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Application of the finite element method for investigating the dynamic plate loading test

Mohamed M. Tawfik *, **Yasser M. El-Mossallamy**

Structural Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt

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KEYWORDS

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Abstract The dynamic plate loading test using the Light Falling Weight Deflectometer (LFWD) is an innovative and very simple method used for quick assessment of the field compaction quality. The basic outcome of the LFWD test is the dynamic resilience modulus of the tested soil. This paper concisely presents the state-of-the-art for the theory and applications of the LFWD test. Moreover, an attempt is made in this study to use the finite element method for simulating the LFWD test and investigating the consequent soil response. An axisymmetric model is established to simulate a realistic case study of in-situ LFWD test. Different soil models are examined for adequately simulating the soil performance, including linear elastic, Mohr–Coulomb and Hardening-Soil models. The finite element analysis is applied to investigate the factors that probably affect the LFWD results. Furthermore, an attempt to ascertain the influence depth of the LFWD is provided.

1. Introduction

Compaction control of engineered fill or constructed subgrade has traditionally been carried out by means of in-situ density measurement tests, such as the commonly used sand cone test. Alternative methods have been employed for direct measurement of the response of the compacted soil to applied loads, such as the conventional static plate loading test (SPLT) and the dynamic plate loading test (DPLT). The dynamic plate loading test is an inventive and very simple testing method that allows for quick assessment of the field compaction quality. Simply, the mechanism of the DPLT comprises acting on the surface of the tested soil by a pulse load (i.e. falling weight) and recording the consequently induced soil movements. A testing device is used, known as the Light Falling Weight Deflectometer (LFWD). The test is predominantly designed to determine the dynamic resilience modulus (E_{vd}) of the tested material. This method has been developed during the last two decades and has already been applied in many parts of the world. It can be applied for different applications of earth works and road construction [2,4]. Many international regulations for the LFWD test procedure and for evaluating the test results have been developed, such as the German standard [1].

The DPLT using the LFWD is considered advantageous over the common SPLT because it can be performed in narrow and inaccessible areas, the test equipment is light weight and easy to handle and there is no necessity for loading truck

* Corresponding author. Tel.: +20 2 0100 3937775.
E-mail addresses: moh_maher_gad@hotmail.com (M.M. Tawfik), y.el-mossallamy@arcadis.de (Y.M. El-Mossallamy).
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Nomenclature

BEM	Boundary Element Method	h	thickness of a covering soil layer above a natural soil deposit
DPLT	dynamic plate loading test	LFWD	Light Falling Weight Deflectometer
D_{Pr}	degree of soil compaction	MC	Mohr–Coulomb soil model
E_{vd}	dynamic soil resilience modulus	SPLT	static plate loading test
E_{v1}	static modulus from loading in SPLT	s	plate deflection
E_{v2}	static modulus from reloading in SPLT	s_{max}	peak plate deflection
E_o	elastic modulus of soil deposit	t_i	duration (time) of pulse impact
E_1	elastic modulus of a covering soil layer above a natural soil deposit	σ_{max}	amplitude of pulse stress
f	frequency of pulse loading	σ_t	generated pulse stress value after time t of the pulse impact
FEM	finite element method	v	soil Poisson's ratio
HS	hardening soil model		

and settlement measurement devices. On the other side, the LFWD test may be more valuable than the customary sand cone test. This can be attributed to the sort of information obtained from the LFWD, e.g. soil response to dynamic/pulse loads, which may be more beneficial than the traditional in-situ soil density measurements. Besides, the LFWD test is non-destructive, as the soil is not excavated during the test, and it can be fruitfully used with gravelly soils where sand cones are not usually suitable. On the other side, there is a shortcoming regarding the availability of a widely accepted correlation between the LFWD test results and the soil compaction characteristics. Therefore, the application of the LFWD test is still limited.

The dynamic resilience modulus (E_{vd}), obtained from the LFWD test results, is not a direct measure of the soil compaction quality. Therefore, approaches have been proposed in the literature and relevant specifications for the indirect use of the E_{vd} modulus in assessment of the compaction quality. Some attempts have been presented in the literature to investigate the correlation between the E_{vd} modulus and the degree of soil compaction (D_{Pr}), e.g. Singh et al. [2]. An empirical E_{vd}–D_{Pr} relationship is provided in the German Guidelines for Earth Works in Road Construction [3]. Alternative contributions have been developed toward correlating the E_{vd} modulus with the static deformation moduli determined from the conventional SPLT, which are effectively linked with the degree of soil compaction, e.g. Tompai [4]. Numerical analyses have been performed in advance, based on the Boundary Element Method (BEM), to understand the soil performance during the LFWD test, e.g. Adam and Adam [5] and Adam et al. [6]. In these numerical studies, two separate mechanical models were proposed for the coupled system of LFWD and tested soil, where equilibrium and compatibility conditions of both subsystems were to be fulfilled via large iterations of BEM computations.

In this paper, a concise state-of-the-art for the theory and applications of the DPLT method is presented, focusing on the German device of the Light Falling Weight Deflectometer (LFWD). The fundamental objective of this paper was to employ the Finite Element Method (FEM) to simulate the mechanism of the LFWD test and to investigate the corresponding soil response. An axisymmetric FE model is established and verified utilizing the field measurements of an implicated case study of in-situ LFWD test. Factors that probably affect the LFWD results, as well as the LFWD influence depth, are examined using the finite element analysis.

2. Light Falling Weight Deflectometer (LFWD)

The Light Falling Weight Deflectometer (LFWD) is the testing device of the innovative technique of dynamic plate loading test (DPLT) used for compaction control of constructed subgrades and compacted soils. Two types of the LFWD have been developed in Europe; the German device and the Hungarian B & C device. The two types of the LFWD are typically associated with a very simple testing mechanism, in which a weight freely falls from a specified height to create a defined pulse force on a loading steel plate that is rested on the surface of the tested soil. The loading plate consequently settles due to the effect of the pulse force, and, thereby, the dynamic resilience modulus (E_{vd}) of the tested material is evaluated. Both the German and the Hungarian devices are similar in shape and setup; however, the latter has a loading plate of smaller diameter. The present study focuses on the widely used

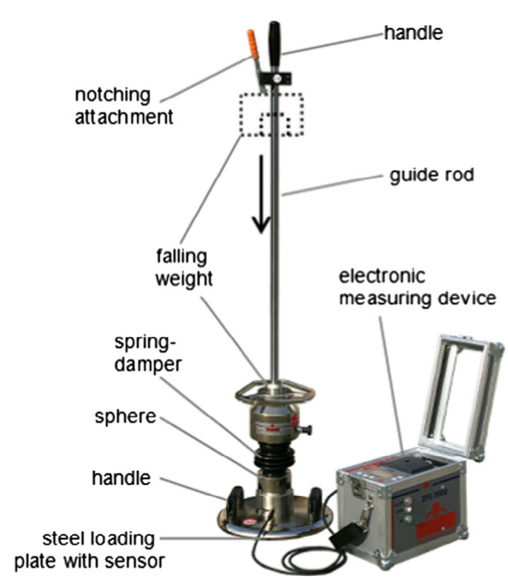


Figure 1 Details and components of the German LFWD.

