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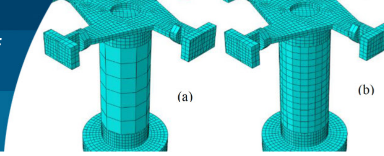

A preliminary study for numerical representation of resonant column experiments in sand

Estudio preliminar de la representación numérica de experimentos de columna resonante en arena

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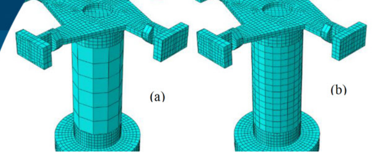
This paper represents a collaborative effort utilizing the finite element method to simulate the resonant column (RC) apparatus. The aim is to explore how soil dynamic properties change with varying strain levels. The RC test, renowned for its ability to analyze soil behaviour under dynamic loads, is the focus of our study. However, accurate measurement of dynamic properties using the RC can be influenced by several factors, necessitating further investigation. These factors, including strain uniformity, base fixity, strain localization, top-platen coupling, sample shape, and soil uniformity, are the key areas of our research. To gain a deeper understanding of the effects of these variables on measured shear wave velocity and damping ratio, we performed finite element analysis using Abaqus/Explicit, a commercial finite element package based on continuum mechanics. The model was based on the specific RC setup configuration at the University of Waterloo. Initial parameters included the low-strain properties of sand (shear modulus, Poisson's ratio, damping ratio) with shear strain adjusted as a loading variable. Torsional loads were applied across shear strains from 10^{-5} to 10^{-4}. The element size of the soil specimen mesh was varied to 25 mm, 10 mm, 7.5 mm, and 5 mm to observe its effect on the outcomes of the RC test. The finite element model analyzed the free vibration of the cylindrical sand sample post-forced vibration, assessing dynamic properties. Modal analysis of the RC configuration was performed to verify the primary influence of the first torsional mode. A Z-factor has been proposed as a multiplier of experimentally obtained damping ratio. Comparisons of damping ratios and resonant frequencies at various shear strains between finite element modelling and laboratory data demonstrate a strong correlation in the case of nonlinear shear strain, with differences firmly ranging from 0.50% to 3.5%.

Keywords: resonant column test, Abaqus, damping ratio, shear modulus, mesh convergence

Este artículo representa un esfuerzo colaborativo que utiliza el método de elementos finitos para simular el equipo de columna resonante (CR). El objetivo es explorar cómo cambian las propiedades dinámicas del suelo con diferentes niveles de deformación. El ensayo CR, reconocido por su capacidad para analizar el comportamiento del suelo bajo cargas dinámicas, es el foco de nuestro estudio. Sin embargo, la medición precisa de las propiedades dinámicas utilizando la CR puede verse influenciada por varios factores, lo que requiere una mayor investigación. Estos factores, que incluyen la uniformidad de la deformación, fijación de la base, localización de la deformación, acoplamiento de la placa superior, forma de la muestra y uniformidad del suelo, son áreas clave de nuestra investigación. Para obtener una comprensión más profunda de los efectos de estas variables en la velocidad de onda de corte medida y la razón de amortiguamiento, realizamos un análisis de elementos finitos utilizando Abaqus/Explicit, un paquete comercial de elementos finitos basado en la mecánica de medios continuos. El modelo se basó en la configuración específica de CR en la Universidad de Waterloo. Los parámetros iniciales incluyeron las propiedades de la arena en pequeñas deformaciones (módulo de corte, coeficiente de Poisson, razón de amortiguamiento) con la deformación de corte ajustada como una variable de carga. Se aplicaron cargas de torsión a través de deformaciones de corte de 10^{-5} a 10^{-4}. El tamaño del elemento de la malla de la muestra de suelo se varió de 25 mm, 10 mm, 7,5 mm y 5 mm para observar su efecto en los resultados del ensayo CR. El modelo de elementos finitos analizó la vibración libre de la muestra de arena cilíndrica después de la vibración forzada, evaluando las propiedades dinámicas. Se realizó un análisis modal de la configuración CR para verificar la influencia primaria del primer modo de torsión. Se ha propuesto un factor Z como multiplicador de la razón de amortiguamiento obtenida experimentalmente. Las comparaciones de las razones de amortiguamiento y las frecuencias de resonancia en varias deformaciones de corte entre el modelado de elementos finitos y los datos de laboratorio demostraron una correlación estrecha en el caso de deformaciones de corte no lineales con diferencias que oscilan entre 0.5% y 3.5%.

Palabras clave: ensayo de columna resonante, Abaqus, razón de amortiguamiento, módulo de corte, convergencia de malla



Introduction

Shear wave analysis has revolutionized the way engineers understand and design structures to withstand seismic forces. This technique, which has found applications in diverse fields such as geotechnical engineering, construction, aerospace, and manufacturing, allows for non-destructive evaluation of material defects. The versatility and broad applicability of essential methodologies like cross-hole and down-hole seismic testing, multi-channel analysis of surface waves (MASW), and seismic cone penetration testing (SCPT) underscore the importance of this technique in revealing subsurface traits (Drnevich, 1978; Cascante *et al.*, 2003; ASTM D4015, 2007).

The Resonant Column (RC) method is particularly effective in laboratory settings, providing detailed insights into the dynamic behaviours of soils and rocks (see Figure 1). It has been crucial for measuring low-strain damping ratios and shear modulus for over fifty years, showing its sustained significance in geotechnical studies. Various enhancements and versions of the RC apparatus aim to boost precision and reliability (Hardin and Richart, 1963; Hardin and Music, 1965; Stokoe *et al.*, 1980; Stoll, 1985; Avramidis and Saxena, 1990; Cascante *et al.*, 1998; d'Onofrio *et al.*, 1999; Menq and Stokoe, 2003). However, achieving accurate results remains challenging, as various critiques of geotechnical testing procedures have pointed out (Ashmawy and Drnevich, 1994).

