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AN EVALUATION OF SOLITARY WAVES FOR COMPACTION CONTROL ON FINE-GRAINED SOILS

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ABSTRACT: This research presents the implementation of a non-destructive procedure for compaction control using a device capable of propagating solitary strain waves. The device is made of a chain of steel spheres excited by a strike at the top. The strain solitary wave is generated by a falling sphere with a constant height. The wave travels through the chain and is reflected when it reaches the boundary of the soil sample. The time gap between the incident and the reflected wave is called "time of flight", and it is measured in the middle of the chain using a piezometric sensor. This "time of flight" is related to the mechanical properties of the tested specimen. The mechanical properties of soil are related to the density and water content that are achieved at the end of a compaction process. The mechanical properties can be used as an indicator for compaction control rather than density. The results suggest that the time of flight is an acceptable indicator to control the bulk density and optimum water content of compacted soils.

Keywords: Solitary waves, Compaction Control, Solitary strain waves, Young modulus.

1. INTRODUCTION

Soil has been used as a construction engineering material in several structures like roads, dams, embankments, among others. Compaction provides benefits to the construction project such as settlement reduction, an increase of the yield resistance, reduction of soil expansivity, among others [1, 2, 3]. During the construction process, the in-situ material's mechanical properties vary from those detailed in the designs [1]. Soil mechanical properties are achieved through mechanical compaction, using density and water content as the control parameters to verify in the field [1, 2]. Therefore, it is always pertinent to evaluate new methodologies to assess the in-situ compaction state.

Several methodologies are carried out for compaction control in civil engineering practice. The nuclear density gauge (NDG) is a procedure that is frequently used in professional practice [6]. This non-destructive methodology is a versatile procedure where control parameters can be acquired immediately [7]. This benefit is blurred due to the radiation exposure that operators are exposed [8]. Therefore, new procedures based on non-nuclear principles have emerged [6, 7, 8]. Among alternative methodologies, an electrical density gauge (EDG) can be used [9]. The main limitation of the EDG method is the calibration complexity that results in a time-consuming experimentation campaign [6, 10]. Another methodology, the light-weight deflectometer (LWD) is an interesting alternative to the NDG method [6]. This equipment measures the deflection caused by an impact load. This information is used to compute the Young Modulus of the material [11]. The problem of this methodology lies in the high strains applied to the sample when the measurements are taken [12].

Density measurements are not a direct indicator of soil's mechanical properties, contrary to the hypothesis that is assumed in most compaction control procedures [13]. Mechanical properties depend on the soil saturation and the compaction stress history. Therefore, it is more convenient to verify and compare the design mechanical properties and the ones achieved in situ [14]. Several methodologies have been developed for compaction control based on the relationship of soil elastic modulus, dry density, and water content [6, 7, 15, 16]. This research will assess the effectiveness of a new device designed to measure the soils' Young modulus. This equipment intends to be applied as a compaction control methodology. The equipment is based on the solitary strain waves reflection principle, where the reflected strain wave depends on the stiffness of the sample, in this case, the underlying soil [5, 17, 4, 18, 19, 20].

Non-linear solitary waves are used due to their high strain peaks which are not easily attenuated when traveling in a medium [21, 22]. The time difference between the incident and reflected wave is measured on a piezoelectric dynamic sensor, and it is named in this investigation the time of flight (TOF). TOF is directly related to the soil's mechanical properties, and consequently to its density. To study this relationship, nine soil samples were compacted and tested with the new equipment. These samples were constructed with different water content and compaction energies to produce two compaction curves. This research aims to study a relationship between the TOF and the compaction curves of fine-grained soils.

Compaction control of subgrades is an important task for engineering projects. There are several methodologies, but the NDG method is frequently used for in-situ measurements. The risks associated with this procedure are the motivation to explore alternative tests. The research objective is to evaluate the viability of using solitary waves for compaction control of fine-grained soils, as an alternative to NDG methods.