German LFWD, which has been recently applied in some civil projects in Egypt. The following subsections depict briefly the basic features of the German LFWD.

2.1. Details and specifications of the LFWD

The details of the German LFWD apparatus are shown in Fig. 1. The apparatus is easy to handle because of its light total weight (about 30 kg) and it can be easily operated. The German LFWD consists of a falling weight, a loading steel plate with sensors, a guide rod and an electronic measuring unit. When being released, the 10 kg falling weight freely falls from a height of 72 cm, along the guide rod, to hit an installed dashpot unit in the middle of the loading plate. The loading steel plate has a diameter of 30 cm and a thickness of 20 mm and its weight is 15 kg. The steel plate is configured such that it is sufficiently rigid to settle with the soil under the impact of the falling weight. A centering sphere is positioned in the middle of the loading plate to entitle for transmitting only the compressive forces. The apparatus is calibrated to deliver a maximum pulse force of 7.07 kN with an impact duration of about 17–20 ms and a corresponding frequency of 8–100 Hz.

A built-in accelerometer (deflectometer) is centered, in a steel case, on the top of the loading plate to record the development of the plate deflection (settlement) during the impact of the pulse force. The deflectometer can record a peak plate deflection in the range of 0.3–1.5 mm. The loading plate is connected with an external electronic measuring unit. The electronic unit evaluates the measurements of the plate acceleration, velocity and deflection, and, subsequently, calculates the E_{vd} modulus. Furthermore, the device is supplied with a GPS-unit to ascertain the coordinates of the test location. The German LFWD can be used for testing coarse grained or mixed-grained soils, for a maximum soil grain size of 63 mm. It can be used in narrow or inaccessible areas because of its relatively small size. Moreover, the potential ground vibrations induced by the apparatus are minimal, and, therefore it can be applied very close to existing structural elements.

2.2. Standardized test procedure

In the standardized testing procedure of the LFWD [1], the loading steel plate is firmly rested onto the surface of the tested soil. Three initial seating drops are to be performed to create full contact between the plate and the tested soil. Three further working drops are subsequently performed, for which the plate deflections are recorded by means of the deflectometer. From the records of the three working drops, the mean value of the peak plate deflection is electronically estimated to be employed in evaluating the E_{vd} modulus.

2.3. Interpretation of test results

According to the classical theory of elasticity, if a rigid circular plate is rested on a soil medium and loaded by a concentrated force (F) to yield a settlement (s), then the soil deformation modulus (E) can be expressed as follows (according to Timoshenko and Goodier [7]):

$$E = \frac{1 - \nu^2}{2}\left(\frac{F}{r.s}\right) \tag{1}$$

where r is the plate radius and ν is the soil Poisson's ratio. In the above elasticity expression, the soil medium is characterized as a linear elastic, homogenous and isotropic half-space. Eq. (1) has been commonly used to forecast the static deformation modulus of the soil. The theoretical approach for interpreting the LFWD test results was investigated by [5,4,6]. In these previous studies, the dynamic resilience modulus (E_{vd}) is typically assumed to be evaluated by means of the classical elasticity form given by Eq. (1), i.e. similar to the static modulus. For evaluating the E_{vd} modulus, the induced contact stress (σ) between the rigid steel plate and the underlain tested soil is commonly considered uniformly distributed and that is in equilibrium with the applied pulse force ($\sigma = F/\pi r^2$). Besides, a constant value of 0.212 is commonly deemed for the soil Poisson's ratio [5,4,6]. Accordingly, a definition for the E_{vd} modulus can be deduced from Eq. (1), as follows:

$$E_{vd} = 1.5r\left(\frac{\sigma}{s}\right) \tag{2}$$

where σ is the soil–plate contact stress (or the applied pulse stress) and s is the corresponding plate settlement. It should be highlighted that the velocity-dependent terms and the inertial forces are ignored in Eq. (2). The maximum induced contact stress ($\sigma_{\max}$), due to the impact of a single pulse on the LFWD loading plate, can be hypothetically assumed of a constant value of 0.1 MPa that is independent of the soil conditions [5,6]. Simply, the value of $\sigma_{\max}$ of 0.1 MPa is the result of 7.07 kN pulse force acting on a circular rigid plate of 0.15 m in radius. Applying the latter assumption in Eq. (2), the following form can be derived for the dynamic resilience modulus (E_{vd}):

$$E_{vd}\ (\text{MPa}) = \frac{22.5}{s_{\max}\ (\text{mm})} \tag{3}$$

where $s_{\max}$ is the recorded peak plate deflection, i.e. maximum soil settlement, during a single pulse impact. Eq. (3) denotes that the interpretation of the E_{vd} modulus from the LFWD test results is exclusively based on the recorded peak plate deflection. It should be mentioned that the evaluated E_{vd} modulus is not a constant soil parameter. It is, however, a measure of the local soil stiffness that can be used to assess the quality of soil compaction.

2.4. Influence depth

The influence depth is a salient feature of the LFWD test. It generally accounts for the maximum propagation depth of the pulse-induced stresses through the tested subsoil. It can be practically defined as the depth below which the changes in the characteristics of the subsoil do not influence the test results. The capability of the LFWD to record the performance of subsoils may be limited to the extent of the influence depth. Some attempts have been presented in the literature to determine the influence depth of the LFWD. Based on results of experimental work, Brandl et al. [8] indicated that the influence depth ranges between 0.6 and 0.75 m. Adam et al. [6] presented a quite close finding, that the influence depth is about 0.50 m, based on results of a numerical study using the BEM. It should be highlighted that no information was available on the type of the tested soil by Brandl et al. [8] and, as well, the numerical examined type of soil by Adam et al. [6].

