Meshless Method for Modelling the Heavy Machinery Foundation Effect on Surrounding Residents

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the Degree of

Doctor of Philosophy
in
Civil Engineering

Eastern Mediterranean University
May 2015
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

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ABSTRACT

There have been many attempts by researchers to solve the problem of wave propagation in the unbounded domains. One of the important problems that can be handled by using this approach is wave propagation due to vibrations of machine foundations in the surrounding region and its effects on the health and comfort of people who work or live in that area. This research used Finite Point Method (FPM), which is considered as one of the best methods for solving problems of wave propagation in unbounded domains. To ensure the reliability of FPM, the properties of wave propagation in homogeneous and non-homogeneous unbounded domains are checked. Also the results of estimating wave propagation in non-homogeneous domain for special cases are compared with results of the generalized Haskell method. When the displacement values for both methods were plotted, it was observed that the FPM method gave better and smoother curves than Haskell method. FPM was used with eight different soil types to solve the problem of the effect of machine foundations on the surrounding area, that is to say, to find the safe distance for people to work and live around this area. It was proposed that, for full time workers 19 m of safe distance and for people living in the area 80 m of comfort distance, from the center of the vibrating machinery foundation, is required. Further study in this field is necessary to introduce guidelines in the existing design codes regarding this matter.

Keywords: Finite Point Method, heavy machinery foundation, meshless methods, people health and comfort, unbounded domain, wave propagation.

ÖZ

Sınırsız ortamda dalga yayılımı problemini çözmek için araştırmacılar tarafından bir çok girişim yapılmıştır. Bu yaklaşım ile ele alınabilir önemli sorunlardan biri titreşimli makine temellerinden dolayı ortaya çıkan dalga yayılımının bu alanda çalışan veya yaşayan insanların sağlığı ve konforu üzerindeki etkileridir. Bu araştırmada sınırsız etki dalga yayılımı sorunlarını çözmek için en iyi yöntemlerden biri olarak kabul edilen Sonlu Noktası Yöntemi (FPM), kullanıldı. FPM güvenilirliğini sağlamak için, homojen ve homojen olmayan sınırsız dalga yayılımı özellikleri kontrol edildi. Ayrıca özel durumlar için homojen olmayan dalga yayılımı sonuçları genelleştirilmiş Haskell yöntemi sonuçları ile karşılaştırılmıştır. Her iki yöntem için yer değiştirme değerleri çizildiğinde, FPM yönteminin Haskell yöntemine göre daha iyi ve daha yumuşak eğriler verdiği gözlenmiştir. Çevredeki makine temellerinin etkisi sorununu çözmek için, sekiz farklı toprak tipleri ile FPM, insanların çalışabilecekleri ve bu alanın çevresinde yaşayabilecekleri güvenli mesafeyi bulmak için kullanılmıştır. Bu çalışma nerticesinde, tam zamanlı çalışan insanlar için güvenli mesafe 19 m ve o bölgede yaşayan insanlar için konfor mesafesi ise titreşimli makina temelinin merkezinden 80 m olarak önerilmiştir. Bu konuyla ilgili, mevcut tasarım kodları yönergeleri tanıtmak için daha fazla çalışma gereklidir.

Anahtar kelimeler: Sonlu Noktası Yöntemi, titreşimli makina temeli, ağsız yöntemler, insan sağlığı ve konforu, sınırsız alan, dalga yayılımı.

DEDICATION

To My Dear Family and Friends

ACKNOWLEDGMENT

I would like to thank Assoc. Prof. Dr. Zalihe Nalbantoglu Sezai and Assist. Prof.Dr. Mürüde Çelikağ for their continuous support and guidance in the preparation of this study. Without their invaluable supervision, all my efforts could have been short-sighted.

I am also obliged to other staff of the Civil Engineering Department at EMU. Besides, a number of friends had always been around to support me morally. I would like to thank them as well.

I owe quite a lot to my family who allowed me to travel all the way from Iran to Cyprus and supported me all throughout my studies. I would like to dedicate this study to them as an indication of their significance in this study as well as in my life.

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FPM	Finite Point Method
FEM	Finite Element Method

Chapter 1

INTRODUCTION

1.1 General Introduction

Ground vibrations can be produced by either natural or artificial reasons, such as earthquake and vibrating machines. These vibrations can produce surface waves: Rayleigh wave, Love wave, body waves: secondary, S and primary and P waves.The surface wave decays due to ground damping much slower with the distance than that of the other waves, based on an amplitude reduction of $1/r^2$ [1] in which r is the distance between stimulating point and the point that magnitude or other parameters of wave are going to be measured. Therefore, according to the Arya et. al. [2] vibration isolation is required when the surface wave propagation is the major phenomena. Vibrations of machine foundations produce waves in soils and these waves may deleteriously affect the surrounding buildings, equipment and the people living in the region[3, 4]. The effect of vibration on the people's body has been studied in many previous researches [5, 6, 7, 8] and also mentioned in some codes such as ISO 2631:2001, "Mechanical vibration and shock – evaluation of human exposure to whole-body vibration" [9] and also BS EN 14253:2003, "Mechanical vibration – measurement and calculation of occupational exposure to whole-body vibration with reference to health practical guidance" [10], ACI 351, "ACI 351.3R-04: Foundation for Dynamic Equipment" [11] and National Iranian Construction Code "Topic 7: Foundations" [12].

But unfortunately, non of these aforementioned codes, consider the effect of vibration on the human's body in the design process of the vibrating machines foundations.

For a complete safe design, this effect on human's body should be considered and some precautions should be taken before construction so that the people living close to such areas will not be affected from these detrimental vibrations. Because of this lack of information on this subject, a new meshless method, Finite Point Method (FPM) is developed to study the wave propagation in the soil as an unbounded non-homogeneous domain. Some real problems related to such vibrating machine foundations were also studied in order to examine the safety and comport of the people living close to these areas.

In this study, the safe distance around these foundations in terms of the human health and comfort were determined based on the European code, ISO 2631:2001 [9]. The results of this study showed worrying discomfort and unsafe area for those people living in these areas.

As it was mentioned in the previous section, only in the ACI 351: "ACI 351.3R-04: Foundation for Dynamic Equipment" [11] there is just one short comment which points to the duty of the designer in the case of including health and safety of the people around such foundations in the design procedure. But there is no other specific guidance for the design of such vibrating machines to save the human's health in such regions.

The only controls which are proposed to be done in designing vibrating machine foundations in the codes of ACI 351.3R (04) and Topic 7 of National Iranian Construction Code are as follows:

- In the case of static loads:
    - a- The foundations should be controlled against shear failure.
    - b- There should not be excessive settlement beneath the foundations.

- In the case of dynamic loads:
    - a- Avoid from resonance by controlling the normal frequency of foundation-soil system to coincide with neither operating frequency nor whole number multiple of the machine frequency.
    - b- Avoid from exceeding the amplitudes of motion to the limiting amplitudes at operating machine frequencies.
    - c- Consider the health and comfort of the people who live or work around this foundation .

Despite the health and comfort of people who work or live around such structures mentioned as one of the points which should be considered in their design, in the existing codes and literature, there are no formula or even any coefficient in the design process. This lacking information related to the health or comfort of people around such structures was also discussed and criticized in the ACI 351.3R (04) [11] but still there has been not enough study performed on this subject. This lacking information in the existing codes led the author in this study to perform further research on this topic.

The existing studies on this topic indicate that for the design of such foundations, the prediction and effect of vibrations in the surrounding soil and structures becomes very important in addition to other parameters which have been already mentioned in the related codes and standards.

Ground vibration decay has many variables. But this decay is primarily a function of soil type, soil bearing capacity, soil's Young's modulus, soil's poisson's ratio, and the frequency and the amplitude of vibration [13, 14, 15, 16, 17].

Wave propagation in the unbounded domains is one of the important engineering issues. To solve this problem, many efforts have been made [18, 19, 20, 21, 22]. In recent years, due to the rapid computer development, researchers from various disciplines have developed a special interest in numerical solution of many problems. A numerical modelling problem among others has been the major focus of the researchers and as such, wave propagation has been argued to be an important element. Also physicists believe that the mass has a wave nature in addition to its particle nature [23], and this bolds the importance of the researches in the field of wave and wave propagation.

1.2 Goals and Objectives

The aim of the present research is to investigate the effect of heavy machinery foundation on the comfort and health of the people who work or live in the surrounding region. To achieve the objective of this study, a new numerical method that is based on the Finite Point Method has been developed and used to study the wave propagation in soil as an unbounded domain.

As it is mentioned in ACI 351.3R (04), the design of heavy machinery foundations is erratic and should be discussed among different teams of study. The codes and efforts in the field of design of such foundations are mostly focusing on the response of structure and soil and partially on the interaction of these two parts [11, 12]. But the comfort and the health of people who work or live around such structures are not considered.

For this reason, within the scope of the present study, the problem will be investigated in two steps. The first step will focus on the wave which is going to be propagated in a non-homogeneous unbounded domain and the results will be used to see the travelling of the waves induce from heavy machinery foundations through the soil. In the second step of the study, the obtained results in the first step will be used to evaluate if the surrounding people's health and comfort are affected by the waves induced from heavy machinery foundations.

1.3 Scope of the Study

1- The aim of the first part of the study in this research was to investigate the wave and wave propagation in unbounded domains and also the numerical methods used to estimate the wave parameters on each point of the domain.

2- The development of a new method based on FPM for estimating the magnitude of wave on each point of the area around vibrating foundations was established and the results of the new method were compared with the results of the existing methods by the other researchers in this area.

3- For the investigation of the comfort and health of the people who face to vibrations, it was tried to discovery the types of waves which may or may not be harmful for the people who work or live around such vibrating foundations.

4- As a part of this research, different parameters which affect and control the design of the foundations so that the comfort and the health of the people living in that region will not be affected were investigated.

5- Finally, the last part of the research concentrated on checking the health and comfort of the people living in the area around the vibrating foundations. In this part foundations are designed according to the ACI 351.3R(04) [11].

1.4 Achievements

1- One of the achievements of this research was the development of a meshless method which shows the magnitude of wave propagated in an unbounded non-homogeneous domain caused by stimulation with the shape of Dirac-Delta which was sinusoidal in time domain. This method primarily was used to estimate the magnitude of wave in homogeneous domains. Then the developed version of this method was used to estimate the magnitude of wave propagated in the surrounding soil. As it is known, the soil is not a homogeneous domain. Also another thing which had to be incorporated in the developed method was the shape of stimulation which was not necessarily Dirac-Delta and its time dependency which can be sinusoidal. Therefore the use of superposition principle can be a good solution to change Dirac-Delta shape to any shape of the load. Also Fourier transformation is a way to model any kind of the load in respect to time with the form of summation of multiple numbers of sinusoidal loads.

2- The other achievement of the present research is the development of an efficient method to show wave propagation in unbounded nonhomogeneous domains. The efficiency of this developed method was shown by comparing its results with the results of another former method in this area.

3- The present study also shows the ineffectiveness of the codes and standards of designing vibrating machine foundations in controlling the health and safety of the people who live or work around such structures. The incompetence of the codes and standards was analysed by comparing two different groups of results: The first group was the wave magnitude estimation in the surrounding area of vibrating equipment foundations using developed method. These foundations are all designed based on the present aforementioned codes and standards. Another group of data are the allowable values for human to be in comfort or healthy based on European Commission: "whole-body vibration guide to good practice, Luxemburg" [8], ISO 2631:2001, mechanical vibration and shock – evaluation of human exposure to whole-body vibration [9] and BS EN 14253:2003 Mechanical vibration – measurement and calculation of occupational exposure to whole-body vibration with reference to health practical guidance [10]. These values are assessed for either people who spend a work time in this area or for the ones who spend the whole day living in this area.

1.5 Guide to the Thesis

In the first chapter of the present thesis, an introduction of the whole work containing the main problem, the idea of the research, the ways of solving this problem, the objectives, the works done and the achievements on this topic were mentioned and explained.

In the second chapter, a broad literature review of the previous works done on wave propagation in unbounded domains. The studied works were mainly on estimating the methods of wave propagation in unbounded domains and specially in non-homogeneous domains. Also some works, codes and standards related to the health and safety of the people living in the vibrating foundations area were studied.

In the third chapter of the present study, the methodology of solving the problem of wave propagation in non-homogeneous unbounded domains, developed by the author was presented. This method is used to estimate the magnitude of wave in the surrounding domain of stimulation. Also the method is developed to be able to model the soil as an non-homogeneous domain. At the last part of this chapter, some examples are presented to evaluate the ability of this method. Moreover some examples of comparison between the results of the developed method and the other methods are presented to show the efficiency of the developed method.

In the fourth chapter of this research, the results of the presented examples in the previous chapters are discussed. These examples are in two groups. The first group includes modelling of one-dimensional waves propagation in the non-homogeneous unbounded domain. The second group covers the two-dimensional waves which propagate in the non-homogeneous unbounded domain.

Finally, in the last chapter of the thesis, the achievements and all the conclusions of the research were presented and some recommendations for further studies were proposed.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Huge equipment is the advantages of new technology and is an unescapable part of new factories. But in this machine world, one of the least addressed subjects in the field of structural designs is the health and comfort of people who are living or working around such factories with these vibrating equipment. Since the subject of the present research is focusing on the health and comfort of the people who live or work around vibrating machine foundations, the literature review of this study will be presented in four parts. The first part is going to review the previous works on vibration and the terms and definitions used on this subject and the works done in the case of whole-body vibration and hand-arm vibration. The second part is going to discuss about vibration adverse effects on the human body. The next part of the literature is going to focus on the works done on preventing the adverse effects of vibration on human health. In the last part of the literature review, the safe distance around the vibrating machine foundation according to the former studies will be introduced.

2.2 What is Vibration?

Vibration is a swinging motion about stability point of the mass and repeats after a specific time [24]. Anything which has mass and the elasticity property can vibrate. Therefore all machinery and tools can cause vibration.

Vibration is a physical factor that can act on the body of workers by passing the energy from vibration producer through workplace [25]. This vibration in work environment can be produced by many factors. Some of these factors are as below :

- Impact and friction caused by the mechanism of the machine.
- Asymmetry or imbalance of rotating masses
- The sudden movement due to the air pressure in the air compressors
- A collection of these three factors

The measurement and control of vibration is usually done in the workplace due to following reasons [25, 26]:

1- Protection of devices and structures from damage and wear which caused by vibration

2- The control of sounds and noises caused by machinery vibration

3- Detection of main vibration resources in workplace

4- Determination of workers' exposure to vibration

5- Protection of people against damages due to vibration

According to the European codes and standards of sanitation and occupational health [27, 28, 29], vibrations entering the body of people are categorized in two groups: hand-arm vibration and whole-body vibration.

2.2.1 Hand-arm Vibration

Hand arm vibration is vibration transmitted from a work activity into workers' hands and arms. It can be caused by regular and frequent use of hand-held tools with hitting or vibrating actions [30].

Exposure to hand arm vibration can lead to a combination of neurological (nerve), vascular (circulation) and musculoskeletal symptoms collectively known as hand-arm vibration syndrome [31], as well as specific diseases such as carpal tunnel syndrome. The health effects include pain, distress and sleep disturbance, inability to do fine work (e.g. assembling small components) or everyday tasks (for example fastening buttons), reduced ability to work in cold or damp conditions (ie most outdoor work) which would trigger painful finger blanching attacks, reduced grip strength which might affect the ability to do work safely.

2.2.2 Whole Body Vibration

Human can exposure whole body vibration in three positions: lying down, sitting, and standing [32]. The first position is usually occurs for people who live around vibration sources. The second position of vibration exposure: sitting position, generally happens for the people who work as drivers of heavy agricultural or industrial machines. The standing position of vibrating exposure can happen for all people who live or work in the vibrating environments [26, 27].

The vibration entering the human body can be in horizontal or vertical directions. Also it should be said that for standing or sitting position, the horizontal vibration that human body may exposure to, can be lateral or along frontal side, i.e. the wave can either come from right to left or left to right or come from back to front or from front side to back.

2.3 Vibration Effects and Diseases

There are many effects caused by the vibration on different part of human's body. Some of these effects are listed as below [33-52]:

1- Local tissue irritation and damage
2- Effect on central nervous system

3- Changes in surface vessels and irregularities in the venous system
4- Damage to the cerebellar cortex and causing stress
5- Changes in texture and chemical composition of living tissue and malnutrition caused by biochemical changes in the body
6- Carefully cut visibility – stricture – reduced sensitivity to light
7- Decreased tactile, thermal and stimulation sensitivity.

There are also some diseases caused by vibration that some of them are listed as below [33-52]:

1- Venous syndrome: Localized vibrations on the body. It causes the white part which is sometimes associated with the injury.
2- Polyneuritis and Angyo-Dystonic syndrome
3- Spasm
4- Irregularities in the venous system of the limbs and the main arteries of the heart and cerebellum.

2.4 Prevent Adverse Effects of Vibration

As it was mentioned in the previous parts, vibration has harmful effects on people's health and the comfort of the people subjected to such vibrations was destructed. Facing less vibration means less adverse effects on human's health. Therefore vibration effects on human body should be minimized so that the harmful effect of vibration on human health will be reduced. To reduce the amount of vibration and prevent the harmful effect of vibration in the surrounding areas, the following preventive measures can be taken prior to construction: The control of vibration during design and production of machines [29].

1- Installing damper in touching place in between machine and body [53].
2- Mobile control of machines [53].

3- Management practices such as reducing exposure and circulating work times [4, 26].

4- Medical interventions for early diagnosis of diseases caused by vibration [4, 26].

5- Design the foundations of vibrating machines safely so that the surrounding people living in that region will not be affected by these vibrations. But unfortunately, in the existing structural design codes and standards [11, 12, 13], there are no coefficients or parameters mentioned for the foundation designs considering the health and safety of people who are exposed to such heavy machinary vibrations.

One of the aim of this research is to show that the machine foundations which were designed according to the present codes and standards [11, 12, 13] usually produce unsafe environments for the people living in the surrounding areas. This shows a big defect in these standards in including the health and comfort of the people who work or live around such structures. As an advice, a new step of controlling the wave displacement value according to the health and safety standards [9] can be added to the design procedure of vibrating machine foundation. This control can be done, using the meshless method represented in this research.

2.5 Safe Range of the Machinery Vibration for the Comfort and Health of People Living in the Adjacent Area

As mentioned previously, one of the most important parts which were missing in the design of heavy machinery foundation is the health and comfort of the people who live in the adjacent area [11]. There is no factor of safety mentioned in the design process of heavy machinery foundations including the health and safety of people who are exposed to such heavy machinary vibrations in the neighbourhood area.