2. RESEARCH SIGNIFICANCE.

The objective of this research is to evaluate the feasibility of a new equipment based on solitary strain waves for compaction control purposes. In this investigation, compacted fine-grained materials are going to be evaluated. This material is assessed due to the assumption of a Hertzian type of contact supposed in the solitary strain wave device. This assumption was used in previous researches [4, 5]. This assumption can be guaranteed if the soil particle size is considerably smaller than the size of the elements of the equipment.

3. MATERIALS AND METHODS

This section is divided into two parts. The first one shows the properties of the soil samples used in this research. The second one describes the procedure carried out to construct the samples, the compaction process, and the experimentation campaign conducted with the new equipment that uses solitary waves.

3.1 Materials

In this research, nine samples were constructed using compacted commercial kaolin. Atterberg limits of compacted soils obtained using ASTM D4318-17e1 were 35% and 17.9% for the liquid limit and of the plastic limit [23]. The specific gravity of the solid particles was 2.68, measured according to ASTM D854 [24]. Two sets of samples were compacted with different energies and different water contents using guidelines of the Standard Proctor Test specifications (ASTM D698-12e2) [25]. Consequently, the samples had the following dimensions: 101.6 mm in diameter and 116.4 mm in height. The first set of samples were compacted using the energy of compaction of 12 hammer blows per layer. The water content of this set ranged from 21.1% to 25.0%. The second set of samples were compacted using compaction energy of 25 hammer blows per layer, and water content ranging from 17.7% to 22.3%.

Fig.1 shows the compaction curves of the two sets of samples. The 12 blow specimens reach a maximum dry density of 1.59 g/cm^3 with an optimum water content of 22.7%. Whereas the 25 blow specimens reach a maximum dry density of 1.66 g/cm^3 with an optimum water content of 20.0%. Table 1 summarizes the soil properties mentioned in this section.

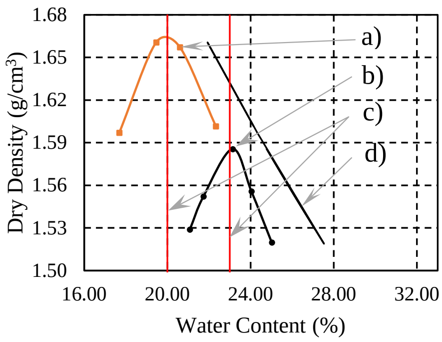

Fig. 1 Compaction curves of soil sample sets with the following curves a) 25 hammer blows, b) 12 hammer blows compaction curve, c) optimum water content, and d) saturation curve.

Table 1 Properties of the compacted samples

Number of Samples	Liquid Limit (%)	Plastic Index (%)	Specific Gravity	Hammer Blows (Compaction Energy KJ/m^3)
5	35	18	2.68	12 (287)
4	35	18	2.68	25 (598)

3.2 Methodology

Soil samples were built according to the Proctor Standard Method [25]. The soil was moistened to achieve different water contents and then sieved through # 4 sieve. These damped soils were stored in hermetic plastic bags for 24 hours to obtain an even water distribution. Then, soils were compacted using the two compaction energies 12 and 25 blows per layer. The water contents used in the first set of samples (i.e., samples with 12 blows) were: 21.1%, 21.7%, 23.1%, 24.0% and 25.0%. Whereas, the water content used to construct the second set of samples (i.e., samples with 25 blows) were: 17.7%, 18.3%, 19.5%, 20.6%, and 22.3%. Water content was measured after compaction, following an oven drying technique. After compaction, samples were extracted from the proctor molds using a hydraulic jack. The proctor mold was previously covered with grease to minimize sample alteration during the extraction process. Finally, the samples were tested using a novel device base on solitary strain waves -SSWD- (showed in Fig. 2). It has a unidirectional vertical chain of sixteen 19.05 mm diameter steel spheres. The impulse is produced by striking the first sphere of the chain with a free fall sphere of the same dimensions. The striker sphere falls from a height of 8 mm above the first chain element. In the middle of the chain, a dynamic load cell (DLC 101) is placed to record the time gap between the incident and reflect wave. The load cell is connected to a signal amplifier and an oscilloscope.

