Numerical Simulation of the Infinite Medium of Dry Soil in Dynamic Soil-Structure Interaction Problems

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ABSTRACT

One of the major issues in the dynamic analysis of soil-structure interaction problems is to model the far field medium. The dynamic analysis of soil-structure interaction problems can be carried out by using a numerical solution procedure such as finite element method. For domains of infinite extension of the soil, using of the standard finite elements method leads to spurious reflections for waves on the artificial boundaries which can seriously affect the results.

This research presents a method based on the mathematical representation of wave propagation to analyze the problems in dynamic soil-structure interaction. In this method, the infinite medium (unbounded domain) of the soil is represented by viscous elements to simulate the radiation damping in the soil. In addition, the material damping of soil is represented by Rayleigh damping and implemented in the bounded domain.

The results obtained from this study indicated that, dissipation in the energy of wave occur due to representing of the infinite medium of the soil by viscous elements and Rayleigh damping. By comparing the results with those obtained from the boundary elements method to simulate the infinite extension of the soil which is proposed by Estorff and Kausel (1989), a good agreement is achieved. In addition, the dynamic response at any depth under the foundation can be estimated by using the present method.

Keywords: Dynamic analysis, infinite medium, soil-structure interaction.

التمثيل العددي للمجال أللانهائي للتربة الجافة في مسائل ديناميك التأثير المتبادل بين التربة والمنشأ

الخلاصة

أن إحدى القضايا الرئيسيةِ في التحليل الديناميكي لمسائل التأثير المتبادل بين التربة والمنشأ أن تمثل مجال التربة البعيدِ. أن التحليل الديناميكي لمسائل التأثير المتبادل بين التربة والمنشأ يمكن ان يجرى بأستخدام أسلوب ألحل العددي مثل طريقة العناصر المحددة. للمجالات ذات الامتداد اللانهائي للتربة فأن إستعمال طريقةِ العناصرِ المحدودةِ القياسيةِ يُؤدّي إلى الإنعكاساتِ المزوّرةِ للموجاتِ على الحدودِ الإصطناعيةِ التي يُمْكِنُ أَنْ تُؤثّرَ على النَتائِجِ بجدية .

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هذا البحثِ يُقدّمُ طريقة مستندة على التمثيلِ الرياضي لأنتشار الموجةِ لتحليل مسائل التأثير المتبادل بين التربة والمنشأ. في هذه الطريقةِ، الوسط اللانهائي (المجال غير المحدود) للتربةِ مُمَثّلُ بالعناصر اللزجةِ والتي تحاكي تَثْبِيط الإشعاع في التربةِ. بالإضافة الى ذلك، فأن التَثْبِيط المادي للتربة تم تمثيله بأخماد رالي وطُبّقَ في المجالِ المحدودِ.

أن النتائج التي تم الحصول عليها من هذه الدراسة تشير الى حدوث تبدد في طاقة الموجة نتيجة تمثيل الوسط اللانهائي للتربة بالعناصر اللزجة وأخماد رالي. وبمقارنة هذه النتائج مع تلك التي نم الحصول عليها من طريقة عناصر الحدود لمحاكاة الأمتداد اللانهائي للتربة ألمقترحة من قبل الباحثين أستورف وكاوسل في عام ١٩٨٩ نجد توافق جيد في النتائج. بالأضافة الى ذلك فأن الاستجابة الدديناميكية على أي عمق تحت قاعدة الأساس يمكن ايجاده بأستخدام الطريقة الحالية.

INTRODUCTION

Most structures are supported by soils. As the supporting soil is much larger in size than the structure itself, it is considered as being unbounded domain. In addition, dynamic loads can be introduced through the unbounded supporting soil by the dynamic loading from machines and impacts, and act directly on the structure (Bazyar, 2007).