According to Alimohammadi [32], for the vibrations with the frequency of 1~3Hz, instability and uncomforting situation will occur for the upper part of the body. Also for the vibrations with the frequencies more than 10Hz, horizontal vibration, especially in the direction of front to back or revise versa can be harmful [32].

The vertical vibrations with a frequency of 4~5Hz, can cause some problems to the daily life of the people living in the surrounding areas due to Monazzam findings [26]. These problems may cause complications in the field of simple activities such as eating, drinking, etc. [26]. If this vertical vibration has a frequency of 10~20Hz, warble will occur in hearing and seeing of the people living in the affected area. In addition, if the frequency of 15~60Hz vertical vibration is transmitted to the human body, people will suffer from serious seeing problems [26].

Generally, the frequency of whole-body vibrations which will be harmful or cause uncomfortable situation to human life are in the range of 0.5~100Hz. Low frequency vibrations, less than 0.5Hz, usually causes motion sicknesses [26, 32].

Also the allowable values of the human whole body vibration exposure can be determined according to the B2 graph of the ISO-2631 [9] as Table 1.

Table 1. Allowable values of human whole-body vibration and exposure time [9]

Resultant acceleration (m/s^2)	**Allowable exposure time (min/day)**
0.63	1440 *
0.70	960
0.87	480 **
1.10	240
1.30	120
1.60	60
1.85	30
2.45	10

* People living in vibrating area
** Full-time workers in vibrating area

2.5.1 Allowable Vibration Values, Displacement, Velocity or Acceleration

The allowable vibration values mentioned according to the codes and standards are in the form of the acceleration entering to human body [3, 11, 26, 32]. But the developed method by the author in this research, estimate the displacement value of propagated wave which will be discussed in the next chapters [54, 55],

Since the Finite Point Method introduced in the reference [54] and the newly developed version for non-homogeneous media discussed in reference [55], are both using frequency domain methods, the frequency of vibration in each point is supposed to be equal to the frequency of stimulation resource [54, 55]. The maximum magnitude of wave is the value which can be determined in this method. If the stimulation resource supposed to be in sinusoidal form as bellow:

$$D = d_{max}\mathrm{Sin}(\omega t) \quad (16)$$

the value of velocity and acceleration can be shown as:

$$V = d_{max}\omega\,\mathrm{Cos}(\omega t) = \mathrm{V}_{max}\,Cos(\omega t) \rightarrow \mathrm{V}_{max} = d_{max}\omega \quad (17)$$

$$a = d_{max}\omega^2 \, \text{Sin}(\omega t) = a_{max} \, Sin(\omega t) \rightarrow a_{max} = d_{max}\omega^2 \quad (18)$$

Therefore a_{max} can be determined as $d_{max}\omega^2$. Since the special form of Finite Point Method which is used in this research can estimate the maximum value of wave magnitude on each point of the domain around the foundation, the method can also estimate V_{max} and a_{max} according to the equations (17) and (18).

This point was emphasized due to the form of allowable values which is mentioned in the codes and standards related to the health and comfort of human [4, 9, 10] which are all maximum acceleration values. These values will be presented versus human exposure time in the next coming chapters.

2.6 Wave Propagation in Unbounded Domains

There are two major groups of used methods to solve the differential equations [54, 55]; with or without mesh network [56]. Former studies demonstrated that using mesh in wave propagation modelling may cause wave to emanate lead [54, 55, 57].

According to Fatahpour [57], the shape of the elements and their positioning with respect to each other can cause this lead. Moreover, Gerdes and Ihelburg [58] and Harari and Nogueria [59], highlighted the effects of the shape function problem of the elements used for wave propagation modelling in unbounded domains in their studies. In addition, the finite element modelling of wave propagation resulted in the phase difference problems of response, numerical approximation and pollution error [58].

Therefore, there are two methods that can be used for solving the wave propagation problems due to the network problems in wave propagation modelling. Meshless method represents solutions despite the problems affiliated with its use, like of stiffness matrices' singularity, general non-stability, and difficulties in certifying the accuracy of number of points in the domain.

On the other hand, one of the oldest numerical methods, finite difference method, can also be used to solve the problems caused by element networks in wave propagations modelling. The limitation of this method is the need of regular grid point in whole domain. However, the solution of mentioned problems is to use of a special storage combination and replication in other parts of the domain. But according to Moazam [60] the use of finite difference does not result as accurate as Finite Point Method .

The following methods are often preferred to the ones mentioned earlier since they are very successful for large number of numerical modelling of unbounded domains.

1) Methods which are based on boundary integral equations. According to Kirsch [61], this method has some limitations associated with the properties of domain, such as, homogeneous, isotropic and linear. This method can further be classified into two subgroups; direct and indirect integral equations that are dealing with the physical [60] and mathematical aspects [62] respectively. Therefore, boundary element method has been used successfully to solve the problems with unbounded equations [63, 64, 65, 66]. However, there are disadvantages of this method which include the inaccessibility to basic functions of different problems, such as, non-homogeneous domains and complicated calculations that sometimes trigger the singularity of integrals.

2) As demonstrated by the first monograph in the world [67], dynamic and transient infinite elements have been developed to solve wave propagation and a broad range of scientific and engineering problems [68, 69]. Zhao et al. established the coupled method of finite and dynamic infinite elements [70, 71] for solving wave scattering problems associated with many real scientific and engineering problems involving semi-infinite and infinite domains. For example, (i) dynamic concrete gravity dam-foundation interaction and dynamic embankment dam-foundation interaction problems during earthquakes [72, 73], (ii) seismic free field distributions along the surfaces of natural canyons [74, 75], (iii) dynamic interactions between three-dimensional framed structures and their foundations [76], (iv) dynamic interactions between concrete retaining walls and their foundations [77]. In addition, Zhao and Valliappan also developed the coupled method of finite and transient infinite elements for solving transient seepage flow, heat transfer and mass transport problems involving semi-infinite and infinite domains [78, 79, 80].

3) Non-reflecting boundary conditions are shape based by placing B on virtual boundary around the stimulation reservoir Ω (Fig 1) in such a way to allow for the waves to go outward without any reflection inside. Therefore, it is costly to simulate the full infinite domain.

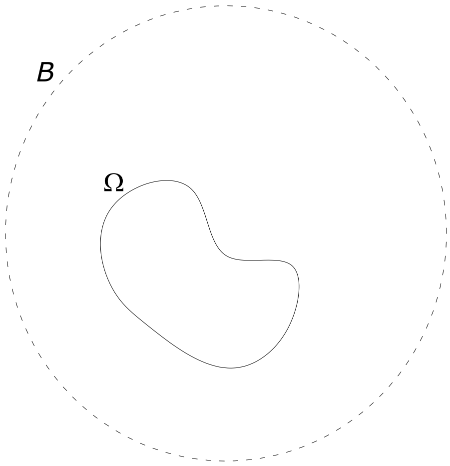


Figure 1. Stimulation and Non-reflecting Boundary

At a glance, this kind of simulation seems easy and simple to perform. But research conducted for the past thirty years have shown that such boundary simulation is hard to perform. In addition, the limited numerical solutions available so far also indicate existence of possible problems with such boundary simulations [81, 82, 83] and researchers not having a consensus on this matter [84]. Therefore, recent studies are aimed at achieving better developed stimulations [85, 86, 87, 88].

4) Absorbing layer or perfectly matched layer method was first introduced by Bérenger in 1990 [89] upon completion of the non-reflecting boundaries. Recently, extensive studies have been conducted on how to develop this method for 2-and 3-Dimensional domains [90].

5) Dynamic solution of unbounded domains using finite element method was first introduced by Boroomand and Mossaiby [91].

6) In a recent research [54] by Moazam et. al. the method invented by Boroomand and Mossaiby [91] developed to solve the wave leading problem caused by element arrangement and shape functions. This solution is done by using meshless method of Finite Point Method .

7) The developed version of what has been represented previously in reference [54] which could model wave propagation in homogeneous unbounded domain was shown in reference [55]. This new version was able to model wave propagation in unbounded non-homogeneous domain with any kind of stimulation. This was done by using Finite Point Method . Due to arbitrariness of domain properties and stimulation shape and value, the recent method was more general and more efficient than the former ones.

Chapter 3

METHODOLOGY

3.1 Introduction

The fast development of computers and simulation methods within the last years encouraged researchers from various disciplines to show more concern to numerical methods. One of these numerical estimation problems is wave propagation which has been a major interest of many researchers. Also in recent years, the physicists realized that the nature of masses not just as particles but also as waves [23] and they vouched the significance the modelling of wave propagation.

One of the main issues in the case of wave propagation researches is the elastic wave propagation in homogeneous and non-homogeneous domains [54, 55, 57, 60].

3.2 Elastic Wave Propagation in Unbounded Domain

In this research work, Finite Point Method was used to study the wave propagation in unbounded domain [54]. The wave equations are given below:

$$\mathbf{S}^T \mathbf{D} \mathbf{S}\, \mathbf{U} - \rho \ddot{\mathbf{U}} = \mathbf{F}(x, y, t), (x, y) \in R^2 \qquad (1)$$

where $\mathbf{U}$ and $\ddot{\mathbf{U}}$ are the value of wave function and the second derivative of wave function of time, respectively; $\mathbf{S}$ is a differential equation that signify the relative deformation; $\mathbf{D}$ is a matrix of material properties, ρ is the unit weight of the domain; and finally $\mathbf{F}$ is the stimulation function of the domain (a Dirac-Delta-Function in the specified direction and time with sinusoidal form). One of the uses of the above formula is the elastic wave propagation in which all functions and operators are written in vector format.

To solve this equation, a Cartesian coordinate system is adopted; while the center of this coordinate system is used as the stimulation point. If $\mathbf{U}$ is considered as:

$$\mathbf{U} = \mathbf{u}e^{i\omega t} \tag{2}$$

Then $\mathbf{u}$ is a Fourier transformation of $\mathbf{U}$, $i = \sqrt{-1}$, and ω is the value of the stimulation frequency. Consequently, these values are substituted in equation (2) to obtain equation (3).

$$\mathbf{S}^T \mathbf{DS}\,\mathbf{u} + \rho\omega^2 \mathbf{u} = \mathbf{f} \tag{3}$$

$\mathbf{f}$ is a Fourier transformation of stimulation function of $\mathbf{F}$.

According to the stimulation function shape, to solve this problem, symmetric and anti-symmetric displacement condition can be used in the domain. Then the equation is given as follows:

$$\mathbf{S}^T \mathbf{DS}\,\mathbf{u} + \rho\omega^2 \mathbf{u} = 0 \qquad x \in [0,\infty) \times [0,\infty) \tag{4}$$

This study considers the importance of the reliability of the domain properties and this can solve the problem. Therefore, the stimulation $\mathbf{f}$ can be applied as a boundary condition and thereby equation (4) can be classified as part of homogeneous equations group with constant coefficients. As a result, one of the significant properties of the differential equations with constant coefficients, such as proportionality, is given in equation (5):

$$\mathbf{u}(x, y) = \mathbf{A}e^{\alpha x + \beta y} \tag{5}$$

$\mathbf{A}$, α and β are constant vector and two undefined scalars. Equation (6) is derived from the exponential function properties in the x and y direction.

$$\mathbf{u}(x+nL_x, y+mL_y) = \mathbf{A}e^{\alpha(x+nL_x)+\beta(y+mL_y)} = (\mu_1)^n (\mu_2)^m \mathbf{u}(x,y) \tag{6}$$

where, L_x and L_y are arbitrary specified values in x and y direction, m and n are positive numbers.

Equation (7) is obtained by substituting equation (5) into equation (4).

$$\mathbf{L}\mathbf{A}e^{\alpha x+\beta y} = 0 \text{ or } \mathbf{L}.\mathbf{A} = 0 \tag{7}$$

$\mathbf{L}$ is a matrix, including values based on α and β. The nullspace of a matrix is equivalent to the matrix when it reaches zero.

$$|\mathbf{L}| = 0 \tag{8}$$

According to the characteristic of equation (7) α and β are the main factors relating to the issue discussed in the results and discussions part of this paper.

One of these variables can be calculated in terms of the other one, $\alpha = f(\beta)$ or $\beta = g(\alpha)$. It must be noted that there may be more than one answer to each of these equations depending on the degree of characteristic of equation,

The homogenous solution of this equation may be obtained by using the superposition of spectral solutions. For example, $\beta = g(\alpha)$ like equation (9) [54]:

$$\mathbf{u} = \int_{\alpha} \sum_{i} \mathbf{A}_i e^{\alpha x+\beta_i y} \, d\alpha = \int_{\alpha} \sum_{i} \mathbf{A}_i e^{\alpha x+f_i(\alpha) y} \, d\alpha \tag{9}$$

The inner sigma in the over nullspace of $\mathbf{L}$ matrix and the overall integration gives the possible values of α.

3.3 Decay and Radiation Condition

Decay condition of amplitude means decreasing amplitude with increasing distance from the stimulation point ($(n \to \infty, m \to \infty) \quad \Rightarrow \quad u \to 0$ equation (6)) that is:

$$|\mu_1| < 1 \quad and \quad |\mu_2| < 1 \tag{10}$$

One should note that μ_1 and μ_2 can have complex values, thus, equation (10) is a circle with the radius of one in Gaussian coordinate. In wave propagation, problems like radiation condition should be considered. Therefore, given the physical nature of such a problem, the energy emitted towards infinity represents the energy returned from infinity and changes the shape of the wave as well as the prerequisite [54] as follows:

$$\mathbf{U} = \mathbf{A}e^{(a+ib)x+(c+id)y+i\omega t} = \mathbf{A}e^{ax+cy}\, e^{i(bx+dy+\omega t)} \qquad a<0, b<0, c<0, d<0 \tag{11}$$

3.4 Finite Point Method

In recent years, Finite Point Method has been developed as one of the numerical methods to solve differential equation problems. Since it is meshless method, there is no need to carry out mesh generation [92, 93, 94] and it is known to be the best method for avoiding the errors which occur as a result of element networks [54, 60, 91]. Using finite point solution in equation (4), where a series of regular and equal intervals are connected to each other in both horizontal and vertical directions (unit size), the equation can be given as:

$$\mathbf{u}(x,y) \approx \hat{\mathbf{u}}(x,y) = \sum_{i=1}^{m} \alpha_i \; f_i(x,y) = \mathbf{f}^T \, \boldsymbol{\alpha} \tag{12}$$

$\hat{\mathbf{u}}$ is a set of point value estimation and $\mathbf{f} = [f_1 \quad f_2 \quad f_3 \ldots f_m]^T$ is an appropriate set of basic functions. In this paper, functions are selected as follows:

$$\mathbf{f} = [1, x, y, x^2, xy, y^2, x^2y, xy^2, x^2y^2]^T \quad and \quad m = 9 \tag{13}$$

In equation (12), the values of α_i and the unknown values called “generalized coordinates” are the estimates obtained when their functions are determinate. Using this method, the value of α_i is determined in the approximate location of the subscales. When the values are equal to the desired function the following equation is established.

$$\hat{u}_j = u(x_j, y_j) = \bar{u}_j, \quad j = 1 \ldots 9 \tag{14}$$

In the above equation $\bar{u}_j$ is the point value of the function in the j^{th} point. This equation can be developed based on equation (12) and it is given as:

$$\mathbf{f}^T(x_j, y_j)\boldsymbol{\alpha} = \bar{u}_j, \quad j = 1 \ldots 9 \tag{15}$$

Accordingly, with this system of equations where both sides are equal, a regular problem can be solved by using Finite Point Method without the need of using other methods, such as, least square method [95, 96].

3.5 Evaluation of FPM in Estimating Wave Propagation in Non-homogeneous Unbounded Domains

The ability of this method is shown in chapter 5, in the form of some examples. But based on the numerical results, the following are the points concluded:

- Discreet Green’s functions [54, 55] can easily be estimated with FPM in both homogeneous and non-homogeneous domains.

- In the term of using this method for simulating elastic wave propagation in homogeneous domains, the results have pollution error like the basic finite element method. However, in the finite element usage, wave lengths in the pressure direction are increased when compared with exact solutions whereas the using of new method which is based on Finite Point Method increases the wave lengths in the shear direction when compared with exact solutions.

- There are two kinds of wave propagation problems commonly encountered in the engineering practice [56, 57]. One of them is the wave radiation problem (the machine foundation vibration is an example of this kind) [56], the other one is the wave scattering problem (the seismic response of a structure is an example of this kind) [57]. Since the source of vibration should be obtained as a boundary condition, only first kind of wave propagation, wave radiation, can be observed in this method.

- Using superposition principle, enable us to apply any shape of the stimulation with any value to the domain while using the new FPM based method represented in this thesis [97].

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the author is going to present some examples of using the developed method in this research to show its ability in showing wave propagation in different kinds of unbounded domain. The domains which are observed in this research to show the ability of the developed method in modelling wave propagation in the unbounded domains can be categorized in two groups of homogeneous and non-homogeneous ones. One of the examples of non-homogeneous domains to be observed for the wave propagation in unbounded domains is different kinds of the soil with different engineering characteristics.

The developed method in this research is able to model the wave propagation in non-homogeneous unbounded domains as presented in reference methodology chapter and also in reference [55]. The wave propagation in non-homogeneous unbounded domains which was observed in the reference [55] was under Dirac-Delta stimulation. In Chapter 3 the use of new developed method for wave propagation in non-homogeneous unbounded domains with sinusoidal Dirac-Delta stimulation using was discussed. In this chapter, the wave propagation in soil as a non-homogeneous domain with the stimulation of a vibrating machine foundation as an arbitrary motivation will be analysed and discussed.

Among the examples which will be discussed and analysed in this study, there are some real vibrating machine foundations which have already been designed and constructed [97]. The process of designing these foundations, according to the reports presented by Adi [97], is according to the foundation design codes and standards: ACI351-3R(04)[11], ACI318-R(02) [98] and ASCE 2005 Index [99] which are already used for the design of vibrating foundations.

After showing the competence of the developed method by the author in modelling the wave propagation in both unbounded homogeneous and non-homogeneous domains, the scope of the present study is also to discuss the wave propagation caused by the vibrating machine foundations in the surrounding area. Related to this topic, some earlier methods [100] and the new method based on FPM which was developed by the author of this study will be introduced and the results will be compared and discussed.

Then the health and comfort of people working or living in the adjacent area of vibrating machine foundations will be analysed. The effect of vibrating machine foundations on the human's health and comport of people living in the surrounding area will be considered in two ways and will be explained in the following paragraphs.

