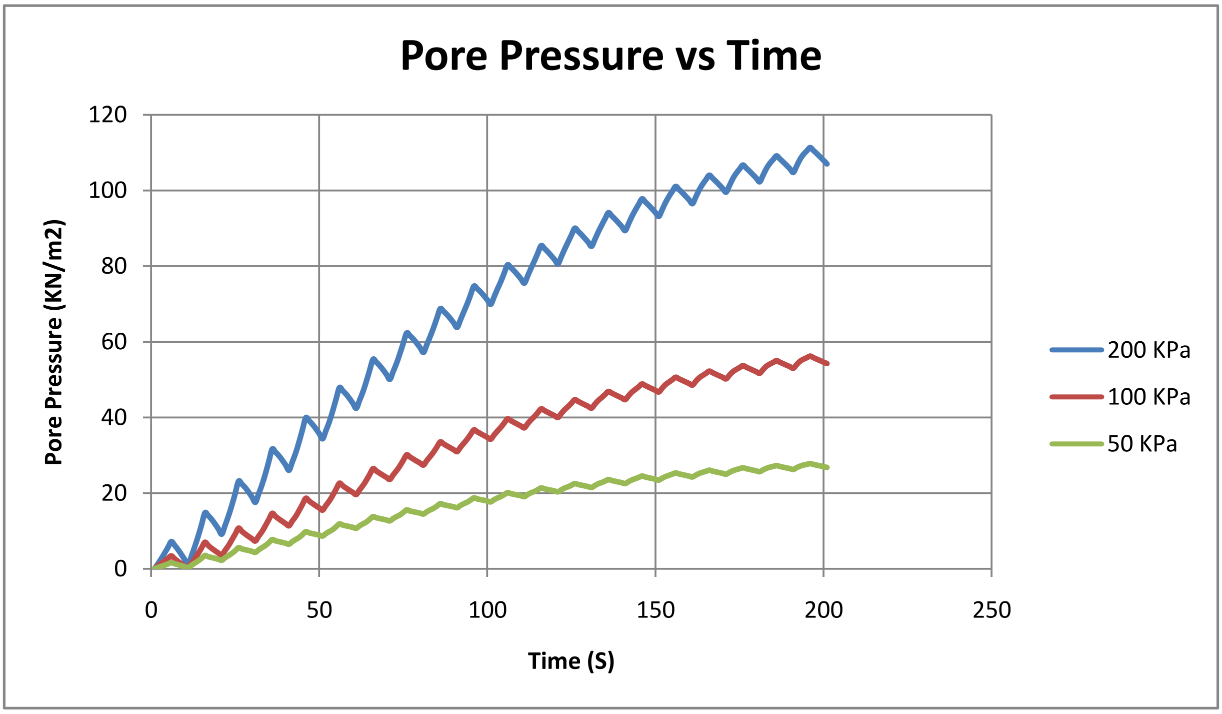

Fig. 4.2 Variation of Pore Pressure with Time for Clay-1.