The analytical methods are applicable only for simple structures, and linear and uniform soil media. An arbitrary-shaped body subjected to dynamic loads requires the use of discrete numerical methods such as finite element method. For system with ainfinite extension, the finite element method requires a large-scale mesh to represent the surrounding soil medium (near-field), which is bounded by the far-field (unbounded domain) that is represented by artificial boundaries. In numerical modeling of wave propagation problems, the artificial boundaries introduce spurious reflections (Genes and Kocak, 2005).

Therefore, the well-recognized numerical problem in dynamic soil-structure interaction is how to simulate computationally the far-field medium at infinity.

Types of Damping in Soil

The decay of the amplitude of waves in body is due to two types of damping (Das, 1983), they are:

(1)Geometrical Damping (Radiation Damping)

It has been observed that far away from a source to man-made ground vibration, the Rayleigh wave leads to strong vibrations whereas primary, P- and shear, S- waves vanish. Apart of the explanation may be that the majority of the energy transmitted to the ground by a surface source leads to the generation of Rayleigh waves. Another reason lies in the fact that the P- and S- waves spread over the volume thus forming spherical wave fronts, whereas Rayleigh waves are abound to the surface, thus spreading like "rings on water". This implies a faster decay of the energy, and hence the displacement amplitudes in the P- and S- waves with the distance from the source than is observed for the Rayleigh wave. The decay of the amplitude of wave due to spreading of the energy over a larger area or volume is denoted as geometrical damping (Andersen, 2003).

(2) Material Damping

This type of damping is related to the transformation of mechanical energy into thermal energy, i.e., heat. From thermodynamics, this transition is known to be a one way process. It is caused by frictional loss and the non-linearity of the stress-

strain relationship of the material. It is independent of the frequency of vibration (Hardy, 2003).

Dynamic Analysis of Foundations onanInfinite Medium

When an impulse is acting on an elastic half space medium, the energy is radiated by dilatational waves with velocity V_p, shear waves with velocity$V_s$and surface Rayleigh waves with velocityV_R.In order for waves to transmit energy at infinity, the displacement amplitude must decays at large distance in a special low (Kellezi, 2000).

The most common way in dynamic analysis of soil-structure interaction problems is to restrict the theoretically infinite computational domain to a finite one with artificial boundaries. The reduction of the solution domain makes the computational feasible, but spurious reflections from the artificial boundaries can seriously affect the accuracy of the results (Kontoe et al., 2008).

In this research, to study the dynamic response of elastic foundation and the supporting soil medium by a more realistic system idealization,a method based on the mathematical representation of wave propagation will be adopted to analyze problems in dynamic soil-structure interaction. The interaction means that the amplitude of structural response is affected by the energy dissipation through radiation and material damping in the soil.

The bounded domain is discretized with elements based on the standard finiteelement. In addition, a viscouselement is included to absorb the wave at the edges of the finite element mesh to represent the unbounded domain. The basic feature of the numerical model is shown in Figure (1).To obtain results of an acceptable of accuracy, the artificial boundary has applied far away from the soil-structure interface
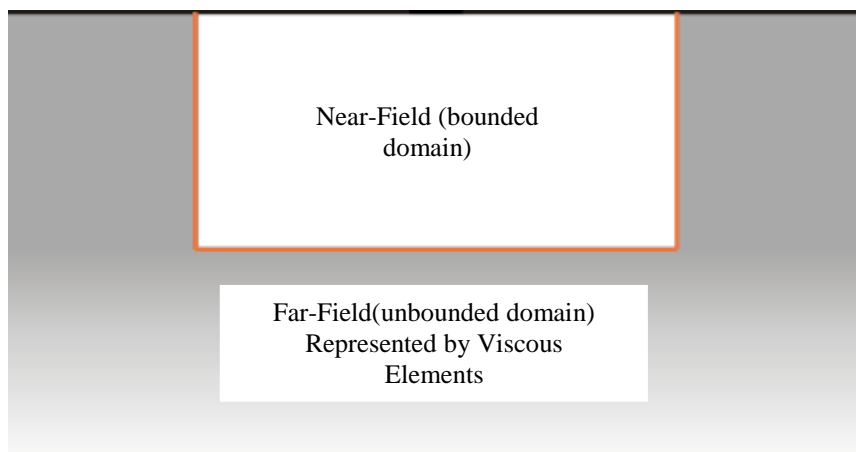
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Near-Field (bounded domain)

Far-Field(unbounded domain) Represented by Viscous Elements

Figure (١) the basic feature of the numerical model for simulationsoil medium.

