QATAR UNIVERSITY

COLLEGE OF ENGINEERING

AN INVESTIGATION OF VIBRATION FROM UNDERGROUND TUNNELS BY USING A PLANE-STRAIN FINITE ELEMENT MODEL

BY

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ABSTRACT

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Title: An Investigation of Vibration from Underground Tunnels by Using a Plane-Stain Finite Element Model.

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In 2013, Qatar Rail announced major rail projects that include an urban rail network for the city of Doha with lines running on the surface and underground which are expected to be in operation by 2020. Railway systems are known as attractive means of transportation that can be implemented to solve traffic problems in urban areas. However, they are associated with noise and vibration that cause disturbance, not only to passengers, but also to occupants of nearby buildings. The purpose of this research is to contribute to the literature by developing an understanding on the dynamic tunnel-soil interaction and the propagation of waves in the ground. In this work, a Finite Element model has been developed that accounts for the specific details of tunnel and ground by a commercial FE software, Abaqus 6-14.

The software is used first to model a single isolated tunnel in 2D (plane strain) with point load (corresponding to line load for the 3D case). Then, the software is used to model 3D tunnel under a line load. The results for the 2D and 3D models were found to be matching each other as well as with results from other models reported in the literature. A 2D plane strain model is then developed for a tunnel embedded in a half space and a good agreement was observed when comparing the results with those reported in the literature.

Finally, the FE package was used to explore the effect of tunnel shape on the propagation of ground-borne vibration. Several FE models of circular, square, rectangular, and oval tunnels embedded in homogenous soil and multi-layered medium representing Qatar soil were created and analyzed. Changing the tunnel shapes have an influence on vibration measurement in y-direction at frequency higher than 50 Hz for a response point located on the ground surface. Under low frequency (1 Hz to 10 Hz), there is no such difference in vibration for a different twin tunnel shapes embedded in multi-layered soil at a response point located on the ground surface. In general, the numerical results revealed that twin tunnels influence the dynamic tunnel-soil interaction in homogenous and multi-layered soil medium.

DEDICATION

To my beloved parents, wife and lovely daughters.

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CHAPTER 1: INTRODUCTION

The purpose of this chapter is to describe in detail the reasons for conducting research in ground-borne vibrations from underground railway tunnels in Qatar by using the Finite Element Package for model tunnel-soil interaction and to set-out the objectives of this research and to provide a brief about the outline of the project.

1.1 Background

Land transportation systems have been developed all over the world where many countries are currently developing safe, fast, modern and highly sophisticated systems including the use of cars, trains, and other means.

Railway transport system is one of the most modern land transportation systems. It is used to transport passengers and goods. This system is directionally guided by the rails which characterizes this type of transportation. Tracks mainly consist of steel rails that are installed on sleepers. The rolling stock (rail vehicles) is fitted with metal wheels that move on a track. Other railway systems use slab track in which the rails are fixed on a concrete foundation that is built on a subsurface or in underground tunnels.

In the 6^{th} century, the first railway was known in Greece as man/animal-hauled railway. In the middle of 16^{th} century, Germany constructed a rail transportation system. In London, the first underground metro built by George Stephenson and his son was opened in 1863 making the UK railway system the oldest railway transportation system in the world. Railway transportation system reduces and minimizes the cost of shipping goods. Many countries followed London’s lead such as America, Thailand, India, Egypt, and the Gulf Cooperation Council Countries (GCC).

The development of the train networks began at a rapid pace in the Gulf States which demonstrates the development and prosperity of their economies. In the United Arab Emirates (UAE), the Dubai Metro was the first underground railway system built. It was opened to the public in 2009. In Saudi Arabia, many railway systems are under development in such cites like Makkah-Medina where a high speed 453-kilometer-long railway is under construction. The Riyadh Metro is also under construction. It consists of six lines with a total length of 176 kilometers and 85 stations. It is expected to open in 2019. In Qatar, Doha metro project had been started in 2013 which is part of the Qatar's national vision achievement program. This vision is to develop the country in four major distinct areas which are:

1) Human development of all its people to enable them to sustain a prosperous society;
2) Social development of a just and caring society based on high moral standards;
3) Economic development with a competitive and diversified economy that can meet the needs of all people in Qatar.
4) Management of the environment to ensure there is harmony between economic growth, social development and environmental protection.

The main purpose of this plan is to transform Qatar in the areas of economic, social, human and environmental into an advanced society with a sustainable economy by 2030. One of the areas of development is the transportation system. As the economy develops, it needs a transportation system that can grow in parallel with the size of the economy. Qatar's government announced a plan in 2011 to develop a world-class railway system, which will provide an attractive and competitive alternative to private transport. Qatar Rail is governmental agency responsible for design, build and operate the rail system in Qatar.

There are three major rail projects in Qatar which are:

1) The Doha Metro: an underground rail network that is connecting Doha with other cities in Qatar such as Al Wakra, Al Khor, Al Rayyan and Al Sadd.
2) The Lusail Tram: a tram network within Lusail city
3) The Long Distance: a rail network that is connecting cities in the north and west with Doha, and the country with the GCC rail system in future.

The plan is to build an infrastructure valued at 13 billion USD with four lines with a distance of 300 Km and 100 stations. The four lines are Gold line, Red line, Green line and Blue line. Those lines are currently under construction and are scheduled to open in 2019. Most of the sections of the proposed project lines are underground, but it also includes at-grade and grade separated sections. The railway lines and underground system are expected to alleviate the traffic problems in Doha and upgrade the quality of life for its residents and visitors. One of the problems that is related to underground railways system is the vibration generated by the movement the train. This vibration is propagating in the soil to the buildings and ground surface which called Ground-borne vibration

Ground-borne vibration is a serious concern for close neighbors of a railway systems and maintenance facilities. It causes structures to vibrate and rumbling sounds to be generated. Ground-borne vibration is a common environmental problem within developed cities. The source of vibration can come from buses and trucks. Another source of ground-borne vibration is construction activities such as blasting, pile-driving and operating weighty earth-moving equipment. The vibration can be generated by the train's wheels roll on rails which makes the vibration energy spread through the track support system into the transit structure. The energy, which is transferred into the transit structure, depends on aspects such as smoothness of wheels and rails. There is integration between the resonance frequencies of the vehicle interruption system and the track support system. These systems, like all mechanical systems, have resonance which amplified the vibration response at specific frequencies, called natural frequencies. The study of vibration has become a very sensitive matter during the operational period of the railway systems. The main reason for that is when the generated vibration frequency amplitude is high, it can damage slab tracks, crack tunnels, cause settlement to the foundations and damage nearby buildings.

Considerable research has been carried-out in recent years with the goal of understanding the physics of vibration generation and propagation as well as helping to develop tools to examine reduction measures. Vibrations propagate in the form of waves through soil and buildings (Auersch 2015a). Railway transportation systems must meet stringent criterion for ground-borne noise and vibration at nearby buildings (Hussein and Hunt 2006a). Trains run on the railway trucks on different levels. For example, at-grade (grade level), elevated structure system (viaducts) or in underground tunnels. The generated vibrations which are propagated away from the track can be experienced as fellable vibration or as audible rumbling noise in the buildings nearby (Triepaischajonsak et al. 2011). The focus of the research will be on the vibrations that are generated from underground railway system. The modeling of ground-borne vibration and noise from underground railway systems is important in understanding the physics of generation and propagation of vibration. It also helps engineers to develop numerical tools that can be used for designing a railway system with minimal environmental impact.

1.2 Research Motivation

Qatar government is developing a land transportation system by introducing a new underground railway system which is currently under construction. The Doha Metro will face vibration problems during the operational phase. The vibration acceptance limit within the surrounding buildings on metro lines in Qatar needs to be studied and examined to have a better understanding of ground-borne vibration and noise within Qatar's soil properties. The outcomes of this research contribute to the knowledge and tools needed to predict vibration from the underground railways tunnel in Qatar.

Building metro lines and stations in Doha within very congested areas with high rise buildings affects the existing foundation system. The Doha Metro alignment will link the South of Qatar, Al Wakra city with the coastal city of Lusail in the North. It will also connect Hamad International Airport with Khalifa International Stadium through the Msheireb Underground Station. The Green line will connect the Education City area with Hamad Hospital and the heart of Doha city. The Doha Metro project passes through densely populated areas. The questions that need to be answered are:

1) What are the impacts of implementing a new underground railway system to the existing building foundation?
2) What will be the reactions, and/or the complaints of residents and people located nearby metro stations or metro lines?
3) What are the vibration measurements on the ground surface due to train operation in Qatar?

All these questions and more need to be answered and that's why force vibration research is so important. Therefore, the vibration problem requires a thorough understanding of the tunnels and soil behavior to determine the most appropriate procedures to isolate vibration in nearby buildings. This research will help develop reliable numerical tools that can ensure that the buildings near underground tunnels satisfy their function without any disturbances from vibration.

This research is very challenging because it requires a strong background and good knowledge of soil and structure dynamics. Railway Engineering is a very important field of study. Therefore, this research advances the knowledge of railway engineering and railway dynamics. The Finite Element Method is a numerical technique to perform dynamic analysis of railways underground tunnel. The FE Model can be performed by using finite element software called Abaqus.

The outcome of this research will strengthen the research of vibration measurements within the soil medium of limestone and rocks. This study helps the urban planning engineers to identify a proper metro line alignment by knowing the vibration measurements at any area within the country. The design engineers can select buildings and foundation types within the area that is impacted by railway vibration. The impact of ground-borne noise and vibration needs to be minimized by:

1) A detailed and accurate model of railway system comprising of track, tunnel, soil type, existing buildings, water table and material used need to be addressed.
2) A study to show how the ground-borne vibration is generated and propagated.
3) Studying of human perception of vibrations need to be addressed.

1.3 Research Objectives

The aim of this research is to utilize a plane strain Finite Element Model to examine the effect of tunnel shape, number of tunnels and soil layering on ground-borne vibration from underground railway systems in Doha. This research will make a major contribution to the field of vibration related problems in ground conditions that have not been dealt with before. The models are compared against existing models in the case of homogeneous soil. This verification lends confidence to the correctness of the modeling exercise before moving to the new modeling to be attempted for the first time through this work. The developed models are used to examine the effects of soil inhomogeneity and tunnel cross-section and to run simulations with parameters representative for Doha to identify the special features associated with tunnel-soil interaction and wave propagation from tunnels in Doha. The objectives of this research can be summarized in the following points:

1) Compare natural frequency of Finite Element Model for a single 2D free tunnel with the literature;
2) Perform vibration analysis of 2D free tunnel with a concentrated harmonic load applied at the bottom center of the tunnel and compare the results with the literature;
3) Perform vibration analysis of a 3D free tunnel with a harmonic line load applied at the bottom center of the tunnel and compare the results with 2D free tunnel with a concentrated dynamic load and the literature;
4) Validate the FE Model of dynamic analysis of underground railway tunnels with homogeneous soil and compare the results against those from existing numerical models reported in the literature;

5) Prepare a FE Model to study the effects of changing tunnel cross-sections (circular, square, rectangular and oval), tunnel depth and soil layering on vibration from underground tunnels in Doha. The results can be compared against the circular tunnel as a reference model; and

6) Study the effects of twin tunnels on the vibration response from underground railways tunnel with homogenous and layered soil medium in Doha.

1.4 Dissertation Outline

This research consists of five chapters, an introduction to research, review of the literature on the previous work, finite element models to confirm the results in the literature, FE Model for vibration measurements in Doha and conclusion the findings.

Chapter 1 explains the research background, research motivations and the objectives of the research.

Chapter 2 covers the literature review of research related topics. It reviews the ground-borne vibration from underground railway tunnels and the causes and effects of the vibration on the buildings. The dynamic properties and responses of railway systems are very important factors to be reviewed. Human exposure to vibration in residential environments and inside the buildings are reviewed closely.

Chapter 3 consists of an introduction to structure and soil dynamics, finite element modeling procedure, FE meshing, element type, element size, artificial of the non-reflecting boundary condition, modeling assumption and Abaqus software that is going to be used on the project. It also contains verification of the models with the literature. Chapter 3 is used to confirm the result of the findings in the literature. Therefore, paving the way to do the FE Modeling for Qatar soil in chapter 4.

Chapter 4 contains the FE model in 2D for a single underground railways tunnel (circular, rectangular and square) embedded in homogenous and multi-layered half-space. The effects of soil inhomogeneity on ground-borne vibration caused by underground railways tunnel are studied for Doha soil. It also includes a FE Model in 2D for twin underground tunnels (circular, rectangular and square) embedded in homogenous and multi-layered soil in half-space.

Chapter 5 contains a comprehensive summary of the thesis and the conclusion of this research. The recommendations are also discussed in detail as well as the future research needed in the field of ground-borne vibration and noise from underground railway tunnel.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews the previous work that was done in relation to ground-borne vibration and noise. This includes ground-borne vibration, influence of vibration, soil-tunnel interaction models, sources of vibration, vibration analysis methods, methods for reduction of vibration, dynamic properties of railways tracks, non-reflecting boundary condition, modeling of twin tunnels and lack of knowledge in ground-borne vibration.

2.1 Ground-Borne Vibration

The literature shows that there are many publications that have conducted research about ground-borne vibration. The recent trains have benefit of high speeds, safety, energy saving and reliability (Lin and Krylov 2000). The serious concern here is the associated environment hazards such as vibration and noise pollution in urban areas within large cities. Some other researchers studied the vibration problem in buildings. According to (Hussein et al. 2015), this phenomenon is attributed to the vibration of trains' wheels due to the unevenness or irregularity of the tracks on which they operate. (Lin and Krylov 1999) touched on tunnel diameter effect on ground-borne vibrations. (Coulier, Lombaert and Degrande 2014) introduced a study about the effects of the interaction between the sources of the ground-borne vibration with vibration receiver in buildings by using a numerical model. (Park et al. 2016) pointed out the dynamic properties of railway tracks. Other researchers have studied human exposure to vibration in residential environments (Sica et al. 2013, Connolly et al. 2015, Tetsuya, Yano and Murakami 2016) and the force and ground-borne vibration reduction of railway tracks. Generations of ground-borne vibration depends on many factors, including (a) source parameters, (b) soil-tunnel interaction, and (c) propagation of the waves through soil.

The generated vibration can be simplified as the wheels vibrate causing dynamic forces over a wide range of frequencies, which causes vibration of railway tracks and its supporting infrastructure. In other words, there is a dynamic interaction forces between the wheels and the tracks due to irregularities of wheels and tracks. That is the source of dynamic forces in railway engineering. Vibration makes movement in floors and causes noise. It is significant to note that the ground-borne vibration problem occurs at frequencies up to 200 Hz. The vibration of flooring and wall systems may cause noticeable vibration and the speed of items such as windows or plates, or a roar noise. The rumble is the noise radiating from the movement of the room surfaces. The room surfaces work like a massive loudspeaker producing what is called ground-borne noise. Ground-borne vibration is almost never annoying to people who are outside. Although the motion of the ground may be apparent without the effects related with the trembling of a building. The motion does not incite the same adverse human response. In addition, the rumbling noise that typically accompanies the building vibration is observable only inside structures. Vibration transmitted to buildings causes serious disturbance, annoyance and degradation in the quality of life as follows: It can be felt directly in buildings that are closed to underground tunnels as floors vibrate. This direct vibration causes discomfort and disturbs activities of residents; Vibration of walls causes movement of household objects, especially mirrors and can cause rattling of windowpanes and glassware. Vibration can be heard as reradiated noise. This is attributed to the generation of sound waves in the air due to vibration of walls and floors. This can be a serious problem for buildings with special functions such as concert halls or recording studios, as the reradiated noise will impair the building acoustics.

Vibration can cause malfunction of sensitive equipment. For example, in hospitals or special laboratories (such as optical laboratories) the level of vibration resulting from underground trains can be larger than the acceptable levels for the safe and serviceable use of the equipment. Vibration could accelerate the propagation rate of micro-cracks such as ancient and historical masonry structures.