3. Use of the E_{vd} modulus as an indirect measure of compaction quality

The evaluated dynamic resilience modulus (E_{vd}) from the LFWD test is not branded as a direct measure of the soil compaction quality. It has been well-recognized, however, that the E_{vd} modulus can be indirectly used for compaction control. Two approaches have been proposed in the literature and relevant specifications to facilitate the use of the E_{vd} modulus in qualifying the compaction process, as discussed in the following subsections.

3.1. Correlating the dynamic modulus with the degree of soil compaction

The degree of soil compaction (D_{Pr}) is a widely adopted measure of compaction quality. It is the ratio between the in-situ dry density of the compacted soil in field and the laboratory (maximum) dry density of the compacted soil material. An approach has been proposed in the literature and relevant specifications that the LFWD test results can be used to indirectly appraise the quality of a compaction process if the D_{Pr} ratio is adequately correlated to the E_{vd} modulus. A rational E_{vd}–D_{Pr} correlation is, therefore, required prior to the use of the LFWD test for compaction control. A case-specific correlation may be developed in field for each project. Attempts have been presented in the literature to examine the E_{vd}–D_{Pr} relationship. Conde et al. [9] and Singh et al. [2] concluded that the E_{vd}–D_{Pr} correlation varies with the soil grains size, moisture content and compaction effort. Empirical E_{vd}–D_{Pr} relationships are in use in some standard regulations, such as that provided in the German Guidelines for Earth Works [3] based on a large amount of in-situ records for a wide range of soil types (Table 1).

3.2. Correlating the dynamic modulus with the static plate load moduli

In several international regulations, the static plate loading test (SPLT) has been referred to as one of the standard methods for assessment of the compaction quality, e.g. the German standard [11] and the ASTM standard [12]. For applications of compaction control, the results of the SPLT are usually interpreted through evaluating two static deformation moduli (E_{v1} and E_{v2}), which account for the soil stiffness during loading and reloading state, respectively. More details on the interpretation of the E_{v1} and E_{v2} static moduli can be found in [11]. Furthermore, the German standard [11] provided criteria for the assessment of the compaction quality, in which the degree of soil compaction (D_{Pr}) is determined based on the evaluated E_{v1} modulus and the moduli ratio (E_{v2}/E_{v1}).

Contributions have been developed in the literature toward correlating the dynamic resilience modulus (E_{vd}), from the LFWD test, with the static moduli (E_{v1} and E_{v2}), from the conventional SPLT. Converting the E_{vd} modulus into static moduli can help in using the LFWD test results for indirectly appraising the compaction quality. In accordance, extensive compaction quality assessment can be achieved based on a large number of LFWD tests substituting the exclusive use of the slow and complicated SPLT. Tompai [4] provided a summary of numerous E_{vd}–E_{v1} and E_{vd}–E_{v2} correlations that have been proposed in the literature and that are in use in some standard regulations. It was concluded that an E_{vd}–E_{v2} correlation may be relatively more consistent than the E_{vd}–E_{v1} correlation [4]. Moreover, for a wide range of soil types, the value of the static modulus E_{v2} was found generally ranging between two and three times the value of the dynamic modulus (E_{vd}).

4. Finite element modeling of LFWD

Several numerical attempts have been presented in the literature to simulate the LFWD test. Throughout these attempts, the Boundary Element Method (BEM) was widely used, e.g. [5,6]. The Finite Element Method (FEM) is an alternative tool of numerical analysis. Therefore, an attempt was made in this paper to employ the FEM for simulating the mechanism of the LFWD test and investigating the consequent soil response. In this regard, a finite element model was established to simulate a practical case study of in-situ LFWD test, as discussed in the following subsections.

Table 1 Empirical relationship between dynamic resilience modulus and degree of compaction (adapted from the German Guidelines for Earth Works [3]).

Soil type according to German standard [9]	Dynamic resilience modulus (E_{vd}), MPa	Degree of soil compaction (D_{Pr}), %
• Gravel–sand mixtures [GW, GI]	⩾60	⩾103
• Gravel–silt–clay mixtures [GU, GT] (with 5–15% by weight of grains less than 0.06 mm in size)	⩾50	⩾100
	⩾40	⩾98
	⩾35	⩾97
• Pure gravelly soils [GE]	⩾40	⩾100
• Sand–gravel mixtures [SE, SW, SI]	⩾35	⩾98
	⩾32	⩾97
• Gravel–silt–clay mixtures [GU_1, GT_1] (with 15–40% by weight of grains less than 0.06 mm in size)	⩾35	⩾100
	⩾25	⩾97
• Sand–silt–clay mixtures [SU, ST] (with 5–15% by weight of grains less than 0.06 mm in size)	⩾20	⩾95

Note: Details on the given soil type descriptors and abbreviations can be found in the German standard [10] for the German soil classification systems according to grain size.

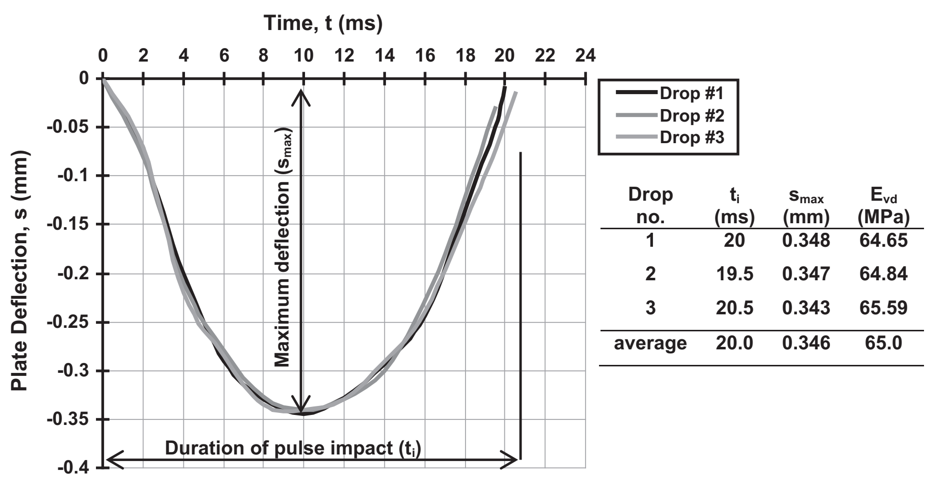
4.1. Implicated case study of in-situ LFWD test

A real case study, incorporating results of in-situ LFWD tests, was implicated in this paper to be used in validating the finite element modeling of the LFWD test. The implicated case study represents a certain phase of compaction quality control using the LFWD in a project site in 10th Ramadan City in Egypt. The compacted soil in the project site was of extended layers of crushed limestone with grain size in the range of 4.75–50 mm. A large number of LFWD tests were performed in the site to assess the soil compaction quality. Fig. 2 shows the results of one chosen LFWD in-situ test. The chosen LFWD in-situ test was deemed as a reference case study for generating and verifying the intended finite element model in this paper.