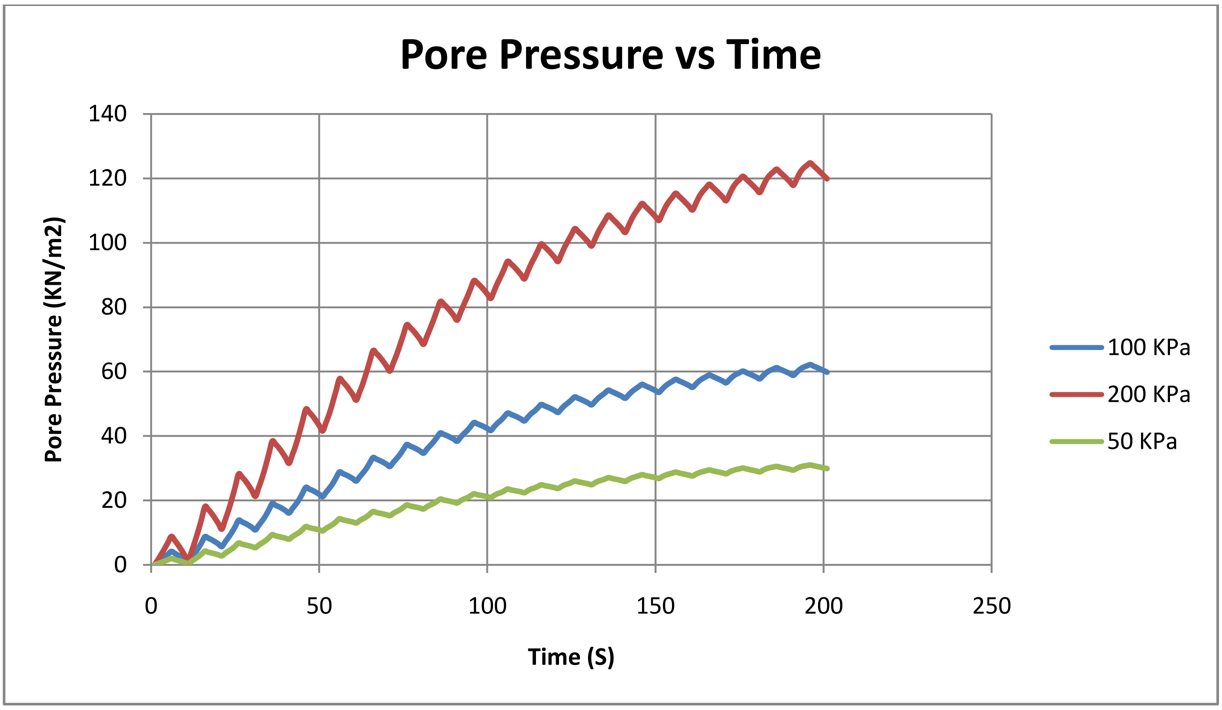

Fig. 4.3 Variation of Pore Pressure with Time for Clay-2.

Fig. 4.2 and 4.3 show the variation of excess pore pressure with time for different confining pressure. As the confining pressure increases excess pore pressure also increases with time for both the soil Clay-1 and Clay-2. Due to higher confining pressure release of water from the soil is restricted with higher amount of force that's why excess pore pressure increases with increase in confining pressure.

4.3 VALIDATION OF THE MODEL

I have validated this numerical analysis result with the experimental result of Organic Clay under Cyclic Loading given by **Rambha Devi et al. (2014)**. They have been used the same soil with 26% organic compound which I have used for this study. They have been performed a Cyclic Triaxial test with 100 kPa confining pressure and the test was strain control with strain rate of 0.01 mm/sec for 200 sec. the test frequency was 0.1 Hz. Their experimental result as well as analytical result of this study has been shown on Fig. 4.4 and 4.5.