2.2 Vibration Influence

The problem with ground-borne vibration is well known and commonly encountered in the cities that have underground railway system. The noise problem was and is still a big problem for people, especially living next to train lines or stations. This problem is not a recent phenomenon and has existed since engineers-built train tunnels, especially in Europe. This problem was discussed in (Fields 1979) research for British Railways which was reported in 1976. The noise that affects the residents is related to the distance from their locations to the railway position. Therefore, during the planning of a new city with a railway system, a careful study needs to be carried-out by engineers to ensure that the buildings are in a position with an acceptable level of noise. (Öhrström 1997) studied the railway noise effects on the people living nearby railway transportation systems (stations and lines). The study used a questionnaire to examine the noise disturbance effects or annoyance, sleeping turbulences and other people's daily activities. An example of complaints about the noise and vibration are the demonstrations organized in the city of Madrid in 2007 for the government to take actions to reduce ground-borne vibration. This was in response to high levels of vibration received inside houses near railway tunnels. Another example is from the UK where 200 potentially affected businesses and residents signed petition to express their concern about the potential high levels of ground-borne noise and vibration during and after the construction of House of Parliament. The businesses and residents were eventually given assurances that mitigation measures would be adopted to reduce vibration to acceptable levels. According to (Hunt and Hussein 2008), there are many negative effects of large amplitude of vibration like damage of the railway tracks, cracking of roadways, settlement of foundations and damaging of the nearby structures. Noise and vibration from railway networks have been a serious social problem which affects the daily activities of people, especially those living near railway networks. Many resent surveys have been conducted to determine the impact of noise and vibration on people's lives. An example of survey research is presented by (Tetsuya et al. 2016) for railway noise before and after the opening of the Kyushu Shinkansen Line. Surveys had been conducted in Kumamoto from 2009 to 2012. The noise and vibration exposures were increased slightly after the opening of the KSL.

According to BS 6841:1987(BS6841 1987), there are many factors affecting human reaction to vibration which are: (a) people (age, sex, size, etc.), experience, expectation, motivation, body posture and activities; (b) vibration magnitude, vibration frequency, vibration axis, vibration input position, vibration duration and environmental influences (noise, heat, acceleration and light); (c) the vibration frequency ranges affect passenger's ability to read and write – typically it is around 4 Hz.

(Connolly et al. 2015) reported that the track vibrations are undesirable because they adversely affect riding quality, cause safety concerns and increase track degradation. It was demonstrated that if the train exceeds both the Rayleigh wave velocity and the track's critical velocity (Rayleigh Velocity) then the train will be subject to large amplitude of vibrations and waves propagation pattern. Rayleigh wave means an undulating wave that travels over the surface of a solid, especially of the ground in an earthquake, with a speed independent of wavelength, the motion of the particles being in ellipses. The speed of the train also contributes to the generation of vibration. The vibrations generated by high-speed trains are mainly dependent on track deflection. On the other hand, light vehicles are characterized by a low speed and a relatively high density of singular rail surface defects. Therefore, dynamic track deflection mainly contributes to ground wave generation. According to (Connolly et al. 2015), the passengers are affected by vibration frequency range [0.25 Hz to 8Hz]. One of the effects is causing weakness in reading and writing at frequency range [0.8 Hz – 8 Hz]. Another effect of frequency on passenger is motion sickness at frequency range [0.25 Hz – 0.32 Hz].

2.3 Soil-Tunnel Interaction Models

Some of the researchers considered that the tunnel-soil interface is continuously bonded in order to make the analysis easy. (Hussein and Hunt 2006b) evaluated the performance of ground-borne vibration countermeasures for underground railways tunnel by using a power flow method. The radiated power can be affected by track properties and soil-tunnel interaction. (Jones and Hunt 2011) introduced the voids at soil-tunnel interface boundary in the dynamic analysis of ground vibration by using a semi-analytical method. The existence of the voids at soil-tunnel interface affect the value of frequency response by $\pm$5 dB between 100 Hz and 200 Hz. (Jones and Hunt 2012) studied the homogeneity of the soil layers as an important factor that influences the surface vibration response from underground railway tunnels. The variability of the soil elastic modules in the horizontal position does not affect the response of soil to underground railway loading. Vertical variation of soil properties must be carefully considered during the dynamic analysis of underground railways tunnel. (Stypuła 2014) had compared the ground-borne vibration caused by train from a shallow underground tunnel with surface vibration caused by trams & buses. The dynamic response of the structure from underground vibrations is different from the response of the ground surface vibration source. Ground vibrations are the result of the vehicle forces acting into the track, which depends on vehicles weight and irregularities or discontinuities at the wheel/rail interface according to (Connolly et al. 2015). The type of vehicle plays a major role in vibration generation and a proper design of the bogie suspension can significantly reduce levels of ground vibration (Paneiro et al. 2015). Some other researchers were focusing on predicting ground vibration from a surface railways track like (Koroma et al. 2017). According to (Lopes et al. 2016), the vibration is generated by the interaction between the train and the track. It is propagated via track-tunnel-ground system to the buildings. The vibrations inside buildings due to underground railway operations are predicted by using an experimental approach and compare it with Finite Element model. The results from both approaches are compatible. (Kostovasilis, Thompson and Hussein 2017) modeled the vertical and lateral vibration in wavenumber domain that caused by a harmonic load of railway tracks by using an improved semi-analytical model of beam on an elastic foundation.

2.4 Vibration Sources

One of the key difficulties in estimating of ground-borne vibration is the levels of the receiver's location. The following points describe the influences that have weighty effects on the levels of ground-borne vibration such as parameters of the transportation facility, geology and the receiving building. Table 1 summarizes the factors that influence the levels of ground-borne vibration and noise.

(Lin and Krylov 1999) developed a theoretical model for generating ground vibrations by underground trains travelling in ideal case of circular tunnels of finite diameter. By means of the reciprocity principle, the displacement field radiated by a point force applied on the bottom of the tunnel. The results show that the velocities of generated low-frequency ground vibrations increase with the increase of the tunnel diameter.

Table 1 Factors affecting ground-borne vibration (Hanson, Towers and Meister 2006)

Source of vibration	
Vehicle Suspension	When the suspension is stiff in the vertical direction, vibration forces are generated.
Wheel Type and Condition	Wheels on rail are stiff to minimize vibration.
Track/Roadway Surface	Rough track is the cause of vibration.
Track Support System	The highest vibration levels are created by track that is rigidly attached to a concrete track bed.
Speed	Higher speeds result in higher vibration levels.
Transit Structure	The heavier the transit structure, the lower the vibration levels.
Depth of Vibration Source	There are variances in vibration physical appearance between the vibration from underground tunnel and from ground level.
Vibration Path	
Soil Type	Vibration levels are higher in stiff soil than in loose soil.
Rock Layers	Vibration levels are typically high near at-grade track. Subways in rock have lower vibration.
Soil Layering	Soil layering has a significant impact on vibration.
Water Table Depth	The presence of the water table effect vibration.
Vibration Receiver	
Foundation Type	If the building foundation is heavy, the coupling loss is more.
Building Construction	Noise and vibration are appraised in terms of indoor receivers, the propagation of the vibration through the building
Acoustical Absorption	Amount of acoustical absorption in the receiver room

2.5 Vibration Analysis Methods and Mechanism

There is a strong relationship between the soil stiffness and ground-borne vibration response amplitude. The vibration is proportional to the degree of hardness and soil durability. If the railway tunnel is constructed in a soft soil medium, the generated vibration will significantly affect the residents and structures nearby due to high frequency response. Therefore, it is very important to use mathematical models to examine the vibration amplitudes due to the source, propagation media and type of structures. (Ono and Yamada 1989) presented an analytical solution for predicting the ground-borne vibration amplitudes. The rail is supported by rail pads on the sleeper, therefore, it is assumed to be elastic an support. (Ganesan and Ramesh 1992) did a project on the effect of railways wheel material type (composite and steel) and the web orientation of the wheel (strait or curved) on the natural frequency by using a Finite Element Model. It found that changing the orientation of the wheel's web has a significant effect on the natural frequency of the railways. (Degrande et al. 1998) used stiffness method to examine the wave propagation in multilayered soil in dry, saturated and unsaturated conditions in half-space. (Wu and Thompson 2001) touched upon the noise that is released from railway rolling due to multiple wheels friction with rail. The dynamic analysis with more than one wheel reflects the vibration waves in the rail. There is a strong relationship between the vibration response and the speed of the train as an influential factor in the value of the force vibration. (Gardien and Stuit 2003) used 2D Finite Element models to perform a parametric study of Japanese metro lines. The magnitude of vibration is examined due to the changing of material properties, soil stiffness, damping and Finite Element size. The amount of released energy is the most important factor in every kind of dynamic event. Considering this approach, energy should be the most suitable parameter for source characterization. The applicable parameter for source characterization is the kinetic energy produced by the circulation of a train in the rail track and, for that, trains gross mass and speed should be known. (Auersch 2015b) tested the influence of soft soil medium and moving load to the dynamic response from underground tunnel. The soil stiffness factor has more effects than the moving load to the vibration response. The vibration in soft soil can be minimized by using a floating slab system. (Forrest and Hunt 2006a) did an analytical 3D model to examine the ground-borne vibration from deep underground railway circular tunnel surrounded by infinite soil by applying harmonic loads at the invert. It also mentioned that the frequency range of interest for calculating the ground-borne vibration from underground railways can be taken as 20 to 100 Hz. (Karlström and Boström 2006) introduced a guidance to railway design engineer to consider a mixture of stiff rail clip and soft slab bearing to reduce the vibration response. (Andersen and Jones 2006) compared the vibration analysis from railway tunnels due to two and three-dimensional analysis by using a coupled boundary and Finite Element analysis methods. The vibration frequencies range was taken as 4 to 80 Hz. Both models have only a small change of the frequency response for a small frequency measured on the ground surface. The calculation time for 3D model takes more time (2 hours per frequency) than the analysis of 2D model (5 seconds per frequency). To predict ground vibration from trains, a detailed knowledge of the dynamic soil properties and layer structure of the ground is required. As the properties of the ground differ widely between locations they must be characterized for a site to make reliable vibration predictions. (Volberg 1983) measured vibration propagation from railways as function of soil properties by using accelerometers.

The vibrations degree is dependent on type of soil and train velocity. (Sheng, Jones and Petyt 1999) investigated the vibration generation by constantly moving load from underground tunnel. The train's vibration is affected by the static and dynamic loads that are applied on the tunnel. Dynamic load is a load having an acceleration/high that is acting on a structure, focused on the effect of the tunnel and soil properties on the generation of ground-borne vibration due to moving loads and noise from underground railways systems by using Finite Element-boundary element models and Pipe-in-Pipe model. The soil is modeled in half-space as a homogenous soil and analyzed with different shear modulus and damping ratio, however, there are few exceptions such as the work done by (Zhou, Wang and Jiang 2009) who studied vibration propagation from a pair of elliptic tunnels. In general, it is found that changing material properties and tunnel shapes have strong influences on vibration response in a homogenous soil. (Triepaischajonsak1 et al. 2010) described the field measurements of the vibration at two sites with soft clay soil in Southern England. The properties of the ground material, including its layered structure, have been identified. Presentation in the wavenumber-frequency domain is particularly helpful for this purpose. Measurements of vibrations from passing trains are then compared with predictions using a semi-analytical model for ground vibration from trains and close agreement was found. (Hussein et al. 2014) had introduced efficient models for calculating vibration from underground railways tunnel for the case of tunnel imbedded in multi-layered half-space. The half-space means the tunnel is imbedded in a semi-infinite soil medium that is extended up down from ground surface level to bedrock level and extended from both sides of the soil medium. Forced vibration frequencies were found to match the Finite-Element-Boundary-Element (FE-BE) model accounting for a tunnel wall in a half-space. (Degen, Behr and Grütz 2006) presented the observations of ground-borne vibration response into the buildings via the floor vibration and air-borne noise radiated. (Gupta et al. 2008) measured the vibration on the line 4 of Beijing metro and compared the results with periodic three-dimensional FE-BE model. The tunnel depth is fixed to be 13.5m from the ground surface to the center of the tunnel. The soil is modeled as a layered soil medium with constant depth. A case study about vibration impression caused by train passages in the shallow underground tunnel (in Warsaw, Poland) in comparison to the results measured for vibration from ground surface transportation (trams and buses). This study is concluded with the dynamic response of the building to underground vibration is essentially different from the response of a building excited by surface sources of transport vibrations (Stypuła 2014). (Hussein et al. 2014) studied the frequency response from underground railways tunnel embedded in multi-layered half-space soil medium by using an extended Pip-in-Pip model. (Yuan et al. 2018) did a research recently to investigate the impact of presenting the pore-fluid in the soil medium to the ground-borne vibration from underground tunnel embedded in a layered half-space. The analysis shows that the surface vibration responses are affected by the movement of water table. (Sheng, Jones and Thompson 2003) modeled ground-borne vibration from the underground railway tunnel generated by a harmonic load applied at the center of a circular tunnel. Noise and vibrations are disadvantages of railways system. Vibration frequencies of interest are introduced to be 15 Hz to 200 Hz. When the force frequency of the structure becomes close to the natural frequency mode of the same structure, the structure is said to be under resonance if the applied dynamic load reach to resonance limit, the structure will fail.

(Hussein and Hunt 2007) studied the effect of floating slab connections to the tunnel wall by introducing 3 different connections type. Those connections are: (a) two lines support, (b) three-line support and (c) uniform line support. The Pip-in-Pip model of underground tunnel in full-space is used to measure the vibration response due to different floating slab connection system. The vibration responses are more affected by slab support system rather than the tunnel-soil interaction. The dynamic load consists of people, wind, waves, traffic, earthquakes and blast. Some studies were done to verify if the railway bridge reached the resonance limit or not. (Galvín et al. 2017) did a study on the dynamic response under a high-speed railway in Madrid. A FE model for a railway bridge is used for dynamic analysis and the result is compared with an experimental data for vibration response. The railway structures must be designed and checked for the expected force vibration generated by the operation of the train.

2.6 Vibration Reduction Methods

Controlling the vibration is one of major elements of railway operation and maintenance period. As areas around the railway lines and stations are developed, the vibrations need to be limited and controlled by different methods to minimize the negative effects of vibration on people's life and structure durability. Noise reduction, that caused by railways systems is also reported in the literature. If trains are operated in high speed with large weight, the source of ground-borne vibration and noise can have high impact on people's live and buildings response frequencies. The level of vibration must be measured to identify its sources, propagation paths, and the criteria of the frequency signal. (Melke and Kramer 1983) had introduced a diagnostic method to investigate the vibration response from railway tunnel in the underground and at grade. This method requires extreme caution during the recording process of vibration signals. The floating slab was introduced by

(Wilson, Saurenman and Nelson 1983) as a method of reducing the vibration from underground railways tunnel. It can reduce the vibration response at frequency level which is more than the resonance level of vibration of the track system.

(Melke 1988) studied the structure-borne noise and vibration by conducting laboratory tests and compared the results with an analytical solution. (Kurze 1996) conducted a study about the tools used for measuring and predicting railways vibration. The weighted sound pressure level LA_{eq}, which is related to air-borne sound can be measured by using omnidirectional microphone. Piezo-electric accelerometer is used to measure structure-borne sound level. One of useful tools in controlling the noise and vibration is to use prediction schemes for outside sound propagation and propagation path description model. (Xin and Gao 2011) demonstrated that the vibration transmission between slab track and bridged in railways elevated system can be eliminated by introducing an elastic material between them. Various vibration mitigation strategies have been identified ranging from ground improvement to wave isolation measures such as trenches backfilled with low acoustic impedance backfill (Connolly et al. 2015). The reduction of ground vibration by elastic elements such as rail pads and sleeper pads has been analyzed by a combined finite-element boundary-element method. It has been found that the soil force transfers an appropriate quantity to predict the reduction of the ground vibration and the effectiveness of isolated tracks. All forces transfer functions of isolated tracks display a vehicle–track resonance where the wheel set on the compliant track is excited by wheel and track irregularities. Sleeper pads are advantageous due to the vibration response to the higher mass that is elastically supported compared to the rail-pad track system (Auersch 2015b). (Yuan, Boström and Cai 2017) investigated the vibration response due to applied moving constant load and a moving harmonic load applied at invert level of the tunnel with different load frequencies and load velocity. The tunnel is modeled as an elastic hallow cylinder which surrounded by half-space soil by using a semi-analytical solution. The tunnel material was assumed to be linear elastic, homogeneous and isotropic material. The soil was modeled as linear viscoelastic material. It concluded with the fact that by increasing the depth and thickness of the underground tunnel, the vibration at grade level found to be reduced.