Integrating finite element methods to simulate low-strain torsional RC tests has improved the understanding of potential inaccuracies in RC test results. For instance, Bae (2008) examined the effects of end platens on effective stresses in RC specimens during consolidation, fine-tuning factors like void ratios and stress history to enhance test precision. This study highlighted how aspect ratios minimally affect outcomes while interface strength and internal friction angles significantly influence stress distributions within soil specimens.

Expanding on these findings, Clayton *et al.* (2009) conducted experimental and 3D numerical analyses to assess the impacts of apparatus stiffness, mass, and specimen fixity on RC results. Their results underscored the importance of calibration bar design and compliance with fixing systems in ensuring test accuracy, pointing out

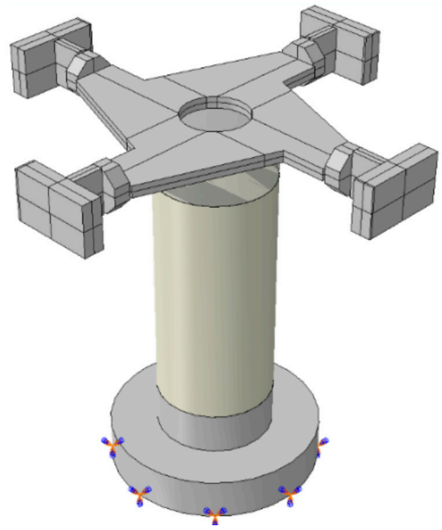


Figure 1: Finite element model of resonant column test setup (1:4.5 cm)

how device components can skew results if not properly managed. In a related effort, Sultaniya *et al.* (2010) investigated soil cross-anisotropy with a 3D numerical model without addressing mesh size effects on anisotropy that could affect shear wave analysis accuracy.

Further developments were seen in studies by Cheng and Leong (2016), who employed a simplified viscoelastic material model in LS-DYNA to mimic RC tests. However, their study was limited by not considering the base pedestal and potential inaccuracies in representing the drive plate shape. Bui *et al.* (2019) introduced a two-spring model to address equipment compliance issues during specimen stiffness determination in the torsional RC test, showcasing the ongoing evolution and refinement of testing methods. These studies collectively stress the need to continue improving and validating geotechnical testing techniques to ensure the reliability and precision of dynamic soil behaviour analysis.

The RC test has been extensively utilized and refined. It is notably adept at evaluating soils under different vibratory conditions, making it indispensable in geotechnical earthquake engineering and other dynamic loading applications. Research has increasingly focused on the effects of vibration cycles, showing that repeated cycles decrease the shear modulus and increase damping ratios, especially under lower confining pressures and relative densities (Cherian and Kumar, 2016, 2017).

Khan *et al.* (2011) explored the discrepancies between RC and cyclic triaxial (CT) tests and emphasized the importance of frequency effects on dynamic properties. Their introduction of the non-resonance (NR) method in RC testing helps reconcile differences between RC and CT test results, especially considering frequency-induced variations in shear modulus. This methodological advancement has allowed for more precise modelling and understanding of soil behaviour under dynamic conditions.

The influence of sample preparation and soil type on RC test outcomes has also been observed. Variations in sand properties, such as particle size and shape, significantly impact the measured dynamic properties, underscoring the need to consider soil characteristics in test setups carefully (Cherian and Kumar, 2016). Recent studies have also explored the use of RC testing in understanding the behaviour of different soil mixtures under dynamic loads, such as sand-bentonite mixtures. These studies have provided insights into soils' viscoelastic behaviour and particle interactions' impact on shear modulus and damping characteristics under varying frequencies and strain levels (Khan *et al.*, 2011). The collective findings from these studies affirm the critical role of RC testing in geotechnical engineering, particularly in the context of dynamic soil analysis. As testing methodologies continue to evolve, incorporating advanced techniques like the NR method, the ability to predict and understand the dynamic responses of soils becomes increasingly refined, offering crucial insights for the design and analysis of geotechnical structures subjected to dynamic forces. Therefore, the present paper has developed a finite element model to accurately and precisely simulate the resonant column (RC) test by incorporating the soil's damping ratio and shear modulus.

Finite element modeling

The FE (finite element) analysis of the RC test has been carried out using Abaqus/Explicit to simulate and validate experimental results obtained at the Infrastructure Non-Destructive Testing Laboratory, University of Waterloo, Canada (Cascante *et al.*, 2003). The present methodology employs a step-by-step procedure to incorporate the physics and mechanics of the RC test accurately using Abaqus/Explicit.