For the considered in-situ LFWD test, Fig. 2 shows the field records of the development of plate deflection during the time of pulse impact of three working drops. For each working drop, the recorded duration of pulse impact (t_i) and peak plate deflection (s_{max}), and the estimated value of the dynamic resilience modulus (E_{vd}) are depicted in Fig. 2. Throughout the three drops records, the forecasted average values of t_i, s_{max} and E_{vd} were 20 ms, 0.346 mm and 65 MPa, respectively. These average estimates were assumed to deterministically represent the field measurements of the implicated LFWD test.

4.2. Description of the finite element model

The implicated case study, described above, was simulated by means of an axisymmetric finite element model, in which the center of the circular loading plate was positioned along the axis of symmetry. The commercial PLAXIS finite element code was exploited in this study. The model boundaries were taken



Drop no.	t_i (ms)	s_{max} (mm)	E_{vd} (MPa)
1	20	0.348	64.65
2	19.5	0.347	64.84
3	20.5	0.343	65.59
average	20.0	0.346	65.0

Figure 2 Field records of the implicated LFWD test.

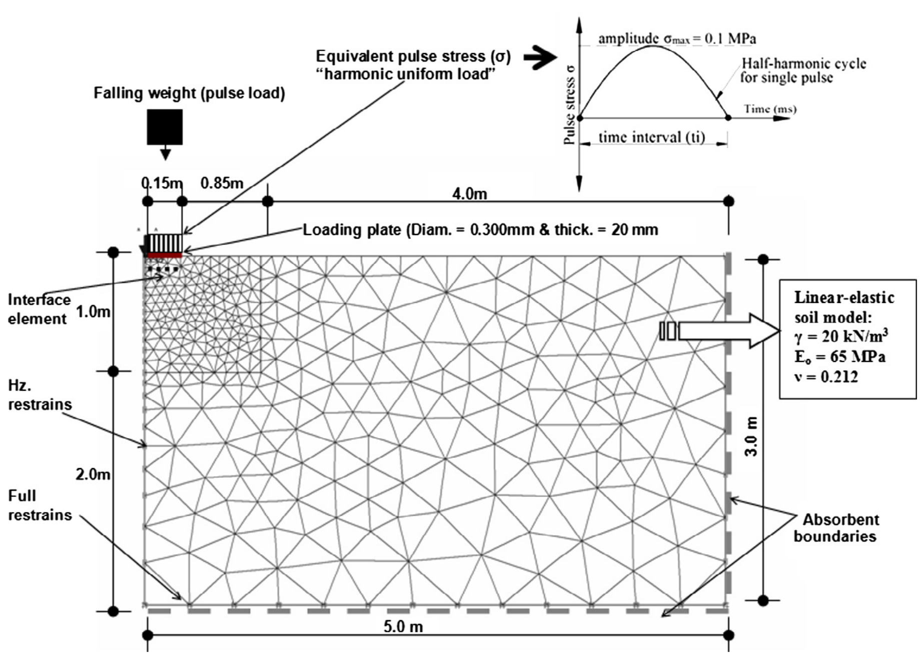


Figure 3 Geometry, boundary conditions and generated mesh of the finite element model.

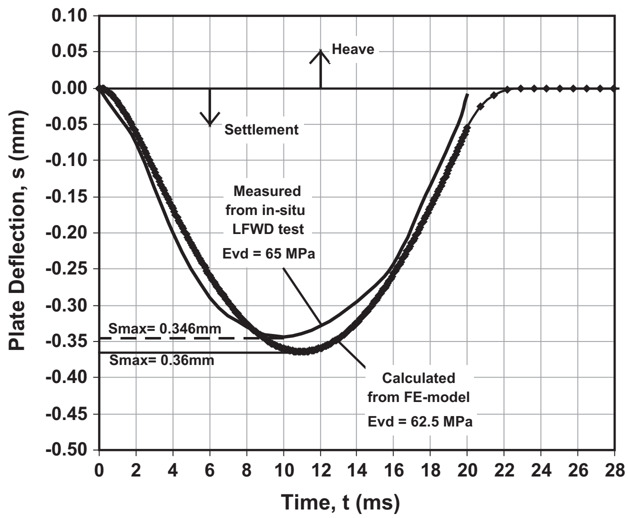


Figure 4 Measured and calculated plate deflection during a single pulse of LFWD.

adequately far from the loading plate to avoid direct influences of the boundary conditions, as shown in Fig. 3. Furthermore, special boundary conditions were used to absorb the dynamic waves that may reach the adopted far boundaries, such that possible reflections of waves on the model boundaries could be eliminated. Absorbent boundaries were, therefore, defined at the model boundaries excluding the top (ground) surface and the axis of symmetry (Fig. 3).

The soil domain was modeled using 15-noded triangular elements with a fourth order interpolation for displacements and twelve Gauss points for numerical integration. The LFWD loading plate was modeled using a plate element with both normal and flexural stiffness that corresponds to a steel circular plate of 20 mm in thickness and 300 mm in diameter. Interface element was placed below the plate to simulate the soil–plate interaction. The automatically generated finite element mesh is shown in Fig. 3. In order to increase the accuracy of the model results, the mesh was refined by reducing the elements size in vicinity of the loaded area, as depicted in Fig. 3.

The impact of the drop weight was simulated using an equivalent uniform dynamic load, i.e. pulse stress (σ), acting on the loading steel plate. The uniform dynamic load was defined as a harmonic load that follows a sinusoidal harmonic function as exemplified in the following form:

$$\sigma_t = \sigma_{\max}.\sin 2\pi f(t) \tag{4}$$

where σ_t is the generated pulse stress value after time t of the pulse impact, $\sigma_{\max}$ is the amplitude of the pulse stress and f is the frequency in cycles per second. The amplitude of the harmonic pulse stress ($\sigma_{\max}$) was taken 0.10 MPa that corresponds to the maximum pulse force of 7.07 kN delivered by the LFWD apparatus on the circular rigid loading plate of 0.15 m in radius. The induced soil/plate contact stress was postulated to be in equilibrium with the applied harmonic pulse stress. The duration of the single pulse impact (t_i) was assumed to correspond to a half-cycle of harmonic loading (Fig. 3). Accordingly, the frequency (f) of the equivalent harmonic pulse stress (σ_t) can be expressed in the following generic form:

$$f\,(\text{Hz}) = \frac{\frac{1}{2}\text{cycle}}{t_i(\text{sec})} = \frac{500}{t_i(\text{ms})} \tag{5}$$

From the field measurements of the LFWD test in the implicated case study, the average of the recorded duration of pulse impact (t_i) was 20 ms. Utilizing Eq. (5), the estimated corresponding frequency (f) was 25 cycle/s (or 25 Hz).