2.7 Railway Tracks Dynamic Properties

The dynamic properties of the railway track are measured in the frequency range of interest to understand the mechanism of the noise generation. The noise can be categorized as a rolling noise and tangent track noise. They are both used to refer to noise produced by the roughness of wheel-rail interaction and material heterogeneity. The dynamic stiffness and damping capability of the railway track in the viscoelastic medium are essential to evaluate the performance on minimizing rail vibration. The flexural wave propagation was found to occur only at frequencies higher than the mass-spring resonance frequency of the rails. The measured dynamic stiffness from the embedded tracks in the laboratory is similar to the field test results (Park et al. 2016).

(Lombaert et al. 2006) validated the use of a numerical model in dynamic analysis of railway with experimental measurements. (Hussein and Hunt 2009) calculated the vibration response due to dynamic load acting on a floating-slab stack by using a numerical model. The track is modeled as a periodic-infinite structure model. This research tried to investigate the effect of continuous and discontinuous slabs on vibration propagation from underground railway tunnel by using Pipe-in-Pipe model for a tunnel in half-space medium. There are significant differences between the force vibration measured at the ground surface due to discontinuous and continuous floating-slab track. The discontinuous slab track has more vibration due to resonance frequencies of the slab. (Dai et al. 2016) measured the vibration of slab track built on a viaduct by using an analytical equation. This model is presented by a 3 layers Euler-Bernoulli beam with an applied harmonic load Viaduct is referred to long span type of bridges that can carry the road or railway over water or another road. The outcome from this study is that using the floating slab track produces lower vibration comparing to slab track. (Ntotsios, Thompson and Hussein 2017) looked at the prediction of ground-borne vibration in wavelength-frequency domain from the point of the correlation level at track loading for wheel-rail line. (Xu et al. 2015) compared the vibration propagation from the underground railways tunnel for two different types of tracks system in 2D and 3D FE Models. The type of track systems used in this study is direct fixation track and steel spring floating slab. The 2D FE model is suitable for predicting the ground-borne vibration from underground railways. The computational time required for 3D model is 44 hours which is higher than 2D model time (4 minutes).

2.8 Non-Reflecting Boundary

Boundary conditions of Finite Element model have been studied and presented in the literature. There are 3 types of non-reflecting boundary conditions, which are the exact non-reflecting boundary conditions, local non-reflecting boundary conditions and absorbing boundary layers. (Liu and Quek Jerry 2003) presented a FE Model for a long plate by using a damped boundary conditions to reflect the non-reflecting boundary and to measure the response of the propagating waves along the plate. The damped boundaries reduce the wave propagation within to the limit of having no waves returned to the plate.

This study concluded with the fact that damping boundaries need to be modeled in layers without a big change of damping ration because the waves are reflecting when they are passing from one layer to another layer due to a high difference in damping ratio.

2.9 Twin Tunnels Modeling

There is a limited number of research that is investigating the effect of multiple lined tunnels on ground-borne vibration and noise. (Zhou, Wang and Jiang 2009) considered a pair of parallel underground elliptic tunnels in the dynamic response by using a semi-analytical method. The soil is displayed as infinite poroelastic medium. The distance between two tunnels and thickness of liner have a great influence on dynamic response of twin tunnels embedded in poroelastic soil. (Hamad et al. 2015) studied the effect of presenting paralleled twin tunnels dynamic response from underground railways embedded in a homogeneous half-space. The dynamic load is presented as a harmonic point load in one of the tunnel’s invert. There is a significant difference between the dynamic response at ground surface for a single and twin tunnel. (Clot et al. 2016) investigated the dynamic response of a double circular tunnel in a 3D full-space soil medium. The harmonic loads are applied on an internal slab deck within the tunnel. The soil-tunnel is modeled by using Pipe-in-Pipe model and the plate is modeled as a thin plate with infinite length. The analytical solutions are used to compare it with the presented model. The conclusion is that there is a big difference of the force frequency response between a simple tunnel and double-deck tunnel. The reasons for that is dynamic behavior of a strip plate.

2.10 Lack of Knowledge in Ground-Borne Vibration

There are extensive studies in the field of ground-borne vibration and noise. Many models were reported in the literature based on soil in half-space, soil in full-space, homogenous soil, layered soil, different boundary conditions, soil properties, layered soil, joint between soil and tunnel, tunnel properties, tunnel depth, tunnel shape, magnitude and position of applied load, floating slab, slab track, joint between slab and tunnel wall and the analysis method used in determining the vibration response. The literature shows that by using 2D plane strain Finite Element model provides quantitative measurements compared to a 3D model. This model can be verified by using site measurements and analytical solution for vibration response. The computing time required for 3D FE model is much more than the 2D model.

The literature reviewed shows that there is a shortage of research in studying the effect of soil layering with different tunnel depth and different tunnel shapes on vibration response. In other words, an investigation is needed to answer the question what the influences of soil in layering with different tunnel location and shape are on ground-borne vibration and noise? Also, there is a need to investigate vibration on the new railway system in the state of Qatar. Another factor that can affect the vibration propagation is layered soil medium with different distance between twin tunnels.

Because of that, there is a great need to develop a 2D plane strain model of vibration from underground railway tunnels to understand the physics of generation and propagation of vibration due to soil layering, tunnel position, tunnel depth and twin tunnels position. Therefore, a 2D Finite Element (FE) model based on Abaqus software is developed for a single and twin underground tunnel in Qatar. The investigation covers the effect of different tunnel cross sections and different tunnel location on vibration measurements.

CHAPTER 3: MODELING VERIFICATION AND VALIDATION

Model validation and verification is an important step to be done before doing the final simulation. The purpose of chapter 3 is to do a model verification with the literature for a finite element model to investigate ground-borne vibration from underground railways tunnel. This step is like a model test for the used software in doing vibration analysis of the tunnel. Therefore, doing a model check is conducted in to verify the outcome results of the displacement response based on test data available in the literature. Sometimes, the simulation may have different results than the test data because of human factor during data entry to the model. The main reason of doing a model verification is the model might have miscast because of wrong assumptions during modeling stage. This mistake can be wrong data entered to the model or wrong information taken out from the model. Minimizing the mistakes can be done by performing a model check to make sure that the model had been done correctly. This step provides a solid confidence level for the researcher to do more complicated models and to get good results. The degree of complexity of the soil-tunnel verification model need to be simplified in three different models which are: (1) two-dimensional free circular tunnel, (2) three-dimensional free circular tunnel and (3) two-dimensional model for circular tunnel embedded in homogenous soil. Reducing and simplifying the FE model for underground tunnel makes it easier for the researcher to understand the results.

To do a model verification, a baseline FE model for vibration analysis needs to be checked first against the literature. That model is a free circular tunnel model with a harmonic load applied on the bottom of the tunnel. In other word, validation of a simple tunnel model can be a good starting point to build up the final model needed for the analysis which is soil-tunnel interaction model analysis. It is easy to compare the outcome results for a simple model than a complicated model especially at the initial stage of the modeling.

The free circular FE model is developed by using a finite element commercial software which is Abaqus (2014) CAE version 6.14 to compare the results with (Forrest and Hunt 2006b). The introduced verification models in this study are done in two-dimensional and three-dimensional finite element analysis. To investigate the displacement response from free tunnel in 2D finite element analysis, comparisons were made between the 2D plane strain (the deformation of the body in which the displacement of all points are parallel to a designated plane and the values of these displacements do not depend on the perpendicular distance to the said plane) and 3D plane stress (if the stress state at a material particle in such that the only ono-zero stress components act in one plane only, this particle is said to be in plane stress.) models. 2D is a model with horizontal and vertical dimensions (X and Y) for the free circular tunnel. The 2D are the interior radius (r_i) and the thickness (h) of the tunnel. The 3D model is adding the length of the tunnel (L) to the 2D model. The 2D FEM is taking less time in the analysis than the 3D FEM as reported in chapter 2. The 2D model is providing quantitative results in less time analysis when it is compared with 3D. The accuracy of the results in 2D model are verified by a 3D model. 3D model is introduced to improve the quality and the accuracy of the results. Also, the visualization of a 3D tunnel model is better than a 2D model because the length of the tunnel is presented in 3D. The results found in 2D & 3D FEM are compared with (Forrest and Hunt 2006b). It should be noted that the difficulty of the model should range from easy to difficult model. Because of that, another verification model is introduced for soil-tunnel interaction in 2D. The soil-tunnel verification model is compared with (Hussein et al. 2014).

3.1 Methodology

The modeling input data used for modeling confirmation works is based on (Forrest and Hunt 2006b). The input data for soil properties for the compression models between the literature and the FEM are used based on (Hussein et al. 2014). The FEM program (Abaqus), is used to examine the natural frequency and vibration for free circular tunnel by doing dynamic analysis. From the analysis, the natural frequencies and displacement response values are determined as major output. Finally, the compression and decisions are drawn. The analysis method used in all models is Finite Element method.

Finite Element method is the method used by Abaqus software. It is a numerical model technique used for solving many engineering problems such as structural analysis. It can solve mainly the differential equations of a system through a discretization process. Using FEM reduces the time and effort of doing the calculations. FEM is making the formulation of the problem results in a system of algebraic equations. This method estimates the values of the unknown parameters at a discrete number of points over the domain. The main rule of FEM is to subdivide a large problem into smaller simpler parts that are called finite elements. The simple equation that models these finite elements is then assembled into a larger system of equations that models the entire problem. FEM then uses variation methods from the calculus of variations to approximate a solution by minimizing an associated error function.

3.2 Dynamics of Soil-Tunnel System

Before introducing the models, some background about soil and structural dynamics need to be reviewed. The magnitude of an applied load in dynamic analysis is varying with time. This load is called a dynamic load. It is an action having high accelerations like earthquake and train movement inside tunnel. There are two types of vibrations: (1) free vibration with and without damping and (2) forced vibration with and without damping. In undamped vibration analysis, the total energy stays the same with time. The frequency at which a system tends to oscillate in the absence of any driving or damping force is called natural frequency of the system. The vibration is the oscillation of motion which can be observed in daily life activities such as heartbeat, hearing and speaking.

The structural dynamic study is important to understand the structure behavior under a dynamic load. The severity of the problem is accruing when the force vibration response value is close to the natural frequency of the structure. At that stage, the structure is said to be under resonant frequency. In other words, if the force frequency matches the natural frequency of the system, large displacement, large velocity and large acceleration will happen to the system. It can cause failure to the structure due to resonance. That's why the vibration response from an applied dynamic load needs to be controlled and limited to an acceptable level of vibration.

The dynamic equation of the model can be expressed in terms of elastic stiffness matrix (K), mass matrix (M) and damping matrix (C) which can be characterized as a complex number. Because of that, using the Finite Element program allows engineers to run a complex-harmonic analysis. The real part of the complex data represents the spring stiffness and the imaginary part represents damping (Maheshwari et al. 2005). Dynamic analysis can be classified according to material behavior as: (1) linear analysis and (2) non-linear analysis. In linear analysis, the applied loads are within the elasticity range of deformation. On the other hand, in non-linear analysis, the loads are beyond the elasticity range of deformation. To simplify the structural dynamic system, a single degree of freedom can be considered as mass, spring and damper system.

3.2.1 General Equation of Dynamic

The general equation for the movement of a system that is under a dynamic load can be written as:

$$M(\ddot{u}) + C(\dot{u}) + K(u) = P(t) \quad (1)$$

Where, C = damping matrix, K = stiffness matrix, M = mass, $\ddot{u}$ = acceleration, $\dot{u}$ = velocity, u = displacement and P(t) = applied load. The stiffness is the rigidity of the structure which resists the deformation in response to the applied load. Damping is the reduction in the amplitude of the vibration because of energy losses due to friction losses or other forces. The free vibration equation with damping that is considered in 2D FEM is:

$$M(\ddot{u}) + C(\dot{u}) + K(u) = 0 \quad (2)$$

The force vibration equation with damping that is considered in 2D and 3D FE models is:

$$M(\ddot{u}) + C(\dot{u}) + K(u) = P(t) \quad (3)$$

$$P(t) = P_0 \sin(2\pi f t) \quad (4)$$

The natural frequency of any system can be calculated by:

$$\omega_n = \sqrt{\frac{K}{M}} = 2\pi f = \frac{2\pi}{T} \quad (5)$$

Where, ω_n = natural frequency, f = number of cycle in time unite (force frequency) and P_0 = the applied concentrated unite load to the system. The applied force used in this research is a harmonic load Figure 1. It means that when the applied load varies as a sine or cosine function, it is called harmonic loading. The response of the system to this load excitation can be named as harmonic response. It is important to understand the level of vibration in the tunnel which results in the soil around the tunnel when the train is operating, therefore, FEM of the underground railway system needs to include the effects of the tunnel and soil dynamics.

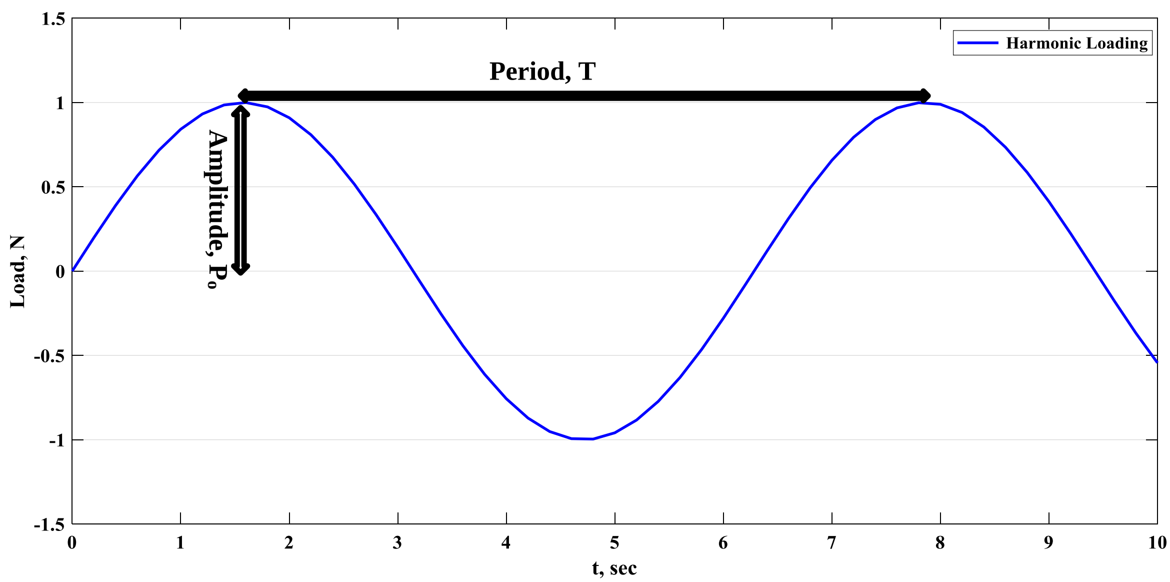


Figure 1 Harmonic load function

3.2.2 Damping

The damping coefficient of tunnel and soil (ξ) influences the study of vibration from underground railway tunnel. Therefore, the presence of damping in the system controls the amplitude of vibration. In general, the soil has higher damping ratio than the structure because the composite modal damping ratio of soil-structure interaction system depends on the foundation damping, the structural damping and the nature and degree of interaction between the structure and the supporting soil. Table 2 shows the damping ratio for some of building materials.

Table 2 Damping rations for some of building materials

Structure material name	**Damping ratio %**
Concrete	5% - 7%
Steel	1% - 2%
Aluminum	0.1% - 1%

If the wave is propagating via a medium (soil), the energy absorption occurred due to damping properties of the medium. The soil damping properties are affected by wave velocity and frequency. Material Damping depends on how it will be applied and assigned to the dynamic model. There are two primary types of damping existing in Abaqus: (1) viscous damping and (2) structural damping.

A. Viscous Damping

It is the most common type of damping available in Abaqus. It also called Rayleigh Damping. The damping matrix is assumed to be proportional to the stiffness K and mass M matrices. $[C]=\alpha[M]+\beta[K]$ (6)

B. Structural Damping

Structural damping occurs due to the friction between the internal planes that slips once the deformations take place. The structural damping is also called hysteresis damping because the stress-strain diagram of the structure under damped material displays a hysteresis loop. This loop demonstrates the loss of energy in the system due to damping.