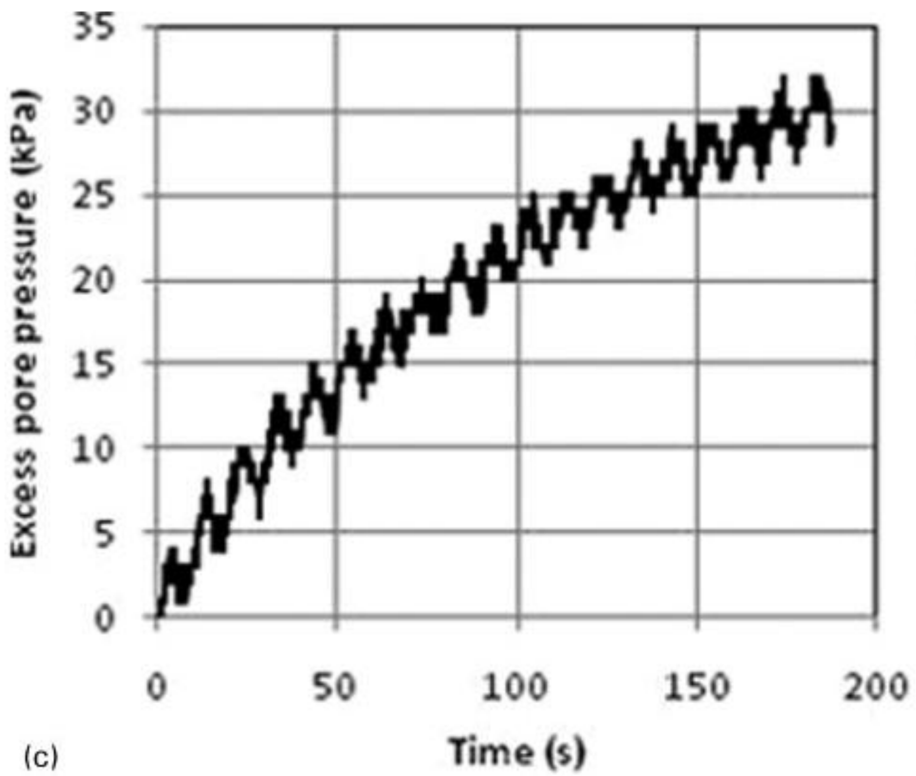

Fig. **4.4** Experimental result of Pore Pressure vs Time.

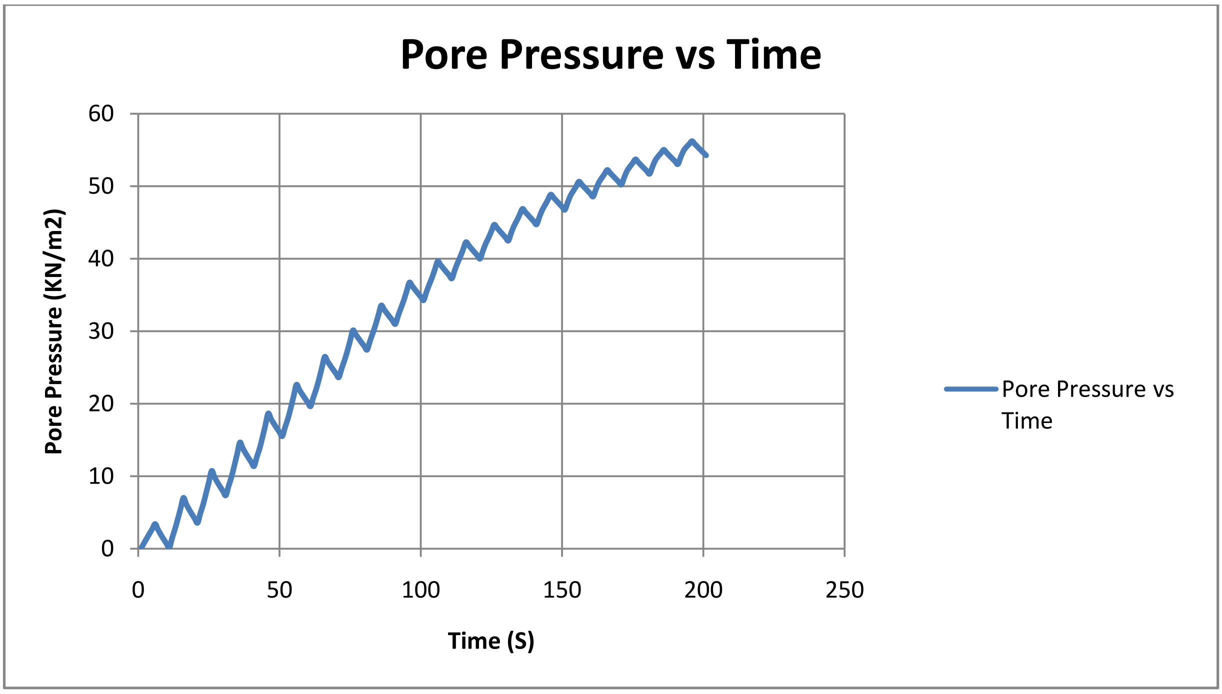

Fig. 4.5 Numerical analysis result of Pore Pressure vs Time.

4.4 SETTLEMENT

The analysis shows a progressive increase in axial settlement with each loading cycle, indicating a cumulative deformation effect typical in clay soils under cyclic conditions. Settlement is initially high in the early cycles, corresponding to rapid pore pressure buildup, and then gradually levels off as the rate of pore pressure increase slows. This trend suggests that most settlement occurs in the initial phases of loading, while subsequent cycles contribute to a slower but continued deformation. Though in this study I have used a soil segment of size 3.6 m width and 7.2 m depth considering a pavement width with one way traffic.

