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Enhancing Nonlinear Solitary Wave Propagation Device using PLA Plate

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Abstract **–** The following research complements the challenge of reducing plastic deformation when measuring the Young's modulus with the nonlinear solitary wave propagation device. Enhancing the device performance of measuring on soft soils was possible by adding plastic polylactide (PLA) plate in between the last sphere and surveyed medium, designed to dissipate the stresses generated in the contact point. The methodology employed involves a finite element model that represents in an axis-symmetric format the contact between the last sphere of the device and the study surface. Adding to this interaction the plate with different materials and thickness to identify the optimal plate configuration that maximizes stress dispersion without compromising the device's measurement capabilities. Upon selecting the PLA plate, extensive simulations were driven to evaluate the influence of the plate in the interaction. The outcomes for different soil configurations were unified into a coefficient, modifying the contact equation to represent the presence of the plate without adding extensive complexity to it. Results suggest that the alternative of incorporating a plate can significantly enhance the device ability to measure in soft soils, and reduce plastic deformations. The representation of the plate effect into a single coefficient within the contact equation allows this approach to further implemented in numerical and experimental validation on future works.

Keywords**:** Nonlinear solitary wave, Young modulus, non-destructive test, compaction control test.

1. Introduction

The assessment of elastic properties holds crucial significance in various geotechnical applications [1, 2, 3, 4, 5, 6, 7]. Therefore, the exploration of non-destructive and cost-effective methodologies becomes important for measuring these properties. The current research is driven by the utilization of a device that employs the propagation of nonlinear solitary waves to assess Young's modulus in soil samples. This innovative approach, originally devised by Rizzo et al. [8] and subsequently modified by Villacreses et al. [1] for application on geomaterials, presents a promising alternative to conventional techniques, overcoming health hazards associated with methods such as nuclear gauges.

When applying the conventional equipment described by Rizzo et al. [2] to soil samples, the technique revealed surface plastic deformation, highlighting the need to explore strategies for reducing stresses within the soil mass. The apparatus comprised a vertical chain of spheres positioned on the sample's surface. An incident wave is generated at the top of the sphere chain, traversing the chain and reflecting over the surveyed medium. The travel time between the incident and reflected waves is subsequently measured using a piezoelectric load cell positioned in the middle of the chain. Employing a numerical analysis based on the Hertz contact equation [9, 10, 5] the Young's modulus of the impacted material can be determined.

Villacreses et al. [2] stress the importance of maintaining the surveyed material within the elastic domain for the practical application of nonlinear solitary waves in non-destructive Young's modulus measurement. However, testing on soft soils introduces challenges due to plastic deformation in the contact zone, directly impacting measurement accuracy. While the research proposes an alternative, its complexity is tied to the surface roughness of the sample. Thus, further exploration is essential to improve the potential of this device.

The aim of this research is to investigate a refinement in the contact between the surveyed medium and the chain of spheres through the addition of a thin plate. This modification efficiently disperses stresses across the top of the sample. The study explores adjustments to the Hertz contact equation to capture alterations in the response when introducing a new element, such as a thin plate. The suggested solution involves inserting a plate between the last sphere and the contact zone, providing a possible remedy to mitigate plastic deformation observed in the original device.

2. Methodology

This research used a numerical simulation approach o explore the alternative of incorporating a thin plate into the device. The numerical model was built in Abaqus software, intended to study the interaction between the last sphere in the chain and the surveyed samples. Then in the model, a thin plate was introduced between the last sphere and the sample. The objective was to calculate, through a finite element approach, the forces and displacement when a plate is in between. The research then compared the results of the numerical model with the explicit formulation of the Hertz contact law. After selecting the material type, the thickness of the rounded plate was studied. Finally, the Hertz equation was modified to fit the numerical results by introducing a new term.

2.1. Abaqus Model Assembly

A 2D axisymmetric finite element model was created using Abaqus. The soil was represented as an infinite element to accurately capture its extensive nature, with dimensions much larger than the sphere, measuring 1 meter by 1 meter. The soil Young modulus was kept in 10 MPa due to the results found by Villacreses et. al. [1]. The test plate, variable in material, was constructed using steel and plastic polylactide. The mechanical properties for steel were set at 21e4 MPa, and for plastic, it was 22e2 MPa. Thicknesses were varied at 0.2mm, 0.4mm, and 1mm. The objective was to discern the impact of material type and thickness on the mechanical response of the indentation phenomenon. The steel sphere, with a diameter of 19.3mm, was positioned initially at the top of the soil and later at the top of the plate. This comprehensive setup allows for an understanding of the interaction dynamics among the soil, test plate, and steel sphere. A compressive study was conducted to examine the influence of plate material properties and thicknesses, and select one possible configuration to implement in futures researches experimentally. The model components, along with the Von Misses stress, are illustrated in Figure 1. A summary of the presented models is presented in Table 1.