Geometry and material properties

The three-dimensional model shown in Figure 1 was constructed in the geometry module, accurately reflecting the dimensions of the experimental RC model. The soil specimen is 7.06 cm in diameter and 14.5 cm in height. Each segment of the drive plate was modelled separately and later integrated into the assembly section. Similarly, the top and base caps of the soil sample were individually crafted and subsequently assembled onto the soil model to ensure proper interaction among the components. The drive plate consists of Al-6061-T6 Alloy, and the caps are made from stainless steel. The current dynamic RC analysis considered the sand's equivalent linear elastic properties, featuring a density of 1630 kg/m³, a Poisson's ratio of 0.2, and a void ratio of 0.614. Figure 2 displays the damping ratio and shear modulus derived from experimental tests by Cascante *et al.* (2003) at various shear strain levels. The damping has been defined in the FE model by using Rayleigh damping. Initially, the shear modulus, Poisson's ratio, and soil density were determined, and modal analysis was carried out using the Abaqus/Frequency module. The

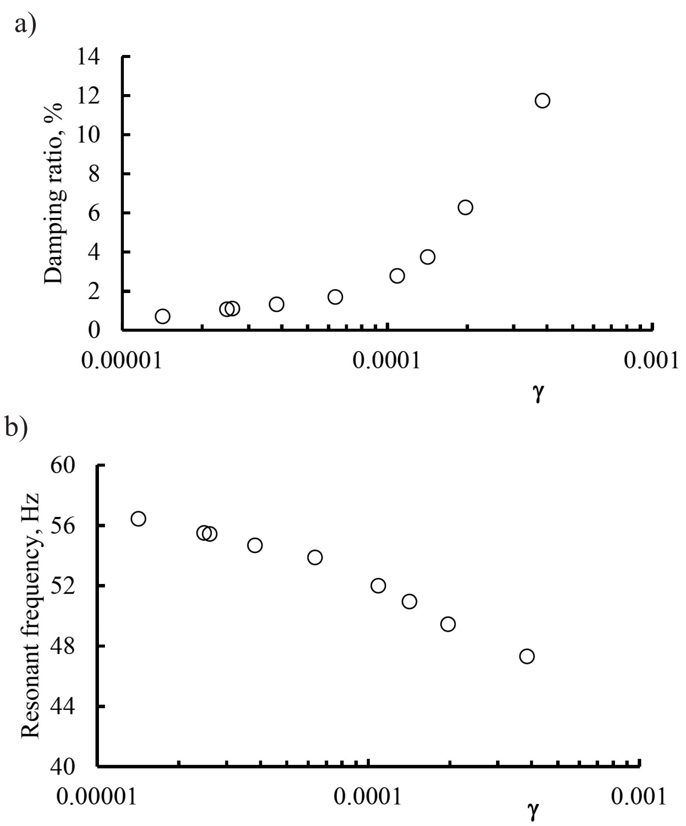


Figure 2: Input properties of soil obtained from laboratory testing by Cascante *et al.* (2003). (a) Damping ratio and (b) resonant frequency

resonant frequency of the torsional mode was noted along with the lowest frequency in the vicinity of the torsional frequency. The Rayleigh damping constants were obtained based on the modal analysis to define the damping ratio in the FE model of the RC test.

Loading and interaction

The different parts of the FE model were assembled, and interaction was assigned between them so that all the parts were bonded together to represent a single model. The interaction between the top cap, soil specimen and base pedestal has been defined using normal and tangential interaction properties with no movement between surfaces. The model's base has been fixed in all directions to restrain any movement at the base of the RC test model. The load has been applied at the center of four magnets to create torsional loading conditions in the RC model. Figure 3 represents a torque with the same frequency as a resonant torsional frequency with a magnitude that causes a shear strain equal to 1.42 x 10^{-5}.

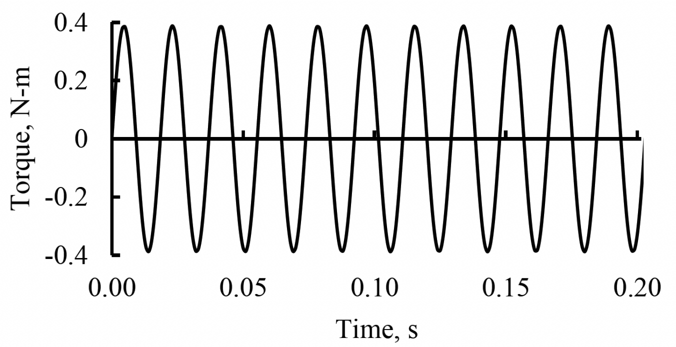


Figure 3: Torque applied at the center of magnets to create shear strain (γ = 1.42 $\times 10^{-5}$) with torsional excitation frequency

Meshing

The 8-noded brick-type element known as C3D8R has been used to mesh all the parts of the RC model. The mesh size of the top loading plate, top cap, and base pedestal have been kept constant at 5 mm, and the mesh size of the soil specimen has been varied at 25 mm, 10 mm, 7.5 mm, and 5 mm (Figure 4).

Post-Analysis

The results were obtained by extracting the time-displacement amplitude at the magnet's center, as shown in Figure 5(a). The loading was applied for 0.2 s, and then the signal was stopped to get the free decay of the model. Figure 5(a) shows the free decay, which has been used to calculate the damping ratio at a given shear strain level. The free vibration's positive and negative peaks have been combined to plot the free-decay curve, and an exponential curve fitting line has been drawn to calculate the damping ratio. A tapered window was used to get the windowed signal (Figure 5(b)) to avoid frequency leakage, while Fast-Fourier Transform FFT (Figure 5(c)) was calculated to obtain the signal's resonant frequency.