3.2.3 Artificial Non-Reflecting Boundary

Non-reflective boundary conditions for wave propagations problem is a very important subject in performing dynamic analysis. There are diverse types of non-reflective boundary conditions such as exact non-reflecting boundary conditions, local non-reflecting boundary conditions and absorbing boundary layers. This means that the boundaries must be far away from the measurement points of interest to minimize the reflections of stress waves and to reduce the distortions in the calculated results. When these waves bounce back from the boundary they mix with the progressing waves. Thus, the magnitude of the waves calculated by the FE package becomes inaccurate. To overcome this problem, a non-reflecting boundary condition should be used to justify the fact that the soil is modeled as a semi-infinite medium to avoid these unrealistic reflections.

3.3 Abaqus Package

Abaqus is one of the most famous commercial Finite Element software used to perform FE analysis and computer-aided engineering which was released in 1978. One of the Abaqus products is Abaqus (2014)/Complete Abaqus Environment CAE). In other words, it is a software application used for both the modeling and analysis of mechanical components, assemblies (pre-processing) to visualize the finite element analysis result. It is also a powerful FEM tool for complicated analysis for 3D or 2D problems. There are no units used in Abaqus, so the units must be specified by the user input as per the Table 3. In this research, SI units is used for all data used in the models.

Table 3 unites used for Abaqus input data and measurements

Quantity	**SI Unite (m)**	**US Unite (ft)**
Length	m	ft
Force	N	lbf
Mass	kg	slug
Time	s	s
Stress	Pa (N/m^2)	lbf/ft^2
Density	Kg/m^3	$Slug/ft^3$

3.3.1 Abaqus modeling steps

Crating a model with Abaqus must follow the following steps:

1) Creating the part;
2) Defining the geometry of the model;
3) Defining the material properties;
4) Defining and assigning the section properties;
5) Configuring the analysis;
6) Conveying the interaction properties between the parts of the model;
7) Choosing the analysis type required;
8) Assigning the boundary conditions, supports and the applied load;
9) Designing the mesh size, element type and element direction; and
10) Creating the job, running the model and extracting the data needed.

3.4 Verification Model Assumptions

To do the FEM in Abaqus, there are some assumptions that need to be specified as described below:

1) The applied load is located at the center bottom of the tunnel. The load is a harmonic concentrated load for 2D tunnel and it is a harmonic line load for 3D tunnel analysis. Therefore, the effects of random force and impulse forces (a very large force acting in very small time with finite interval) are not considered in this research. Also, the applied loads in the x-y plane do not vary in the Z direction.
2) The frequency domain is used directly by Abaqus to compute the displacement response due to the applied dynamic load.

3) The magnitude of the applied concentrated load is taken as unite load (1N). The reason for that is to simplify the FE model and to minimize the effects of applied force value on the results. In other word, the amount of the applied force in all models is not the area of interest in this research because whatever results found for the unite load can be implemented to different load values.
4) The initial conditioning effect for the system has been neglected. This means that the transient state of the applied load is ignored because the effects will be finished within a few minutes.
5) The dynamic analysis is assumed to be a steady state dynamic analysis (time goes to infinity) with small deformation.
6) The damping properties of the material are used as Rayleigh damping coefficients alpha α and beta β.
7) The system is modeled as isotropic/linear elastic material because the strain is very small so a linear analysis can be assumed to simplify the models.
8) It is well noted that the elastic behavior of the soil is non-linear and stress dependent. To simplify the models, the soil is considered as linear elastic material under small strain condition.
9) The effects of surface vibration due to existing train on grade and road traffic are not considered in this research.
10) The vibration is measured in y-direction. The response points of vibration are taken in different location surround the tunnel.

11) The soil properties at infinite boundary is assumed to be like the soil surrounding the tunnel. The damping property is also presented in the infinite element conditions.

12) The points at boundary conditions are not considered as a response points because they are critical points due to changing element type from CPE8R to CINPE5R.

3.4.1 Linear Elastic Model

All components of stress and strain for an isotropic linear elastic material follow Hooke's law and can be expressed in terms of two Lame's constant λ and μ. The elastic stiffness properties of the material can be defined as: (1) Young's modulus and (2) Poisson's ratio. When the E-modulus and Poisson's ratio are constant, the equations can be used as linear equation. That means there is no such limit of failure for the soil system because it is a linear elastic soil model. The applied load within the simulation needs to be limited to stress the limit to avoid the non-linear behavior of the soil-tunnel model. Poisson's Ratio is defined as how the material deforms laterally when the compression or tension loads are applied along one axis. Because of the applied load, the material is strained parallel and orthogonally to its axis. The relation between those two strains is called Poisson's ratio and it is limited to be from 0.1 to 0.495.

3.5 Parameter Values for Verification Models

The data used in the models are extracted from the literature. Table 4 provides the data used for the verification work models of 2D and 3D free circular tunnel.

Table 4 Data for 2D and 3D circular tunnel FE model (Forrest and Hunt 2006b)

Concrete tunnel properties
E is the young's modulus for the concrete tunnel = 50×109 Pa
ν is the ratio Poisson's ratio for the concrete tunnel = 0.3
ρ is the density of the concrete = 2500 kg/m^3
$\boldsymbol{\alpha_R}$ is the mass-proportional Rayleigh damping factor = 10s^{-1}
$\boldsymbol{\beta_R}$ is the stiffness-proportional Rayleigh damping factor = 40 ×10^{-6}s
a is the radius of the shell = 3.125m
h is the thickness of the shell = 0.25m
r is the external radius of tunnel = 3.25m
$\mathbf{P_o}$ is the unite load applied inside the tunnel = 1N
L is the length of the tunnel model in 3D = 100m

3.6 2D Free Circular Tunnel Model

The tunnel is conceptualized as an infinitely long cylindrical tube surrounded by infinite soil layers. If the tunnel wall is thin compared to its radius, the cylindrical shell theory can be used to model the tunnel's response. Despite the absence of a free-soil surface, useful results are concerning the propagation of vibration into the soil near the tunnel where building foundations are located.

The coordinate system used in Abaqus for 2D Model is the Cartesian coordinate system in x and y direction. The x-direction can be described as a horizontal line. The y-direction is a vertical line that is perpendicular to the x-direction. The point (0,0) is located at the center of the ring. The material used for the circular tunnel is mentioned in Table 4. The circular tunnel material is concrete with Young's Modulus E, Poisson's ratio ν, and density ρ. The damping effect of concrete is presented as Rayleigh damping coefficients α (mass coefficients) and β (stiffness coefficients). The applied load P(t) is harmonic concentrated load which is acting at the bottom surface of the tunnel as shown in Figure 2. Figure 3 shows the 2D free circular tunnel model layout in Abaqus.

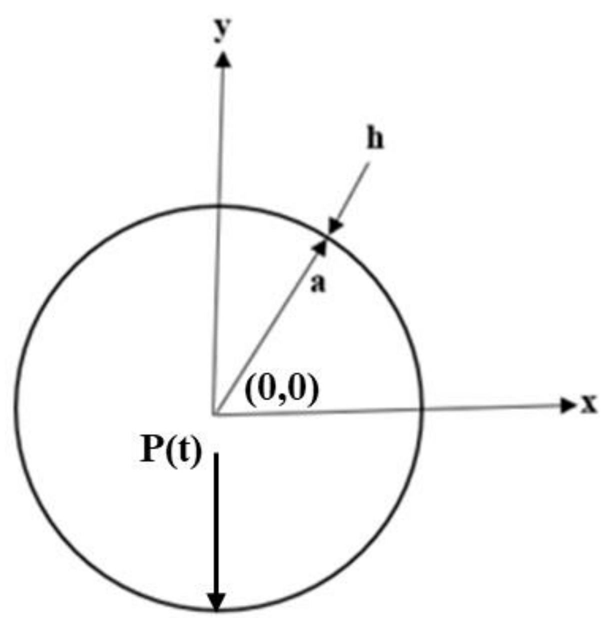


Figure 2 Coordinate system used for the 2D circular tunnel.

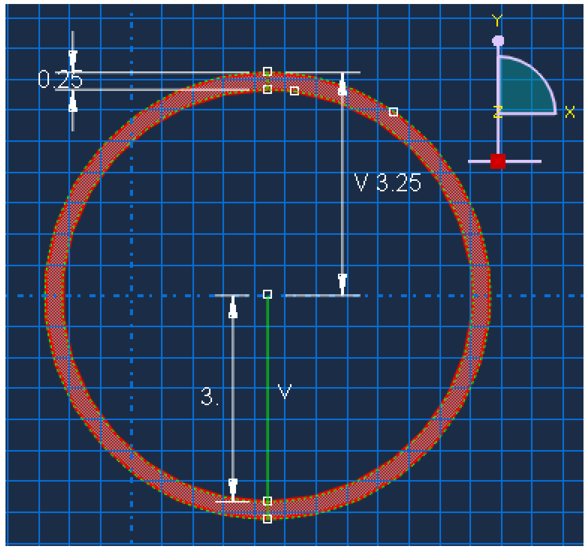


Figure 3 2D Circular tunnel model layout in Abaqus.

The most important step in modeling the tunnel in Abaqus is to mesh and specify the element's size and type. The element type used for 2D circular tunnel is a quadratic plane strain element. Plane strain is defined as a state of strain in which the strain is normal to x-y plane, ε_z and the shear strain γ_{xz} and γ_{yz} are assumed to be zero. In the plane strain, the dimensions of the structure in one direction, say the z-coordinate is very large in comparison to the dimensions of the structure in the other directions (x & y coordinates). The geometry of the body is essentially that of prismatic cylinder with one dimension much larger than the others. The accuracy of the results depends on the compatibility and consistency of mesh size and element type used in the model.

2D FE model of a free circular tunnel were developed and analyzed. This case also represents a real scenario when the stiffness of soil is very soft compared to the stiffness of tunnel. The resulting natural frequencies and frequency response functions were verified against those reported in the literature. The model dimensions and material properties, given in Table 4, are based on Forrest and Hunt, 2006.

Figure 4 presents the element type used for 2D model was quadratic quadrilateral plain strain CPE8R. Figure 5 shows the resulting mode shapes for the 2D models. These results are compared in Figure 6 with the values reported in (Forrest and Hunt 2006b). The comparison shows that there is a little difference in frequency values for mode 9 and 10, however, the other modes (n=1 to n=8) are in good agreement with values given by (Forrest and Hunt 2006b).

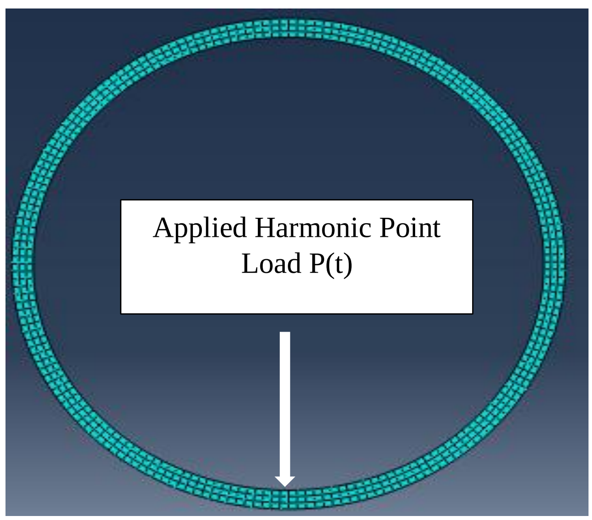
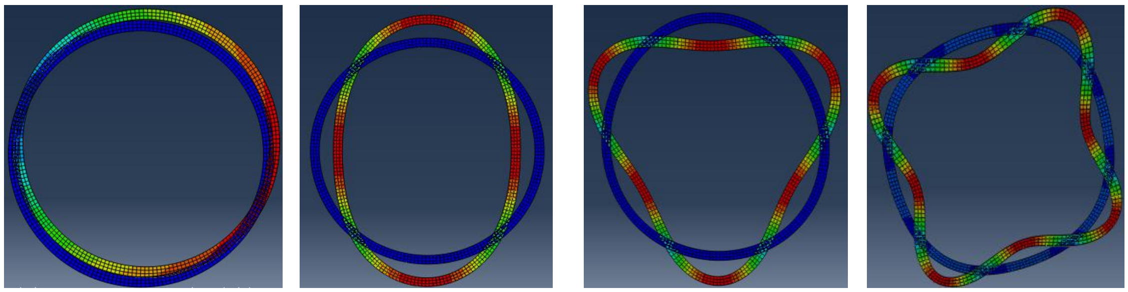


Figure 4 Mesh and applied load for the 2D FE circular model in Abaqus

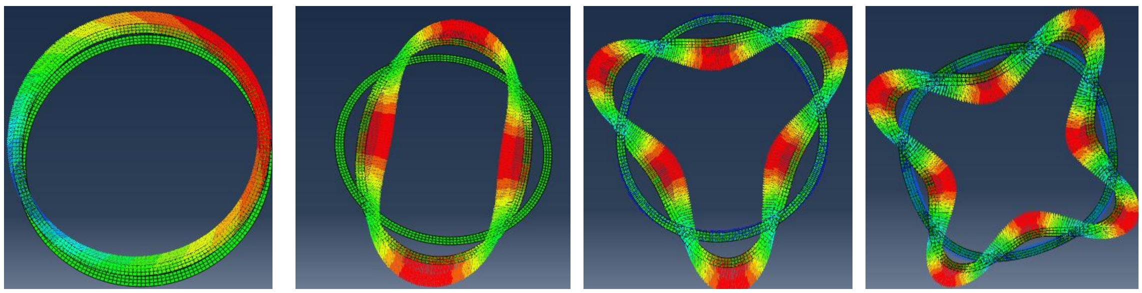
For the ring model, two analyses are running. First, analysis is the free vibration analysis without any applied load. The purpose of the first analysis is to measure the natural frequencies of the ring and the mode shapes. The second analysis is the force vibration analysis for the ring with an applied harmonic unit load. The purpose of the second analysis is to measure the force displacement frequency response. The applied load and the response point are at the same location where x=0m and y=-3.0m, respectively.

In the analysis, the step for frequency is made and the dynamic model step is chosen as steady state dynamic model. The upper and the lower frequency are chosen to be [1 Hz – 100 Hz] for free circular model verification work only as reported by (Forrest and Hunt 2006b).The number of points measured is an important factor for the accuracy of the results, so the numbers of points are chosen to be 100 points so the drawn curve of frequency vs. displacement response will have enough data sets to compare it with the literature. The frequency range starts from 1 because zero frequency lets the matrix of coefficients during the analysis process to be singular. Therefore, the results for the first value of natural frequency can't be computed.

As a result, from natural frequency analysis of a single tunnel, the tunnel can be observed and identified in different mode shapes (n) with different natural frequency (f_n). Figure 5 indicates the mode shapes of a circular tunnel based on data given by (Forrest and Hunt 2006b). The number of modes is an integer number n for waves that are developed around the circular tunnel circumferences. For the flexural modes on Figure 5(a), n=1 is corresponding to one full wave, n=2 corresponds to two full waves. Figure 5(b) shows the displacement as out-of-plane flexural modes.



(a) n=1, f_n=0.00 Hz (b) n=2, f_n=14.75 Hz (c) n=3, f_n=41.49 Hz (d) n=4, f_n=78.95 Hz



(e) n=1, f_n=0.00 Hz (f) n=2, f_n=14.75 Hz (g) n=3, f_n=41.49 Hz (h) n=4, f_n=78.95 Hz

Figure 5 (a-d) Natural frequencies and mode shapes of the 2D FE model. (e-h) Natural frequencies and model shapes of the out-of-plane flexural ring of the 3D model.

3.6.1 Natural Frequency for free Circular Tunnel

The natural frequency values of the ring tunnel can be computed from Abaqus FEM and are provided in Table 5 for the first ten values of n. There are some modes in the circular tunnel that have natural frequency below the driving frequency. As indicated in the review of the literature, the interested frequency range is from 1 to 100 Hz for free circular tunnel. Therefore the modes up to n=4 are used to compare the results from the Abaqus analysis with (Forrest and Hunt 2006b). After running the model (plane strain 2D) and changing the mesh size to see the effect of the mesh sizing in Abaqus, it is determined that there is a small difference between the defaults meshes size and the defined size. With changing the mesh type and size, there is no major change in the results.