It was suggested that the anticipated soil strains due to the impact of the light falling weight are very small, such that the corresponding soil behavior can be assumed of true linear elastic. This assumption coincides with the majority of the relevant numerical analysis works presented in the literature, e.g. [5,4,6]. Therefore, the linear-elastic model was adopted in the established finite element model to cope with the LFWD-soil response. The suggested elastic properties of the soil are shown in Fig. 3. The inherent elastic modulus of the soil deposit (E_o) was taken 65 MPa to match the field measurements of the LFWD test in the implicated case study. The soil Poisson's ratio (v) was taken 0.212 as a commonly recommend value in relevant studies in the literature [5,4,6]. The soil unit weight (γ) was assumed of 20 kN/m^3. It was suggested that soil damping may occur in axisymmetric models of single-source type of dynamic problems due to, in essence, the radial spreading of wave, i.e. geometric damping. Accordingly, soil Rayleigh damping was ignored in this study because of the well-defined model geometries and the used absorbent boundary conditions. The damping coefficients (α and β) were, therefore, taken equal to zero.

4.3. Model verification

The established finite element model could be realistically verified by comparing the model results with the measurements of the implicated case study of in-situ LFWD test. During the adopted time of pulse impact, the plate deflection (at central point) was obtained from the results of the finite element

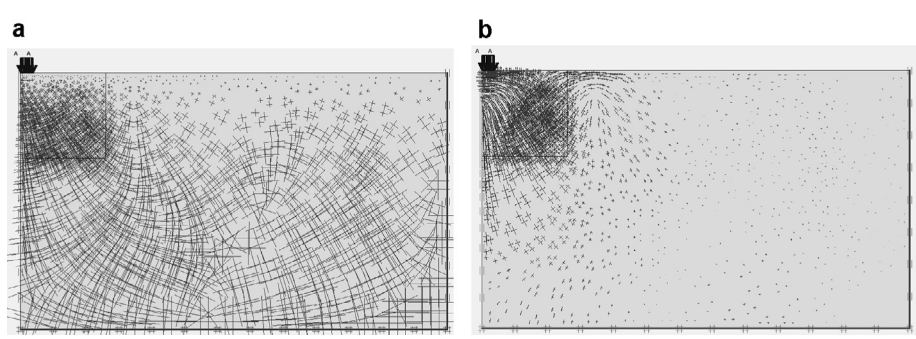


Figure 5 Samples of results from the finite element model: (a) principal stresses field, and (b) principal total strains field.

model and compared with that measured in the field, as shown in Fig. 4. It may be evident that the model results are in good agreement with the field measurements. The obtained peak plate deflection (s_{max}) from the model results was 0.36 mm, which yields a value of the soil dynamic resilience modulus (E_{vd}) of about 62.5 MPa (using Eq. (3)). The percentage of divergence between the calculated E_{vd}-value from the finite element model and the obtained E_{vd}-value from the in-situ measurements, i.e. model uncertainly, was about −4%. This degree of uncertainty was considered minimal and, thus, was ignored. Fig. 5a and b exhibits samples of the finite element results, comprising the fields of principal effective stresses and total strains, respectively. From the finite element calculations, curves were obtained for the development of pulse stress and the consequent development of plate deflection through the adopted duration of pulse impact, as shown in Fig. 6a and b, respectively.

4.4. Assessment of the adopted soil model

As previously exhibited in the description of the established finite element model, the linear-elastic soil model was adopted. Supplementary, the Mohr–Coulomb (MC) model and the Hardening Soil (HS) model were examined in this study to figure out the most efficient model that can adequately simulate the soil response in the LFWD test. The MC-model is based on elastic-perfectly plastic constitutive law with a bi-linear stress–strain relationship and a fixed yield surface. The HS-model, on the other hand, is a hardening plasticity model with a hyperbolic stress–strain relationship. The HS-model consid-

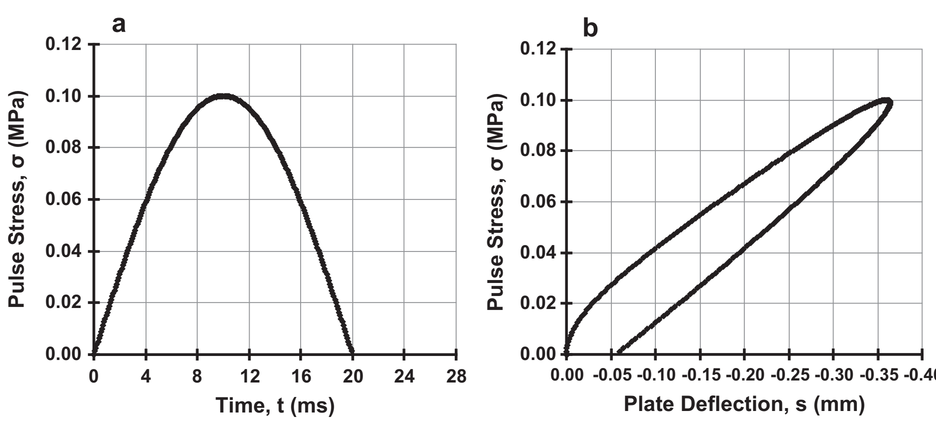


Figure 6 Curves from the finite element calculations: (a) development curve of pulse stress, and (b) development curve of plate deflection (stress loop).