For frequencies near zero, Rayleigh waves transmit most of the power. As frequency increases, the importance of Rayleigh waves compared to dilatational waves and shear waves decreases rapidly (Meek and Wolf, 1993).

The viscouselement used to represent the unbounded domain includes normal and tangential energy absorption to simulate the radiation damping in the soil. This element absorbs the propagating waves in such a way that any incident waves produce zero energy being reflected back into the domain.

The viscous element consists of discrete dashpots attached to all degreesoffreedom on the boundaries. The dashpots perpendicular to the boundary are specified to absorb dilatational waves, and those tangential to the boundary to absorb shear waves as shown Figure (2).
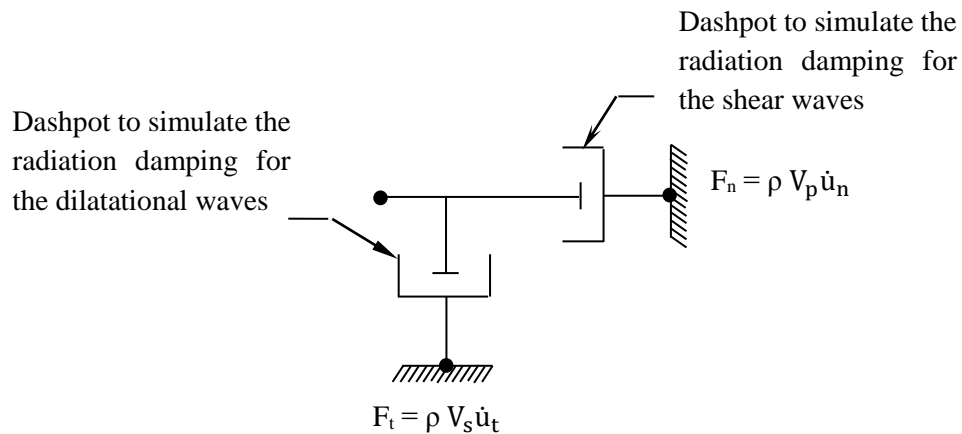
Dashpot to simulate the radiation damping for the shear waves

Dashpot to simulate the radiation damping for the dilatational waves

$F_n = \rho \, V_p \dot{u}_n$

$F_t = \rho \, V_s \dot{u}_t$

Figure (2) the basic feature of the viscous element.

The coefficients of these dashpots are constant quantities dependent only on the dilatational and shear wave velocities and the density of the soil immediately at the boundaries. The damping constants per unit area defined as (Kontoeet al., 2009):

$$C_n = \rho \, V_p \qquad \qquad \dots (1)$$

$$C_t = \rho \, V_s \qquad \qquad \dots (2)$$

where:
C_n=damping constant in normal direction,
C_t =damping constant in tangential direction,
ρ = density of soil.
V_p and$V_s$are the dilatational and shear wave velocities of the soil, respectively.

Therefore, for waves traveling normal to the edge of the elements at the boundary, the force of the dashpot per unit length which applied at specific boundary nodes parallel to the wave propagation direction is obtained by:

$$F_n = \rho \, V_p \dot{u}_n \qquad \qquad \dots (3)$$

Similarly, the force of the dashpot per unit length which applied normal to the wave propagation direction is obtained from:

$$F_t = \rho \, V_s \dot{u}_t \qquad \qquad \dots (4)$$

where: $\dot{u}_n$ and $\dot{u}_t$ are the normal and tangential components of velocity.
For the finite element method, the forces of the dashpots are applied at the boundaries. These dashpots are only meant to absorb the impinging waves, and not to simulate intrinsic damping in the system. Reflections are assumed to be sufficiently damped by material damping so that their effect on the foundation response is minimal.
In practice, it is not generally possible to define or determine damping in solids. It is therefore, a common practice to adopt Rayleigh damping which can be expressed as (Paul, 1982):