Table 5 Natural frequencies for plane strain model for a circular tunnel in Abaqus

n	f_n (Hz)	n	f_n (Hz)
1	0	6	183.4
2	14.7	7	249.2
3	41.5	8	323.1
4	79.0	9	404.5
5	126.5	10	533.0

Figure 6 shows the natural frequency values of the FEM by using Abaqus and by (Forrest and Hunt 2006b). Both points are approximately applying above each other up to mode number n=7. From mode number n=8, the points for natural frequency are slightly different but both results show agreement with each other. It can be noted that using FEM by Abaqus gives a much-closed result to the values reported in the literature.

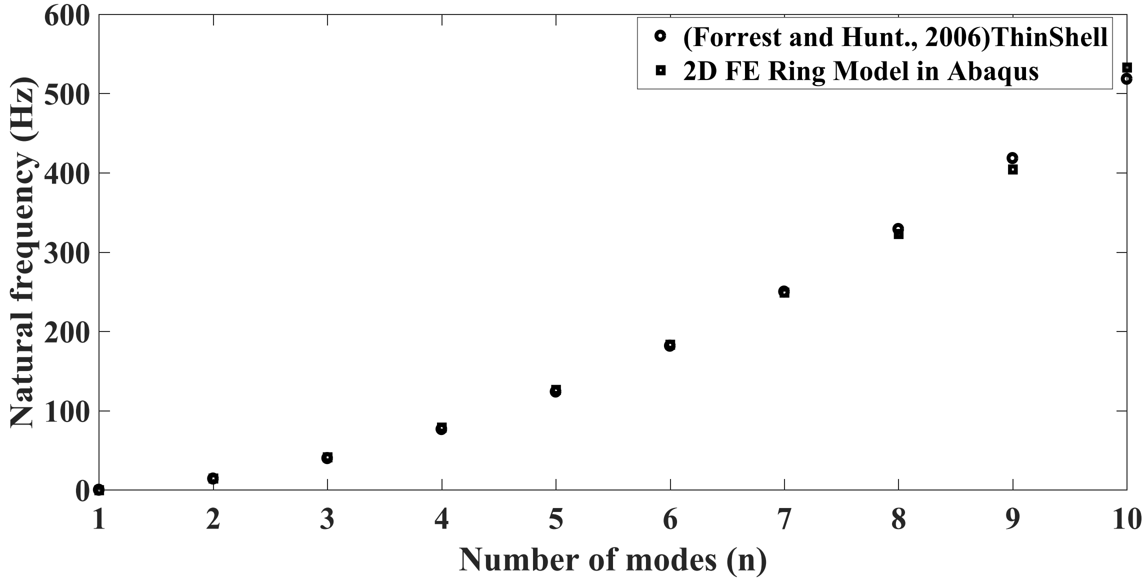


Figure 6 Comparison between the natural frequencies of the 2D FE model and the values reported in (Forrest and Hunt 2006b)

After conducting free vibration analysis of a circular tunnel, the dynamic properties of the tunnel are added as Raleigh damping coefficients alpha (α) and beta (β). They are artificial parameters used for computational software (example: Abaqus) to replace the actual material damping ratio. Those parameters are taken as reported by (Forrest and Hunt 2006b).

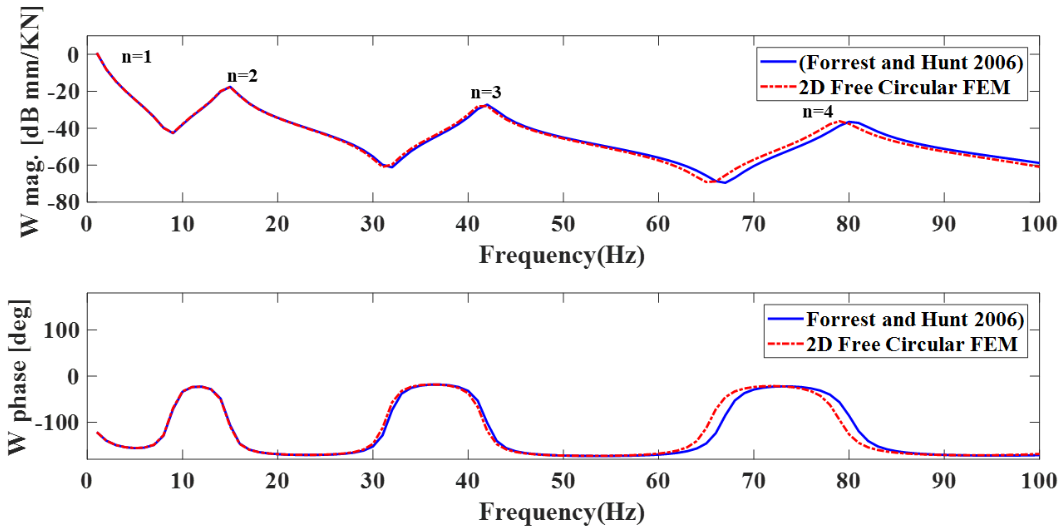


Figure 7 Comparison between the displacement response obtained by the 2D model against the results reported by (Forrest and Hunt 2006) at the point (0, -3, 0) m.

Figure 7 demonstrates the force frequency response values and the phase angle of the applied harmonic load at the bottom of the circular tunnel (x=0, y=-3). The results are calculated by using: (1) FEM in Abaqus and (2) by Shell Theory Method (Forrest and Hunt 2006b) results for thin-walled cylinder. The graph shows that the displacement frequency response values for circular tunnel by using FEM closely matches the results reported in the literature up to n= 3. For n=4, the frequency response started to be slightly different between the two computation methods. This difference is due to accuracy limit of the methods used and a different in defining the damping properties between the shell theory and FE method. The quality of the results at each peak point (n=1, 2, 3 and 4) for the frequency response matches the natural frequency results for the circular tunnel. It is noted from the literature reviewed that the interested points of study are the points where the natural frequency of the tunnel is close to or equal to the frequency response of that tunnel.

Therefore, the FEM provides very close results for the frequency response and phase angle when it is compared with the literature.

3.7 3D Free Circular Tunnel Model

A 3D FEM for a circular tunnel with harmonic line load applied at the bottom of the tunnel parallel to x-direction is used to confirm the results found in 2D FEM and the literature. The coordinate system used in Abaqus for 3D model is the Cartesian coordinate system in x, y and z direction. Figure 8 shows the 3D coordinate system used in Abaqus. The z-direction is a direction that is perpendicular to the paper surface (outside of the page). The cross-section geometry of 3D FEM model is like the 2D FEM. The material properties and the magnitude of the applied harmonic line load are given in Table 4. The differences between 2D FEM and 3D FEM are the types of applied load (point load and line load) and length of the tunnel. The length of the tunnel used for 3D model is 100 m. The frequency response point for 3D model must be same as the response point of 2D mode to get same frequency response values for the 2D model. The measurement point for the force frequency response is at coordinate of (0, -3, 0). The element type used for 3D model eight-node shell elements S8R (Figure 9). Figure 10 presents the applied harmonic line load at the bottom line of the 3D free circular tunnel.

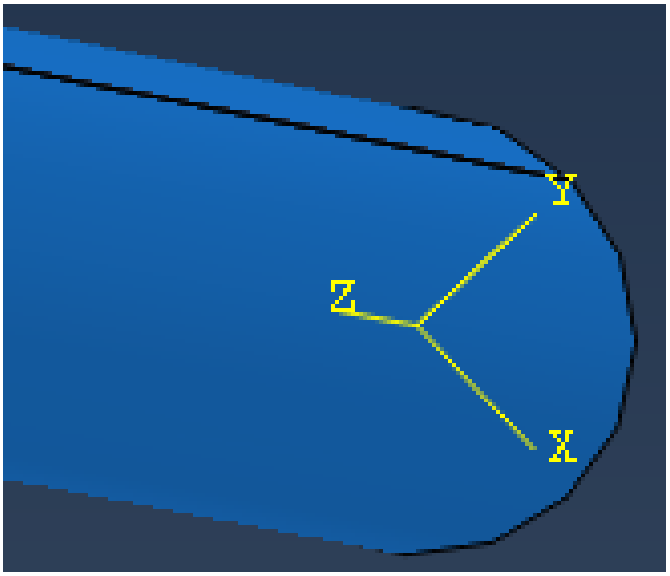


Figure 8 3D coordinate system (x, y, z) in Abaqus

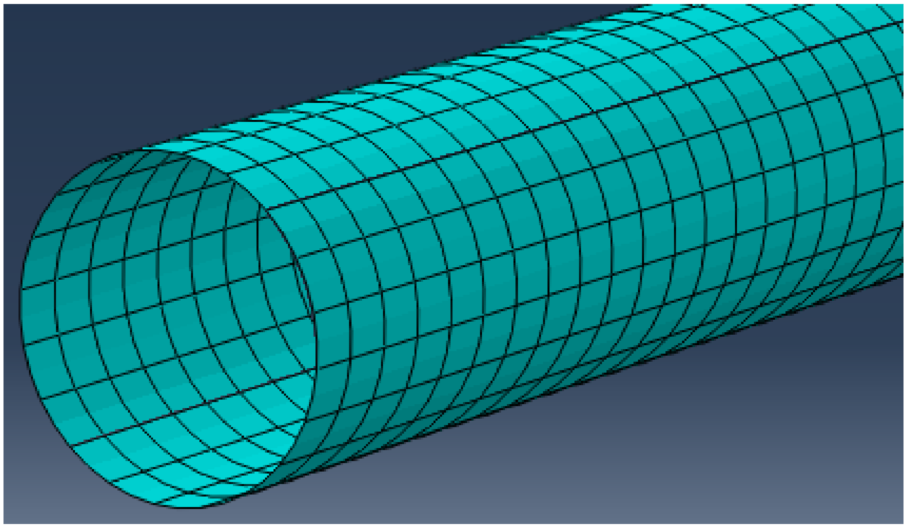


Figure 9 Mesh of the 3D circular tunnel model in Abaqus

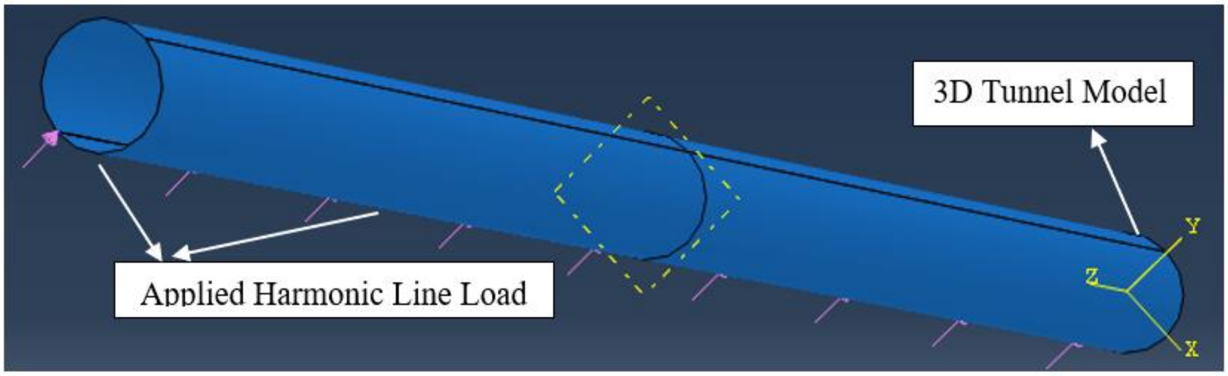


Figure 10 Applied harmonic line load for 3D FE model in Abaqus

After doing all the modeling steps as stated in section 3.3.5, a dynamic analysis for the 3D tunnel model is analyzed and the data was measured at the point of interest (0, -3, 0). Figure 11 demonstrates the vibration values and the phase angle of the applied harmonic load along the horizontal direction of the circular tunnel coordinate system (x=0, y=-3 and z=0). The results are calculated by using: (1) FEM in Abaqus and (2) Shell Theory Method by (Forrest and Hunt 2006b). The graph shows that the displacement frequency response values for circular tunnel by using FEM closely matches with the results reported in the literature and with 2D FE model up to frequency response equal to 65Hz. For n=4, the frequency response is started slightly to be different between the two computation methods. The quality of the results at peak points (n=1, 2, 3 and 4) for the frequency response matches the natural frequency results for the circular tunnel. It can be concluded that the fact that the FEM for 3D circular tunnel gives very close results for the frequency responses and phase angles when it is compared with the literature.

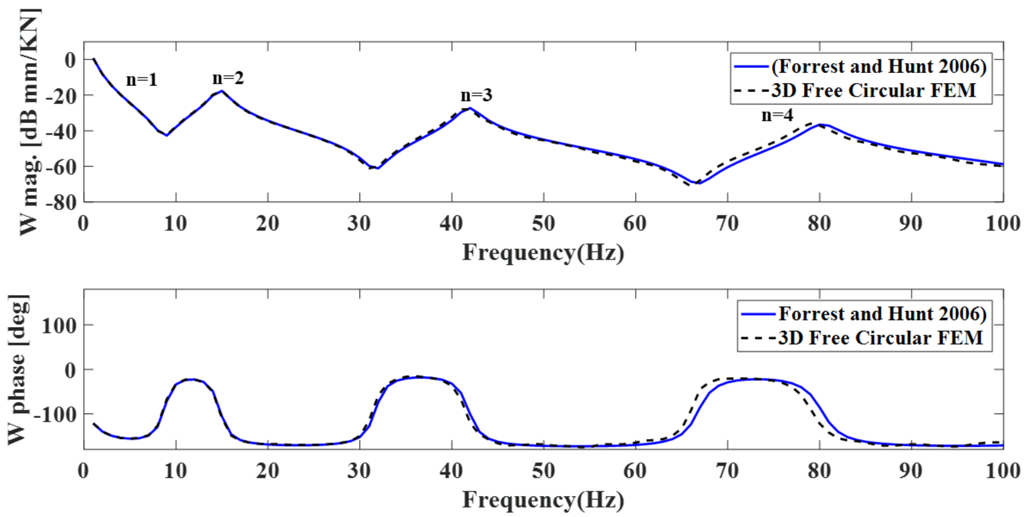


Figure 11 Comparison between the displacement response obtained by the 3D model against the results reported by (Forrest and Hunt 2006) at the point (0, -3, 0) m

3.7.1 Comparison between 2D & 3D FEM with shell theory method

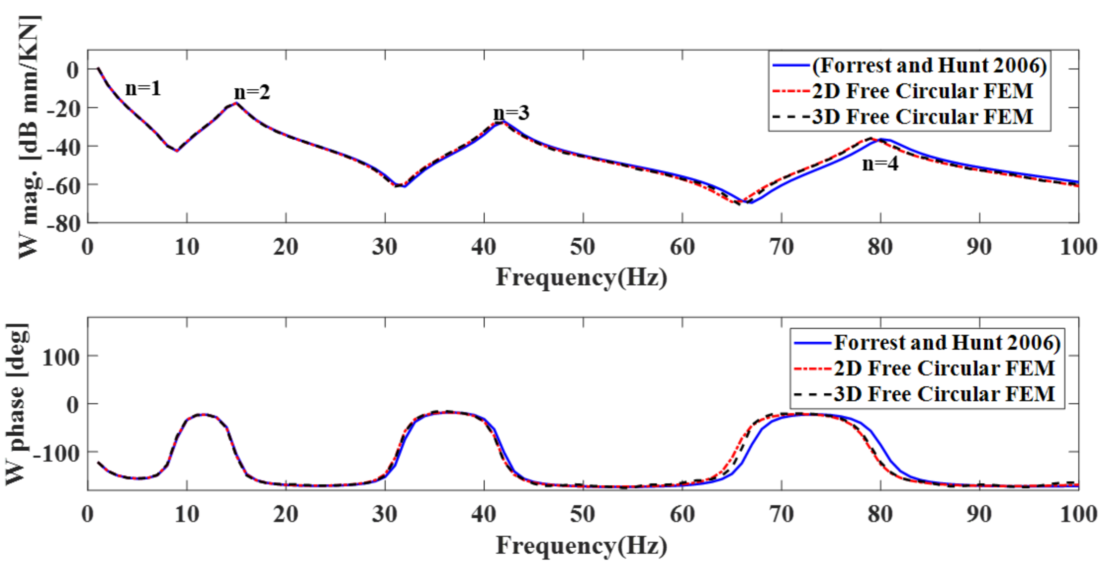


Figure 12 Comparison between the displacement response obtained by the 2D and 3D models against the results reported in [7] at the point (0, -3, 0) m

Figure 12 shows the force frequency response of an applied dynamic load to a circular tunnel in different analysis methods. The Shell Theory Method for dynamic analysis was used by (Forrest and Hunt 2006b) for a 3D infinite tunnel length. The blue line in Figure 12 demonstrates the frequency response for the Shell Theory Method. The measurement point for Shell Theory Method is at the bottom of the tunnel (0, -3, 0). A 3D FEM is modeled by using Abaqus software. It is modeled to analyze the dynamic response for an applied line load parallel to the x-direction of the tunnel. The dash black line shows the relationship between the frequency response and the respective displacement value in dB scale. A 2D FEM is made by Abaqus package to find out the displacement response values at each frequency point between [1Hz -100Hz]. The red dash line in Figure 12 represents the 2D frequency response. All the three lines have peak points at the frequency response close to the natural frequency of the tunnel. The three lines are matching each other from 1Hz to 50Hz. For frequency response above 60Hz, the lines started to diverge slightly from each other, but the values of the frequency responses at peak points for all three lines are relatively equal. In short, it is determining that the force frequency response from 2D and 3D FEM by using Abaqus matches the results found in the literature. Therefore, using Abaqus as Finite Element software to conduct modeling for tunnel can reach an acceptable level with the literature.

