Application of energy absorbing layer to soil-structure interaction analysis

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Abstract Simulating for wave spread in geomechanics can be considered as an important subject within dynamic analysis. Chiefly, studying the soil-foundation interaction represents a stimulating matter in geotechnics studies. This paper presents the development of a reliable and efficient technique for the numerical simulation of unbounded domain (the semi-infinite extension). Absorbing layer is used to create boundaries that significantly decrease the wave reflecting into bounded area.

The current work is divided into two parts. The first part is evaluation of the absorbing layer properties such as damping constants ($\alpha_d$, $\beta_d$), modulus subgrade reaction (K), modules of elasticity (E), and natural frequency of the soil ($\omega_n$). The second part includes the dynamic analysis of strip foundation carried out by using the finite element software, OpenSees 2D. The foundation is exposed to harmony excitation and the soil is assumed as linear elastic.

The results suggest that, attenuation in wave is observed once the soil’s unbounded area gets signified via the energy’s layer of absorption. Furthermore, the numerical model show that the maximum amplitude of displacement will be reduced due to the presence of absorbing layer.

Keywords: Dynamic analysis, absorbing layer, finite element method, machine foundations.

1. Introduction

The dynamic soil-structure interaction system differs from dynamic structure system by two significant features. The first feature is nature of unbounded. Another influence which is also taken into consideration concerns the damping model due to radiation influence, which provides both a more realistic boundary condition as well as the structure’s interaction by means of the foundation, this offers a better realistic boundary form along with the damping model due to geometrical effect Werkle, (2014).

The absorbing layers are alternatives to local boundary. They are created by replacing the domain of unbounded by energy layers of absorption having limited thickness which significantly decreases the wave reflecting from the boundary.

The Finite element method (FEM) represents an influential instrument to analyze complicated geometries as well as nonlinear conducts, so that the domain near foundation is always modeled by FEM. While the study of foundation’s far-field part can be observed in preceding investigations, for
example Lysmer’s boundary condition \cite{Lysmer1969}, boundary conditions of rational \cite{Feltrin1997}, boundary elemental method \cite{Yazdchi1999}, Dirichlet to Neuman mappings \cite{Givoli1999}, scale boundary element method \cite{Song2000, Wolf2000}, infinite elemental \cite{Kim2000, Fattah2011}, discontinuous methods of Galerkin \cite{Park2002, Park2004} were implemented.

The computation domain can be bounded via layers having limited thickness where dissipated wave spread in a predetermined direction that points to infinity and can be presented into the dominant equation to the unbounded domain. Since the spread of a wave within other sovereign direction is not dissipated, the plane waves transmitting from the domain of importance to the layer of absorption is developed. Spreading waves of non-tangential angle and with non-zero frequency is attenuated \cite{Basu2003}. The material damping is presented into governing equations where the medium having perfect match could be taken to mean as a non-homogeneous viscoelastic medium.

Wave spread is a difficult challenge to be studied as shown in Literature review.

Al-Wakeel et al. \cite{Al-Wakeel2011} presented a method for typical unbounded domain and it used saturated clay, where the domain of unbounded can be substituted via an energy layers of absorption with limited thickness which have features that significantly decrease the reflecting of wave through bounded domain.

Al-Wakeel \cite{Al-Wakeel2013} used a technique that depends upon the mathematical representation of wave’s spread for studying the problem of dynamic soil-structure interaction. In such technique, the soil’s unbounded area can be signified by viscous factors for simulating the soil’s geometrical damping. Additionally, the soil’s material damping was applied in the bounded domain by Rayleigh damping.

Khazaee and Lotfi \cite{Khazaee2014} utilized the perfectly matched layers (PMLs) within the dynamical analysis of dam-reservoir system. The researchers presented appropriate boundary condition to the formulation of perfectly matched layers in such reservoir. The results of their study demonstrate that the perfectly matched layers method can be a professional technique to the transient analysis of dam reservoir schemes and the time-harmonic, once boundary condition of the perfectly matched layers area is used.

Fattah et al \cite{Fattah2015} studied the efficiency of transmitting boundaries in dynamical analysis of soil-structure interaction by Mod-MIXDYN program. Three conditions analyzed were traditional boundaries, infinite boundaries and viscous boundaries and it was found that the reflections disappeared when using transmitted boundaries. This result also applies with mapped infinite elements and viscous boundaries.