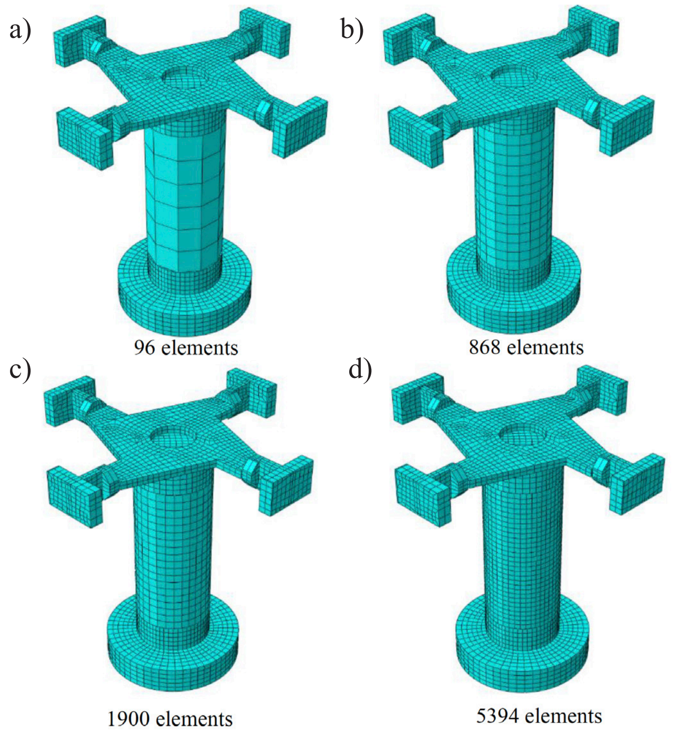


Figure 4: Variation of element size of mesh for convergence study, (a) 25 mm, (b) 10 mm, (c) 7.5 mm and (d) 5 mm

Results and discussion

The present FE modelling and analysis focuses on understanding the effect of mesh element size on the resonant frequency and damping ratio for accurate representation in the numerical models using the present methodology. The analysis has two parts: (a) Frequency or modal analysis and (b) Damping ratio calculation. The modal analysis was carried out at different shear strain levels for each mesh element size, and it was compared with the Experimental results reported by Cascante *et al.* (2003) (see Figure 6). At low shear strain (γ =1.42 x 10^{-5}), the resonant frequency obtained from the FE model was 3.98% (54.19 Hz) lower than the experimental value of

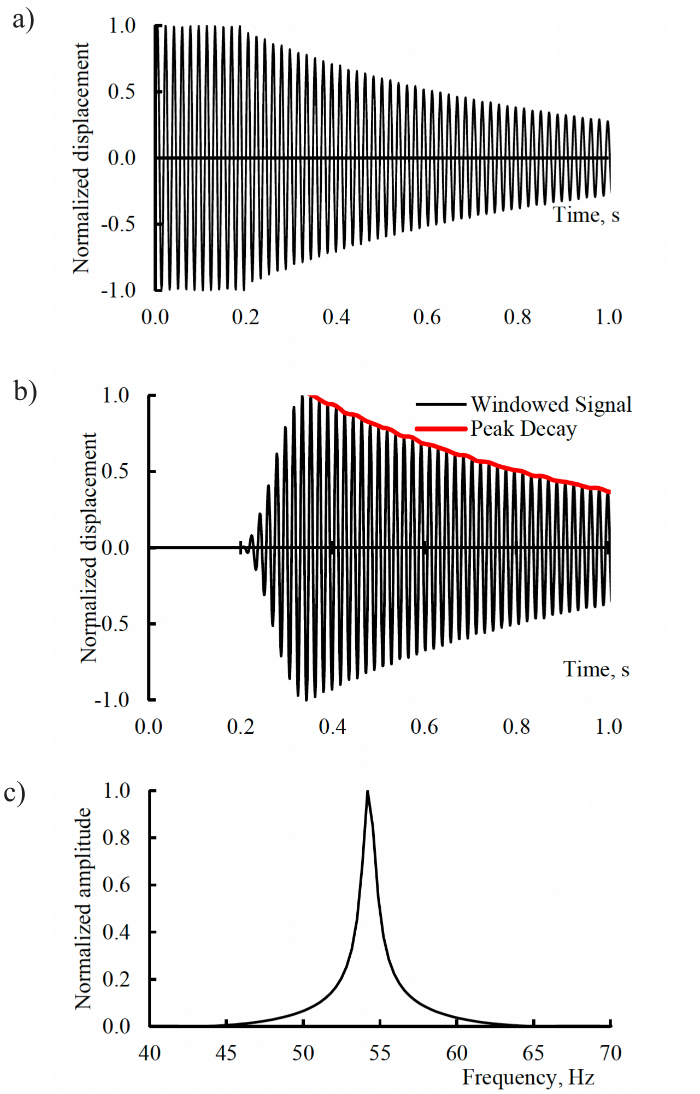


Figure 5: Post-processing of the FE output results in: (a) forced and free vibration of the FE model, (b) windowed signal, and (c) Fast-Fourier Transform of the windowed signal

56.44 Hz. Similarly, the error between the numerically obtained resonant frequency and the experimental value for mesh element size of 10 mm, 7.5 mm and 5 mm was 2.76%, 2.61% and 2.52%, respectively. However, at higher shear strain levels (3.85 x 10^{-5}), the error increases with decreasing the mesh element size, such as 0.64%, 1.73%, 1.85% and 1.93% for 25 mm, 10 mm, 7.5 mm and 5 mm, respectively.

The observed increase in error with decreasing mesh size can be attributed to several interrelated factors. First, finer meshes can lead to numerical instability as they are more sensitive to variations in stress and strain, particularly at high strain levels where material behaviour is complex. Second, these finer meshes often face challenges in achieving convergence, especially under conditions involving non-linear material behaviours, which are more pronounced at higher strains. Third, as mesh resolution increases, it accurately captures local changes in material properties, but errors can increase if the constitutive models do not accurately represent these non-linearities. Additionally, finer meshes can introduce new stress concentrations due to more detailed geometrical representation, which may not be apparent with coarser grids. Lastly, the computational precision required for finer meshes increases, which can lead to accumulated round-off errors, further increasing the simulation error. These factors collectively contribute to the increase in error rates as the mesh size decreases in high-strain simulations.