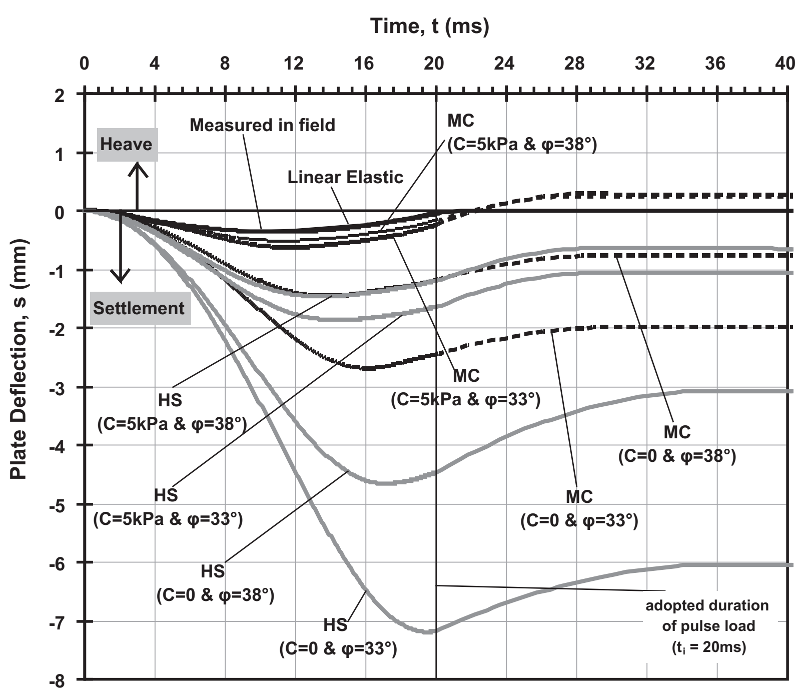


Figure 7 Calculated plate deflection from different soil models due to a single pulse.

ers the stress dependency of the soil stiffness, i.e. the soil stiffness modulus varies with the stress level in the soil mass according to a power law and with reference to a certain initial value. In the present study, a reference stress value of 100 kPa and a power value of 0.5 were assumed.

The MC-model and the HS-model were applied in the established finite element model of the LFWD test. For the two soil models, the value of the Poisson's ratio (ν) was constantly taken 0.212. To match the field measurements of the simulated case study, a value of 65 MPa was given for both the elastic stiffness modulus in the MC-model and the reference stiffness modulus in the HS-model. In order to account for the soil plasticity, both MC and HS models require the soil shear parameters (c and φ) to be defined. Therefore, two values of 33° and 38° for the soil friction angle (φ) and two values of 0 and 5 kPa for the soil cohesion (c) were subjectively proposed, representing previously observed bounds of shear parameters for the compacted soil in the implicated case study.

The plate deflection development due to a single pulse was obtained from the finite element results of each examined soil model with the associated shear parameter values, as shown in Fig. 7. It was revealed that the results of finite element modeling of the LFWD using either the MC-model or the HS-model, i.e. models associated with soil plasticity, are highly sensitive to the defined values of the soil shear parameters (c and φ). In general, by increasing the values of c and φ, the peak plate deflection ($s_{\max}$) decreases and, consequently, the dynamic resilience modulus (E_{vd}) increases. Particularly, when a value was defined for the soil cohesion ($c \neq 0$), the results of the two soil models were found slightly affected by changing the value of the soil friction angle (φ). At constant values of c and φ, the HS-model generally resulted in greater $s_{\max}$-value, and thereby smaller E_{vd}-value, than the MC-model. The developed plate deflection from either the MC-model or the HS-model was not found to dissipate by the end of the adopted duration of pulse impact, i.e. residual plate deformations were detected due to soil plasticity. The residual plate deformations generally decreased by increasing c and φ. For the case of $c \neq 0$ in the MC-model, the plate exhibited heave residual deformations (Fig. 7).

The acquired plate deflections from the different examined soil models in this study (i.e. linear elastic, MC and HS) were compared with the measured plate deflection in the implicated LFWD field test, as shown in Fig. 7. It can be noticed in Fig. 7 that the results of both MC and HS models, for all examined values of c and φ, significantly deviate from the field measurements, whereas the results of the linear elastic model are in relatively very good agreement with the field measurements. Accordingly, the linear elastic model could be appraised as a realistic soil model for simulating the soil response in finite element modeling of the LFWD test.

5. Finite element investigation of factors affecting the LFWD results

The adopted finite element model, using the linear elastic soil model, was exploited in this study to investigate the potential influences of some factors on the results of the LFWD test. Discussions on the investigated factors are provided in the following subsections.

5.1. Influence of the soil Poisson's ratio

The effect of varying the value of the soil Poisson's ratio (ν) on the evaluated dynamic resilience modulus (E_{vd}) was investigated. Six ν-values of 0.2, 0.212, 0.25, 0.3, 0.35 and 0.4 were examined with five different values of the elastic modulus of the soil deposit (E_o) of 25, 50, 65, 75 and 100 MPa. The variation of E_{vd} with the ν-values, as obtained from the finite element results for the different investigated values of E_o, is shown in Fig. 8. The results shown in Fig. 8 generally dedicate that the E_{vd} modulus slightly increases with the increase of ν. It can be concluded, therefore, that the influence of varying the ν-value on the evaluated E_{vd} modulus is minor and, thus, can be ignored. This finding well coincides with that acquired by Adam et al. [6] on bases of the BEM. Consequently, the assumption of adopting a constant value of 0.212 for the soil Poisson's ratio during the evaluation of the dynamic resilience modulus can be considered justified.

5.2. Influence of the duration of pulse impact

The effect of the duration of pulse impact (t_i) of the LFWD on the evaluated E_{vd} modulus was investigated. The t_i-value was corresponded to the time interval of a half-cycle of harmonic loading due to a single pulse. The common range of t_i for the LFWD apparatus is about 17–20 ms. For a quite wider range, seven values of t_i, ranging between 10 and 25 ms, were examined. The corresponding frequency (f) of the harmonic load ranged between 10 and 50 Hz, as calculated from Eq. (5). Fig. 9 depicts the variation of E_{vd} with the assumed values of t_i, as obtained from the finite element results at different investigated values of the soil elastic modulus (E_o). The influence of the time of pulsing on the evaluated E_{vd} modulus was found minor. Generally, the E_{vd} modulus slightly decreases with the increase of t_i, as shown in Fig. 9. By increasing the duration of pulse impact, under the same constant pulse stress ($\sigma_{\max}$ = 0.1 MPa), the plate deflection increases and, thereby, the E_{vd} modulus to some extent decreases.