As discussed in Chapter 2, in the existing codes and standards: ACI-351.R (04) [11], ACI-318.R (02) [98], and ASCE 2005 Index [99], there are no recommendations for the health and comfort of the people who work or live in the surrounding area of the vibrating machine foundations. Because of this lack of information, the health and comfort of people living around these structures was considered and some safe foundation sizes can be proposed in the design so that the health and the comfort of the people living in these areas would not be affected deficiently.

The second sight of the study involves considering the health and comfort of those people living close to vibrating machine foundations which were already constructed according to the existing health and safety codes and standards and propose a health or comfort area around such structures. The related codes and standards in the field of health and comfort of people who work or live around such structures can be listed as:

- "Control the risk from whole-body vibration-advice for employers on the control of vibration at work regulations 2014" by HSE [4].

- "Whole-body vibration guide to good practice, Luxemburg" by Office for official publications of the European communities [8].

- ISO 2631:2001 "Mechanical vibration and shock – evaluation of human exposure to whole-body vibration" [9].

- BS EN 14253:2003 "Mechanical vibration – measurement and calculation of occupational exposure to whole-body vibration with reference to health practical guidance" [10].

4.2 Wave Propagation in Arbitrary Domain

In this part of the study, some examples of wave propagation in unbounded domains are presented to show the ability of the newly proposed method based on FPM [54]. These examples are response of unbounded domains to the point sinusoidal motivation. According to the furrier transformation, the sinusoidal function can be represented as any other time dependent function. Also based on the superposition principle, the point load can be generalized to any shape of the stimulation. Therefore the samples chosen in this study were decided to be solved under sinusoidal stimulation functions so that it can be generalized and applied to any other functions. These examples are categorized in two groups: one-dimensional waves and two-dimensional waves propagated in the non-homogeneous unbounded domain.

4.2.1 One-Dimensional Waves Propagated in the Non-homogeneous Unbounded Domain

There are many examples in the field of one-dimensional waves which propagate in the unbounded domains. Among these heat, magnet, electric and elastic shear waves can be named. Since the method is a general method, the parameters can be verified according to the type of wave which is going to be modelled with this method. In this research, different elastic shear waves are chosen to be studied for wave propagation in different soil types around vibrating machine foundations.

In this section, discrete Green's functions for some special elastic wave problems are presented. Figure 2 shows the circular stiffer part at the center of unbounded domain. The circular shape of foundation was used for this example. However, the method developed in this study can be used for any shape of the foundation. Hence, all of the results are presented in the upper right quarter of this shape.

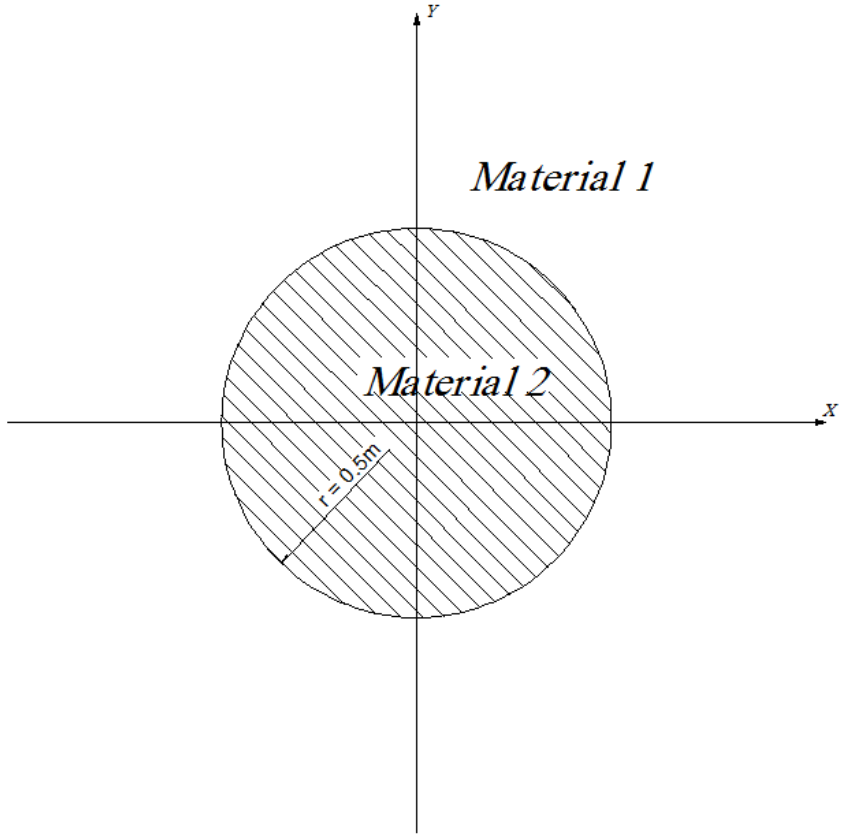


Figure 2. Circular Foundation Concentred with the Unbounded Domain:
Material 1, is Unbounded Domain Made up of Soil around the Foundation
Material 2, Concrete Circular Foundation with the Radius of 0.5 m

As a real example problem, the stiffer part can be assumed to be made up of concrete and surrounding part made up of soil. Thus, to evaluate the ability of the method to model the interaction of two different materials of concrete and soil in a wave propagation problem in unbounded domain, with point stimulation on the center of concrete part, the type of soil was considered to be different values for different samples solved in this chapter. It means that the problem was solved for four different types of soils surrounding the concrete foundation which is motivated at the center point.

The compressive strength of concrete assumed to be in the range of allowable values mentioned in the related codes and standards. In the present research, the codes and standards which are selected to be used are: ACI 318 [99], ACI 351-R [11] and Iran national codes for concrete structures and foundation design [12, 101]. The minimum allowable value of specified 28-day concrete strength, due to these standards, is $f_c' = 20(MPa)$. Therefore the modulus of elasticity of concrete can be calculated as bellow [11, 12, 98, 101]:

$$E_c = 0.043\, w_c^{1.5}\sqrt{f_c'} \quad (16)$$

in which all values are in SI units and in this formula:

E_c , modulus of elasticity of concrete, is in MPa,

w_c, the unit weight of concrete, in kg/m^3 and

f_c' , specified as 28-day compressive strength of concrete, in MPa.

The above formula can be written as below for the concrete with normal weight and normal density:

$$E_c = 4700\, \sqrt{f_c'} \quad (17)$$

Poisson's ratio of concrete is $\nu = 0.21$ [101]. Therefore, the shear modulus of concrete [102] can be calculated as:

$$G_c = \frac{E_c}{2\,(1+\nu)} \quad (18)$$

Based on the above formulas and the assumption of 20MPa for specified 28-day compressive strength of concrete, the other properties of concrete are presented in Table 2.

Table 2. Concrete properties assumed for circular foundation

Concrete properties	**Formula and values**
Specified 28-day concrete strength	$f'_c = 20 \text{ MPa}$
Modulus of Elasticity	$E_c = 4700 \sqrt{f'_c} = 21019 \text{ MPa}$
Poisson's Ratio	0.21
Shear Modulus	$G_c = \frac{E_c}{2\,(1+\nu)} = 8.686 \text{ GPa}$

To evaluate the ability of the newly introduced FPM based method, the circular foundation with the geometry shown in Figure 2 was used with four different soil types which were surrounding circular concrete foundation. The properties of these four types of soils are given in Table 3.

Table 3. Shear modulus of soils used for the evaluation of the newly developed method [103]

	Soil Description	**Shear Modulus (Pa)**
Type-1 sand	Very Loose Sand	2.4×10^{6}
Type-2 sand	Loose Sand	2.4×10^{7}
Type-3 sand	Medium Sand	3.4×10^{8}
Type-4 sand	Dense Sand	3.8×10^{9}
Type-5 sand	Very Dense Sand	1.9×10^{10}
Type-1 clay	Soft Clay	9.6×10^{7}
Type-2 clay	Medium Clay	4.8×10^{8}
Type-3 clay	Stiff Clay	2.4×10^{9}

5 types of sand and 3 types of clay soils as described in Table 3 were decided to be used in the analyses of the new method. This number of sand and clay types is

decided to cover the maximum range of different soils to see if the method is applicable to these types of the soils or not.

In this part of the study, the time harmonic dynamic behaviour of shear wave propagation is studied. The problem is a simplified version of a more general three dimensional cases represented by the following equation.

$$\sigma_{ij,j} + \rho\omega^2 u_i = 0 \quad , \quad u_1 = u = 0 \quad , \quad u_2 = v = 0 \quad and \quad u_3 = w \tag{19}$$

which can also be shown as the following differential equation:

$$\frac{\partial\sigma_{31}}{\partial u_1} + \frac{\partial\sigma_{32}}{\partial u_2} + \rho\omega^2 u_3 = 0 \quad , \quad \sigma_{31} = G_{(u_1,u_2)}\frac{\partial u_3}{\partial u_1}, \quad \sigma_{32} = G_{(u_1,u_2)}\frac{\partial u_3}{\partial u_2} \tag{20}$$

Shear modulus of the material is shown with the notation of $G_{(u_1,u_2)}$ which was the considered variable with respect to coordinate. Therefore:

$$\boldsymbol{S} = \begin{bmatrix} \frac{\partial}{\partial u_1} \\ \frac{\partial}{\partial u_2} \end{bmatrix} \quad and \quad \boldsymbol{D}_{(u_1,u_2)} = G_{(u_1,u_2)}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{21}$$

With such a definition for the problem, the essential boundary conditions are those in which w is prescribed and the Neumann boundary conditions are those in which $\boldsymbol{Gn}^T\boldsymbol{S}w$, with $\boldsymbol{n}$, a unit normal to the boundary, is prescribed. For evaluation of discrete Green’s functions the Neumann boundary conditions are considered as:

$$G_{(x,y)}\frac{\partial w}{\partial u_2}\Big|_{u_2=0,u_1\neq 0} = 0\,, \qquad G_{(x,y)}\frac{\partial w}{\partial u_1}\Big|_{u_1=0,u_2\neq 0} = 0 \tag{22}$$

The harmonic source term is applied in u_3 direction at $\mathrm{u}_1 = 0$ and $\mathrm{u}_2 = 0$. In these examples, the geometry of Material 1 (soil) and Material 2 (concrete), are considered as shown in Figure 2. Also it is assumed that G is material dependent and ρ is constant over the unbounded domain and has the unit value.

The problem with material geometry of Figure 2, has physical interpretation as scattering shear waves in unbounded domains with infinitely long pile.

The frequency is selected as $\omega = 1$. The numerical solution is performed over an area containing 50×50 points. The number of integration points selected to be 50 for integration on r and 50 for integration on θ. The details of the convergence studies for this method can be found in reference [60]. Unit sinusoidal value is used for motivation frequency in all solved problems in this section.

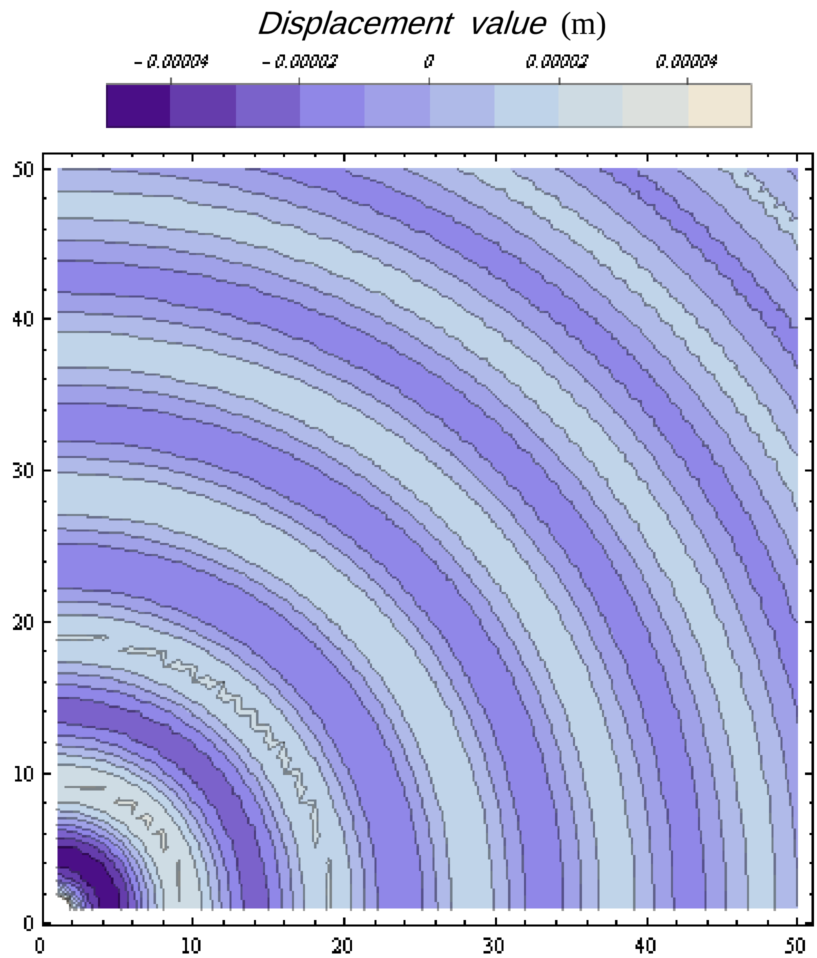


Figure 3. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center- $G_{Foundation}$=8.686GPa and G_{Soil}=2.4MPa

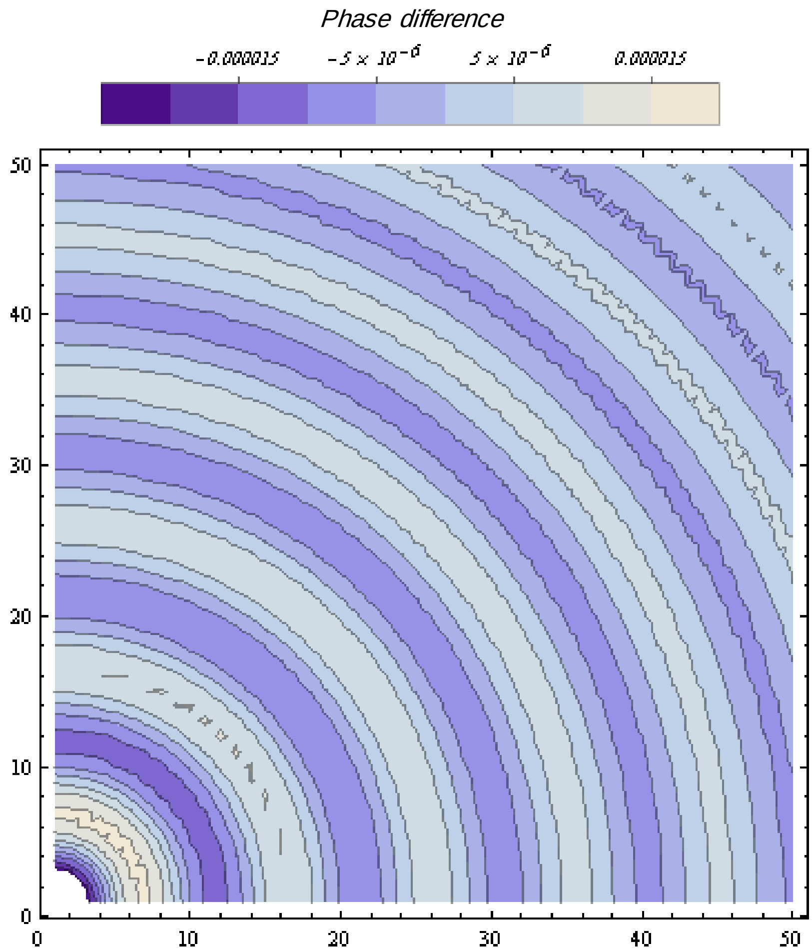


Figure 4. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center- $G_{Foundation}$=8.686GPa and G_{Soil}=2.4MPa

The real part and imaginary part of the domain response to the sinusoidal unit stimulation at the coordinate center are presented in Figures 3 and 4, respectively. In these two figures, the foundation is circular with the radius of 0.5m and the shear modulus is 8.686GPa. Also Type-1 sand is used for the surrounding area according to Table 2. Therefore the shear modulus of this surrounding area is 2.4MPa.

The numbers written on both axes of all graphs indicate the distance of each point of the domain from the centre of the coordinate in (m). The real part of the result is shown in Figure 3 and it is the displacement value caused by the unit sinusoidal stimulation in the coordinate center. The imaginary part of the result is shown in

Figure 4 and it is the phase difference between the stimulation and each point of the domain.

Figures 5 and 6 show the real and imaginary part of the results related to the unit stimulation applied to the coordinate center of the geometry shown in Figure 2. In these two figures, the assumed values of shear modulus for Material 1 (the surrounding soil) and Material 2 (concrete foundation) are $G_{Foundation}$=8.686GPa and G_{Soil}=24MPa, as given in Figures 5 and 6.

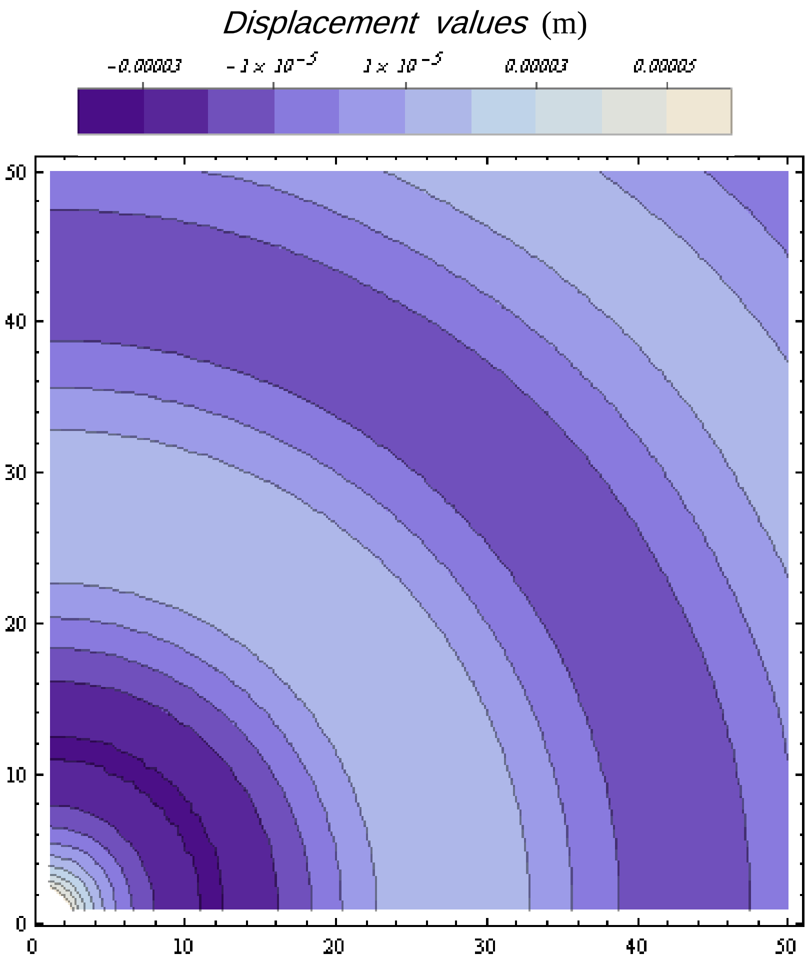


Figure 5. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=24MPa

The value of soil shear modulus is related to the Type-2 sand based on the materials given in Table 2.