3.8 2D Tunnel Modeling in Elastic Homogenous Half-Space

Hussein et al., 2014 investigated the displacement response values due to harmonic point load acting on the center point of the tunnel. The analysis methods used are Finite Element-Boundary Element and Pipe-in-Pipe model for a half-space soil medium. A FEM made by Abaqus to be used in verifying the results found by (Hussein et al. 2014). Two FEMs are made with two different tunnel depths (5m and 20m). The reason for choosing two different tunnel depths is to consider whether the FEM does not differ with changing the depth or not.

The tunnel depth (De) is assumed to be from the grade level to the center point of the tunnel. The circular tunnel is made of concrete. The Concrete properties are similar (Forrest and Hunt 2006b). The interior radius of the tunnel is ri =2.75 m and the outer radius is r0 =3.0 m.

A 2D FE model of a tunnel embedded in a homogenous half-space medium was created and verified. The soil properties used here (Table 6) are based on Hussein et al.,2014. The properties of the tunnel were taken from (Forrest and Hunt 2006b). The model has dimensions of 80×60 m. Quadratic quadrilateral plain strain CPE8R elements were used to model both soil and tunnel. Additionally, as shown in Figure 13, quadratic quadrilateral plain strain CINPE5R infinite elements were used as non-reflective boundary to minimize the reflections of stress waves and reduce the distortions in the calculated results.

Table 6 Data for 2D soil- tunnel FE model (Hussein et al. 2014)

E (Pa)	**ν**	**ρ (Kg/m3)**	**h (m)**	α_R **(s^{-1})**	β_R **(s)**	**r (m)**
550×10^{6}	0.44	2000	0.25	0.473	82.4×10^{-6}	3.0

3.8.1 Rayleigh Damping Coefficients

The damping properties of the soil and concrete are defined in Abaqus by using Rayleigh damping coefficients values alpha α and beta β. For concrete, the values of those coefficients are taken as reported by (Forrest and Hunt 2006b). For the soil medium, alpha α and beta β values need to be calculated based on the damping coefficient used by (Hussein et al. 2014) for soil medium is 2%. The shear wave velocity for soil medium is given by Vs=308.94 m/sec. Based on the shear wave velocity and the depth of soil, the natural frequency of the soil medium can be calculated. Therefore, the dimensions of the soil medium are needed to be assumed to calculate the natural frequency of the soil medium, then the Rayleigh damping coefficients can be calculated accordingly. The following steps show the calculation for alpha α and beta β:

- Calculate the natural frequency of the soil layer.
    - Take soil layer depth as H equal to 40m and the number of modes as n equal to 1, natural frequency of the soil layer can be calculated for the first mode as:

$$f_n = \frac{V_s.(2n-1)}{4*H} = \frac{308.94*(2*1-1)}{4*40} = 1.931\ cycles/sec$$

- Used the value of natural frequency for mode 1 and mode 20 in rad/sec. It is important to note her that the variation between the natural frequency and the assumed damping ratio is linear, so it can be concluded that by taking the first 10 to 20 modes of the soil system to calculate the Rayleigh damping coefficients can avoid the calculation error at the first few modes of the system.

$$\omega_1 = 12.134\,rad/sec \quad and \quad \omega_{20} = 473.242 rad/sec$$

- Take the damping coefficients as 2% as reported by (Hussein et al. 2014);
- The damping confidents can be calculated from the following equations;

$$2\xi_i\ \omega_1 = \alpha + \beta\ \omega_1^2 \qquad (7)$$

$$2\xi_i\ \omega_{20} = \alpha + \beta\ \omega_{20}^2 \qquad (8)$$

- Calculate the alpha α and beta β.

The material damping used for FE model was Rayleigh damping governed by two parameters α and β in Table 7.

Table 7 Rayleigh damping coefficients α and beta β for homogenous soil

T (s)	f (cycles/sec)	*ω* (rad/sec)	Damping	α (s^{-1})	β (s)
0.5178	1.9313	12.1344	2.00%	0.473242	0.0000824
0.0133	75.3188	473.2417	2.00%		

3.8.2 Non-reflective Boundary Conditions

The model layout is shown in Figure 13. It must be taken into consideration that different model dimensions may affect the outcome results, so a trial and error method is used to finalize the outer parameters of the soil medium. The tunnel is modeled as an opening hole inside the soil with thickness of 0.25m and interior radius of 2.75m. The boundaries are taken as non-reflective boundary conditions by using infinite quadratic element type of 'CINPE5R'. The interested region for measuring the displacement response values is within box dimensions 40m×40m. The medium used for the in-finite element boundary condition is assumed to be like the soil medium that surrounds the tunnel.

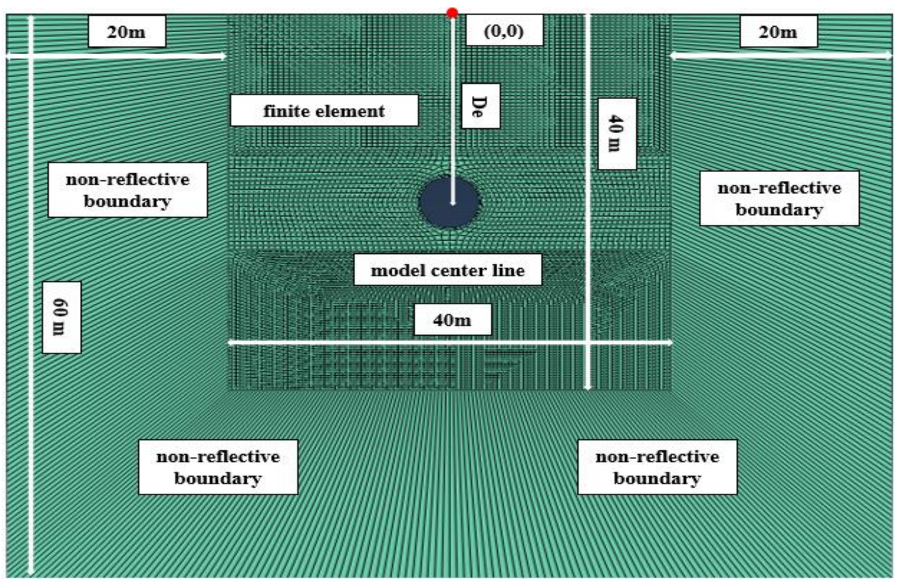


Figure 13 2D FEM for tunnel embedded in half-space

The coordinate system definition for the 2D tunnel-soil interaction model is taken as (x, y) coordinate system which is same as the coordinate system used for 2D and 3D tunnel models. The point of origin (0,0) is located on the ground surface along to the center line of the tunnel. The element size used for model 1 and model 2 are 0.54m and 0.5m, respectively. The element type for the soil within 40m×40m box surrounds the tunnel is taken as standard quadratic plane strain element. The tunnel element type is taken as a plane strain element. For model 1, the load is applied at the center bottom of the tunnel with coordinate point of (0, -8m). For model 2, the load is applied on point of (0, -23m). The load is taken as a harmonic concentrated load. The dynamic analysis is performed for both models and the displacement responses are measured for different point locations. The frequency range is taken as 1Hz to 80Hz which is similar to (Hussein et al. 2014). The number of measured points is taken as 200 points to get accurate results. The outcome results from model 1 and model 2 are then compared with the literature.

3.8.3 2D FE Modeling for Circular Tunnel Depth

Figure 14 shows the response point locations at different horizontal and vertical distances from the tunnel.

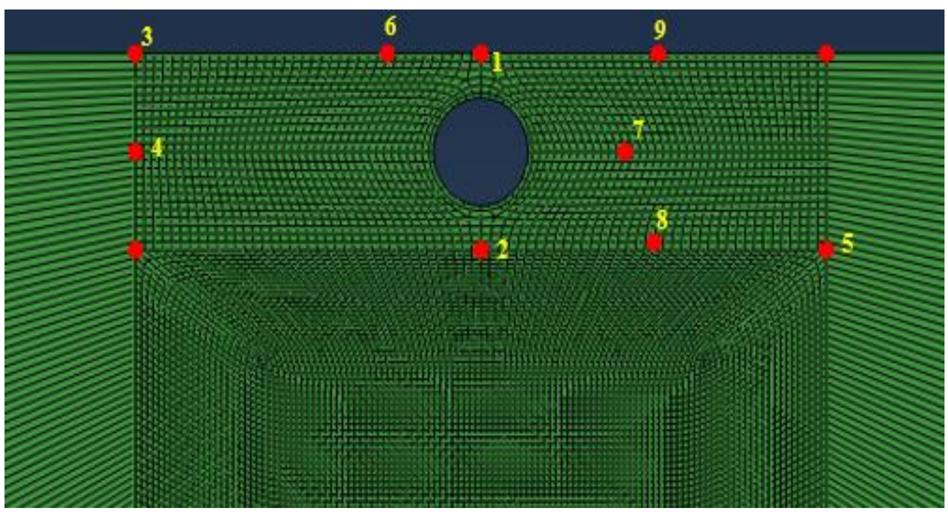
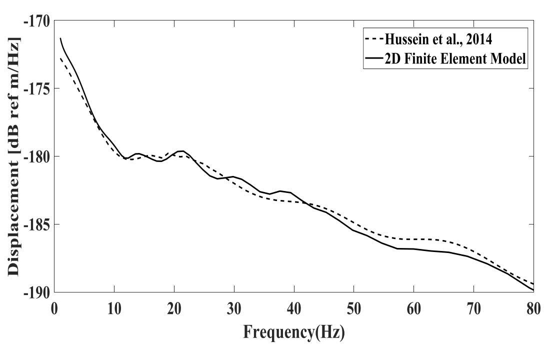


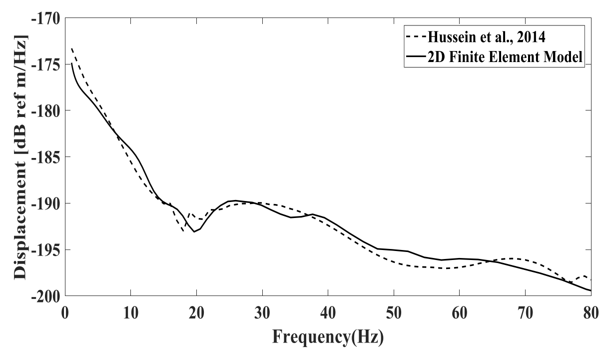
Figure 14 Soil-tunnel FEM for circular tunnel embedded in homogenous soil at depth 5m in Abaqus

The points of interest are located based on the nearest building locations, ground surface and any deep foundations or retaining structure system within the tunnel zone.

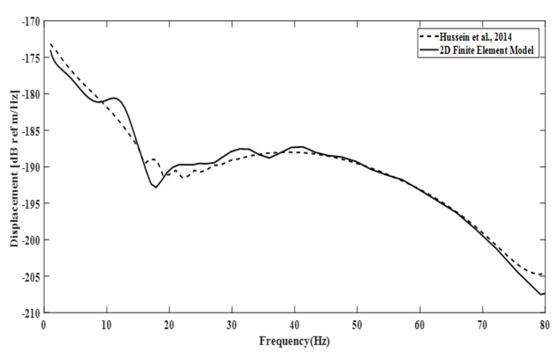
These points can be changed according to the site conditions. They are chosen randomly to cover the expected location of buildings or any other adjacent structure. After running the dynamic analysis for model 1, the displacement responses are measured for each designated point of interest. A graph for the frequencies and the response displacement values is plotted by using MATLAB. It is a software that can solve numerical problems and visualize the outcome data by using plot command. It is powerful software that most of the engineers are using. The displacement is measured in two directions which are x-direction and y-direction.



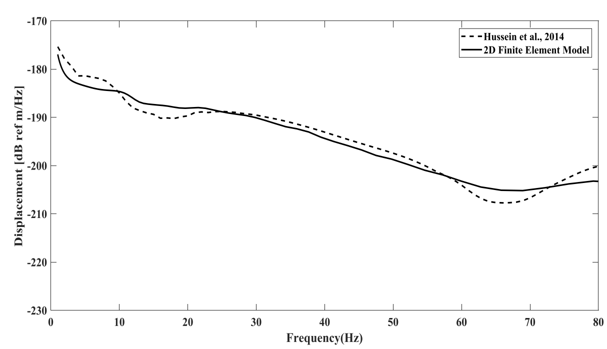
(a) At point 2 (0, -10) m.



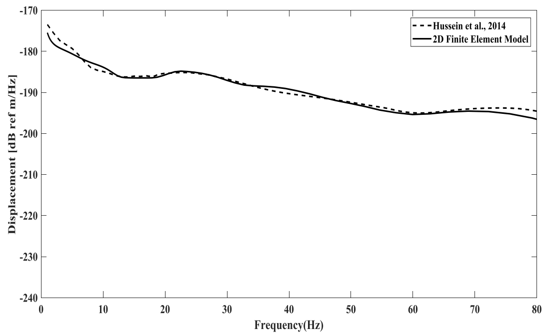
(b) At point 7 (8.368, -5) m.

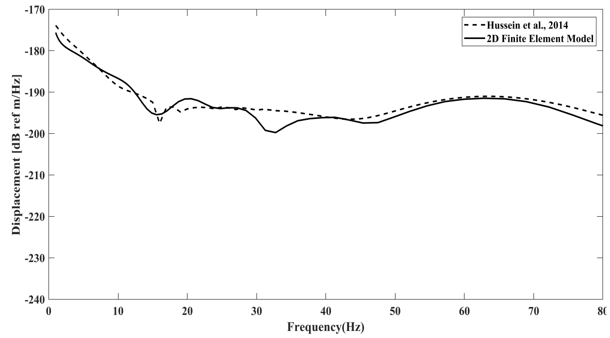


(c) At point 1 (0, 0) m.



(d) At point 5 (20, -10) m.





(e) At point 8 (10.03, -9.520) m.

(f) At point 9 (10.27, 0) m.

Figure 15 Displacement response in y-direction for 2D FE and Pipe-in-Pipe model at depth of 5 m (Hussein et al. 2014)

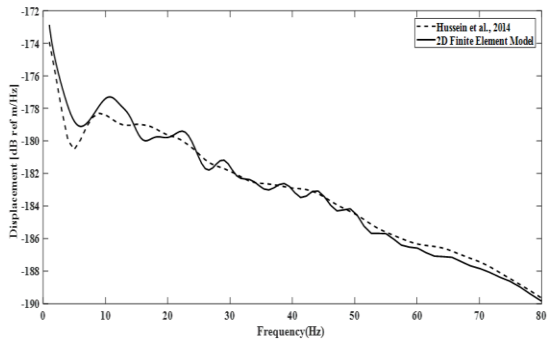
Figure 15 (a-f) shows the displacement response magnitues in six different locations by using FEM and Pipe-in-Pipe model by (Hussein et al. 2014). The response points of intrest were chosen based on the location of nearest foundation and at grade level. The location of response point is taken on the grade level and in the soil to examin the displacement response and compare it with the litreture. The graph shows that the lines are almost too close together. There is a small difference between FEM and Pipe-in-Pipe because of different damping difenition in both models, but still the diffrence is relativly small. On the other hand, the force response lines for graphs a, b, c, d, e and f are identical to each other. The points at boundary conditions are not considered as a response points because they are critical points due to changing of element type from CPE8R to CINPE5R.