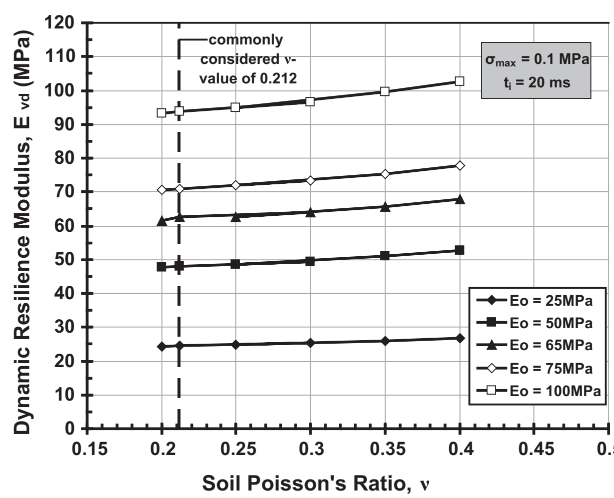


Figure 8 Influence of the soil Poisson's ratio on the E_{vd} modulus.

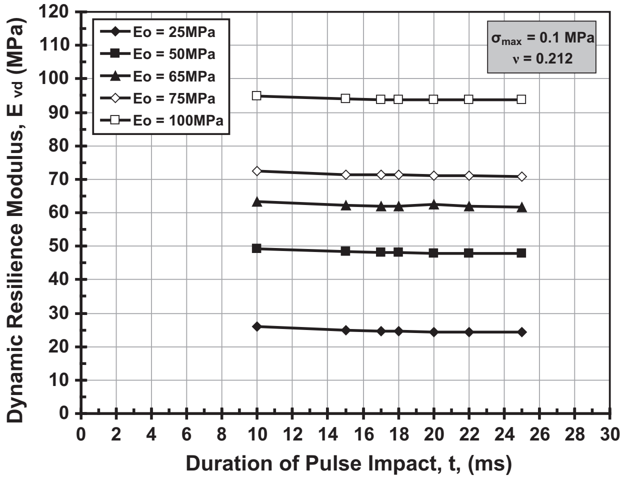


Figure 9 Influence of the duration (time) of pulse impact on the E_{vd} modulus.

5.3. Influence of the soil stratification

Compaction control of a constructed fill layer with definite thickness over a natural soil deposit of different stiffness is one major example of the application of LFWD test for stratified (layered) soil. The influence of soil stratification on the evaluated E_{vd} modulus from the LFWD test was investigated in this study utilizing the finite element modeling. A system of layered soil was proposed in this study, as shown in Fig. 10a, comprising an extended natural soil deposit with elastic modulus E_o and a covering soil layer with elastic modulus E_1 and thickness h. The moduli ratio E_1/E_o was carefully deemed. The smaller value of E_1/E_o than 1.0 represents a softer covering soil layer than the lower soil deposit, whereas the greater value of E_1/E_o than 1.0 represents a stiffer covering soil than the soil deposit. The case of E_1/E_o equals 1.0 stands for a homogeneous soil domain. Practical examples of the cases of $E_1/E_o < 1.0$ and $E_1/E_o > 1.0$ can be represented by the construction of granular fill material on jointed rock and soft soil deposits, respectively.

In the present study, the moduli ratio E_1/E_o was varied from ¼ up to 4. Three values of 10, 40 and 60 MPa were assumed for the E_1 modulus of the covering soil layer. The E_o modulus of the lower soil deposit was calculated corresponding to the proposed ratios of E_1/E_o. The thickness of the covering soil layer (h) was varied from 0.15 to 1.0 m. The variations of the calculated E_{vd} modulus of the layered soil system with the assumed values of h are shown in Fig. 10b–d, respectively, with regard to the assumed three values of the E_1 modulus of the covering soil layer. In these three figures,

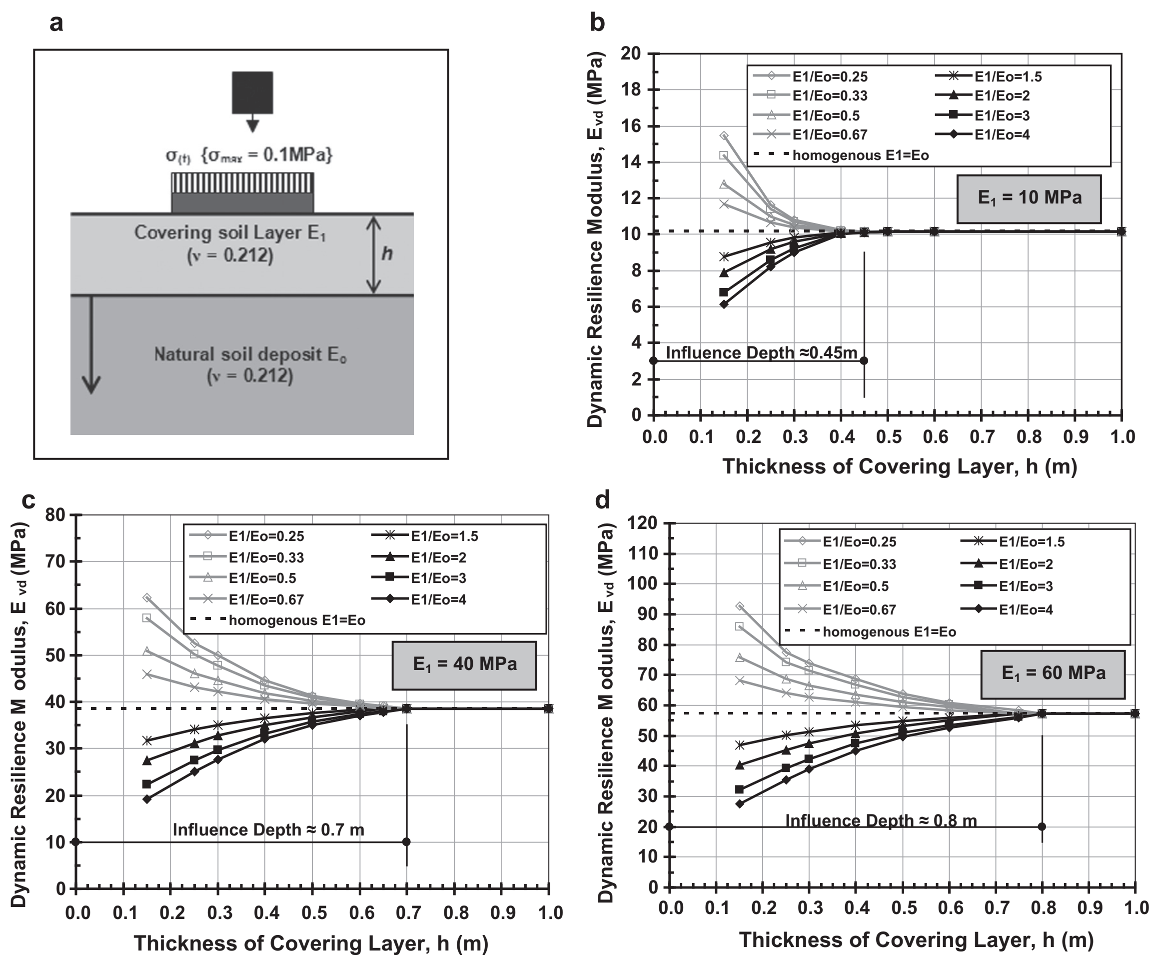


Figure 10 Influence of soil stratification on the E_{vd} modulus: (a) proposed layered soil system, (b) case of $E_1 = 10$ MPa, (c) case of $E_1 = 40$ MPa, and (d) case of $E_1 = 60$ MPa.