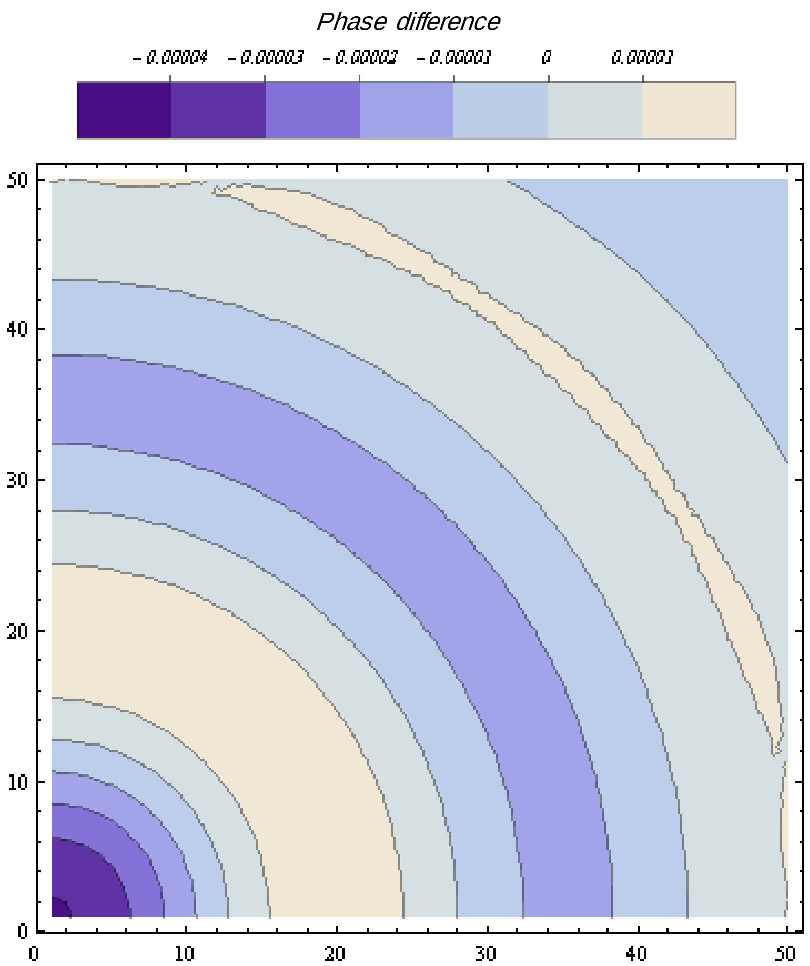


Figure 6. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=24MPa

Figures 7 and 8 provide the response of the domain against a unit sinusoidal motivation. The assumed domain for this problem contains a circular concrete foundation with a radius of 0.5m and shear modulus of 8.686GPa and the surrounding part of this foundation is assumed to be Type-3 sand as defined in Table 2 and it has a shear modulus of 340MPa.

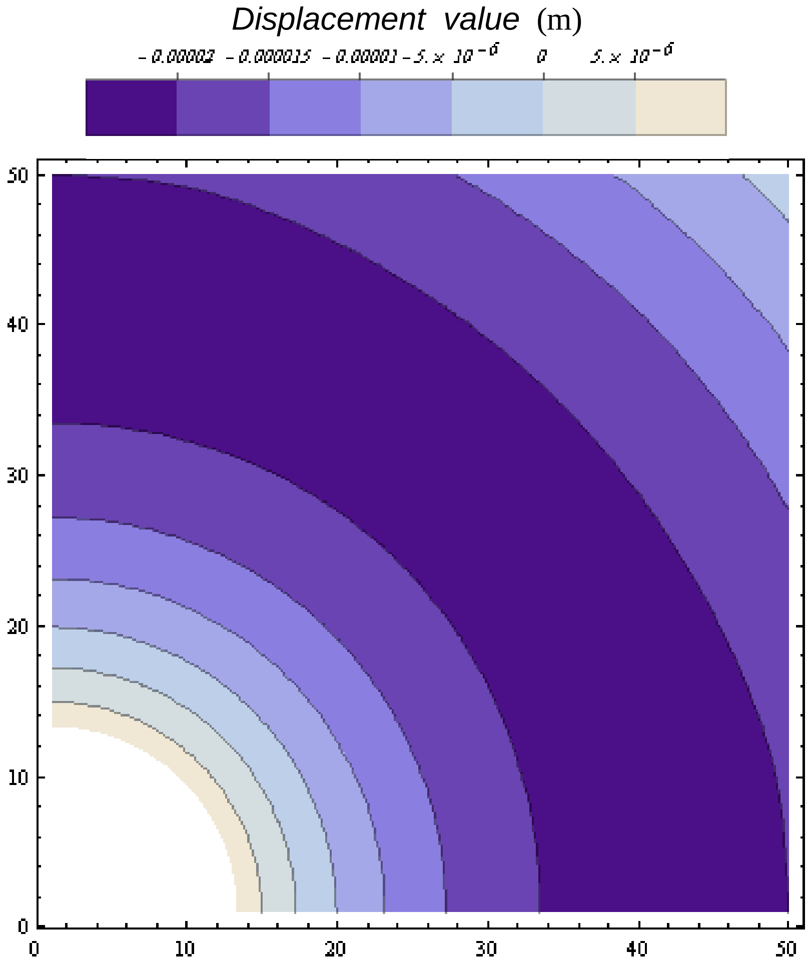


Figure 7. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=340MPa

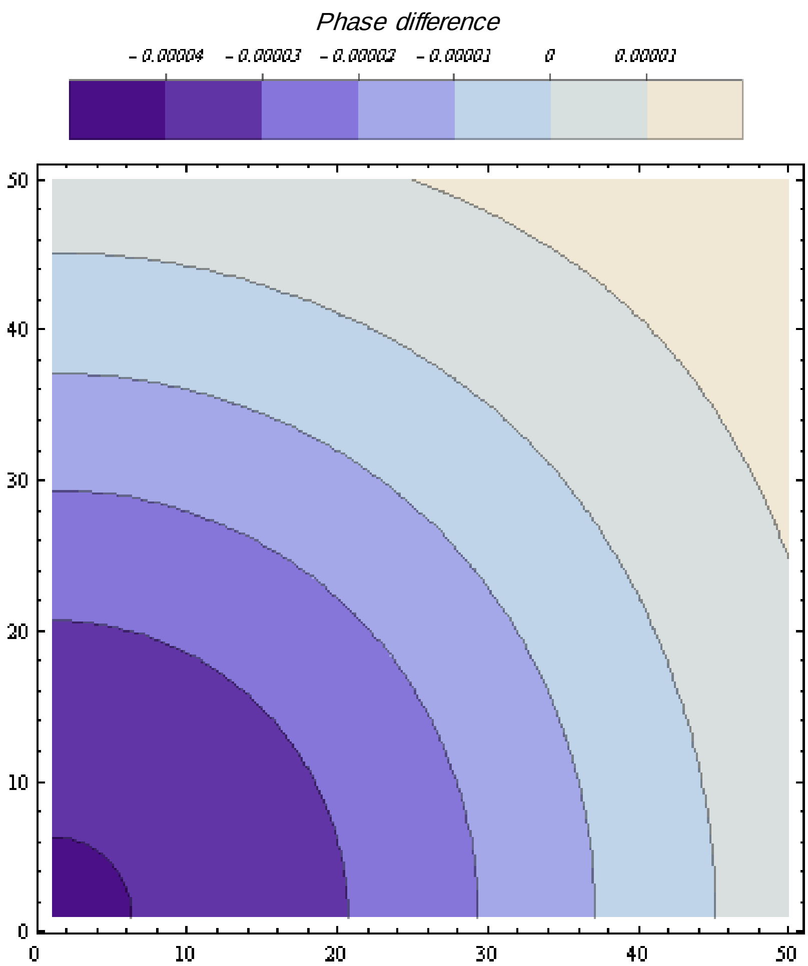


Figure 8. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=340MPa

The real part of the result which is the displacement value in the domain is presented in Figure 7. The values depicted in Figure 8 are the imaginary part of the results achieved from the method explained in this study using the $G_{Foundation}$=8.686GPa and G_{Soil}=340MPa with the same geometry of foundation and soil as shown in the Figure 2.

In Figures 9 and 10, the results of the motivation of the center point of a circular foundation in Figure 2 with $G_{Foundation}$=8.686GPa and the surrounding soil media with G_{Soil}=380MPa, are represented. The results of these two Figures are consequently related to the imaginary part and real part of the results which show the displacement of each point of the media and the phase difference of each point of the media with the motivation point.

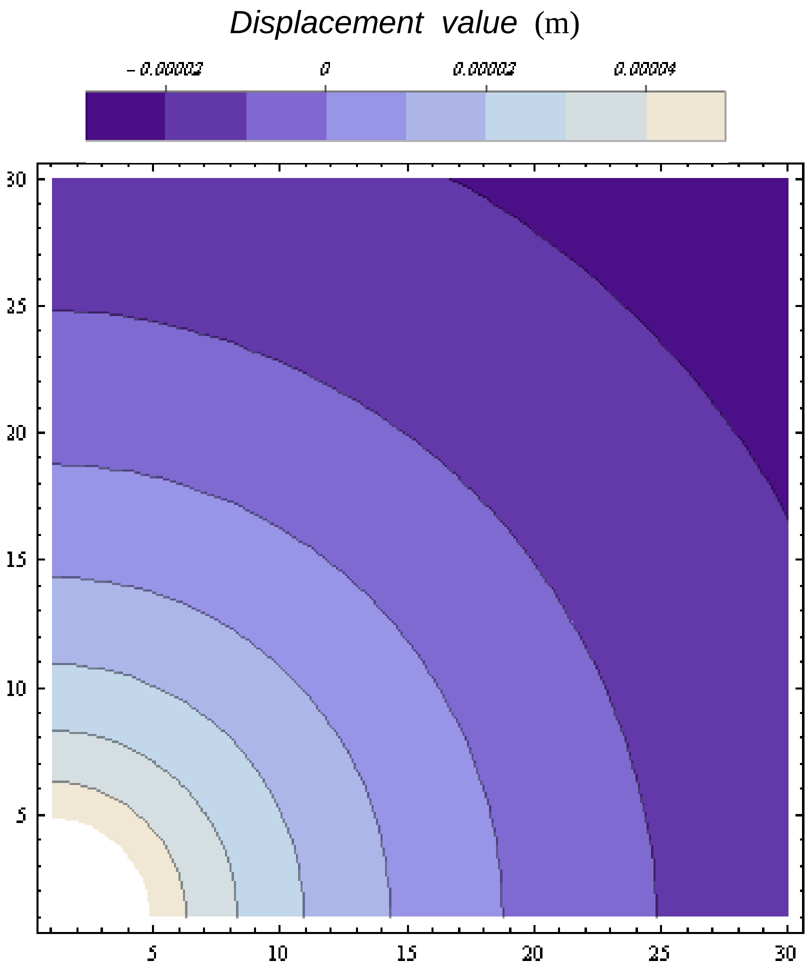


Figure 9. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=380MPa

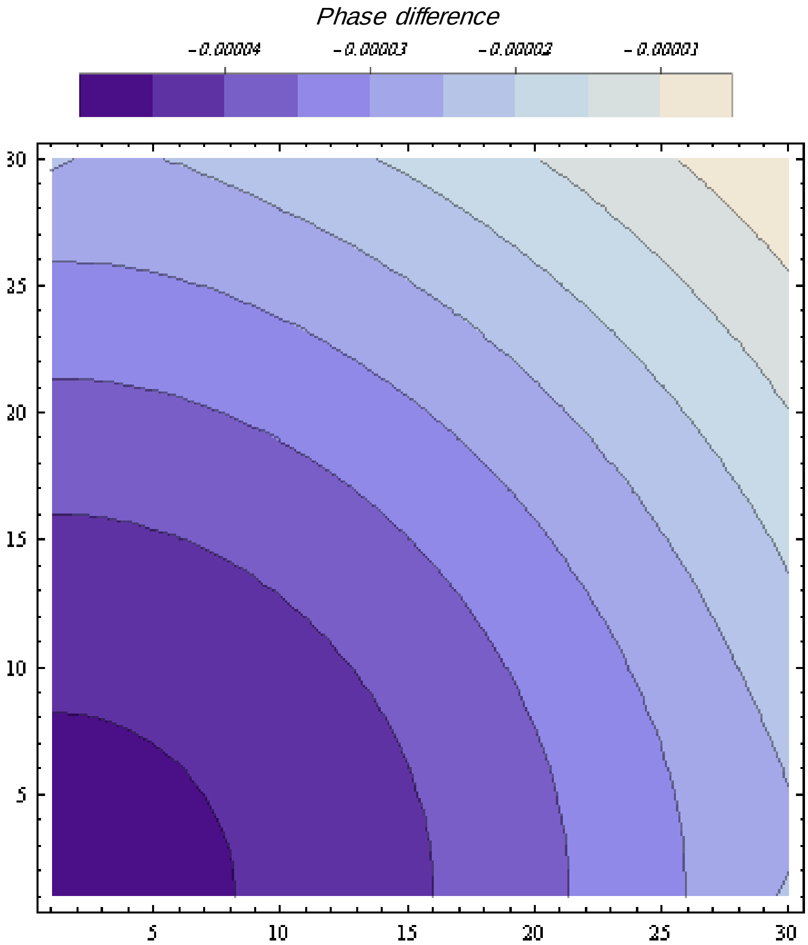


Figure 10. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center- $G_{Foundation}$=8.686GPa and G_{Soil}=380MPa