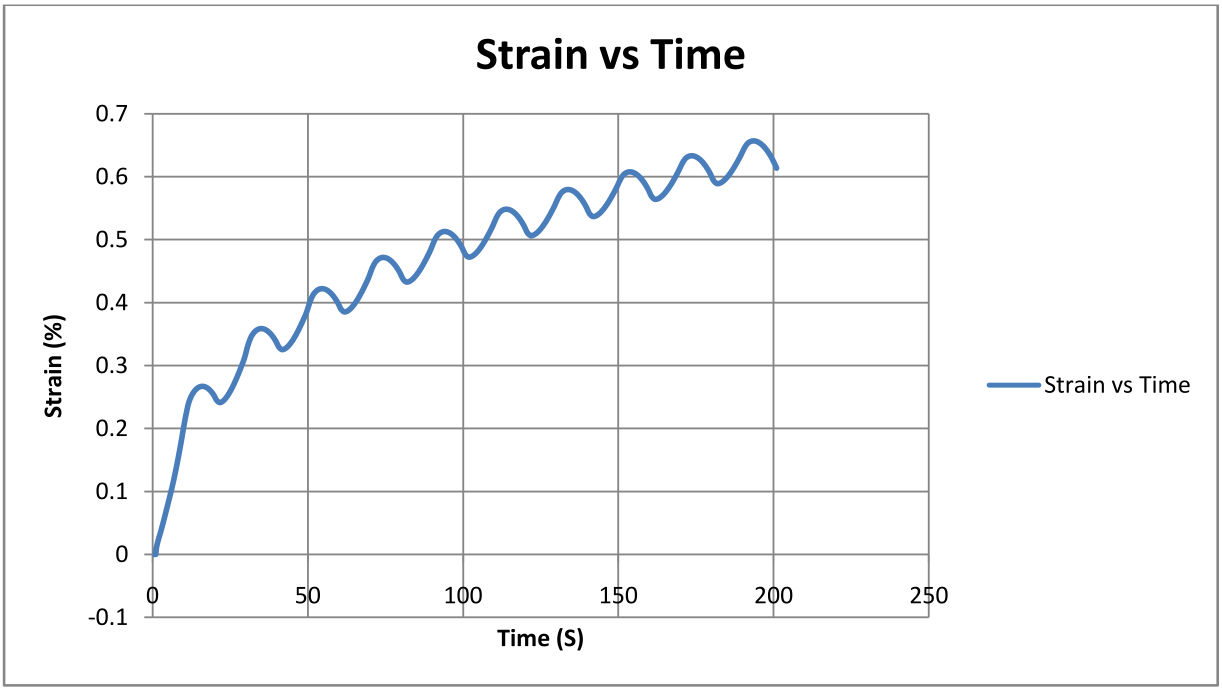

Fig. 4.6 Numerical analysis result of Strain vs Time.

Rambha et al. (2014) have been done a Cyclic Triaxial Test calculate the strain (%) with time. It also shows the sudden increase in settlement in initial stage. Following Fig. 4.7 shows their experimental result which is quite relevant to my numerical analysis result of Fig. 4.6.