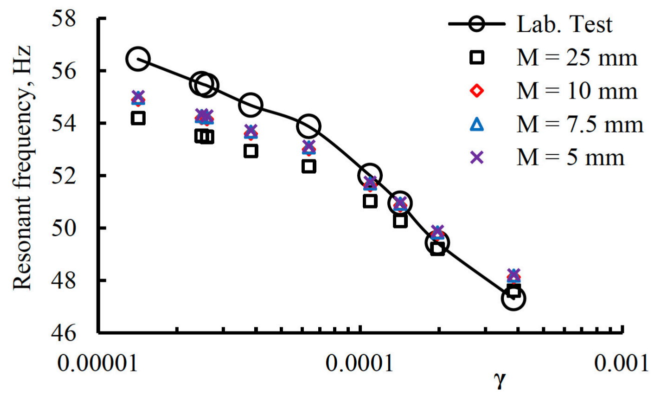
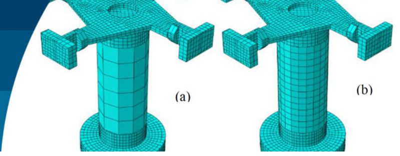


Figure 6: Effect of element size of mesh on the resonant frequency

In RC tests, a higher damping ratio is observed at higher shear strains due to the nonlinear behaviour of the soil and the increased mobilization of friction and particle rearrangement under more significant deformations. As shear strain rises, the particles within the soil experience more significant displacement, leading to more substantial energy dissipation through inter-particle sliding and collision, resulting in higher damping ratios. The shear modulus is typically higher at low shear strains, and the damping ratio is lower because the soil behaves more elastically, with minimal energy dissipation. Conversely, at higher shear strains, the reduction in shear modulus reflects the soil's decreased ability to resist deformation elastically, leading to higher energy dissipation and, consequently, a higher damping ratio. The RC tests simulations were carried out at different shear strain levels ranging from 1.42 x 10^{-5} to 38.5 x 10^{-5}, and for each shear



strain level, the size of the mesh element has been varied as 25 mm, 10 mm, 7.5 mm and 5 mm. The free-decay plots of each case have been plotted and shown in Figure 7, along with the corresponding damping ratio. A finer mesh does not significantly impact the damping ratio at low-shear strains since the soil behaviour is closer to linear and less sensitive to localized discrepancies. However, the mesh size influences the damping ratio at higher shear strains, where the behaviour becomes markedly nonlinear. A finer mesh captures more detailed interactions and localized phenomena, potentially leading to a more accurate depiction of increased damping. However, if not adequately refined, it also introduces numerical errors due to the increased sensitivity of the solution to the discretization quality.

Figure 8 has been plotted to compare the damping ratio obtained in the laboratory and the effect of mesh size on the numerically calculated damping ratio. The influence of mesh size on the damping ratio in resonant column tests for sand, particularly at different shear strains, reveals complex dynamics in how numerical simulations capture soil behaviour. The effect of mesh size on the damping ratio is more pronounced at low-shear strains. This is because, in this regime, the soil's response is more elastic, and the precision of mesh discretization can significantly affect the accuracy of capturing subtle energy dissipation mechanisms. A finer mesh at low strains might resolve small-scale heterogeneities and boundary effects more effectively, influencing the calculated damping ratio.