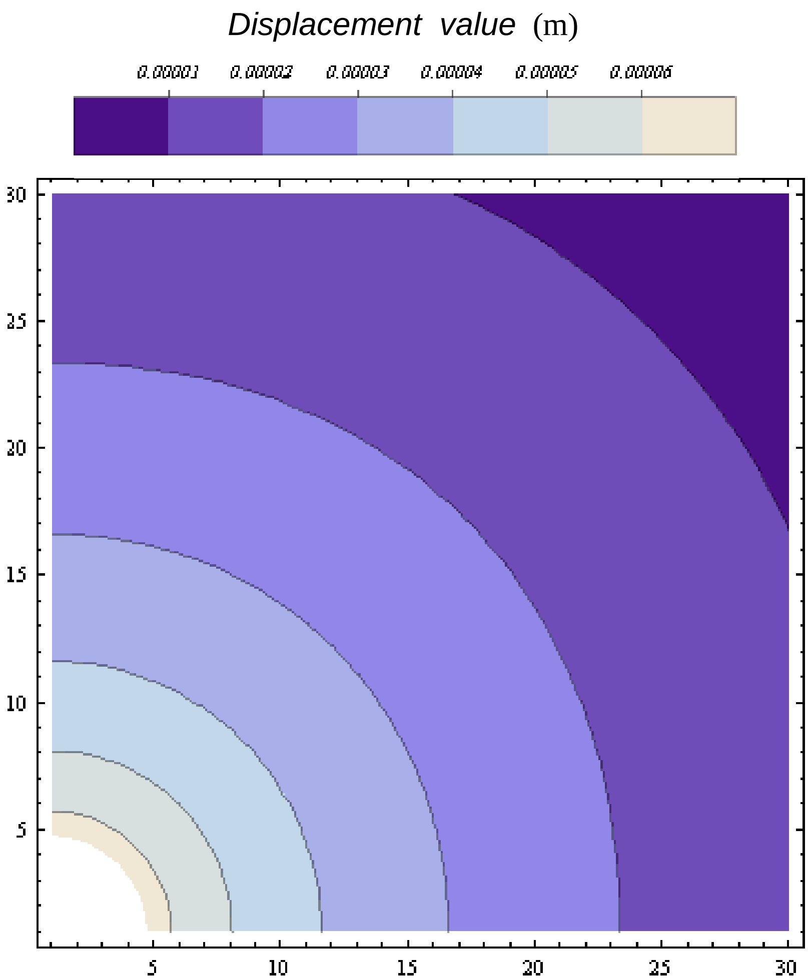


Figure 11. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=1.9GPa

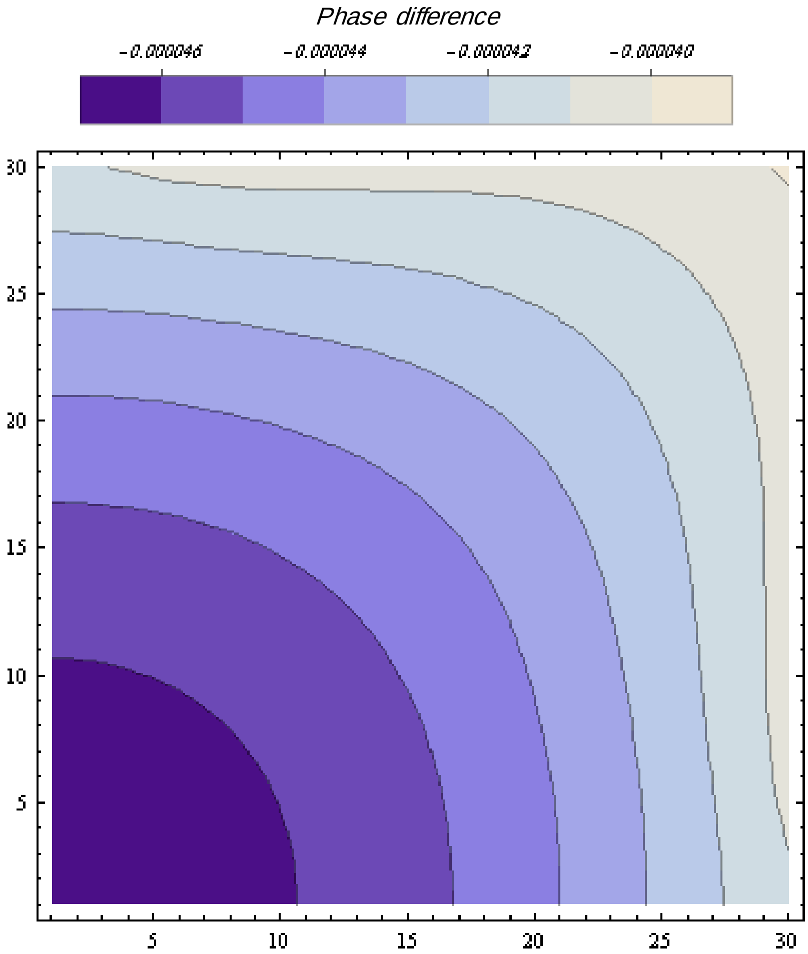


Figure 12. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=1.9GPa

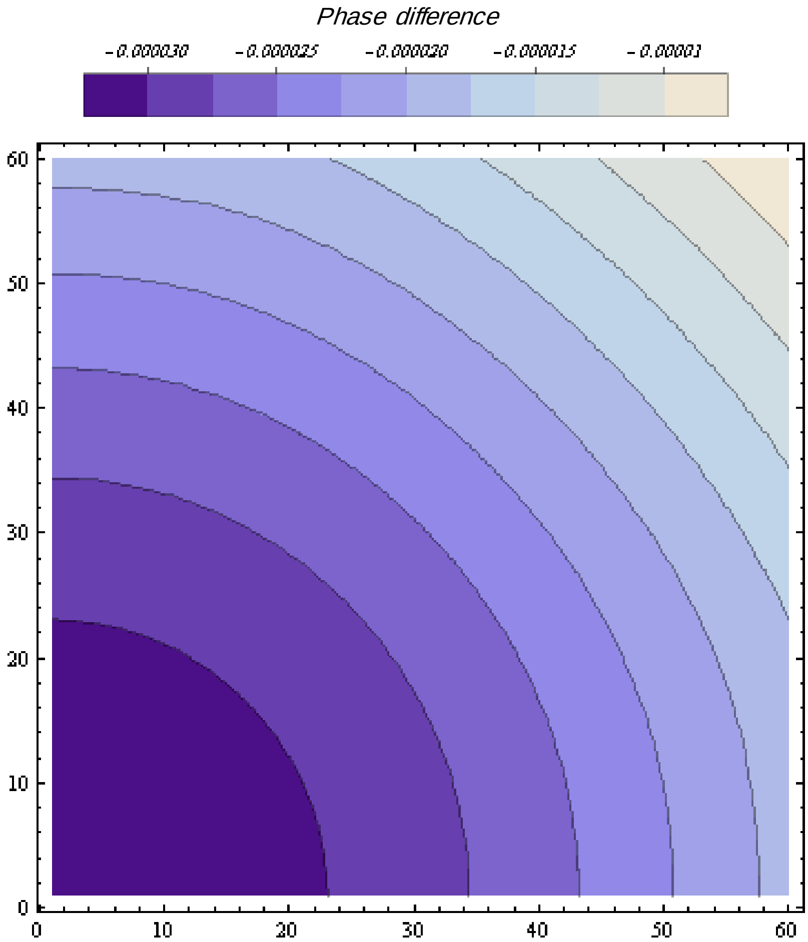


Figure 13. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=1.9GPa with a 60 × 60 Point Domain

So far, 5 types of sand with different shear modulus were used as the surrounding domain around the circular concrete foundation (Figure 2 and Table 2). In this part of the study, 3 types of clay with different consistency described in Table 2 were used as the surrounding domain around the concrete circular foundation to evaluate the accuracy of newly developed method in measuring the domain response to the unit sinusoidal stimulation on the coordinate center. Firstly, the type-1 clay has been used as the surrounding media. Figures 14 and 15 consequently show the real and imaginary part of the response to the unit sinusoidal point stimulation at the center of a concrete circular foundation with $G_{Concrete}$=8.686Gpa, radius of 0.5m and surrounding clay soil with G_{Soil}=96MPa. The real part of the result shows the displacement value on each point of the domain and the imaginary part of the result presents the phase difference between motivation and each point of the domain.

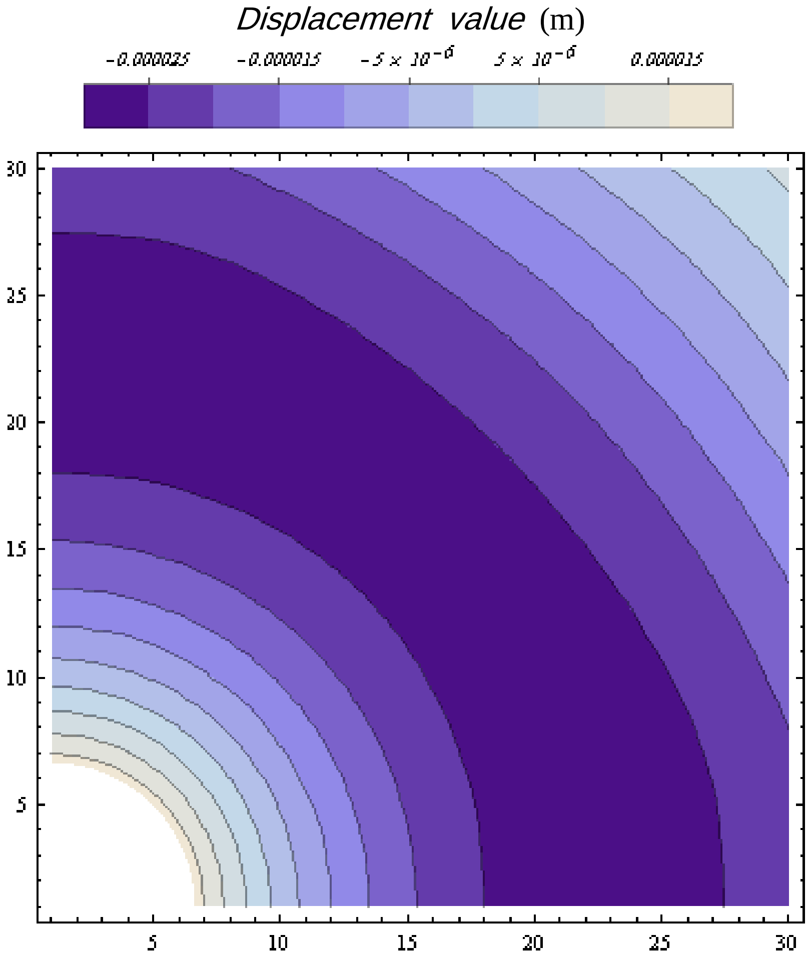


Figure 14. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=96MPa

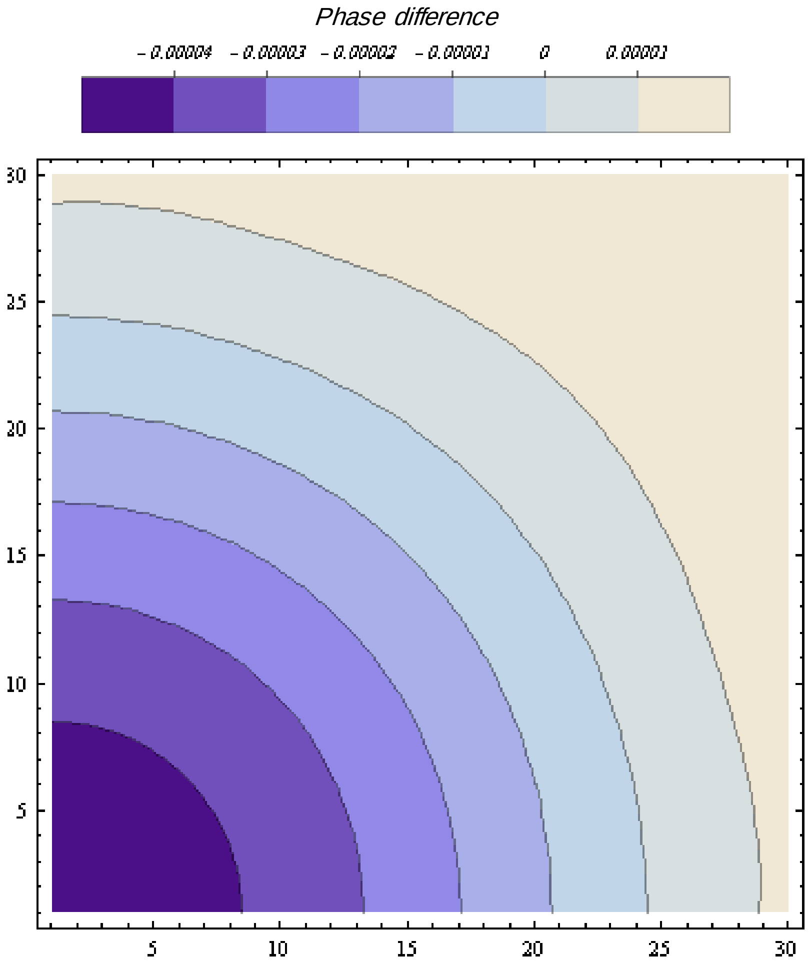


Figure 15. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=96MPa

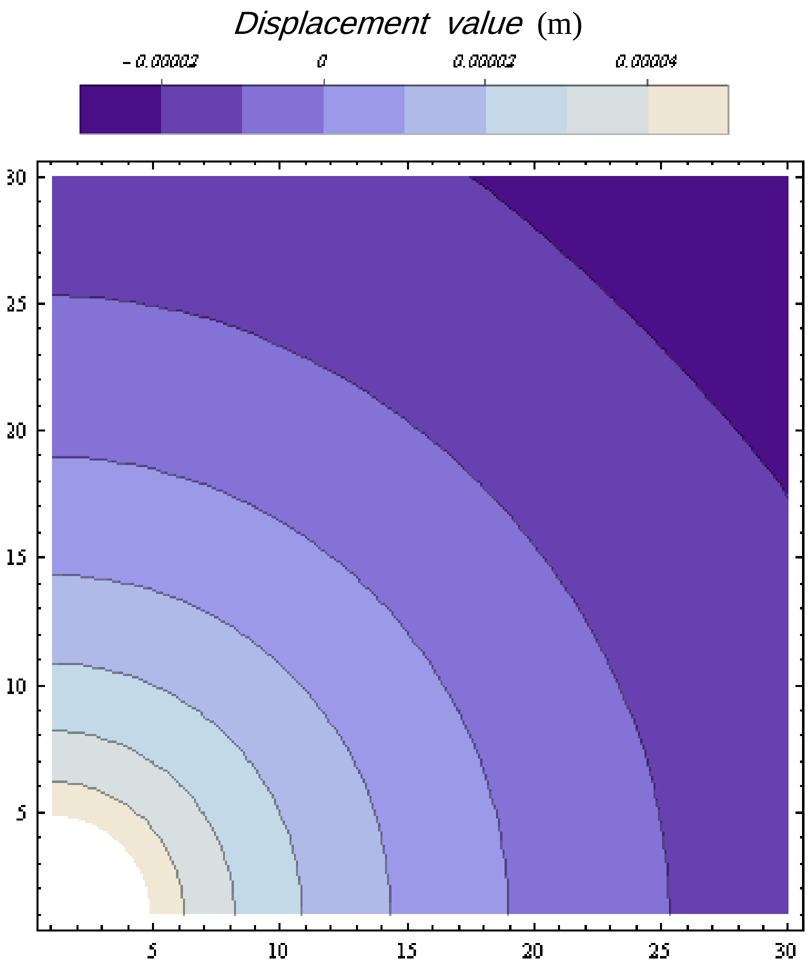


Figure 16. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=480MPa

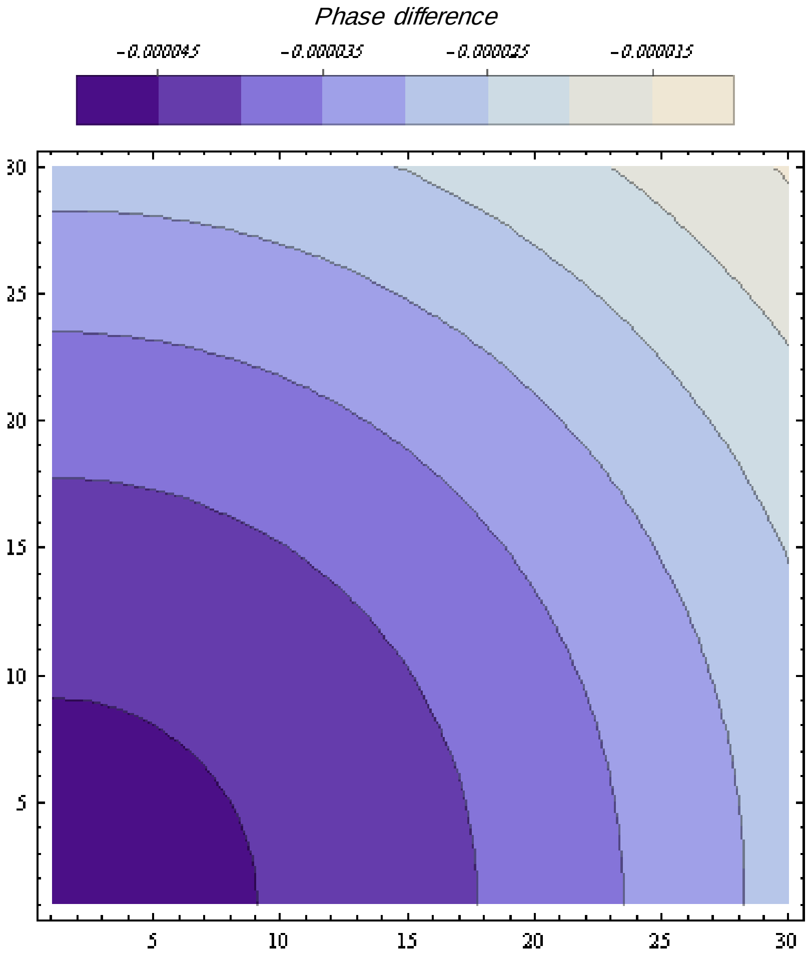


Figure 17. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center, $G_{Foundation}$=8.686GPa and G_{Soil}=480MPa

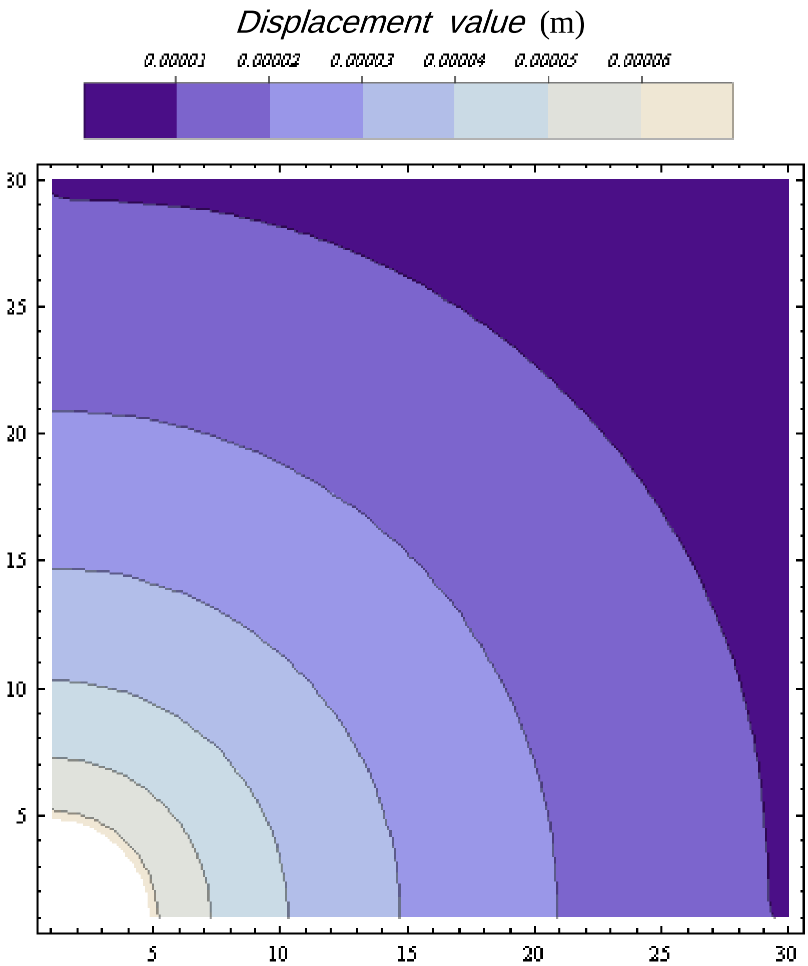


Figure 18. Real Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center- $G_{Foundation}$=8.686GPa and G_{Soil}=2.4GPa

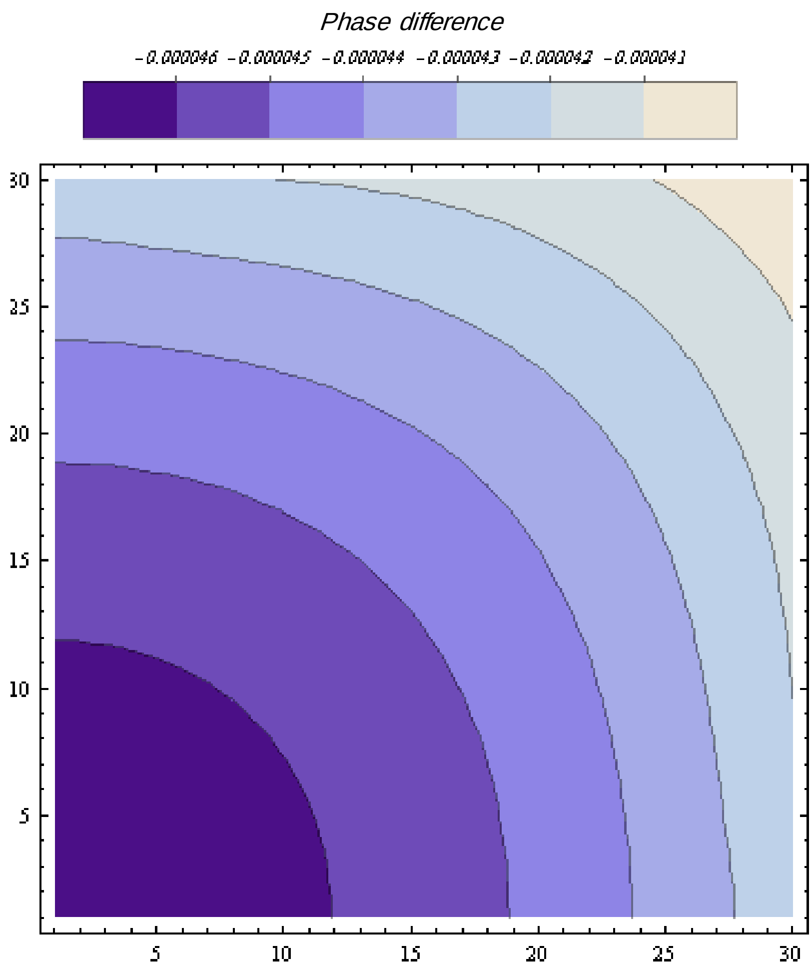


Figure 19. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center- $G_{Foundation}$=8.686GPa and G_{Soil}=1.9GPa