$$C = \alpha \, M + \beta \qquad \qquad \dots (5)$$

where C is the damping matrix, M is the mass matrix and K is the stiffness matrix. The damping coefficients α and β are determined by experience (Clough and Penzien, 1993). In this study, the analysis is performed using stiffness proportional Rayleigh damping of $\beta = 0.0005$ and mass proportional damping $\alpha = 0.001$.

Dynamic Analysis of Foundations on an Elastic Dry Soil:
The dynamic response of foundations placed on, or embedded in, an elastic soil medium was extensively treated in recent years. Most studies, however have addressed the issue of rigid foundations, which appears to reasonable for massive structures, but may be inappropriate for other system like machine foundations or thin mat foundations (Estorff and Kausel, 1989).
The investigation of the soil-structure interaction problems can be carried out with numerical solution procedures such as the finite element method. Basically, two components are of importance in the soil-structure interaction analysis: the finite size structure and the semi-infinite soil. Therefore, to study the transient response of an elastic strip footing a soil-foundation system has to be considered. The geometry of the problem consists of a flexible strip footing of a width (B) equal to 2.0m and height of 0.25m resting on the ground surface. The foundation is subjected to a vertical impact load of 16 kN acting in time as a rectangular impulse during the first 5 time steps with $\Delta t = 0.000563$ second as shown in Figure (3).
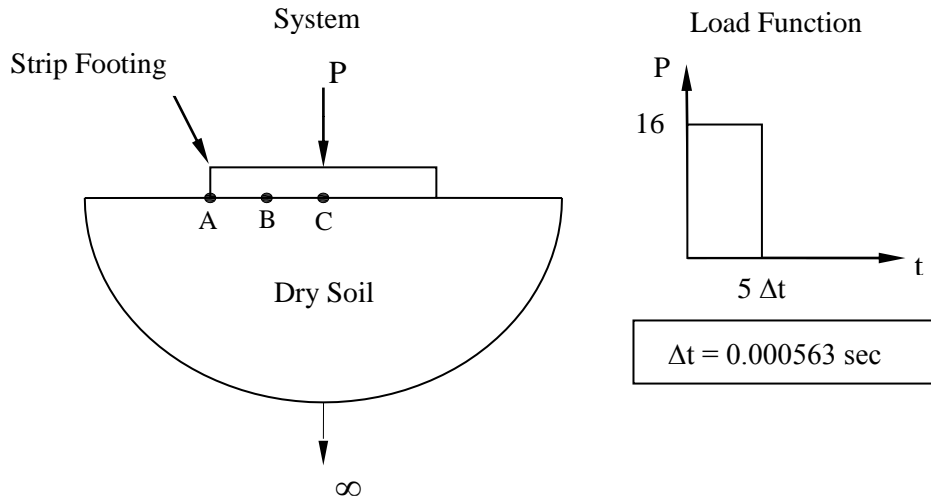
Figure (3): Elastic foundation on a semi-infinite medium of dry soil

(after Estorff and Kausel, 1989).

Assuming that the modulus of elasticity of the soil E_s is to be constant, and the material stiffness of the foundation E_f is ratio of E_s / E_f which is 1/10. The material properties of the soil are shown in Table (1).

Table (1): Material properties of the soil (Estorff and Kausel, 1989)

Parameters	Symbol	Value	Units
Poisson's ratio	ν	0.33	–
Modulus of elasticity	E	2.66×10^5	kN/m^2
Dry density of soil	γ	20.0	kN/m^3

The dimensions of the bounded domain of the soil are selected to be 4B in horizontal direction from the center of the foundation, and the same size in vertical direction from the surface.