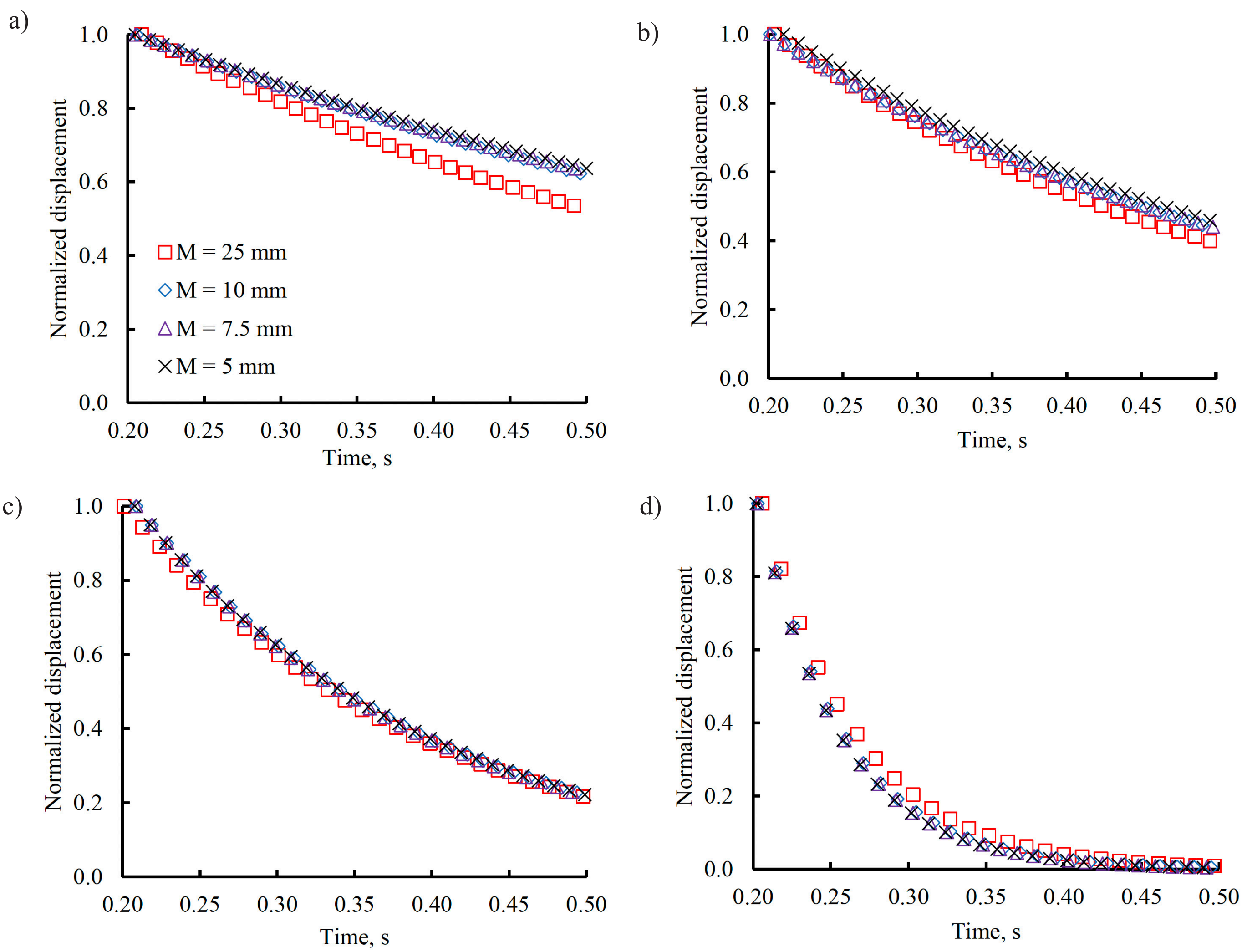


Figure 7: Free-decay of peak amplitude (+ve and -ve peaks) at different shear strains (x 10^{-5}). (a) $\gamma = 1.42$, (b) $\gamma = 3.82$, (c) $\gamma = 10.9$ and (d) $\gamma = 38.5$ to compare the effect of the mesh size.

Conversely, at higher shear strains, the effect of mesh size on damping becomes less significant. In this range, the soil behaviour is dominated by non-linear mechanisms such as particle rearrangement and more significant deformations, which overshadow the finer details that different mesh sizes might capture. As the strain increases, these non-linear behaviours become the primary drivers of energy dissipation, thus diminishing the relative impact of mesh refinement on the results. Essentially, the coarse-scale dynamics of particle movement and interaction, adequately captured by finer and coarser meshes, become more critical than the detailed local interactions. Interestingly, despite these variations in mesh sensitivity at different strains, the overall damping ratios converge towards relatively narrow ranges: around 15% at low and 6% at higher strains. This suggests that while the mesh size can influence the precision of the damping ratio measurements, the inherent material properties and the dominant energy dissipation mechanisms at different strain levels ultimately govern the damping behaviour. Therefore, in practical numerical modelling, while it is essential to consider the appropriate mesh size to achieve accurate results, understanding the behaviour of the soil under different loading conditions is crucial for interpreting the effects accurately.

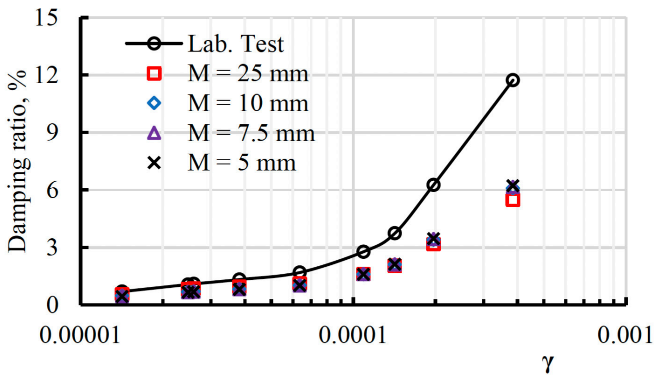


Figure 8: Effect of mesh element size on the damping ratio and corresponding error representation

Understanding the sources of error is crucial in the present analysis. The damping ratio obtained at 10 mm, 7.5 mm, and 5 mm sizes of mesh elements are in close proximity, such as 4% at the low shear strain level and 0.9% at the higher shear strain level. This led us to focus on the 7.5 mm size for further investigation. We observed the lowest error of 34.7% at a low shear strain level, compared to a 47.5% error at a higher shear strain level. The primary reason for such a significant error is the numerical damping introduced in the finite element solution. Numerical damping refers to the artificial reduction of oscillations or energy within a numerical model that is not a physical property of the material being modelled but rather an artifact of the numerical methods used. This damping is often introduced unintentionally through the discretization process and the numerical algorithms employed to solve the equations of motion. In finite element analysis, numerical damping can arise from factors like time integration methods, element formulation, and how the mesh handles deformations and stress redistributions. At low shear strains, the material's behaviour (such as sand in resonant column tests) is closer to linear elasticity, where the energy dissipation is naturally low. Here, numerical damping may not severely alter the physical realism of the model, leading to relatively lower errors. The damping introduced by the numerical scheme might slightly smooth out the results, but it aligns somewhat with the expected physical damping at these strain levels.

However, the material behaviour becomes significantly nonlinear at higher shear strains, with larger displacements and more complex particle interactions. In such cases, physical damping should increase due to mechanisms like particle rearrangement and friction. However, if numerical damping is not accurately calibrated or is too high relative to the physical phenomena, it can mask or inaccurately represent these crucial non-linear behaviours. This discrepancy between the physical reality and the numerical model's ability to represent it can lead to higher errors in simulation outcomes at higher strains. Therefore, the more significant error at high shear strains highlights the challenge of accurately modelling complex non-linear behaviours in geotechnical materials and underscores the importance of carefully managing and validating the numerical damping effects in finite element simulations to ensure they do not overpower the intrinsic material properties and behaviours being studied.