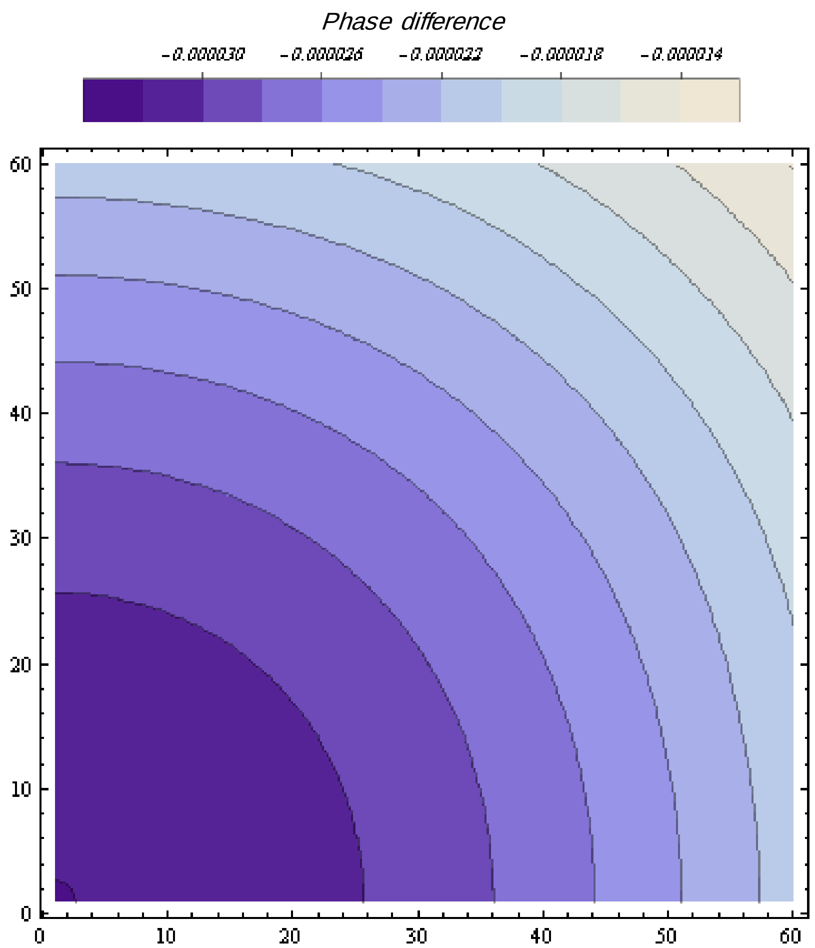


Figure 20. Imaginary Part of Domain Response to the Unit Sinusoidal Stimulation on the Coordinate Center- $G_{Foundation}$=8.686GPa and G_{Soil}=1.9GPa with a 60 × 60 Point Domain

Figure 18 is the real part of solution related to the problem of a circular concrete foundation stimulated on the center point with a point unit sinusoidal force. This foundation has the radius of 0.5m. The surrounding media of the foundation is the Type-3 clay as described in Table 2 with G_{Soil}=2.4GPa.

In Figures 19 and 20, as it was seen before in the case of sandy soils (Figures 12 and 13), the solution domain selected to use the developed method in this research is smaller than the wave length propagated in. The imaginary part of the results cannot be acceptable and will be polluted with the errors specially in the parts near the outer boundaries. Therefore the domain which was selected to be used with the method should be growing to achieve acceptable results. In the example represented in Figures 19 and 20, after different domain sizes tested to achieve the acceptable values for imaginary results, the double sized domain, 60×60 meters, in comparison with the original size selected for all other examples decided to be used.

4.2.2 Comparison of the Method Developed in this Study with the Former Methods

Comparing the results of the developed method in this thesis with a reliable former method justifies the reliability of the new method. For this reason, the method which was presented by Jiangfeng and Youming [100]: numerical simulation of elastic wave propagation in non-homogeneous media based on generalized Haskell matrix method, is selected by the author. This method is able to model the wave propagation in the domains combined with soil and concrete, like the condition chosen in this research. Therefore the problems which were solved with the presented method in this study are solved with the method presented in reference [100] to show the efficiency of the new developed method in this thesis.

To have a better sight of view in the comparing process, it is decided to see a section graph of wave instead of whole three dimensional graphs of results. Therefore, a straight section through the stimulation point in the domain is decided to be shown. Since the problems are all symmetric, a straight section through center point which is the same stimulation point is taken to represent the whole domain response.

In Figures 21, 22 and 23 the comparison between the results of the generalized Haskell matrix method [100] and the method which is presented in this study are shown. The maximum distance shown in these figures from the center of foundation is 50 (m).The radius of circular foundation in Figures 21, 22 and 23 is 0.5 (m) and since this foundation is made up of concrete, its shear modulus is 100 (MPa). The shear modules of the surrounding soils in these three Figures are respectively 10 (MPa), 20 (MPa) and 50 (MPa).

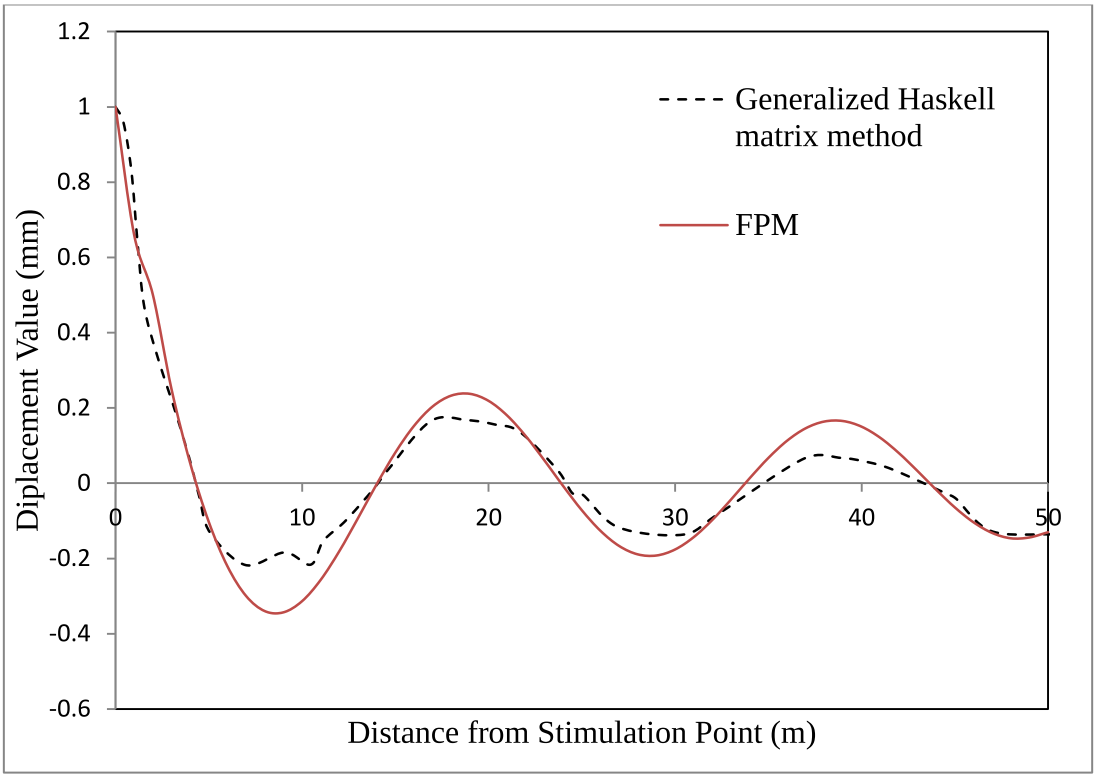


Figure 21. Real Part of a Domain Response to the Sinusoidal Dirac-Delta Dirichlet Motivation, Shear modulus of the Soil 10 MPa

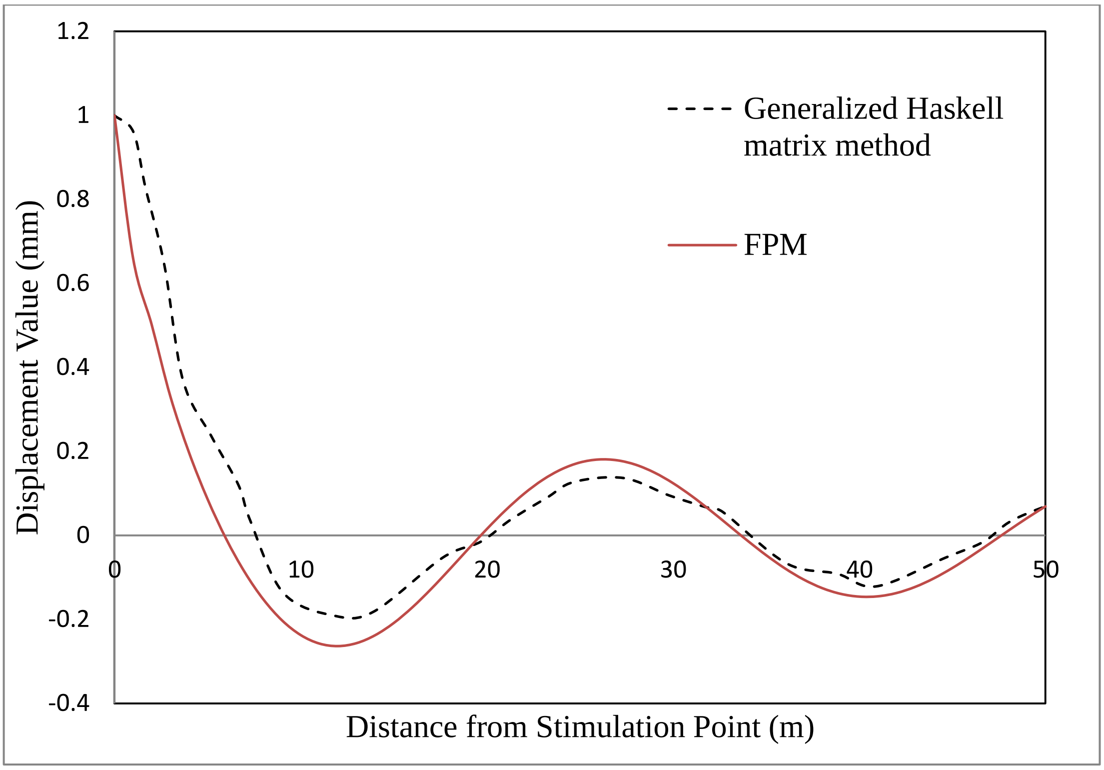


Figure 22. Real Part of a Domain Response to the Sinusoidal Dirac-Delta Dirichlet Motivation, Shear Modulus of the Soil 20 MPa

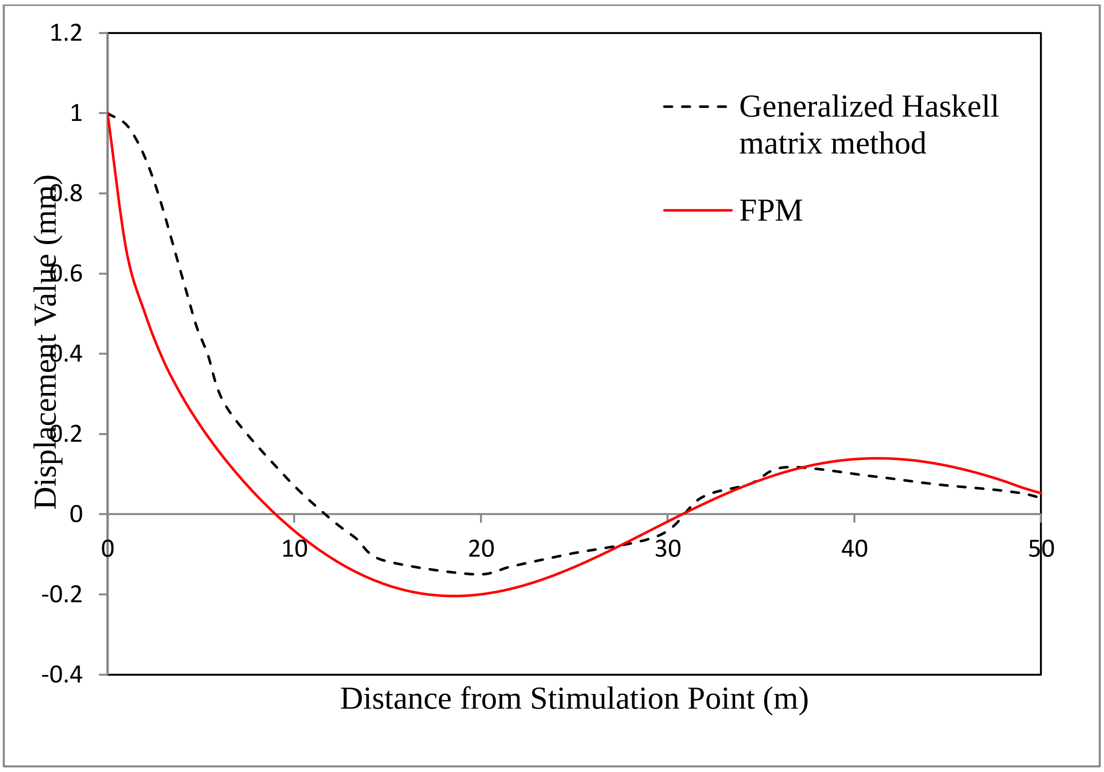


Figure 23. Real Part of a Domain Response to the Sinusoidal Dirac-Delta Dirichlet Motivation, Shear Modulus of Soil 50 (MPa)

According to the Figures 21, 22, and 23 it can be clearly seen that the method which is presented in this study shows smooth curves. The generalized Haskell matrix method does not have such smooth curves as the developed method in this study despite it is known that the wave value does not change in one material suddenly and the changes in real will be smooth.

4.2.3 Three-Dimensional Waves Propagated in the Non-homogeneous Domain

In order to define a safe distance from the vibrating machine's foundations in the area where the people will not suffer from these vibrations, a case study was presented and the safe distance was determined using the special form of FPM which is developed in this research considering also the present codes and standards of health and safety [9, 26, 32]. As mentioned in Chapter 2 of this study, the effect of vibrating machine foundation on the health and comfort of people living and working in the surrounding area has not been considered in the design of such foundations and needs to be investigated.

The example which had been selected to be studied for a safe distance from the vibrating machine's foundations was a foundation of rotating blower with rigid block. This foundation is located in the "Industrial Site of Jubail 2" which is in the west coast of Persian Gulf in Saudi Arabia [97].

For the solution of this problem in which the foundations were designed according to the ACI 351.3R (04) [11], the assumed parameters of the soil are presented in Table 2. All these assumptions are real and are according to what have been mentioned in reference [97].

As it is described in the reference [97], the designed process of vibrating machine foundations according to , ACI 351-3R.04, ACI-318-02 and ASCE 7-05, and the values of loading due to rotating blower, were presented in Table 5, and the results of foundation design are presented in Figure 24.

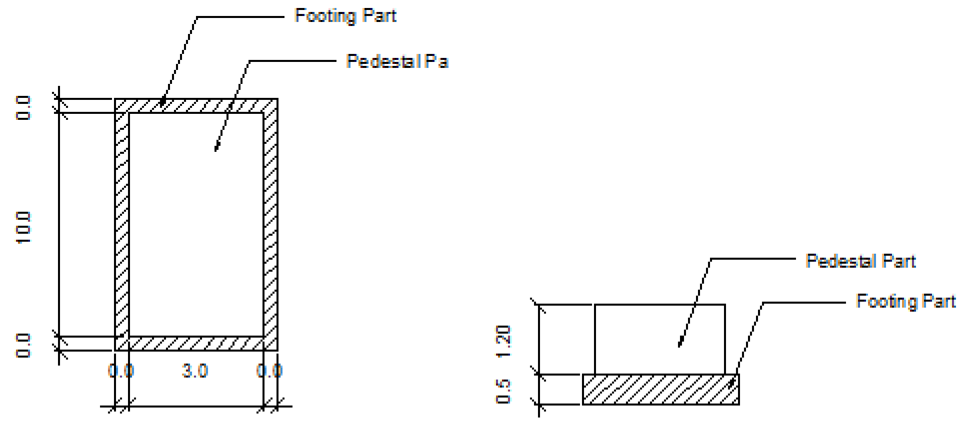
Table 4. Design parameters assumed for soil based on real values [97]

Soil Properties	Values
Allowable soil bearing capacity, kN/m^2	200.0
Shear modulus, G, kN/m^2	82.6
Soil internal damping ratio	0.040
Poisson's ratio, ν	0.321
Unit weight of soil, γ, kN/m^3	17.0

Table 5. Air blower specifications due to real data [97]

Element	Weight (tonnes)
Weight of Blower	13.0
Weight of Motor	9.4
Weight of Base Plate	2.6
Weight of Silencer	6.0
Total Weight	31.0

The foundation which is selected to be discussed in this part of the research was designed based on the ACI 351-3R (04) [11]. The procedure of this design is represented in the related report [97]. The results of this design are as sketch in Figure 24.



(a) Plan of the Foundation (b) Section of the Foundation

Figure 24. Sketch of Plan and Section of the Foundation Designed for Air Blower [97]

Properties of the soil where foundation of the Air Blower constructed on, based on the reference [97] is shown in Table 3. According to the reference [97], all design procedure was done to meet the requirements of ACI 351-3R (04) [11]. The properties of used concrete and the values of loading both static and dynamic are also according to the real data from the reference [97]. Using all these data and the method presented in the methodology chapter: the new developed method based on FPM, the following vibration values given in Figure 25 were obtained in the surrounding areas close to the vibrating machine foundations.

The value of horizontal surface vibration due to the stimulation caused by the blower in the surrounding region is as depicted in Figures 25 and 26. Both the method used and the software developed in this research are able to resolve the horizontal wave in x and y directions. In order to achieve the overall results these two values should be added to each other as vectors for all points of the solution area. The graphs are made supposing the shorter dimension of the foundation, 3 m, and the vibration stimulation are both along y axis.