the gray lines correspond to the proposed ratios of $E_1/E_o < 1.0$, whereas the black lines correspond to the proposed ratios of $E_1/E_o > 1.0$. The dotted line in each figure represents the calculated E_{vd}-value for a homogeneous soil system consists of the covering soil material (i.e. $E_o = E_1$).

The results shown in Fig. 10b–d indicate that the evaluated E_{vd} modulus from the LFWD test can be significantly influenced by the soil stratification. The thickness of the covering soil layer (h) and the moduli ratio between the covering soil and the lower soil deposit (E_1/E_o) are dominant affecting factors. When carrying out the LFWD test on the surface of an upper soil layer that is followed by a relatively softer soil deposit (i.e. $E_1/E_o > 1.0$), the test results will be affected by the presence of the lower soft soil. In such a case, the resulted E_{vd} modulus of the layered soil system will be smaller than that specific E_{vd}-value of the upper soil material in a homogeneous soil system. On the contrary, if the lower soil deposit is relatively stiffer (i.e. $E_1/E_o < 1.0$), then the E_{vd} modulus of the layered soil system will exceed the specific E_{vd}-value of the upper soil material, due to the influence of the lower stiff soil. By increasing the thickness h of the upper (covering) soil layer, the influence of the softer/stiffer lower soil deposit gradually diminished. As the h-value increases, the E_{vd}-value of the layered soil system either steadily increases (for the case of $E_1/E_o > 1.0$) or steadily decreases (for the case of $E_1/E_o < 1.0$) until reaching the specific E_{vd}-value of the upper soil material. It should be emphasized, in compliance, that the presence of the lower soil deposit with different stiffness affects the evaluated E_{vd} modulus of the layered soil system to a certain limit of h, i.e. influence depth.

6. Finite element investigation of the LFWD influence depth

On the bases of the demonstrated results of this study in Fig. 10b–d, the influence depth of the LFWD was defined as the thickness h of the covering soil layer beyond which the presence of the lower soil deposit does not affect the evaluated E_{vd} modulus. Different values of the influence depth were detected corresponding to the assumed three values of the E_1 modulus of the covering soil layer. Throughout the examined values of the moduli ratio between the covering soil and the lower soil deposit (E_1/E_o of ¼ up to 4), the influence depth was found ranging between 0.40 and 0.45 m, certainly at a value of E_1 of 10 MPa. At a value of E_1 of 40 MPa, the influence depth ranged between 0.65 and 0.70 m, whereas it ranged between 0.75 and 0.8 m at a value of E_1 of 60 MPa. It may be evident that the absolute value of the E_1 modulus of the covering soil layer predominantly affects the influence depth of the LFWD.

The results of the present study are quite consistent with the experimental results provided by Brandl et al. [8], who introduced a range of 0.6–0.75 m for the LFWD influence depth. Moreover, the results of the numerical analysis carried out by Adam et al. [6] utilizing the BEM showed that the influence depth is about 0.50 m at $E_1 = 32$ MPa, which approximately lies between the obtained results from the present study at E_1 of 10 and 40 MPa. It should be mentioned that most of the relevant previous studies in the literature investigated the LFWD influence depth corresponding to variable moduli ratio (E_1/E_o), whereas the impact of the absolute value of the upper soil modulus (E_1) was ignored. The results of the present study revealed, however, that the LFWD influence depth can be more affected by the absolute value of the modulus of the tested soil (i.e. the soil below the loading plate) than the moduli ratio between the tested soil and the lower soil deposit.

7. Conclusions

In this paper, a state-of-the-art was briefly introduced for the theory and applications of the dynamic plate loading test with German apparatus of Light Falling Weight Deflectometer (LFWD). An attempt was made in this paper to employ the FEM for simulating the mechanism of the LFWD test and investigating the consequent soil response. An axisymmetric finite element model was established to simulate a real case study of in-situ LFWD test conducted in a certain site in Egypt. The LFWD field measurements in the implicated case study were used to verify the established model. The linear elastic model was found more realistic than the Mohr–Coulomb and the Hardening Soil models for adequately simulating the soil response during the LFWD test. The results of the conducted finite element analyses in this study showed that the evaluated dynamic resilience modulus (E_{vd}) from the LFWD is slightly influenced by the adopted values of both the soil Poisson's ratio (v) and the duration of pulse impact (t_i). Moreover, the E_{vd} modulus was found significantly affected by the tested soil stratification. The influence depth of the LFWD was numerically investigated. It was revealed that the LFWD influence depth is more affected by the absolute value of the E_1 modulus of the tested soil than the moduli ratio (E_1/E_o) between the tested soil and the lower soil deposit. The results of the conducted numerical analysis showed that, for a range of the moduli ratio (E_1/E_o) of ¼ up to 4, the LFWD influence depth ranges between 0.4 and 0.8 m corresponding to values of the E_1 modulus of 10–60 MPa.

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Dr. Mohamed Maher, Assistant Professor of Geotechnical Engineering, Structural Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt. The author is interested in fields of numerical analysis of various geotechnical applications, rock engineering, probabilistic analyses and soil dynamics.

Dr. Yasser M. El-Mossallamy, Professor of Geotechnical Engineering, Structural Engineering Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt. The author is interested in project management, field supervision, numerical analyses, monitoring, in-situ measurements, stability analyses, remediation works, design of high rise building foundation, foundation of wind power stations, bridge foundations, tunneling, deep pit excavation, soil improvement measures for rail- and highways, quality control and quality assurance, risk analyses, risk management, rock stability and rockfall hazards.