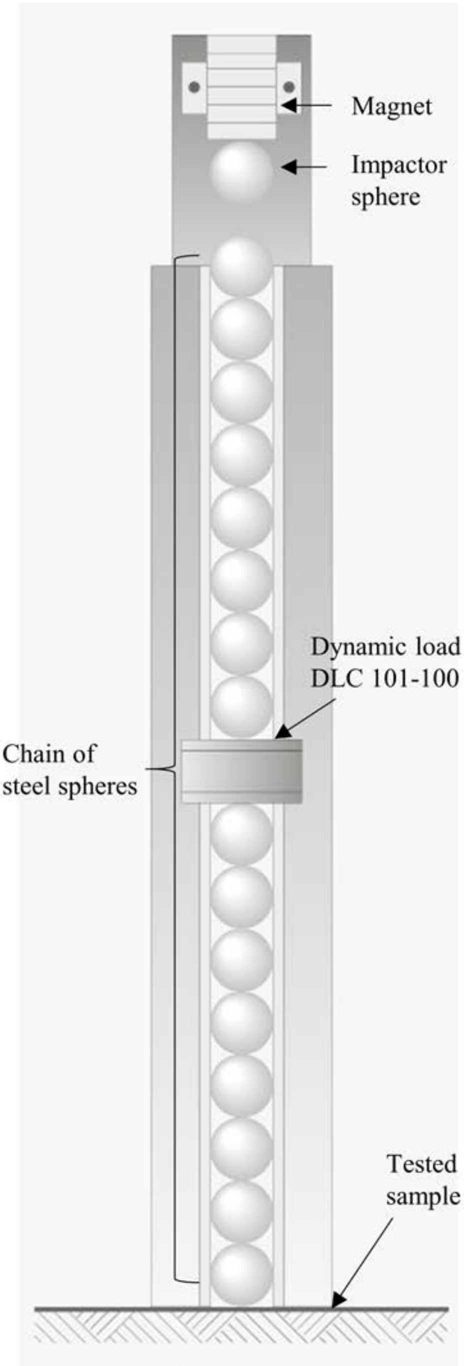

Fig. 2 Equipment Sketch (Modified from **[5, 4]**)

Fig. 3 shows the experimental setup including the soil sample, an oscilloscope, a signal amplifier, and the SSWD device which is placed in the middle of the sample top face. Based on the investigation in [5] the Young modulus of the compacted samples can be computed using the experimental TOF. The signal registered by the oscilloscope was used to determine the TOF of the sample, as the distance between the two peaks of the time domain signal register.

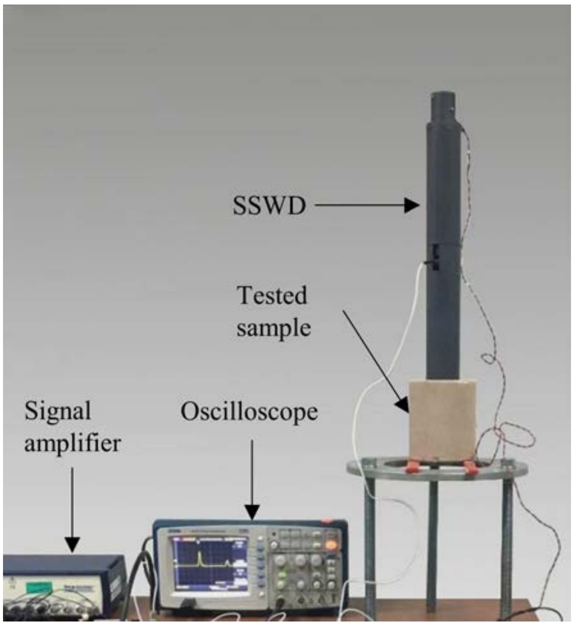

Fig. 3 Experimental configuration of the proposed methodology

When the impactor sphere is released and hits the chain of steel spheres, the solitary wave is induced and recorded. A signal registered of a tested sample is shown in Fig. 4. The first peak of the signal indicates the arrival of the incident wave. Whereas the second peak of the register shows the arrival of the reflected wave. The distance between the first and second peak (TOF) is measured for each sample. The experimental TOF is used to estimate the Young modulus of the tested specimen.