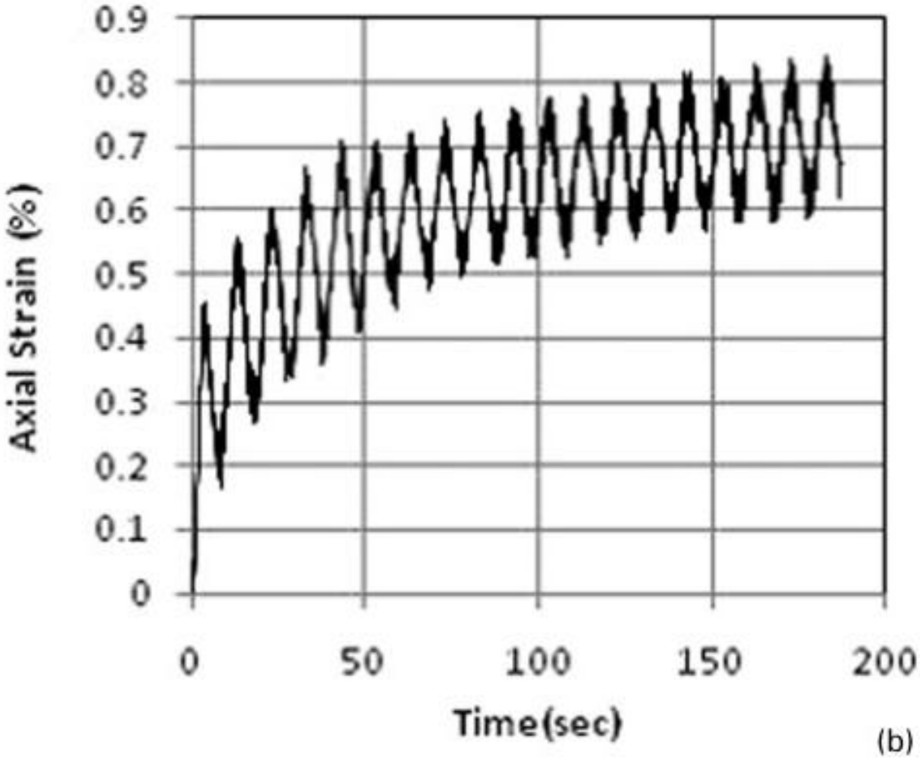

Fig. 4.7 Experimental result of Strain(%) vs Time.

4.5 DISCUSSION

The findings from this analysis provide valuable insights into the behavior of organic clay soils under cyclic loading, specifically in terms of excess pore pressure generation and settlement. The results emphasize the role of confining pressure and loading frequency in influencing the rate and magnitude of pore pressure and settlement. The simulation results validate the effectiveness of using Abaqus for cyclic loading studies, showing that the finite element model can reasonably predict soil behavior under varied loading conditions, albeit with some limitations in capturing high-frequency response.

From an engineering perspective, these results underscore the importance of accounting for cyclic loading effects in the design of foundations and earth structures on organic clay soils. The study highlights that structures subjected to cyclic loads, such as offshore platforms, transportation infrastructure, and buildings near vibrating machinery, require careful analysis to mitigate risks associated with pore pressure buildup and cumulative settlement. The sensitivity analysis further suggests that adjusting parameters like confining pressure and loading conditions can improve the resilience of foundations in cyclic loading environments.

4.6 CONCLUSION

a) From the extensive literature review done as a part of this study, it was found out that excess pore water pressure generated in soil sub grade due to cyclic loading. Cyclic loading generally occurs due to roadway traffic repeated loading, railway repeated loading, machine vibration, earthquake, etc. Due to this kind of loading voids of the soil get clogged and releasing of excess pore water prevented and result of this with increase of number of cycle excess pore water pressure goes on increasing. In this study we get that increase in excess pore water pressure depends on several parameters like types of soil, permeability, confining pressure, etc. And that of increase in excess pore water pressure is same as the experimental result of **Konsam Rambha Devi et al. (2014).** But there is a difference in numerical value of excess pore water pressure between analytical result and experimental result about 15 to 20 KN/m2 after same number of cycle.

b) It is also found that for different types of soil the excess pore water pressure generation is different. Clay with higher stiffness generation of excess pore water pressure is higher. Also in the same soil with different confining pressure excess pore water pressure is different. It is show that with increase in **50 kP**a confining pressure excess pore water pressure increases around **30 kPa**.

c) Similarly from study of several literature reviews it is found that with increase in number of cycle settlement of the soil increases. In this study I have used 3.6 m width and 7.2 m depth soil sample. It gives the same pattern of settlement curve as that gives the experimental result of **Konsam Rambha Devi et al. (2014).** Though size of the sample of their experiment was 75 mm diameter and 150 mm height. There is a slight difference in percentage of strain around 0.18% between the analytical result and experimental result.

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