Transient Response ofFoundations Using Numerical Simulation of the Semi-Infinite Medium of Soil

Elementary boundaries (hinges, rollers) are conditions of zero-displacement. They do not absorb impinging waves but reflect them, keeping wave energy constrained inside the discretized region. This can be a source of error in estimating dynamic responses if the boundaries are not placed at a far enough distance for intrinsic damping to damp out the waves before hitting the boundaries.

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In this study, the bounded domain of the soil medium is discretized using bilinear isoparametric finite elements. In the first part, the boundary conditions are applied so that the bottom is fixed. The boundary conditions at the sides are applied via vertical rollers which have a constraint displacement in x-direction as shown in Figure (4).In the second part, the unbounded domain of the soil medium is simulated by using the viscous elements as shown in Figure (5).

The finite element method is used to analyze the problem in time domain employing the computer program Open System for Earthquake Engineering Simulation (OpenSees).The transient response of the foundation using the elementary boundary and viscous elements at points A, B and C under the foundation is shown in Figures (6), (7) and (8). The permissible amplitudes for low-speed machinery and hammer foundations are 0.2 mm and 1.0 mm, respectively (Srinivasulu and Vaidyanathan, 1990).
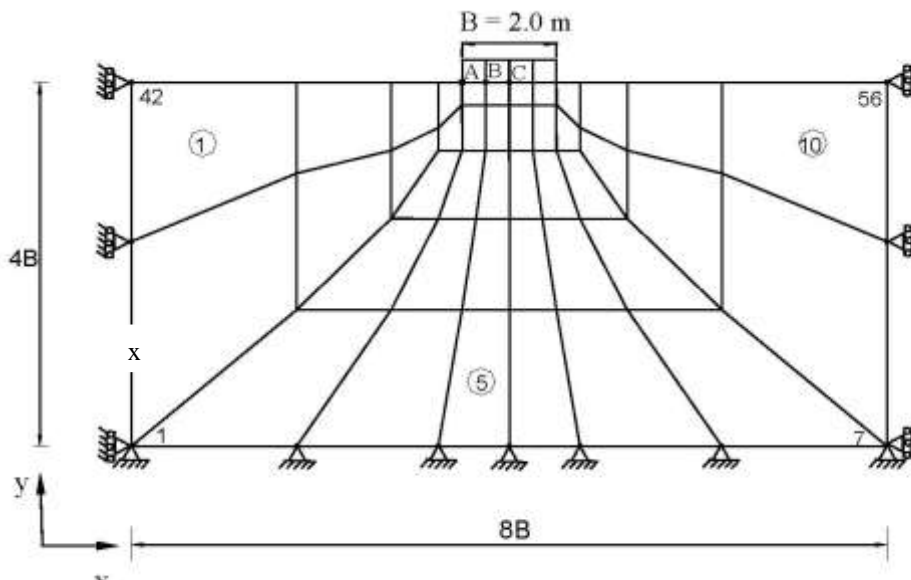

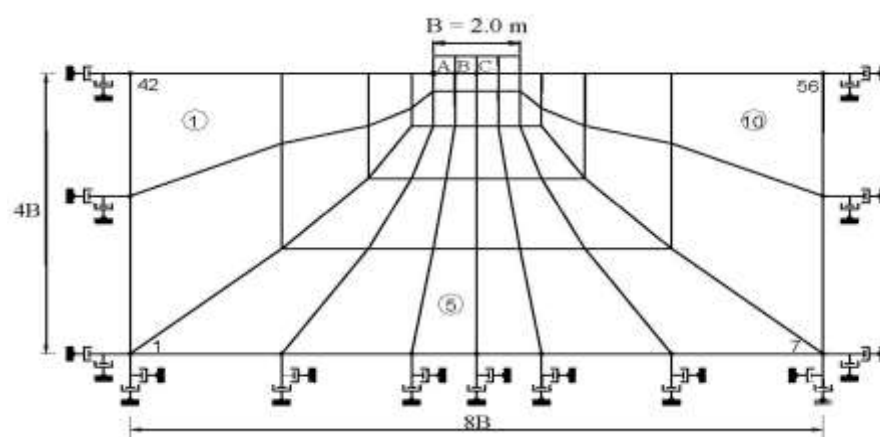**Figure (4): Discretizationof with elementary boundary .**