Farzhanian et al \cite{Farzhanian2016} developed the finite element modeling for unbounded heterogeneous domain with geometrical damping created via perfectly matched layers and it was based on displacement. Researchers investigated the heterogeneous modeling by means of the closed-form solution with an unrestricted rod having dual-part modulus exposed to an identified period history.

This paper presents a type of absorbing layer, which has been experienced by some experiments and then it was inserted into the finite element modeling for simulating the radiation state in dynamic analysis.

2- Definition of the Problem
Geometrical damping is of concern when modeling dynamic soil-foundation interaction. In this study, concentration is made upon the applicability of absorbing layer in geometrical damping simulation.
Before the wave propagation simulation, some tests were carried out to determine the properties of each absorbing layer, foundation, and soil. To find the modulus of elasticity of steel foundation, the tensile test for the steel foundation was performed according to the ASTM-E8M, (2004) specification. The results of material properties of the foundation are listed in Table 1. The soil parameters are shown in Table 2. The Unconsolidated Undrained (UU) triaxial testing is performed for find the elasticity modulus of the clay soil as shown in figure 1.

### Table 1. The foundation’s Physical properties.

| Properties                  | Value | Units       |
|-----------------------------|-------|-------------|
| Modulus of elasticity (E)   | 3641  | kN/m²       |
| Poisson’s ratio (ν)         | 0.28* | -           |
| Unit weight (γ_t)           | 78*   | kN/m³       |

### Table 2. Properties of the soil.

| Properties                      | Value | Units       |
|---------------------------------|-------|-------------|
| Initial water content           | 2.5   | %           |
| Liquid limit (LL)               | 47    | %           |
| Plastic limit (PL)              | 23    | %           |
| Plasticity index (PI)           | 24    | %           |
| Specific gravity (G )           | 2.67  | -           |
| Gravel                          | 0     | %           |
| Sand                            | 3     | %           |
| Silt                            | 38    | %           |
| Clay                            | 59    | %           |
| Modulus of elasticity (E)       | 7445  | kN/m²       |
| Poisson’s ratio (ν)             | 0.47* | -           |
| Unit weight (γ_t)               | 18.3  | kN/m³       |
| Classification (USCS)           | CL    | -           |

* Assumed

**Figure 1.** Stress-strain curve from the unconsolidated undrained triaxial test of clay.
Experiments of forced vibrations are performed by means of counter-rotating masses to find the absorbing layer parameters. This machine is also called as a two-mass oscillator. This system (machine) consists of two shafts operating together but rotating in opposite directions. Each shaft possesses an eccentric weight, demonstrated in dark in Figure (2), which has been mounted to disk that the horizontal component of force cancels out the corresponding component of the eccentric weight on the machine's different shaft, and the other way around. Just the vertical part of the force remains; Figure (2) shows that the force is changed by a sinusoidal curve and achieves a greatest descending value at stage b as well as a most max upward value at stage d.

![Figure 2](image)

**Figure 2.** Graphical representation of the harmonic motion of the two-mass oscillator.

Two absorbing layers are placed under machine foundation. The sensor of acceleration and displacement is positioned between layers. Each layer consists of three materials (Foam Board, Rubber layer, and Polystyrene foam) as shown in Figure 3.

To determine damping constants \((\alpha_d, \beta_s)\) for particular elements in the energy absorbing layer, equation 1 is used, as described by Chopra, (2012).

\[
C = \alpha_d M + \beta_s k \quad \ldots 1
\]

\[
\begin{bmatrix}
\frac{1}{\omega_{n1}} & \frac{1}{\omega_{n1}} \\
\frac{1}{\omega_{n2}} & \frac{1}{\omega_{n2}}
\end{bmatrix}
\begin{bmatrix}
\alpha_d \\
\beta_s
\end{bmatrix}
= 
\begin{bmatrix}
\xi_1 \\
\xi_2
\end{bmatrix}
\quad \ldots 2
\]

where \(C\) is damping matrix, \(\omega_n\) is the natural circular frequency, \(M\) and \(K\) are the mass and stiffness matrices, respectively.
In this study, two frequencies 2500 and 3000 cycles / min were used to find C, K and $\omega_n$ for each frequency. After that, the equations have been solved for the two frequencies to find the damping constants ($\alpha_d$, $\beta_s$). The Absorbing layer parameters as shown in table 3.