To counter the effects of numerical damping, a factor named "Z-factor" has been introduced, a multiplication factor. Therefore, the damping ratio obtained from laboratory testing should be multiplied by the Z-factor while calculating the Rayleigh damping constants to define the damping of soils in numerical simulations. Figure 9 has been plotted to show free-decay peaks at different shear strain levels when a constant Z-factor has been used to define damping in the RC test model. It has been observed that the damping ratio increases with the increasing magnitude of the Z-factor, reducing the effects of numerical damping.

Figure 10 summarizes the damping ratio obtained from the FE model when different Z-factors (constant) were used. It has been observed that the error in damping ratios obtained from FE analysis was reduced by 50% with an increased Z-factor. It suggests that the initial setup (with a lower Z-factor of 1.3) was perhaps under-damping the system. This under-damping might have allowed for unrealistic oscillations or dynamic responses that did not accurately reflect the physical behaviour of the material under test conditions. These inaccuracies manifest as errors in calculated parameters like the damping ratio, a critical measure in assessing material response under dynamic loading. Increasing the Z-factor to 1.6 likely provided a better balance of numerical damping, aligning the FE model more closely with the actual dynamic behaviour of the material. This adjustment helps mitigate excessive numerical oscillations or instabilities, thus delivering more accurate and reliable damping ratios. The damping ratio, after applying the Z-factor, shows an error range of 0.5% to 3.5% compared to laboratory test data. The significant reduction in error signifies that the Z-factor tuning effectively captured the actual material behaviour, emphasizing the importance of carefully calibrating such parameters in dynamic FE analyses to achieve both computational stability and physical accuracy.

Introducing a varying Z-factor in finite element (FE) analysis is a sophisticated approach to enhancing the

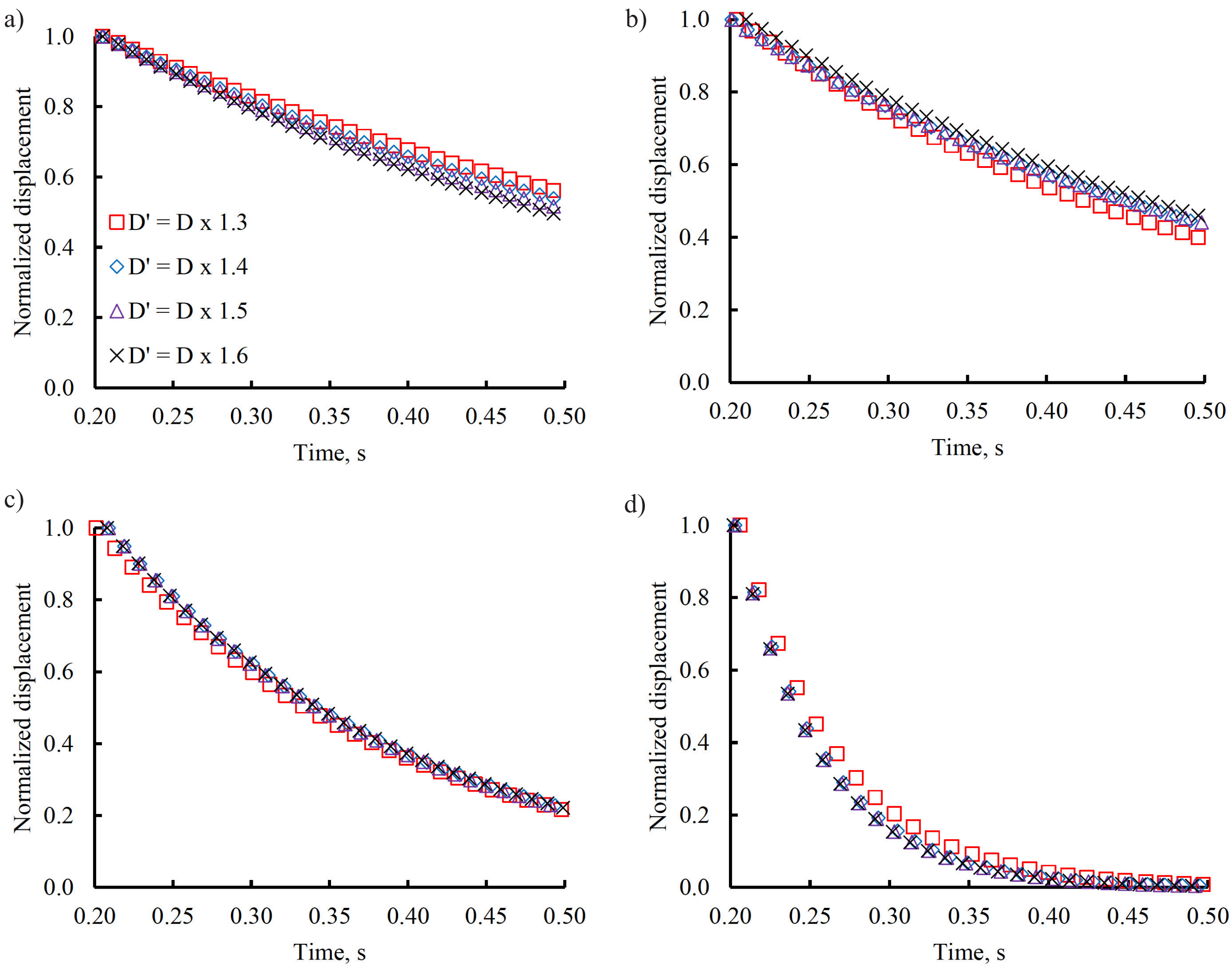
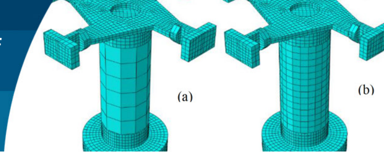