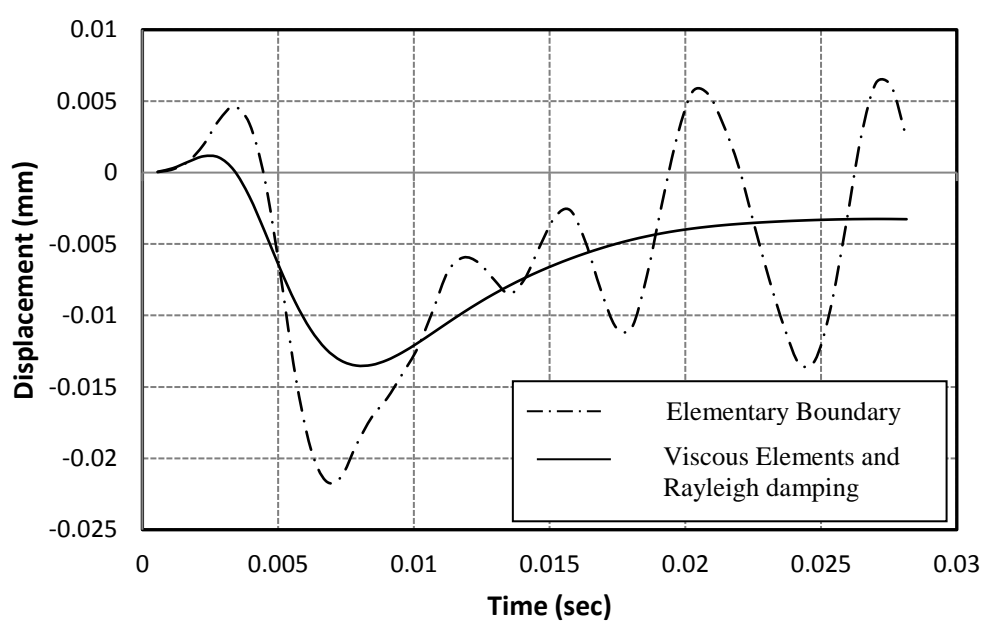**Figure (5): Discretization of the unbounded domain with viscous elements**

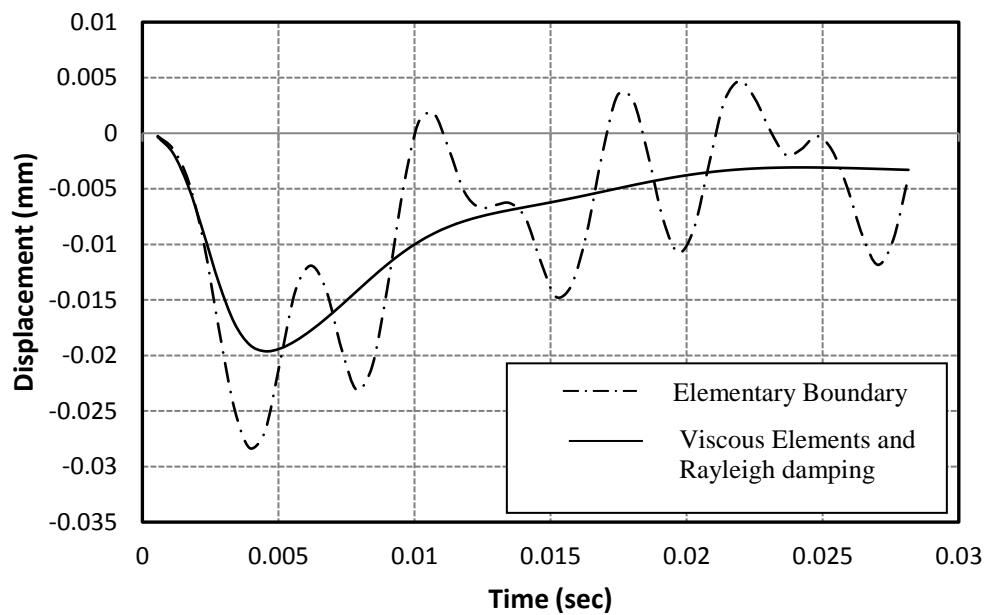**Figure (6) Vertical displacement at point A of the strip footing on dry soil.**