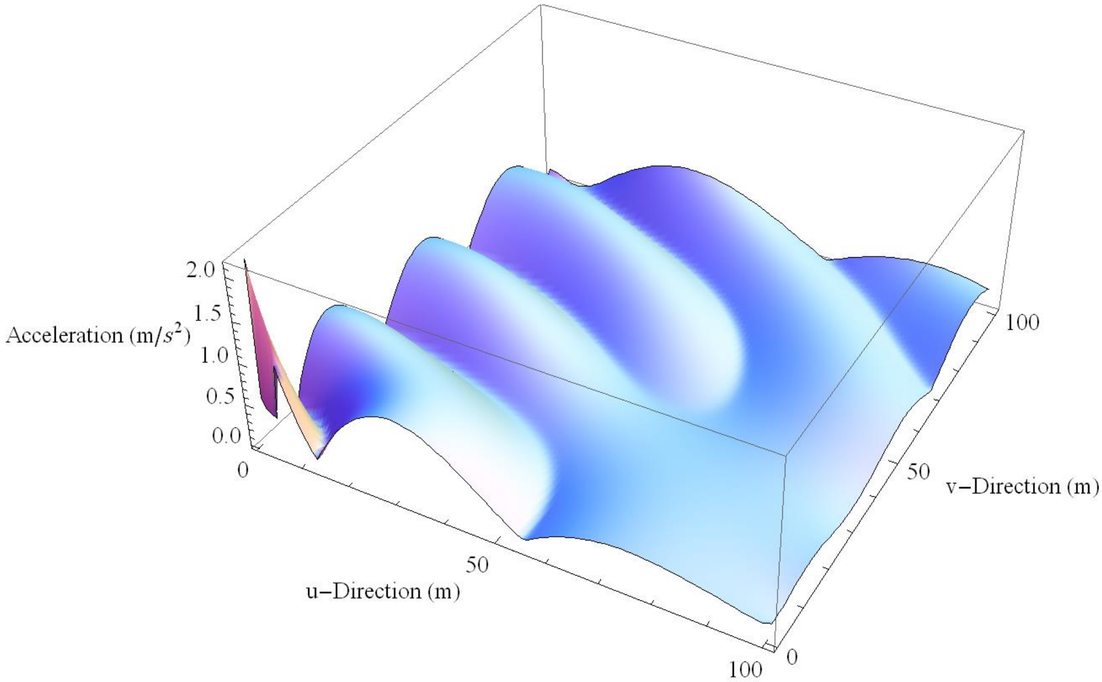


Figure 25. 3D Graph of Surface Absolute Horizontal Acceleration Around the Foundation

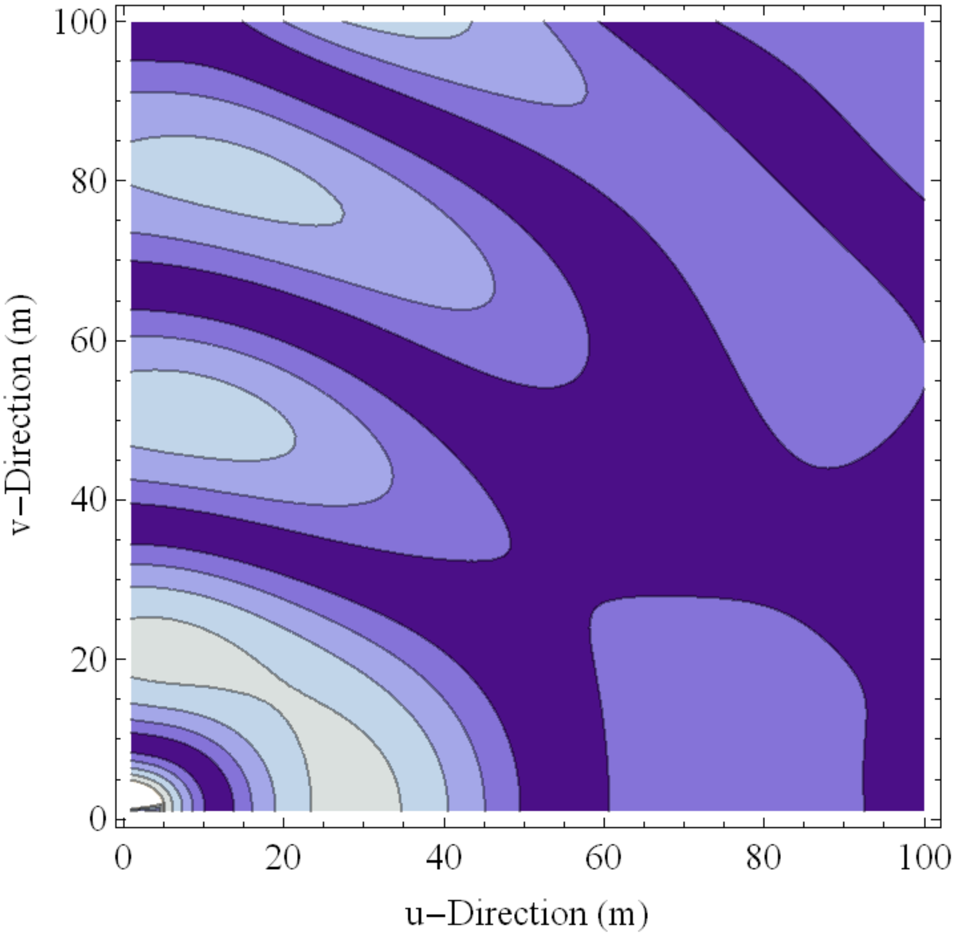


Figure 26. Contour Graph of Surface Horizontal Vibration Magnitude Around the Foundation

These results are all due to the foundation presented in the reference [97] for the air blower. This foundation is designed with ACI 351.3R (04) related to the foundation of vibrating equipment.

The value of displacement in the surrounding area is calculated using the FPM based developed method in this thesis which is presented in Chapter 3. The resulting displacements values were compared with the allowable magnitude of horizontal vibration values for the people who work in the surrounding area as presented in references [26-32]. Being there for 8 hours per day means to work in this area [26]. Also being more than 8 hours in such areas means living there [26]. The safe area for work or live in the surrounding region of this foundation can be detected by the mentioned allowable values in the HSE and ISO standards and mentioned in Table 1 for working or living persons in vibrating regions [26-32].

Figure 27 is a section of graph shown in the Figure 26 along y axes. This is the same direction of the shorter dimension of Air Blower foundation. Since this direction is the same direction of the stimulation, the values of displacement and acceleration are the most in the domain. This fact previously has been discussed in reference [60].

In Figure 28 another section of the graph represented in Figure 26 is shown which is along x axes. This axis is perpendicular to the direction of stimulation. Therefore the responses of the domain to the stimulation are the least along this section [60].

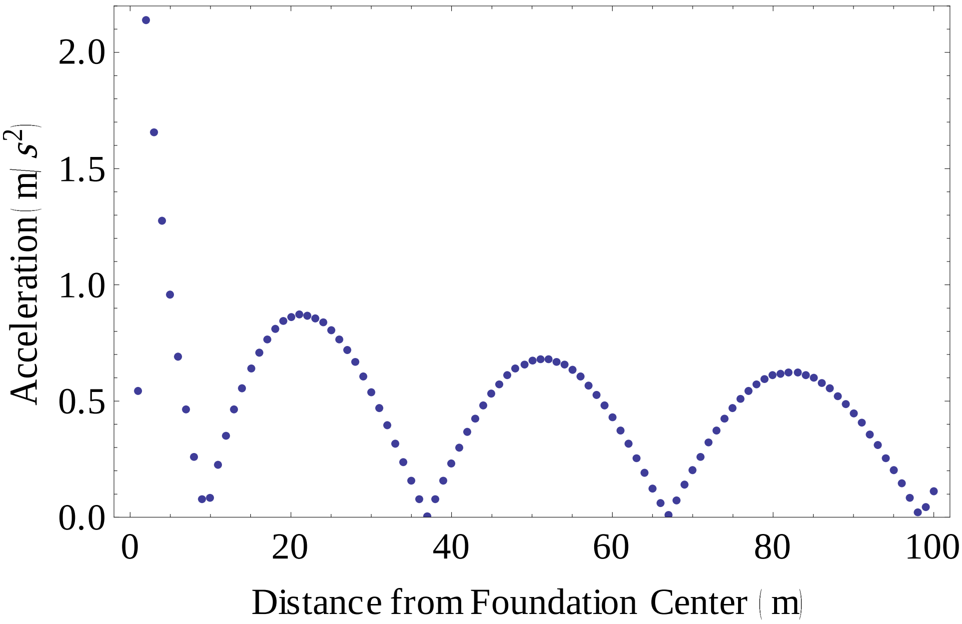


Figure 27. Section of Acceleration Graph Along y-axis

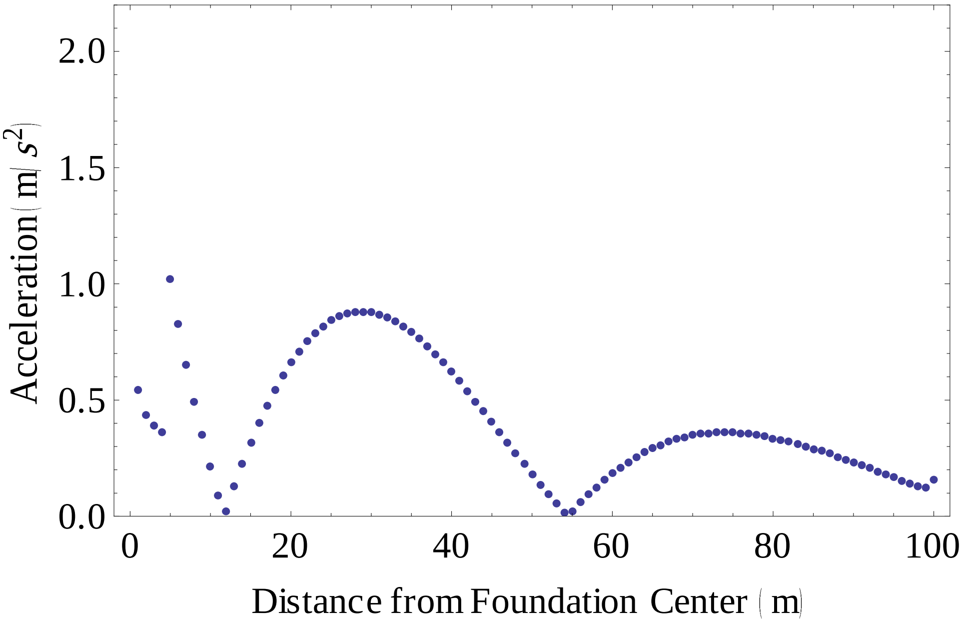


Figure 28. Section of Acceleration Graph Along x-axis

The Figure 29 shows a push graph from Figures 27 and 28. According to this graph and based on the allowable values of exposure vibration to the human body shown in Table 1, the comfort and health distance from the foundation center can be measured.

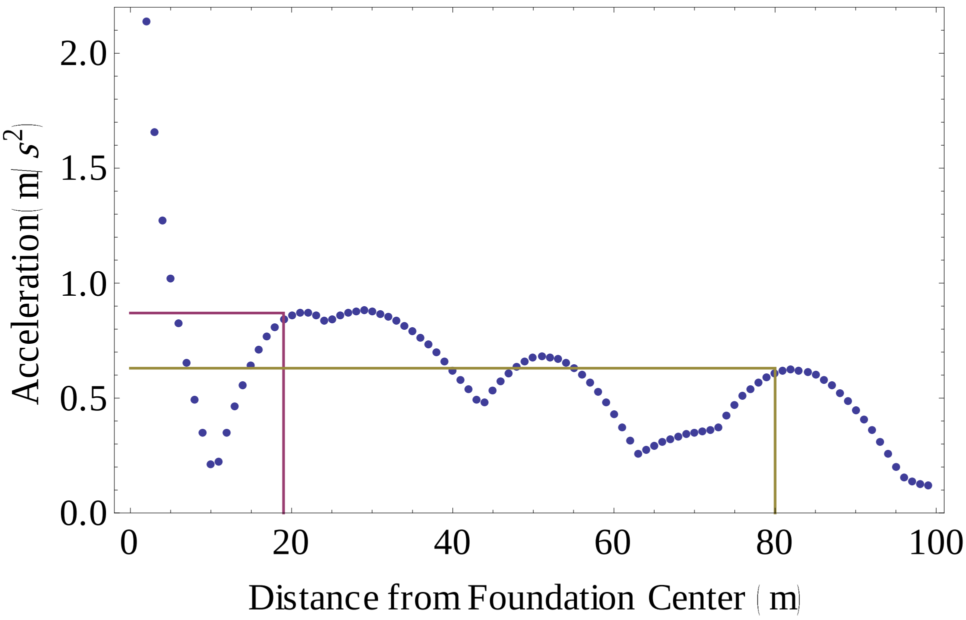


Figure 29. Push Graph of the Acceleration around Air Blower Foundation

Since the health value, the allowable acceleration for full-time workers, in Table 1 is mentioned as 0.87 (m/s^2) the health area based on the push graph shown in the Figure

30 is 19 m from the center of the foundation. It means that the full-time workers are not allowed to work in the distance nearer than 19 m from the center of this foundation. Also according to the comfort value of the acceleration mentioned in the Table 1, 0.63 (m/s^2) the comfort area from center of this foundation is 80 m. This means that living in a distance of at most 80 m from the center of this foundation is forbidden.

4.3 Convergence in Developed Method

The convergence of the solution in terms of the number of points used along x and y axes as well as the number of points used in Gaussian plane for the summations required in the formulation are given below.

An L_2 norm for nodal values of one dimensional wave problems is used for this convergence study. It is defined over a bounded area as given below.

$$\|\bar{\boldsymbol{u}}\| = \sqrt{\sum |\bar{u}_i|^2} \tag{23}$$

In this formula, $|\cdot|$ denotes absolute values of the quantity noting that the nodal quantities can be complex values.

To study the convergence of the solution, different number of integration points are used in a series of solutions. Figure 30 demonstrates the results. Note that the numbers given for integration points represent the number of points used along each direction in Gaussian plane, i.e. along r or θ, and thus one point increase in Figure 30 represents increase in the total number of points used in each quadrant of the unit-radius circle. Sixty points are used along each axis for satisfaction of the boundary conditions and the norms are calculated over an area of 60 × 60 points.

Maximum difference between the norm values for above 56 integration points is less than 0.02% as can be seen in Figure 30. Therefore, there is a good convergence for FPM used in this study.

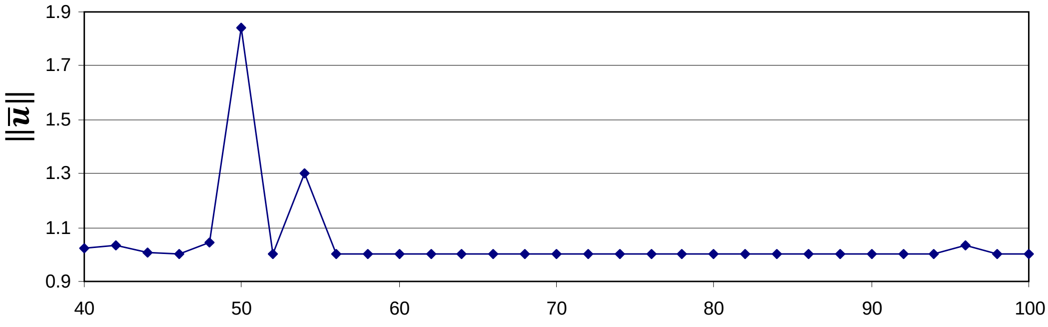


Figure 30. Variation of L_2 Norms of the Solutions for Scalar Wave Problem Versus the Number of Integration Points

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

In this research a new method, which was based on Finite Point Method , has been developed and proposed to be used for modelling the vibrating machinery foundation effect on surrounding residents. The capability of this new method is discussed through its application to some real life cases.

Considering the results obtained from this research and comparing them with the results of the other methods in the area of wave propagation in unbounded domains and the information provided on health and safety in the codes and standards, the following conclusions can be made:

- Since there is no scattering shown in the results of the one-dimensional wave propagation, it can be said that the method presented in this research can clearly model a change of domain phase from concrete to different types of soils.

- The FPM developed in this research is able to show the change of wave length occurred with the change of shear modulus of multi-phase domains from one phase to the other.

- The newly proposed method is able to model the unbounded domain without any effect of reflecting waves from outgoing boundaries.

- The results of the proposed method in this research showed that, the more the distance from the stimulation point, the less the wave displacement value. Therefore, this shows that the method has the capability of showing decay in the wave propagation modelling in different types of soil.

- In the present research, the modelling of one-dimensional shear wave propagation in unbounded domains with two phases: concrete as first phase and different types of soils as second phase, has been done. The results indicated that the wave length is a function of shear modulus of media in which the wave propagates in. The imaginary part of the results achieved from the presented method depends on the part of the media selected to solve the unbounded problem. This means that if the wave length is more than the dimension of part which is selected to solve the problem, then the imaginary part of the results cannot be in an acceptable form.

- The comparison of the results of using developed method in the present research with the results of generalized Haskell matrix method showed a better ability of modelling the wave propagation in a two phase media around the motivation point.

- Convergence of the results, in terms of the number of points along the main axes and integration points in Gaussian plane, has also been addressed. The studies showed that there is good convergence in results.

- When the vibration parameters around the vibrating machine foundations are calculated by using the allowable values suggested by the existing design codes on health and safety, it is clear that this approach creates an uncomfortable and unsafe zone around such foundation. Hence, using the method proposed in this research, the safe distances from the vibrating machine foundations were found to be 19 m and 80 m from the center of this foundation for fulltime workers and people who live nearby, respectively.

The results of this research introduce a method based on FPM to calculate the vibration values around vibrating machine foundations. In the design of such foundations, the obtained values of vibrations with FPM should be compared with the allowable values in the health and safety codes and standards to provide a safe and comfortable area for people around such structures.

5.2 Recommendations for Future Works

Additional design norms considering the health and safety of the people working or living in the vibrating machine foundations should be added in the design codes and standards and further analysis for the determination of the safe distance to such foundations should be performed.

These controls could be done for foundations with variable shapes and sizes and also for different soil types.

Since in this study, the vertical variation of the soil parameters was not considered then further research is recommended to consider this effect.

REFERENCES

[1] Erwing, W.M., Jardetzky, W.S., and Press, F. (1957). *Elastic waves in layered media*, McGraw-Hill Book Company, Inc, New York.

[2] Arya, S.C., O'Neil, M., and Pincus, G. (1979). *Design of structure and foundations for vibrating machines*, Gulf Publishing.

[3] Mobley, R.K., (1999). *Vibrations Fundamentals*, Butterworth-Heinemann; a member of the Reed Elsevier group.