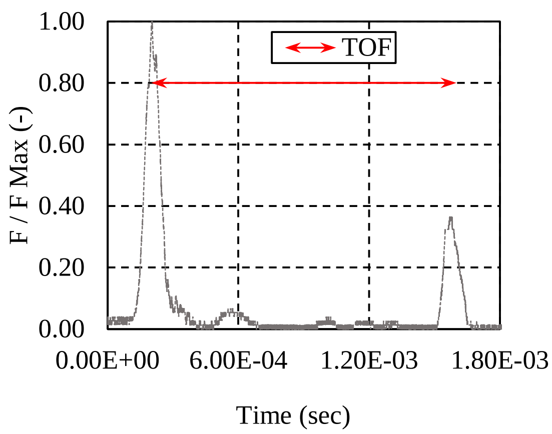

Fig. 4 Measurements obtained in the dynamic load cell, for 12 blows compaction energy, 21.7% water content

Fig.5 shows the calibration curve from the investigation conducted in [5]. This figure is based on a numerical model of the SSWD operation [5, 20, 19], expressing the relationship between TOF, Young modulus, and Poisson ratio. The numerical model was developed using a finite-difference formulation where an equation of motion was developed for each element of the chain of spheres. The equations of motion produce a set of simultaneous differential equations that were solved using an implicit formulation [15]. The numerical simulations were conducted varying the Young modulus (E) from 10^1 to 10^5 MPa and the Poisson ratio (μ_m) from 0.1 to 0.5. Fig. 5 is used to estimate the Young modulus of the tested samples. To achieve this, the experimentally TOF was used as an input and the modulus was interpolated from this figure. The results could be determined from a range of TOF values between $6.0\text{x}10^{-4}$ to $2.4\text{x}10^{-3}$ seconds. In the research conducted by [5] the calibration curves are presented for rocks (Fig. 5a) and soils (Fig. 5b).

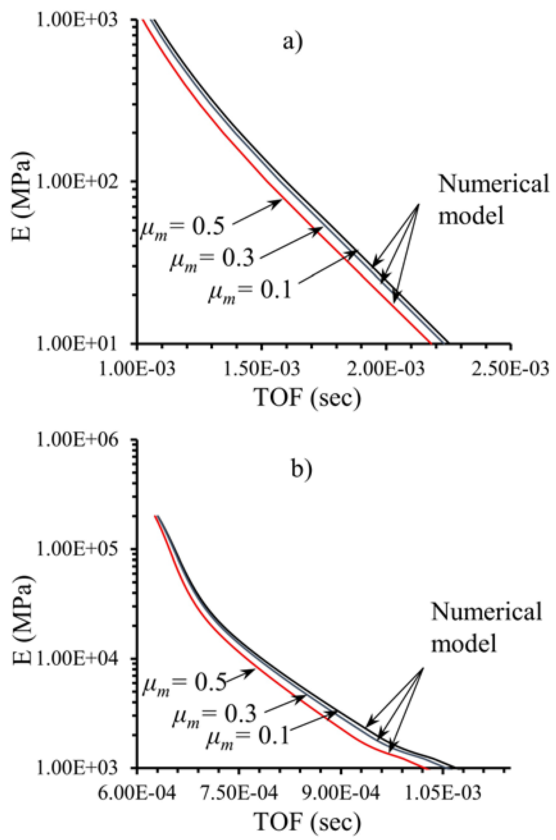

Fig. 5 Calibration curve of the used equipment **[5]**

4. RESULTS AND DISCUSSION

The results obtained in this research are organized according to the compaction energy (i.e., 12 or 25 hammer blows). The first results explore the relationship between Young modulus and water content where Young modulus was computed using the experimental results and the calibration curves presented in **[5]**. The second results show the relationship between bulk density and TOF. The bulk density was selected as a comparison variable due to its effect on strain wave velocities (i.e. P and S waves). Finally, the relationship between TOF and water content is presented. Some common characteristics are observed between the compaction curve and the measured TOF.