Table 3. Properties of the absorbing layer.

| Properties                  | Operating frequency (2500 cycle/min) | Operating frequency (3000 cycle/min) | Units   |
|-----------------------------|-------------------------------------|-------------------------------------|---------|
| Natural frequency ($\omega_n$) | 35.4                                | 33.8                                | rad/s   |
| Spring constant (K)         | 312036.8                            | 284467                              | N/m     |
| Displacement                | 7.83                                | 8.55                                | mm      |
| Damping coefficient (c)     | 277.9                               | 265                                 | N-s/m   |
| Damping ratio ($\xi$)       | 0.0223                              | 0.0222                              |         |
| Alpha ($\alpha_d$)          | 0.69                                |                                     |         |
| Beta ($\beta_s$)            | 0.0007                              |                                     |         |

The dynamic model of machine foundation is implemented in the program system OpenSees 2D. The model of finite element consists of a domain of dimensions 720 X 560 mm with strip foundation 100 mm width and height of 12 mm resting on the ground surface. This dimension was used to simulate container box as shown in figure 4. The properties of soil have been taken as uniform all through the layer’s depth; it is a popular assumption within the dynamics of soil. The soil is modeled as linear elastic.

The unbounded domain was represented by viscous element. This element consists of spring and dashpots in each degree of freedom on the boundaries for simulating the soil’s geometrical damping.
The foundation is subjected to a sinusoidally varying force of the form \( F = F_0 \sin(\omega t) \) with amplitude of force 0.369 kN as well as circular frequency, \( \omega \) of 314 rad/sec.

It should be observed that the vertical vibration is applied at centric point in the foundation and displacements are measured with different points (A, B, C and D) as shown in Figure (5). Regarding analysis, it should be noted that each case is investigated for time of (25000 sec) with time step taken as (\( \Delta t = 0.02 \) sec). The time integrating has been carried out by generalized Newmark method (Katona and Zienkiewicz, 1985).

Figure 4. Placement of absorbing layer material boundaries in the container box.

Figure 5. Two-dimensional finite element model with unbounded domain.
3. Results of Analysis

Some error occurred in estimating dynamic responses due to the reason that waves are reflected on boundaries if the boundary is not positioned at sufficient distance for geometrical damping. The effect of boundary without absorbing layer on machine foundation is investigated first. Figures 6, 7 and 8 show the results of the displacement–time responses at special points. After that, the infinite domain has been inserted for absorbing waves spread in the soil. The effect of absorbing layer on dynamic response is shown in figures 9 to 11. Figure 12 shows the absorbing layer’s influence on the dynamic response of machine foundation at point A.

Figure 6. Representation of displacement with time at point B.

Figure 7. Representation of displacement with time at point C.

Figure 8. Representation of displacement with time at point D.
Figure 9. Representation of displacement with time at point B when using absorbing layer.

Figure 10. Representation of displacement with time at point C when using absorbing layer.

Figure 11. Representation of displacement with time at point D when using absorbing layer.
Figure 12. Displacement of the foundation at point A due to a harmonic load with and without the absorbing layer in the boundary.

From the results, it can be noted that the wave does not dissipate due to reflection when using boundary of elementary material. Attenuation in wave can be observed when semi-infinite soil has been represented via the energy’s layer of absorption. The vertical displacements decreased obviously by (0.001, 0.0003 and 0.0013 mm), at B, C, and D respectively, when using absorbing layer. When the infinite domain is used, this will lead to a decrease in the displacement response of foundation compared to the elementary boundaries.

4. Conclusions
1. The main advantage of this work is to simulate the dimensions of container box in the experimental work. This box represents the use of infinite domain in wave propagation problems.
2. The wave spread manner within the model demonstrates that the enforced vibration created by any vertical load could be damped and completely absorbed via absorbing layer.
3. Compared to others, this model can be considered as a better solution and suits the wave spread. Moreover, the absorbing layer offers an efficient and reliable approach for modeling geometrical damping mechanism.

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