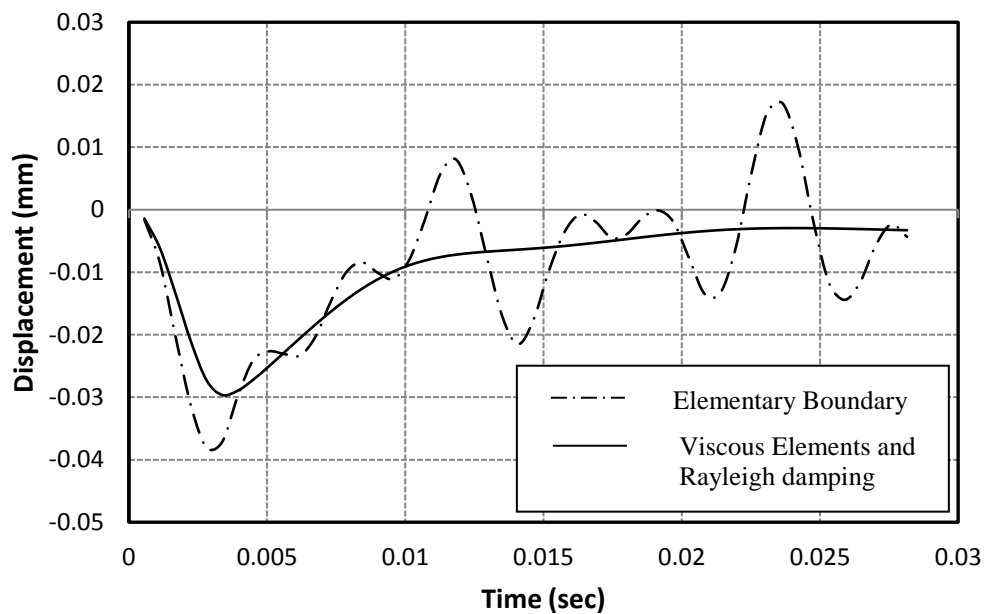**Figure (7) Vertical displacement at point B of the strip footing on dry soil.**

Figure (8) Vertical displacement at point C of the strip footing on dry soil.

From these figures, it can be noted that, the wave is dispersing due to the impingement at the boundary and reflects to the system when using the elementary

boundary. While decay in the amplitude of wave occurred when the semi-infinite of soil is represented by the viscous elements and Rayleigh damping.

Verification of the Method

Estorff and Kausel (1989) solved the same problem in this study by using a boundary element-finite element coupling procedure, developed for general dynamic response analysis of arbitrary shaped elastic bodies, which is applied to represent soil-structure interaction problems. The method consists of a combination of the time domain boundary element method used to represent the infinite soil medium, and the finite element method used to model the elastic structure.