3.8.1 2D FE Modeling for Circular Tunnel Depth =20 M

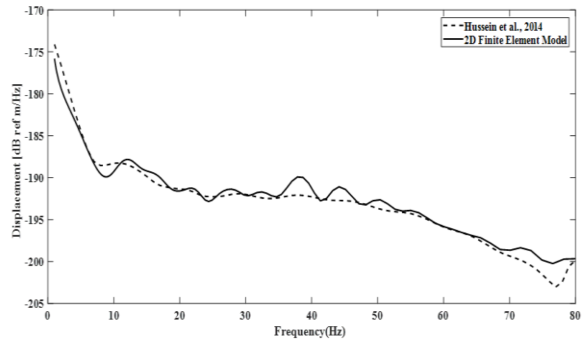
Figure 16 shows the response point locations at different horizontal and vertical distances from the tunnel.

Figure 16 Displacement response in y-direction for 2D FE and Pipe-in-Pipe model at depth of 20 m (Hussein et al. 2014)

Figure 17 (a, b) describes the frequency response due to harmonic point load which is applied at the bottom of the underground railways tunnel which is located at depth of 20 m. The displacement responses are varying from one point to another. The reason for this difference is the distance from the source of the vibrations to the response point of interest. The ground surface is affected by the vibration response which is generated from underground railways tunnel and propagated into the soil medium. It can be said that whenever the response point moves into the soil cavity and away from the interface boundary with the infinite element medium, the displacement response for FEM agrees with the literature. It is observed through the graphs in Figure 17(a, b) that the results are compatible between the FE model and (Hussein et al. 2014).



(a) At point 4 (0, -25.050) m.



(b) At point 5 (7.026, -20.0) m.

Figure 17 Displacement response in y-direction for five points in half-space FEM as compared with (Hussein et al., 2014)

3.9 Conclusion on Model Verification

In this chapter, complete FEM models are made to simulate the dynamic harmonic load of an underground railway tunnel and the generated wave propagation in soil. Finite Element is a technique developed for numerical solutions of complex problems in structural mechanics. The software used to simulate the dynamic analysis of plane strain tunnel and 3D tunnel is Abaqus. FEM has many applications such as linear and non-linear structural analysis, dynamics of complex structures, soil mechanics, etc. In FEM, the structural system is modeled by a set of appropriated finite elements interconnected at discrete points called nodes.

The first and second models of verification are FE models for free tunnel with no surrounding soil that is modeled in 2D and 3D dimensions. The main objective of both models are to compare the results found with Shell Theory by (Forrest and Hunt 2006b). The displacement responses are measured at different point locations. The damping properties for soil and tunnels are taken as Rayleigh damping coefficients α and β.

The third and fourth models are for circular tunnels which are modeled with solid elements and infinite element boundary conditions in 2D dimensions. The material properties are taken as reported by (Hussein et al. 2014). Different response points are taken to consider the vibration on ground surface and the vibration on the foundations of nearest building. The only difference between the two tunnel-soil dynamic models is the tunnel depth (De) which is 5 m for third model and 20 m for fourth model. The damping of soil and concrete is presented by α and β coefficients by taking the damping ratio of 2.0%. The outcome results are drawn in diagrams and compared with the results presented by (Hussein et al. 2014) for half-space model condition. The outcome results from model verification work show that there is a simple difference between FEM and Pipe-in-Pipe model due to different calculation method of damping ratio in both models. In Pipe-in-Pipe, the damping is defined as loss factor η= 0.04 associated with both Lamé constants. On the other hand, the damping ratio was defined in FEM as Rayleigh damping coefficients α and β. It can be concluded from chapter 3 that the results from FEM for 2D soil-tunnel interaction is matching with the literature.

CHAPTER 4: EFFECT OF TUNNEL SHAPES ON GROUND-BORNE VIBRATION

4.1 Introduction

In Chapter 3 the vibration response from the Finite Element Model (FEM) for a single circular tunnel in a homogenous half-space soil medium is supported by the literature. This model confirms the starting point to investigate vibration from underground railway tunnel with different shapes in homogenous half-space and multi-layered soil. The analysis is carried-out in 2D representing plane strain scenario. The reasons for using 2D FEM are that it provides qualitative results with 3D analysis as reported in Chapter 2. Also, the required time for the dynamic analysis in a 3D model is more than the required time for 2D model.

The 2D FEMs were created by using Abaqus for circular, square, rectangular and oval tunnels embedded in a homogenous and multi-layered soil medium to examine the effect of soil inhomogeneity and the tunnel shape on propagation of ground-borne vibration. The soil is modeled in two cases. Case 1 is for homogenous soil which was presented in Chapter 3 with different tunnel shapes and depths. Case 2 is about typical soil layers in Qatar. It is modeled with different tunnel shapes at different depths. The purpose of this Chapter is to examine the effects of single underground railway tunnels and twin tunnels with different tunnel shapes (circular, oval, rectangular and square) on ground-borne vibration and noise. Also, the effect of double tunnel is studied to determine if there is a relationship between the number of tunnels and vibration propagation in a layered soil medium. The soil layer parameters are taken for soil in the Msheireb area in Qatar. The reason for choosing the Msheireb area is because it is in the heart of Doha metro lines. Also, there are three underground metro lines passing through Msheireb area at different levels.

In short, a parametric study is performed to understand the effects of tunnel shapes, number of tunnels (single or twin), soil layers (homogenous, multi-layered soil) and the depth of the tunnel on the vibration from underground railway tunnels.

The objectives of this chapter are:

1. To study the effects of changing single tunnel cross-sections (circular, square, rectangular and oval) on the vibration from underground tunnels in homogenous half-space soil medium.
2. To investigate the effects of changing twin tunnel shapes (circular, square, rectangular, and oval) on the vibration from underground tunnels in homogenous half-space soil medium.
3. To study the effects of changing the depths (5m, 10m, 15m, 20m and 25m) with different tunnel shapes (circular, square, rectangular and oval) in half-space on the vibration from underground tunnels in Qatar.
4. To study the effects of changing single tunnel cross-section shapes (circular, square, rectangular, and oval) in half-space from the ground surface on the vibration from underground tunnels in Qatar.
5. To investigate the effects of different twin tunnels shapes (circular, square, rectangular, and oval) from the ground on vibration response from underground tunnels in Qatar.

4.1.1 Shapes of Underground Tunnels

The tunnel shapes can be classified by the soil condition, by cross-sectional shapes and by construction method. The underground railway tunnel is studied in four different shapes. The soil conditions presented in this research is a homogenous soil as reported in chapter 3 and rock layers in Qatar. The tunnel cross-section shapes can be circular, square, rectangular and oval. The FEMs for different tunnel shapes are made with different tunnel depths 5m, 10m, 15m, 20m and 25m. The material properties for all tunnel shapes are used as reported by (Forrest and Hunt 2006b) in Table 8. The thickness of all the tunnel shape is 0.33m. The concrete lining method can be in-situ concrete (square, rectangular and oval) and can be a preformed segments (circular). The segments are precast parts of the tunnel walls that can be connected by bolts. For all tunnel shapes used in the modeling, the concrete wall is modeled as one unit without any segments.

A. Circular Shape

The construction method for circular tunnel is using Tunnel Boring Machine (TBM). It is widely used in underground railway transportation systems, especially in medium to hard soil conditions. The inner diameter of the tunnel is 6.17m. The cross-section area is 29.9 m2.

B. Square Shape

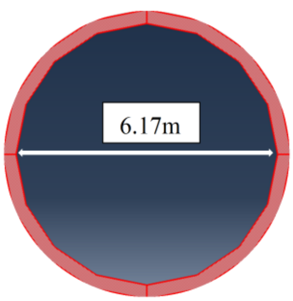
The construction method used for square shaped tunnels is the cut-and-cover method. The tunnel dimension is 5.5 m. The area of the square tunnel is 30.25 m^2 which is close to the circular cross-section area.

C. Rectangular Shape

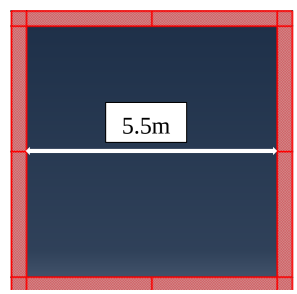
The construction method for rectangular shaped tunnels is the cut-and-cover method. With this method, a trench is excavated, a tunnel lining is placed, and the tunnel is backfilled to ground level. The dimensions of the rectangular are 6 m×5 m. The cross-section area is 30 m^2.

D. Oval Tunnel

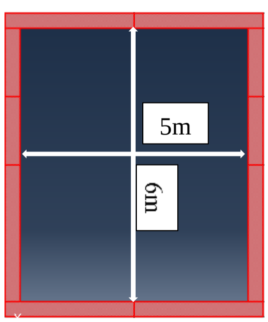
The oval tunnel diameters are 5m and 7.6m. The cross-section area is 29.84m2 which is close to circular, square and rectangular tunnels. Figure 18 demonstrates the single tunnel shapes used in the FE modeling.



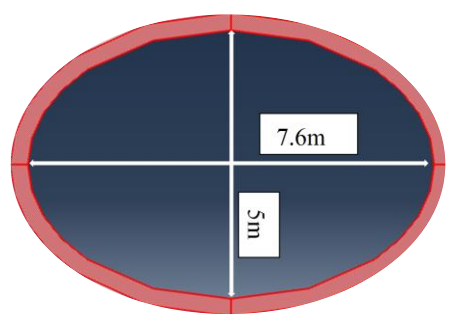
(a) Circular tunnel



(b) Square tunnel



(c) Rectangular tunnel

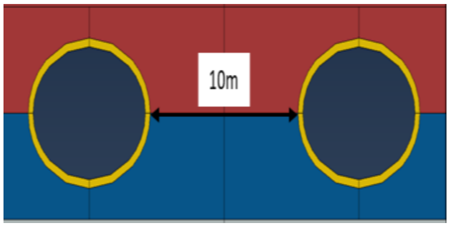


(d) Oval tunnel

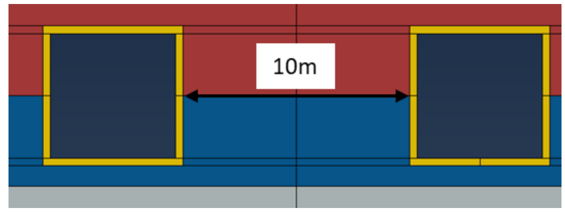
Figure 18 Different shapes of underground railways tunnels, (a) Circular, (b) square, (c) rectangular and (d) oval

4.2 Twin Tunnels

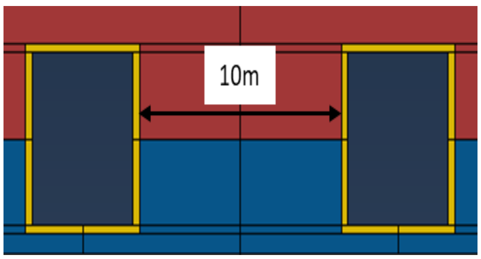
The twin tunnel shapes used in the models are (circular, square, rectangular and oval). The dimensions of the twin tunnels are same as a single tunnel. The horizontal distance between twin tunnels is 10m for all tunnels shapes. The FEM for twin tunnels is used to examine the effects of shapes on vibration values from the underground railway tunnel embedded in homogenous or multi-layered half-space. The FEM for circular twin tunnels is taken as a reference model to compare the results with the other twin tunnel shapes (square, rectangular and oval). The twin tunnels are modeled with the same positions (same depths). The dimensions of soil cross section for twin tunnel FEMs are taken as 160 m×100 m. Figure 19 (a, b, c, d) presents the cross-sections layout for twin tunnel shapes which are: (a) twin circular tunnel, (b) twin square tunnels, (c) twin rectangular tunnels and (d) twin oval tunnels.



(a) Twin circular tunnels



(b) Twin square tunnels



(c) Twin rectangular tunnels

(d) Twin oval tunnels

Figure 19 Different twin tunnel shapes, (a) Circular, (b) square, (c) rectangular and (d) oval

Table 8 Data for single and twin tunnels as reported by (Forrest and Hunt 2006b)

E (Pa)	**ν**	**ρ (kg/m³)**	α_R **(s⁻¹)**	β_R **(s)**	**h (Thickness, m)**
50×10^9	0.3	2500	10	40×10^{-6}s	0.33m

4.3 Convergence Study for Element Size

4.3.1 Element Description

Finite element type and size are major elements in any FEM because they affect the outcome of the analysis. Choosing FE type can be done based on three major factors, which are the dimensions of the model, type of the analysis and the time frame of the analysis.

The mesh size was examined to validate and compare the accuracy of the results found with another FEM with different mesh sizes. Before conducting the final model analysis for vibration from underground railway tunnels, it is necessary to do a convergence study to determine results with respect to the element size. If the results with different element sizes are closed to each other, they are converged, and the element size is used for modeling. On the other hand, if the result is not converting, the element size needs to be reduced and the analysis repeated. To achieve this target, a convergence study was conducted to determine the FE element size. The sizes are taken as 0.25m, 0.5m, and 1.0m. As shown in Figure 20, the results obtained for an element size of 0.5m are very close to those obtained for 0.25 m elements. Therefore, for all FEMs, a global approximate element size of 0.5m was used to minimize the computational time and effort.

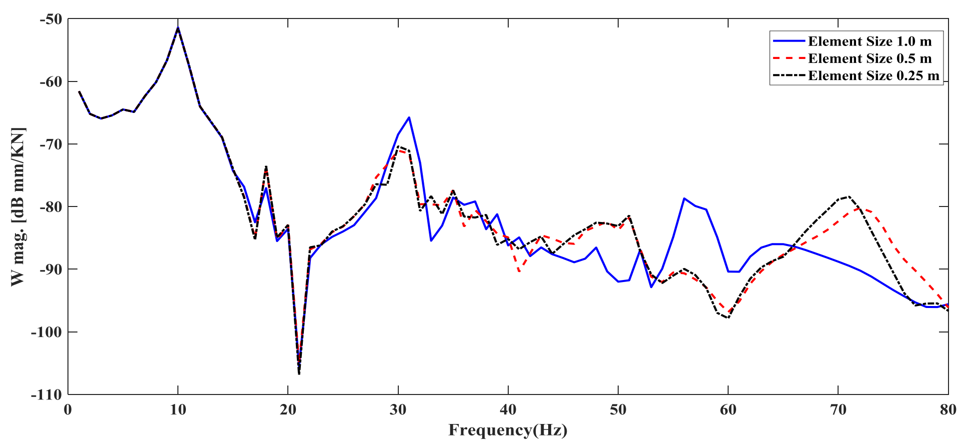


Figure 20 Frequency response in y-direction for FE circular tunnel model with different element sizes

4.3.2 Modeling Assumptions

To do the FEM in Abaqus, there are some assumptions that need to be specified. First, the presented study in this chapter is focusing on the effect of the tunnel shape and soil layering on ground-borne vibration generated from underground railway tunnels in Doha. Second, the tunnel walls are assumed to be fully and tightly attached with the soil surrounding without any voids. It is significant to mention here that the effect of any force vibration from the ground surface is not considered in the analysis. Third, the applied load in all models is a harmonic concentrated load in y-direction only. For twin tunnels, the load is applied at the bottom of the right tunnel only because it is assumed that one of the twin tunnels has a train passing through it. It also makes the results clearer than having a situation of two trains since there is no interface between the two sources of vibration waves. It is the simplest twin tunnel model that can gives an initial figure about vibration response for twin tunnels in a simple model.

4.3.3 Non-reflecting Boundary Conditions

The main purpose of the non-reflecting boundary conditions is to control the wave reflections from the assigned system boundary to the model which minimizes the error from reconsidering the reflected waves in the vibration magnitude. It also minimizes the reflections of stress waves and reduces the distortions in the calculated results. The magnitude of the vibration is measured at different locations/distances from the center of the tunnel. Those locations are based on the existence of any foundation to the nearest building and the closest distance that people can live in within railway effective zones. Quadratic quadrilateral plane strain CPE8R (8-node biquadratic, reduced integration) finite elements were used to model the soil and tunnel (circular, square and rectangular). On the other hand, the element type used for the oval tunnel is a quadratic triangle, type CPE6M (6-node modified, with hourglass control) to make the elements more consistent with each other. Also, quadratic quadrilateral plain strain CINPE5R infinite element was utilized as non-reflective boundary. Figure 21 displays element types used in 2D FE modeling for rectangular, square and circular underground tunnels. Figure 22 shows the element types used in 2D FE modeling for oval underground tunnel.