Table 1. Material properties used in the models.

Model	Plate thickness (mm)	E soil (MPa)	E plate (MPa)	E sphere (MPa)
Model 1	0.4	10	2200	210000
Model 2	0.4	10	210000	210000
Model 3	-	10	-	210000
Model 4	0.2	10	2200	210000
Model 5	1	10	2200	210000

The model assembly took place within the Static, General step module of Abaqus. A load increment of 1.5e-6 N was applied at the top of the sphere, and the resulting displacement was recorded for each load increment. The contact between the plate and soil was characterized as frictional contact, with the friction angle set at 0.75 of the material's friction angles. The specified boundary conditions were as follows: Constraints on horizontal movement were imposed on the sphere, plate, and soil, reproduce the physical constraints inherent in the axisymmetric problem. The model's bottom was restricted for displacement in both directions, and the lateral right boundary had its displacement restrained horizontally. The meshing size was established at 1 mm, and convergence was verified through a systematic reduction of the mesh size. Subsequently, force and displacement were systematically recorded at the top node of the sphere for each variation of plate material and thickness, as well as for the scenario without a plate. These results were analyzed to determine the material and thickness that best aligned with the Hertz contact equation, presenting the possible solution for a future experimental research.

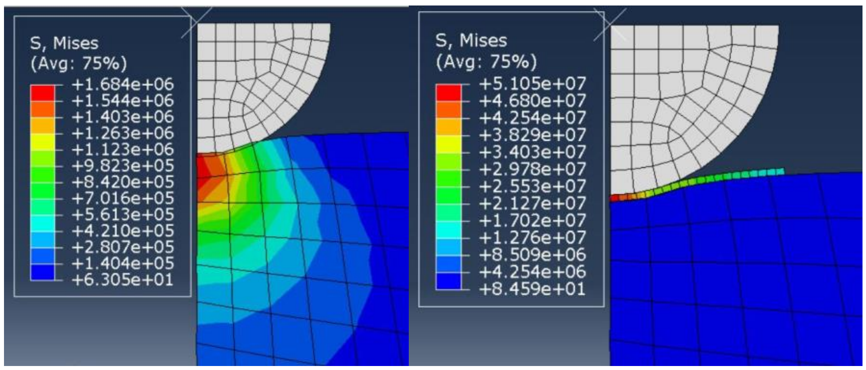

Fig. 1: Abaqus Modelling

2.2. Unified Coefficient Analysis

Having identified the plate configuration through the Abaqus model, the subsequent phase involves analyzing its response across various sample Young moduli. This step is crucial for evaluating the plate's performance during interactions with different soil compactions. The goal is to approximate changes in the plate's behavior within the contact equation. Using the finite element results, modifications were made to the Hertz contact equation [9] by introducing a new term aimed at capturing the interactions between the sphere, plate, and the surveyed medium. To achieve this, the force and displacement relationships computed in the finite element model were employed to refine the Hertz equation. This refinement involved adding an extra term denoted as K. The Hertz contact equation is described in terms of force (F), indentation displacement (d), sphere radius (R), and equivalent young modulus (E*).

$$F = \mathrm{K}\frac{4}{3} \cdot E^{*} \cdot R^{1/2} \cdot d^{3/2} \tag{1}$$

$$\frac{1}{E^{*}} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \tag{1}$$

The equivalent young modulus is defined computed using the Young modulus (E_1) and Poisson ratio (v_1) of the surveyed material soil and the Young modulus (E_2) and Poisson ratio (v_2) of the steel spheres.