In their study, the foundation is discretized by linear finite elements and the semi-infinite medium of the soil is represented by boundary elements along the interface and on each side of the foundation, and their results are shown in Figure (9). The results of the same problem obtained from the present study are shown in Figure (10).
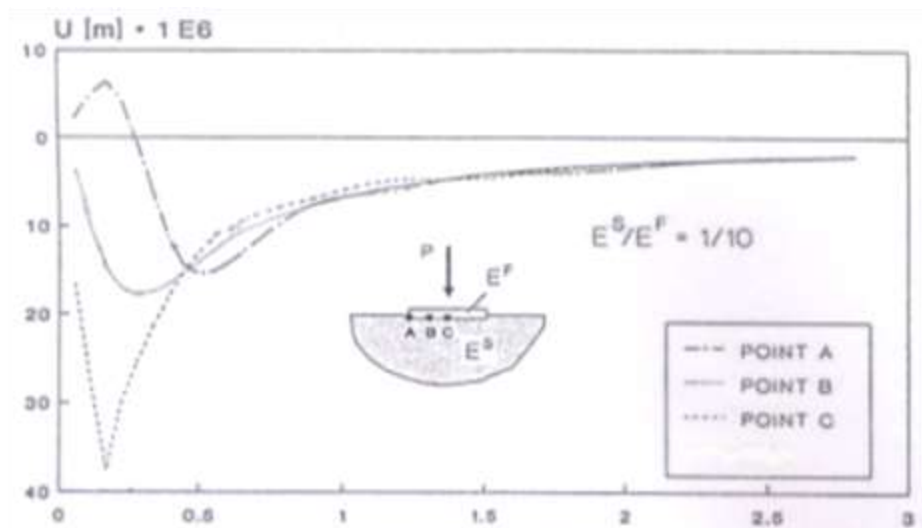

Figure (9): vertical displacement at points A, B and C of the strip footing (after Estorff and Kausel, 1989).
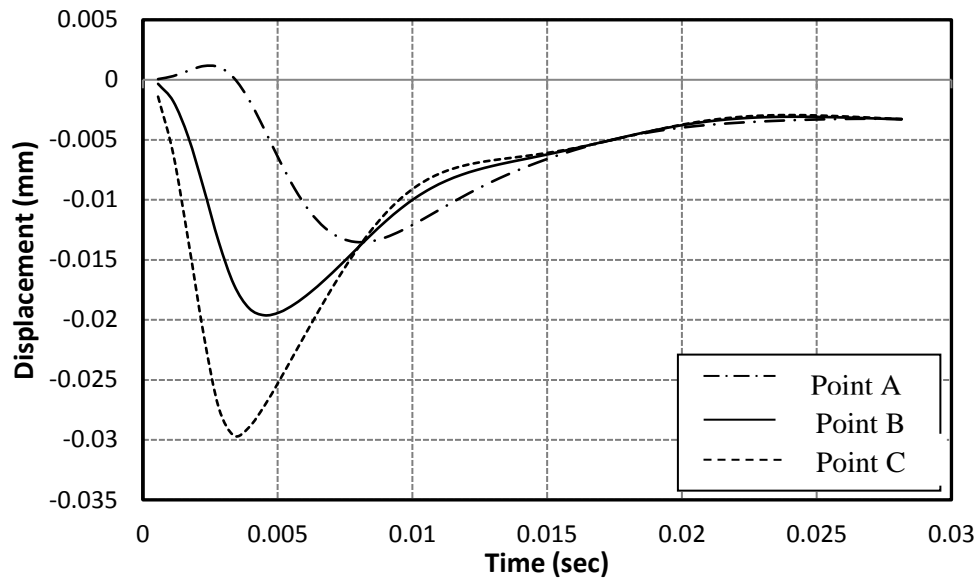
Figure (10) Vertical displacement at points A, B and C of the strip

Footing(From the present study).

The foundation by using viscous elements (see, Figure 10) with those obtained from the proposed procedure by Estorff and Kausel (1989), it can be seen that a good agreement is achieved. In addition, the dynamic response at any depth under the foundation can be estimated by using the present method. In contrasts, this cannot be achieved by using the method proposed by Estorff and Kausel (1989).

CONCLUSIONS

(1) The main benefit of the research is to determine a method to represent the infinite medium of dry soil in dynamic soil-structure interaction problems.

(2) In dynamic soil-structure interaction problems, the infinite medium (unbounded domain) of the soil can be represented by viscous elements to simulate the radiation damping. In addition, the material damping of soil can represented by Rayleigh damping.

(3) The results presented in this study clearly demonstrate that a decay of the amplitude of wave is occurred due to spreading of the energy of wave.

(4) The method is flexible and its results are in good agreement when compared with the boundary element-finite element method.

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