Fig. 6 shows the relation between the sample's water content and Young's modulus. The modulus was computed using the equipment calibration curve proposed in [5]. The figure suggests that the sample Young modulus reduces as the water content increases. Therefore, the TOF is related to the sample´s Young modulus as it is observed in [5, 18, 19, 20]. For samples compacted using the energy of 12 blows, the modulus reduces markedly when water content exceeds the optimum content. On the other hand, samples constructed using the energy of 25 blows per layer show a gradual decrease in the Young modulus as the water content increase. The Young modulus of the compacted specimen is associated with the fabric strength and the interparticle forces. This fact shows that the TOF could provide information about the soil compaction state [22].

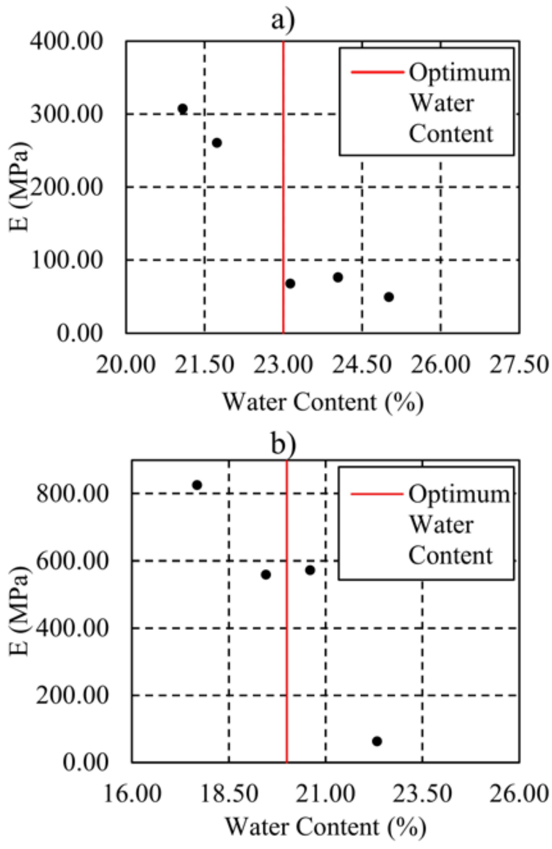

Fig. 6 Water Content Vs Young Modulus for a) 12 Drops and b) 25 Drops.

Fig. 7 shows a comparison between bulk density, TOF, and water content. It evidences a change of behavior of the measured values TOF when water content increase above the optimum. This information is reflected in how data groups are formed for values above and below 27.7%. Therefore, TOF can reflect if the soil fabric is close to its optimum configuration. It is important to mention that TOF measurements should be conducted as soon as the machine compaction finishes the construction process in the field. This, to reduce the effect of matric suction in the elastic properties of soil [5, 22].

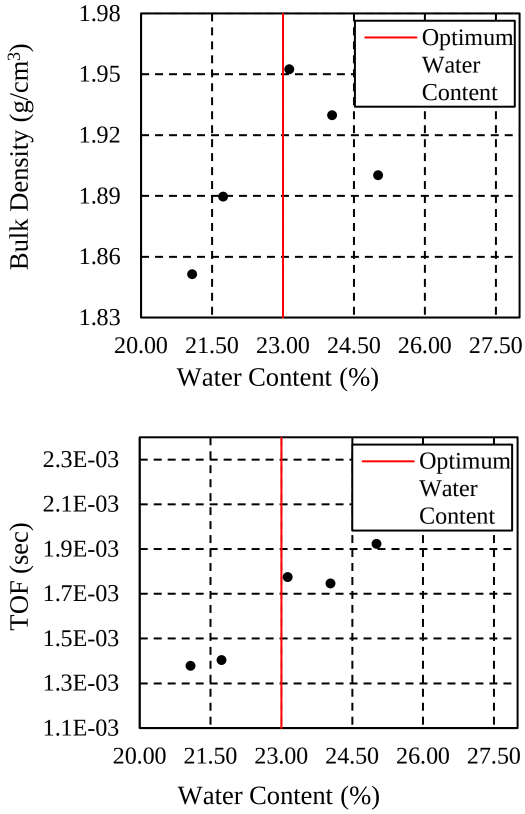

Fig. 7 Relationship between TOF and soil's bulk density for 12 blow samples.