3. Results

Figure 2 (a) illustrates the computed results, showing forces (F) and displacements (d) from various numerical models corresponding to different plate materials. It is evident that plastic polylactide (PLA) exhibits a closer alignment with Hertz's contact equation. Consequently, PLA has been chosen as the preferred material for the device modification. The impact of plate thickness on PLA is further examined in Figure 2 (b). The figures reveal a divergence in numerical results as the plate thickness increases, attributed to the plate's stiffer response. Notably, the good agreement observed for PLA plates of 0.2 and

0.4 mm with Hertz's contact equation guides the selection of these geometries for the experimental setup. With the plate geometry finalized, the subsequent step involves exploring the fitting between the numerical results and the Hertz

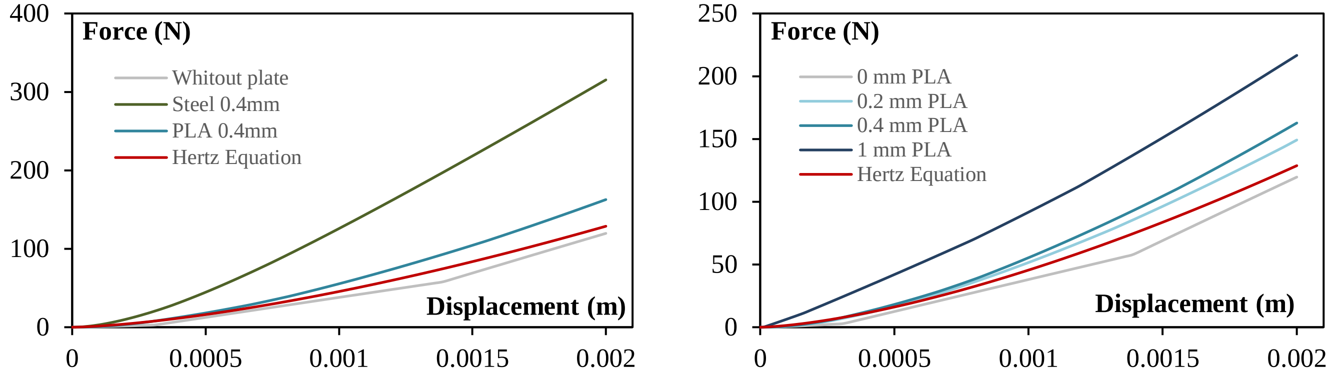

Fig. 2: Material and thickness modelling optimization

Figure 3 illustrates the results obtained from applying the derived K factor to a soil sample of 10MPa, showing the potential to encapsulate the plate's effects in a singular coefficient incorporated into the Hertz equation. Nevertheless, achieving a robust fit for these coefficients necessitates a thorough analysis of diverse soil samples to determine their respective K factors aligned with the Young's modulus of each sample. This comprehensive approach ensures the generation of a dataset comprising K factors, which can then be utilized to fine-tune the device in numerical simulations, providing valuable insights to enhance its performance. The resulting K value from this fitting process for numerical simulations is 1.25 (Fig. 3).

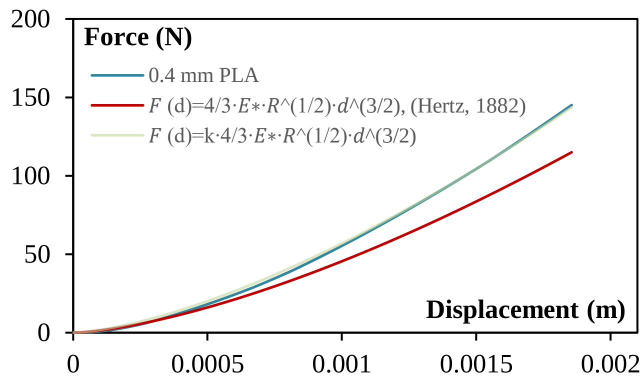

Fig. 3: Thickness Modelling Optimization

4. Conclusion

A finite element methodology was employed to discern that PLA stands out as the optimal material for modifying the solitary strain wave device. This alteration demonstrated minimal impact on results derived from the contact equation. The recommended use of a 0.4 mm PLA plate strikes a balance between ease of manipulation and durability. The incorporation of the derived K factor, encompassing plate effects, has proven effective, streamlining integration into the Hertz equation. However, for practical application, a comprehensive analysis of various soil samples is imperative to ascertain their respective K factors.

The trends observed present a novel approach to measuring Young's modulus in soft soil conditions. Employing a unified coefficient will facilitate measurements in soil, enabling the application of the equipment for compaction control and other purposes. While our study significantly enhances Young's modulus measurement with the device, further analyses must be undertaken to rigorously test the equipment with these modifications.

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