[4] Health and Safety Executive, (06/2014). *Control the risk from whole-body vibration-advice for employers on the control of vibration at work regulations 2014*, free leaflet, HSE books, Sudbury.

[5] Melzig-Thiel, R., Kinne, J., and Schatte, M., (2005). *Vibration load in the construction industry – assessment and protection measures*, Federal institute for occupational safety and health, Dortmund.

[6] Popov, K., (2003). *Fireplace, catalog of technical protection measures vibration*, Federal institute for occupational safety and health.

[7] Professional committee-news sheet 008, (02/2006). *Operational implementation of the EG-Directive 'Vibrations'*, professional engineering committee, manufacturing system, Stahlbau.

[8] European Commission, (2006). *whole-body vibration guide to good practice, Luxemburg*, Office for official publications of the European communities.

[9] ISO 2631:2001, (2001). *Mechanical vibration and shock – evaluation of human exposure to whole-body vibration*.

[10] BS EN 14253:2003, (2003). *Mechanical vibration – measurement and calculation of occupational exposure to whole-body vibration with reference to health practical guidance.*

[11] ACI committee 351, (2004). *ACI 351.3R-04: Foundation for Dynamic Equipment.*

[12] Office of national building regulations, (2013). *Topic 7 of National Building Regulations Foundations*.

[13] Pakash, SH. and Puri, V.K., (2006). "Foundations for Vibrating Machines", *Journal of structural Engineering*, SERC, Madras, India, Special Issues, April-May.

[14] Bazyar, M.H. and Ghanad, Z., (2013). *Soil Dynamics*, 4rd Edition, Iran University of Science and Technology, I.R.Iran.

[15] Vrettos, Ch., (2014). *Soil Dynamics with Application in Vibration and Earthquake Protection*, John Wiley & Sons, Inc.

[16] Sokol, M., (2006/3). "Reduction of Soil Vibration Induced by Traffic", *Slovak Journal of Civil Engineering*, 33-36.

[17] Hölscher, P., Hopman, V., and Degrande, G., (09/2004). “The influence of dynamic soil characteristics on vibration predictions”, *Proceedings of the eighth International Workshop on Railway Noise*, Buxton.

[18] Wang, C.D., Lin, Y.T., Jeng, Y.S., and Ruan, Z.W., (2010). “Wave Propagation in an inhomogenous cross-anisotropic medium”, *International Journal for Numerical and Analytical Methods in Geomechanics*, 34:711-732.

[19] Wang, C.D., Tzeng, C.S., Pan, E., and Liao, J.J., (2006). “Diplacements and stresses due to a uniform vertical circular load in an non-homogeneous transversely isotropic half-space”, *International Journal of Geomechanics (ASCE)*, 6:1-10.

[20] Daros, C.H., (2008). “A fundamental solution for SH-waves in a class of non-homogeneous anisotropic media”, *International Journal of Engineering Science*, 46:809–817.

[21] Ke, L.L., Wang, Y.S., and Zhang, Z.M., (2006). “Love waves in an non-homogeneous fluid saturated porous layered half-space with linearly varying properties”, *Soil Dynamics and Earthquake Engineering*, 26:574–581.

[22] Bazyar, M.H. and Song, C., (2006). “Time-harmonic response of non-homogeneous elastic unbounded domains using the scaled boundary finite-element method”, *Earthquake Engineering and Structural Dynamics*, 35:357–383.

[23] Halliday, D, Resnick, R., and Walker, J, (2005). *Fundamentals of physics*, 7th Ed, John Wiley & Sons, Inc, USA.

[24] Kurowski, P.M., (2014). *Vibration Analysis*, Stephen Schroff (SDC Publications).

[25] Das, B.M., (2014). *Principles of Foundation Engineering*, 8th Edition, Global Engineering: Timothy L. Anderson.

[26] Monazzam, M.R., (2014). *Detection of the Hazardous Physical Agents Workplace (Vibration)*, Nakhl Publication.

[27] HSE Contract Research Report, (333/2001). *Whole body vibration and shock: A literature review*, Stayner RM.

[28] NIOSH, (1997). *National Institute of Occupational Safety and Health*.

[29] International Organization for Standardization, ISO 2631-2, (2003). *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration*, 2nd edition.

[30] Health and Safety Executive, (06/2014). *Hand Arm Vibration-A guide for employees*, leaflet, HSE books, Sudbury.

[31] Health and Safety Executive, (2012). *Hand Arm Vibration at work-A brief guide*, leaflet, HSE books, Sudbury.

[32] Alimohammadi, I., (2007). *Human Vibration*, Fanavaran Publication.

[33] Bovenzi, M. and Betta, A., (1994). "Low back disorders inagricultural tractor drivers exposed to whole body vibration and postural stress", *Applied Ergonomics*, 25. 231- 240.

[34] Bovenzi, M. and Hulshof, C.T.J., (1999). "An updated review of epidemiologic studies on the relationship between exposure to whole body vibration and low back pain (1986-1997)", *Int Arch Occup Environ Health*, 72: 351-365.

[35] Bovenzi, M., Pinto, I., and Stacchini, N., (2002). "Low back pain in port machinery operators". *Journal of Sound and Vibration*, 253(1):3-20.

[36] Bovenzi, M. and Zadini, A., (1992). "Self-reported low back symptoms in urban bus drivers exposed to whole body vibration", *Spine*, vol 17, no 9.1048-1058.

[37] Donati, P., (2002). "Survey of technical preventative measures to reduce whole body vibration effects when designing mobile machinery", *Journal of Sound and vibration*, 253(1),169-183.

[38] Dupuis, H., (1994). "Medical and occupational preconditions for vibration-induced spinal disorders: occupational disease no. 2110 in Germany", *Int Arch Occup Environ Health*, 66: 303-308.

[39] Dupuis, H., (2006). *Diseases due to whole-body vibration. In: Manual of Occupational Medicine: Occupational physiology*, occupational pathology, prevention. Konietzko, Dupuis. and sberg a.L.: ercomed-Verl.-Ges, Loose-leaf-edt. Chap.IV-3.5. (In German)

[40] Griffin, M.J., (1990-1996). *Handbook of human vibration*, Published: Academic Press, London, ISBN: 0-12-303040-4.

[41] Griffin, M.J., (1998). “A comparison of standardized methods for predicting the hazards of whole-body vibration and repeated shocks”, *Journal of Sound and Vibration*, 215,(4), 883-914.

[42] Griffin, M.J., (2004). “Minimum health and safety requirements for workers exposed to hand-transmitted vibration and whole-body vibration in the European Union; a review”, *Occupational and Environmental Medicine*; 61,387-397.

[43] Hartung, E., Heckert, Ch., Fischer, S., and Kaulbars, U., (2006). *Load by mechanical vibration*, Knietzko, Dupuis, Letzel (Hrsg.): Manual of Occupational Medicine, Ecomed Landsberg, Chap. II-3.1,1-16 (33. Completion 8/08). (In German)

[44] Kjellberg, A., Wikstrom, B.O., and Landstrom, U., (1994). “Injuries and other adverse effects of occupational exposureto whole body vibration”, *A review for criteria document Arbete och halsa vetenskaplig skriftserie*, 41.1-80.

[45] Mansfield, N.J., (2004). *Human Response to vibration,* ISBN 0-4152-8239-X.

[46] Palmer, K.T., Coggon, D.N., Bendall, H.E., Pannett, B., Griffin, M.J., and Haward, B., (1999). *Whole-body vibration: occupational exposures and their health effects in Great Britain*, Health and Safety Executive Contract Research Report 233/1999, HSE Books, ISBN: 0-7176-2477-3.

[47] Palmer, K.T., Griffin, M.J., Bednall, H., Pannett, B., and Coggon, D., (2000). “Prevalence and pattern of occupational exposure to whole body vibration in Great Britain: findings from a national survey”, *Occupational and Environmental Medicine*, 57, (4), 229-236.

[48] Palmer, K.T., Haward, B., Griffin, M.J., Bednall, H., and Coggon, D., (2000). “Validity of self-reported occupational exposure to hand transmitted and whole body vibration”, *Occupational and Environmental Medicine*, 57, (4), 237-241.

[49] Sandover J., (1998 a). “The fatigue approach to vibration and health: is it a practical and viable way of predicting the effects on people?”, *Journal of Sound & Vibration*, 215(4) 688-721.

[50] Sandover J., (1998 b). “High acceleration events: An introduction and review of expert opinion”, *Journal of Sound& Vibration,* 215 (4) 927-945.

[51] Kjellberg, A. and Wikström, B.O., (1987). “Acute effects of whole-body vibration. Stabilography and electrogastrography”, *Scand J Work Environ Health,* 13(3):243-6.

[52] Sarafraz, Z.A., (2001). “study on the vibration and electrical stimulation effect on maximum voluntary spasm”, *University of Social Welfare and Rehabilitation Sciences. Rehabilitaion Journal,* 38 (6-7): 270-289.

[53] Nani, V.M. and Cires, I., (2014). “Vibration Control for two Air Compressors Units Used in Tandem”, *World Journal of Engineering and Technology*, 2, 314-321.

[54] Moazam, S., Boroomand, B., Naimi, S., and Celikag, M., (2014). “Wave Propagation in Unbounded Domains under a Dirac Delta Function with FPM”, *Mathematical Problems in Engineering*, vol., Article ID 470346, 8 pages, 2014. doi:10.1155/2014/470346.

[55] Moazam, S., Nalbantoglu, Z., and Celikag, M., (2015). “Use of Finite Point Method for Wave Propagation in Nonhomogeneous Unbounded Domains”, *Mathematical Problems in Engineering*, vol., Article ID 914207, 9 pages, 2015. doi:10.1155/2015/914207

[56] Duarte, C.A., (1995). “A review of some meshless methods to solve partial differential equations”, *TICAM Report*, 95-106.

[57] Fatahpour, R., (2006). *Dynamic analysis of semi-finite domains, using finite element method*, Master Thesis, Civil Engineering Department, Isfahan University of Technology.

[58] Gerdes, K., and Ihlenburg, F., (1999). “On the pollution effect in FE solutions of the 3D-Helmholtz equation”, *Comput. Methods Appl. Mech. Engng.*, 170, 155-172.

[59] Harari, I. and Nogueria, C.L., (2002). “Reducing dispersion of linear triangular elements for the Helmholtz equation”, *J. of Eng. Mech.*, 128:3, 351-358.

[60] Moazam, S., (2007). *On wave propagation in unbounded domains with FDM and FPM*, Master Thesis, Civil Engineering Department, Isfahan University of Technology.

[61] Kirsch, C., (2005). *Non-reflecting boundary conditions for the numerical solution of wave propagation problems in unbounded domains*, Ph.D. thesis, Basel University.

[62] Roach, G.F., (1970). *Green's functions: Introductory theory with applications*, Van Nostrand.

[63] Kaifeng, H. and Ruiqi, C., (2014). "Numerical Study of Elastic Wave Propagation Characteristics in Cracked Rocks", *Journal of Applied Mathematics and Physics*, 2, 391-396.

[64] Banerjee, P.K. and Israil, A.S.M., (1990). "Advanced time-domain formulation of BEM for two-dimensional transient elastodynamics", *Int. J. Num. Methods Engng,,* Vol. 29:7, pp. 1421-1440.

[65] Li. G., Paulino, G.H., and Aluru, N.R., (2003). "Coupling of the mesh-free finite cloud method with the boundary element method: a collocation approach", *Comput. Methods Appl. Mech. Engng*, Vol. 192, pp. 2355-2375.

[66] Ochiai, Y., (2003). "Multidimensional numerical integration for meshless BEM", *Engng. Analysis Bound. Elem*, Vol. 27, pp. 241-249.

[67] Zhao, C., (2009). *Dynamic and Transient Infinite Elements: Theory and Geophysical, Geotechnical and Geo-environmental Applications,* Springer, Berlin.

[68] Zhao, C., (2010). “Computational simulation of wave propagation problems in infinite domains, Science in China Series G: Physics, Mechanics and Astronomy”, 53(8), 1397-1407.

[69] Zhao, C., (2010). “Coupled method of finite and dynamic infinite elements for simulating wave propagation in elastic solids involving infinite domains”, *Science in China Series E: Technological Sciences*, 53(6), 1678-1687.

[70] Zhao, C., Valliappan, S., and Wang, Y, (1992). “A numerical model for wave scattering problems in infinite media due to P and SV wave incidences”, *International Journal for Numerical Methods in Engineering*, 33, 1661-1682.

[71] Zhao, C. and Valliappan, S., (1993). “A dynamic infinite element for three-dimensional infinite-domain wave problems”, *International Journal for Numerical Methods in Engineering*, 36, 2567-2580.

[72] Zhao, C., Xu, T.P., and Valliappan, S., (1995). “Seismic response of concrete gravity dams including water-dam-sediment-foundation interaction”, *Computers and Structures*, 54, 705-715.

[73] Zhao, C., Valliappan, S., and Tabatabaie, J., (1993). “Effect of impervious members and reservoir bottom sediment on dynamic response of embankment dams”, *Soil Dynamics and Earthquake Engineering*, 12, 199-208.

[74] Zhao, C. and Valliappan, S., (1993). "Seismic wave scattering effects under different canyon topographic and geological conditions", *Soil Dynamics and Earthquake Engineering*, 12, 129-143.

[75] Zhao, C. and Valliappan, S., (1993). "Incident P and SV wave scattering effects under different canyon topographic and geological conditions", *International Journal for Numerical and Analytical Methods in Geomechanics*, 17, 73-94.

[76] Zhao, C. and Valliappan, S., (1993). "Effect of raft flexibility and soil media on the dynamic response of a framed structure", *Computers and Structures*, 48, 227-239.

[77] Zhao, C. and Xu, T.P., (1994). "Effects of backfill soils and incident wave types on seismic response of a reinforced retaining wall", *Computers and Structures*, 53, 105-117.

[78] Zhao, C. and Valliappan, S., (1993). "Transient infinite elements for seepage problems in infinite media", *International Journal for Numerical and Analytical Methods in Geomechanics*, 17, 324-341.

[79] Zhao, C. and Valliappan, S., (1993). "Mapped transient infinite elements for heat transfer problems in infinite media", *Computer Methods in Applied Mechanics and Engineering*, 108, 119-131.

[80] Zhao, C. and Valliappan, S., (1994). “Transient infinite elements for contaminant transport problems”, *International Journal for Numerical Methods in Engineering*, 37, 1143-1158.

[81] Givoli, D., Harari, I., (1998). “Special issue on exterior problems of wave propagation”, *Comput.Math. Appl. Mech. Engng*, Vol. 164, Issue 1.

[82] Astley, J., Gerdes, K., Givoli, D., and Harari, I., (2000). “Special issue on finite elements for wave propagation”, *J. Comput.Acoust*, Vol. 8:1, pp. 257-261.

[83] Turkel, E., (1998). “Special issue on absorbing boundary conditions”, *Appl. Num. Math*, Vol. 27, Issue 4, pp. 341-365.

[84] Givoli, D., (2004). “High-order local non-reflecting boundary conditions: A review”, *Wave Motion*, Vol. 39, pp. 319-326.

[85] Givoli, D., (1991). “Non-reflecting boundary conditions: A review”, *J. Comput. Phys*, Vol. 94, pp. 1–29.

[86] Engquist, B. and Majda, A., (1979). “Radiation boundary conditions for acoustic and elastic calculations”, *Commun. Pure Appl. Math*, Vol. 32, pp. 313–357.

[87] Keller, J.B. and Givoli, D., (1989). “Exact non-reflecting boundary conditions”, *J. Comput. Phys*, Vol. 82, pp. 172–192.

[88] Appelo, D., (2003). *Non-reflecting boundary condition for wave propagation problems*, Ph.D. thesis, Royal Institute of Technology, Department of Analysis and Computer Science.

[89] Bérenger, J.P., (1994). "A perfectly matched layer for the absorption of electromagnetic waves", *J. Comput.Phys*, Vol. 114, pp. 185–200.

[90] Berenger, J.P., (1996). "Three-dimensional perfectly matched layer for the absorption of electromagnetic waves", *J. Comput.Phys*, Vol. 127, pp. 363-379.

[91] Boroomand, B. and Mossaiby, F., (2006). "Dynamic solution of unbounded domains using finite element method: Discrete Green's function in frequency domain", *Int. J. Num. Methods Eng.*, 67, 1491-1530.

[92] Onate, E., Idelsohn, S., Zienkiewicz, O.C. and Taylor, R.L., (1996). "A Finite Point Method in computational mechanics-applications to convective transport and fluid flow", *Int. J. Numer.Meth. Engng.*. Vol. 39, pp. 3839-3866.

[93] Onate, E., Idelsohn, S., Zienkiewicz, O.C., Taylor, R.L. and Sacco, C., (1996). "A stabilized Finite Point Method for analysis of fluid mechanics problem", *Comput. Meth. Appl. Mech. Engng.*, Vol. 139, pp.315-346.

[94] Onate, E., Perazzo, F. and Miquel, J., (2001). "A Finite Point Method for elasticity problems", *Compt. Struct*, Vol. 79, pp. 2151-2163.

[95] Zhang X., Liu X.H., Song K.Z., and Lu M.W., (2001). "Least-square collocation meshless method", *Int. J.Num. Methods Eng.*, 51(9), 1089–1100.

[96] Boroomand, B., Tabatabaei, F., and Onate, E., (2005). "Simple Modification for Stabilization of the Finite Point Method ", *Int. J. Num. Methods Eng.*, 63(3), 351-379.

[97] Adi, R., (2011). "Calculation Report: Design for Blower Foundation", *Saudi Aramco Total Refining and Petrochemical Company*.

[98] ACI committee 318, (2002). *ACI 318-02: Building code requirements for structural concrete (ACI-318-02) and commentary (ACI 318R-02).*

[99] ASCE Index. (2005). *Minimum Design Loads for Buildings and Other Structures*: ASCE/SEI 7-05, pp. 385-388.

[100] Jiangfeng, Zh., Youming, L., (1997). "Numerical solution of elastic wave propagation in non-homogeneous media", *Wave Motion*, Vol. 25, pp. 109-125.

[101] Office of national building regulations, (2013). *The National Building Regulations Topic 9: Concrete Structure Design*, National Building Regulations of I.R.Iran.

[102] Ghavami, P., (2015). *Mechanics of Materials: An Introduction to Engineering Technology*, Springer International Publishing Switzerland.

[103] Kaniraj, A. and Kaniraj, Sh.,R., (2008). *Design Aids in Soil Mechanics and Foundation Engineering*, Tata Mc Graw-Hill, 10^{th} reprint.