Fig. 8 shows the experimental results for samples compacted with an energy of 25 hammer blows. The results show similar behavior to those obtained for the 12 blows samples. TOF is almost constant when the water content is close to optimum. For example, for a water content of 22.3% the measured TOF is 1.82E-3 s which is the highest value for this set of samples. Consequently, the TOF increase as soil fabric weakens and the interparticle forces decrease.

The experimental results suggest that the TOF increase as water content increase beyond the optimum content. Therefore, TOF could be used as a soil compaction indicator, but this procedure needs to be conducted accompanied by a field water content test. This fact arrives due to the relationship between bulk density and travel wave velocity, which is accepted in soil dynamic applications. This can be evidenced in Fig. 7 and 8. In these figures, for water content above the optimum, the TOF increases as the bulk density decrease. This fact can be explained using unsaturated soil mechanics principles. Samples construed with water contents below the optimum develop negative pore water pressure, opposite to samples compacted close to saturation. This negative pore water pressure increases the effective stress and consequently the modulus.

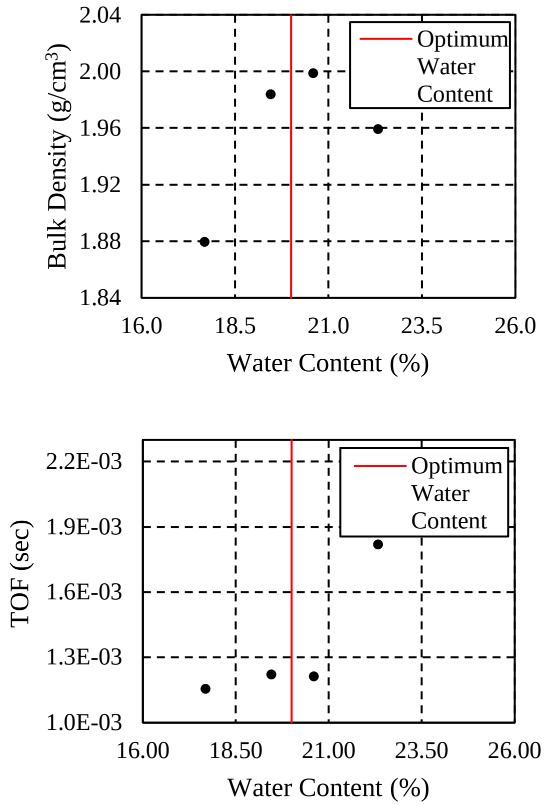

Fig. 8 Relationship between TOF and soil's bulk density for 25 blows samples.

5. CONCLUSION

This research explored new equipment based on solitary strain wave propagation to control the compaction process. The constructed equipment is called the SSWD, and its implementation is based on the investigation conducted by [5]. In the research, the time between the incident and the reflected strain wave (TOF) is measured at a particular point of the device. This research explores the possible relationships between the compaction control parameters (i.e., density and water content) and the TOF. The main findings could be summarized as follows:

1. The TOF increased 28% percent as the sample pass from the dry to the wet side of the compaction curve for the 12 blow specimens.

2. The TOF increased 50 % from the dry to wet side of the compaction curve for samples fabricated using 25 hammer blows.
3. This gap between the TOF of the compacted specimens at the wet or dry side of the compaction curve could be used as an indicator of the compaction state.
4. The TOF test should be used together with a water content test to check the compaction state of soil samples.
5. Additionally, the new device allows measuring the Young modulus of compacted specimens.
6. Further investigation needs to be conducted to study the behavior of the SSWD on different types of soils such as sands and silts.

6. ACKNOWLEDGMENTS

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