Figure 9: Free-decay of peak amplitude (+ve and -ve peaks) at a 7.5 mm element size of the mesh at different shear strains (x 10^{-5}). (a) γ = 1.42, (b) γ = 3.82, (c) γ = 10.9 and (d) γ = 38.5 to compare the effect of the Z-factor.



accuracy and adaptability of simulations, mainly when dealing with complex dynamic behaviour such as damping in materials. The Z-factor, which controls the level of numerical damping within the simulation, is typically used to stabilize the numerical response and ensure more accurate and realistic modelling of physical phenomena. The decision to employ a varying Z-factor likely stems from observations that different parts of the model or other dynamic conditions might require different levels of numerical damping for optimal simulation accuracy. This variation can be crucial because a single, constant Z-factor might not be adequate across all conditions—especially in simulations involving complex material behaviours or a wide range of operating conditions. For instance, in areas or scenarios within the model where high-frequency oscillations are prevalent, a higher Z-factor may dampen these oscillations and prevent numerical instability effectively. Conversely, in parts of the model where the response is smoother and less prone to such oscillations, a lower Z-factor might suffice, preserving the physical accuracy without unnecessarily smoothing out the material's response. The following expression has been introduced to define varying Z-factor.

$$Z-factor = \frac{\sqrt{\omega_R}}{\left|\ln\left(\frac{\gamma}{3.2}\right)\right|} \tag{1}$$

A varying Z-factor allows for tailored damping adjustments that align more closely with the local dynamic characteristics observed in different parts of the model or under various loading conditions. This approach helps in: (a) enhanced stability and accuracy, (b) adaptability, and (c) improved representation of physical behaviours. Ultimately, using a varying Z-factor reflects a more nuanced understanding of the material being modelled and the dynamics of the simulation process. It indicates a move towards more sophisticated, adaptive simulation techniques that strive for a balance between computational stability and the accurate representation of complex physical phenomena. This method enhances the utility and applicability of FE analysis in research and practical applications, where dynamic response and material behaviour under various conditions are critical.

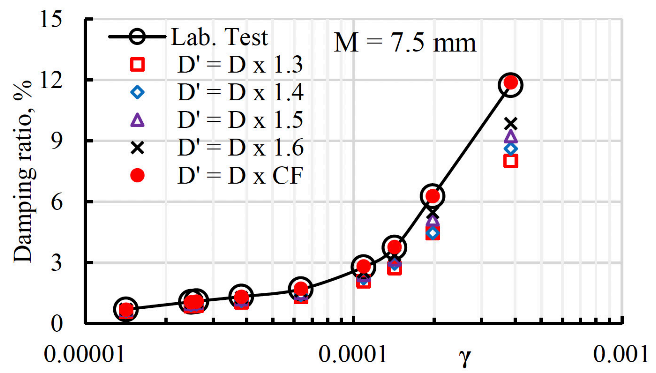
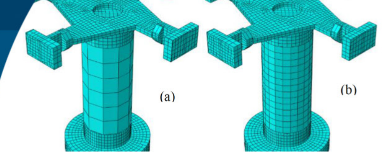


Figure 10: Variation of damping ratio obtained from the FE analysis results at different shear strain levels.

Conclusions

- The present study of FE modelling and analysis of RC test has been carried out using Abaqus/Explicit, and the following significant conclusions have been drawn:
- Accuracy at Low and High Shear Strains: At low shear strains, the resonant frequency obtained from the FE model showed a minimal error (around 3.98%) compared to the experimental value. However, the error increased with decreasing mesh size at higher shear strains, indicating that finer meshes are more prone to errors in complex, non-linear strain scenarios.
- Influence of Mesh Size on Damping Ratio: At low shear strains, where soil behaviour is relatively linear, the effect of mesh size on the damping ratio is more significant. This is because finer meshes can more effectively capture subtle energy dissipation mechanisms. At higher shear strains, the effect of mesh size on damping becomes less significant due to the dominance of nonlinear behaviours like particle rearrangement, which are less sensitive to changes in mesh resolution.
- Numerical Damping Impact: The error in damping ratio calculations at higher shear strain levels was substantially higher, mainly due to numerical damping introduced by the finite element solution. This suggests that the damping mechanisms modelled numerically may not align perfectly with the physical behaviours at higher deformations, leading to increased error rates.
- Introduction of the Z-factor: A varying Z-factor was introduced to address the challenges of numerical damping. Adjusting the Z-factor effectively reduced the



error in damping ratios by 50% when increased from 1.3 to 1.6. This indicates that a well-calibrated Z-factor can significantly enhance the accuracy of damping predictions in dynamic soil analyses.

- Variable Z-factor for Enhanced Accuracy: Employing a variable Z-factor across different model parts or under varying dynamic conditions allows for more tailored and accurate damping adjustments. This approach leads to better stability and accuracy in simulations, adapting the numerical damping to reflect the physical damping observed experimentally better.

These conclusions highlight the importance of mesh size optimization and the calibration of numerical parameters like the Z-factor to achieve more accurate and reliable FE simulations, especially when dealing with complex material behaviours under dynamic loading conditions.

Future scope

All future RC test simulations should be carried out after a detailed mesh convergence study for different cases. For the continuation of present study 7.5 mm of mesh size should be adopted.

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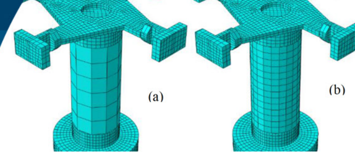

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