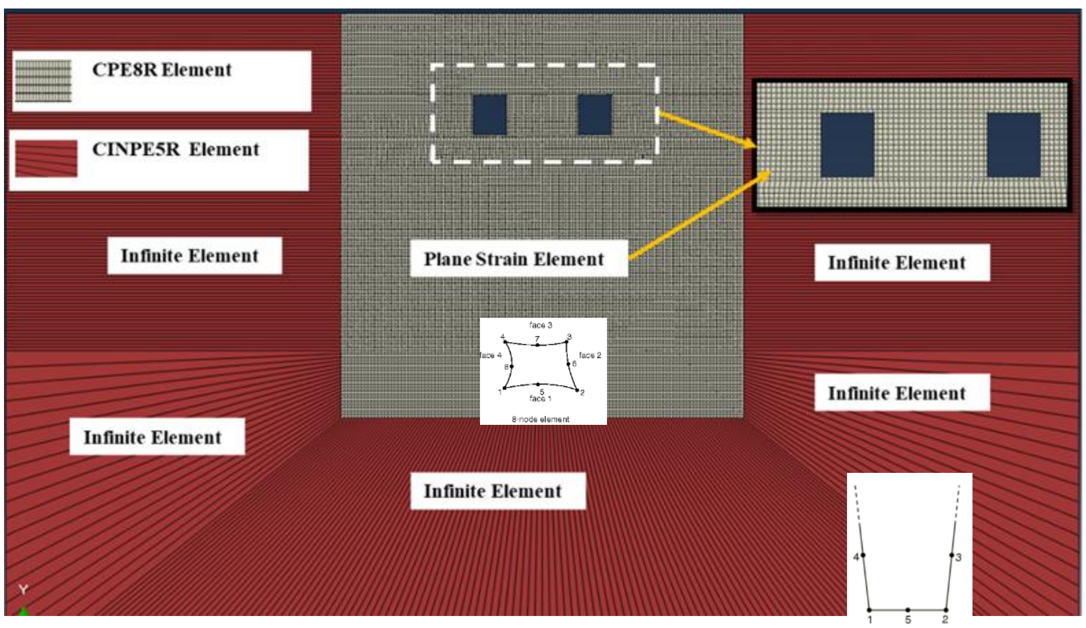


Figure 21 Element types used in 2D FE modeling for rectangular, square and circular tunnels

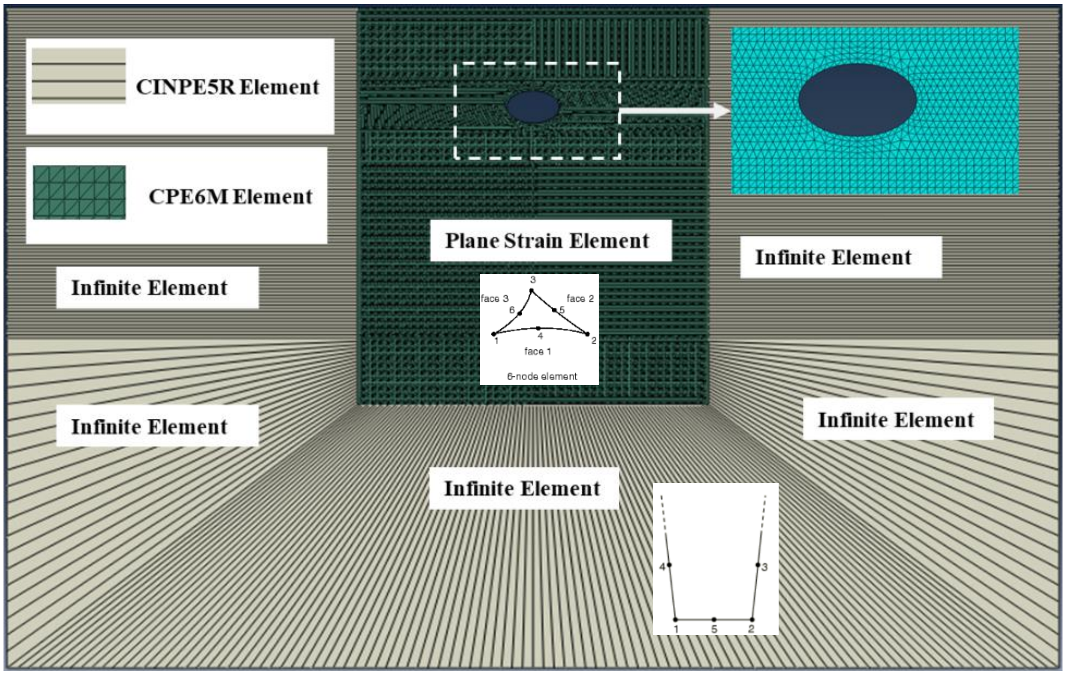


Figure 22 Element types used in 2D FE modeling for oval tunnel

4.4 Abaqus Axis Description

The coordinate system used in Abaqus is a global rectangular Cartesian axis system (x, y). It is a coordinate system that stipulates every point in the plane by a couple of numerical coordinates. A (0,0) is a point located at the top center of the ground surface as demonstrated in Figure 23.

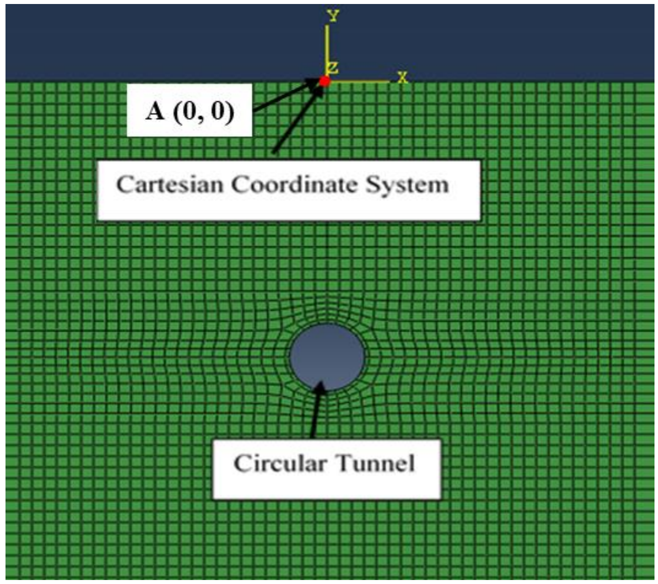


Figure 23 Cartesian coordinate system in Abaqus

4.5 Effect of tunnel shape in elastic homogeneous half-space

A 2D FEM of a tunnel embedded in a homogenous half-space medium was created. The soil properties used are provided in Table 6 which are based on (Hussein et al.,2014), while the properties of the tunnel were taken from (Forrest and Hunt 2006b). Figure 24 describes the model's dimensions of 150 m×100 m. The depth of the tunnel (De) was taken as 15 m measured from the ground surface to the center point of the tunnel. The element size for the FE elements was taken as 0.5 m.

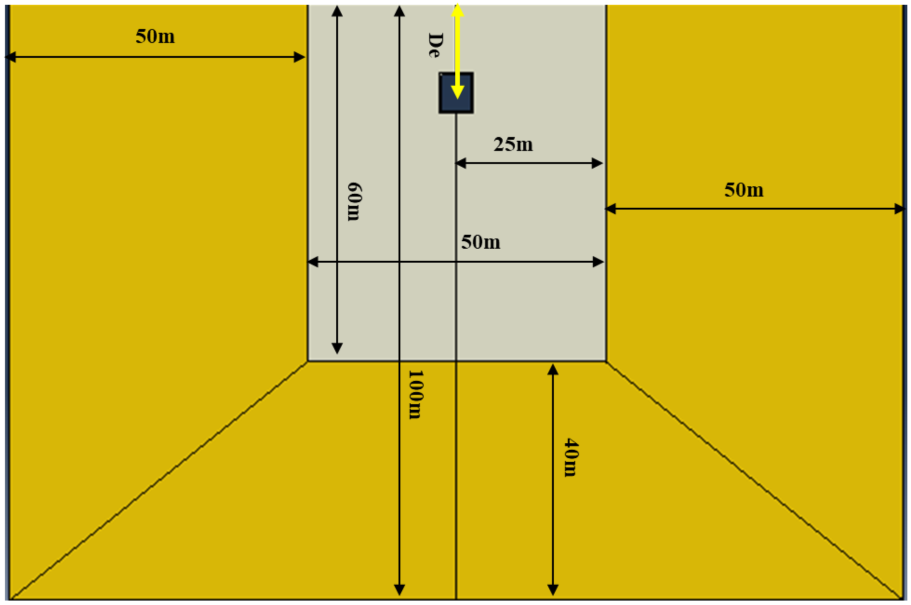


Figure 24 2D FEM dimensions for tunnel embedded in homogenous half-space.

4.5.1 Comparison Between Different Tunnel Shapes

The displacement response was measured at points (15, -15) m and (10, 0) m in y-direction. Table 9 displays the response points coordinates for single tunnel embedded in homogenous half-space. The cross section at Figure 25 shows the response point positions for single underground tunnel model.

Table 9 The location of response points in single tunnel FE model in homogenous half-space

No.	Location (x, y)
Point 1	(15, -15) m
Point 2	(10, 0) m

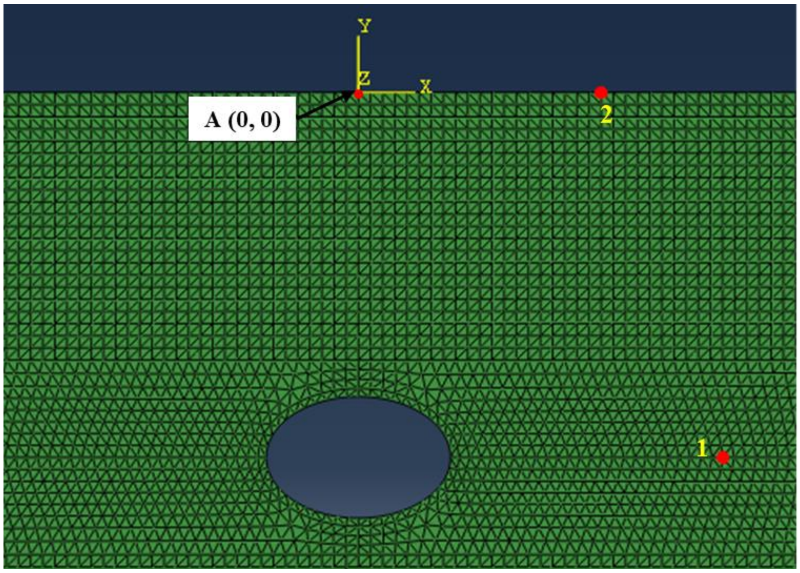
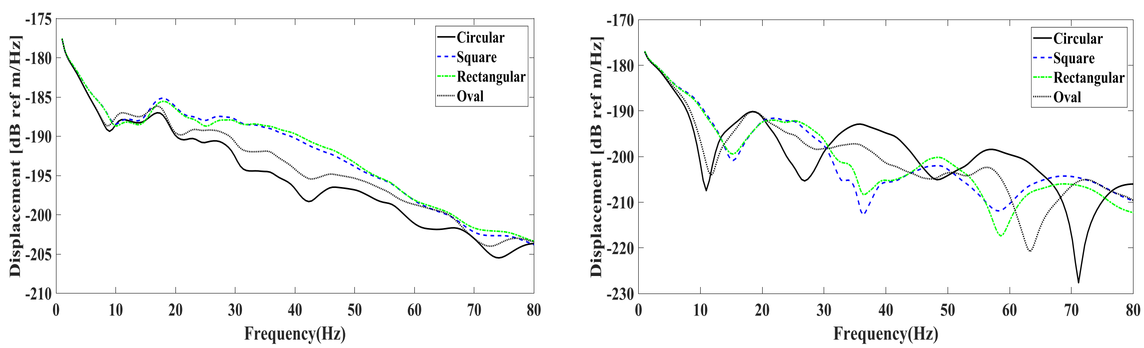


Figure 25 Response point locations (1 and 2) for single tunnel models in homogenous soil

The graphs in Figure 26(a) at point (15, -15) m inside the soil medium confirms that the displacement response for homogenous soil at a depth of 15 m for different tunnel shapes is varies by tunnel variation in shapes. The tunnel was placed at depth of 15 m because it is an appropriate average depth level for the different tunnel depths (5m, 10m, 15m, 20m, 25m) used in the analysis of multi-layered soil. It is observed that at a small frequency range [1Hz -6Hz], the displacement responses for different tunnel shapes are not much different at the ground surface and inside the soil medium. The smallest vibration can be observed for the circular tunnel and the highest value of the displacement response is for the rectangular section. Figure 26(b) shows the displacement response on the ground surface. The reason for the difference between the displacement response on the ground surface and inside the soil is that on the surface there is a presence of the effect of the wave reflection.



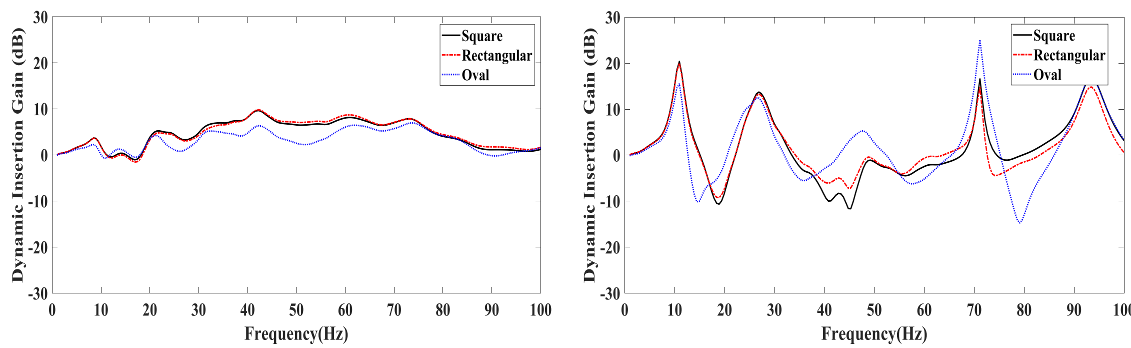
(a) Point (15, -15) m. (b) Point (10, 0) m.

Figure 26: Displacement response at the points (15, -15) m and (10, 0) m for different tunnel shapes in y-direction in homogenous half-space

The insertion gain can be computed as (Hussein and Hunt 2003)

$$[\boldsymbol{dB}] = \mathbf{20}\,\boldsymbol{log_{10}}\left(\frac{\boldsymbol{D_2}}{\boldsymbol{D_1}}\right) \qquad (9)$$

Where D_2 is the displacement response of a square, rectangular, or oval tunnels and D_1 is the displacement response for the reference (i.e. circular) tunnel. Again, the analysis displayed in Figure 27 shows that changing the tunnel shape influences the dynamic response measured at a point inside the soil for frequencies between 25 Hz to 70Hz. However, the response at the surface appears not to be affected significantly by tunnel shapes because insertion gain lines are consistent is most of the points.



(a) Point (15, -15) m. (b) Point (10, 0) m.

Figure 27 Dynamic insertion gain at the points (15, -15) m and (10, 0) m for different tunnel shapes in homogenous half-space

4.5.2 Twin Tunnel Modeling

The twin tunnel FEMs are made for a depth of 15 m from the surface to the center point between the twin tunnels. The circular twin tunnels are taken as a reference model to compare the results with another shape of twin tunnels (square, rectangular and oval). The harmonic concentrated load is taken as 1 N and is applied at bottom of right tunnel. It should be noted that the twin tunnel model is symmetric around y-axis, so the load can be either in left or right tunnel. The displacement responses were measured at different locations which covers the area of interest. Those points are located on ground surface, inside the soil between the solid elements and infinite elements and between the twin tunnels. Table 10 shows the response point locations in twin tunnel homogenous soil models. Figure 28 response point locations for twin tunnel models in homogenous soil.

Table 10 The location of response points in twin tunnel FE model in homogenous half-space

No.	**Coordinate (x, y)**
Point 1	(8m,0)
Point 2	(-8m,0)
Point 3	(15, -15)
Point 4	(-15, -15)
Point 5	(0, -1.5m)
Point 6	(0, -15m)

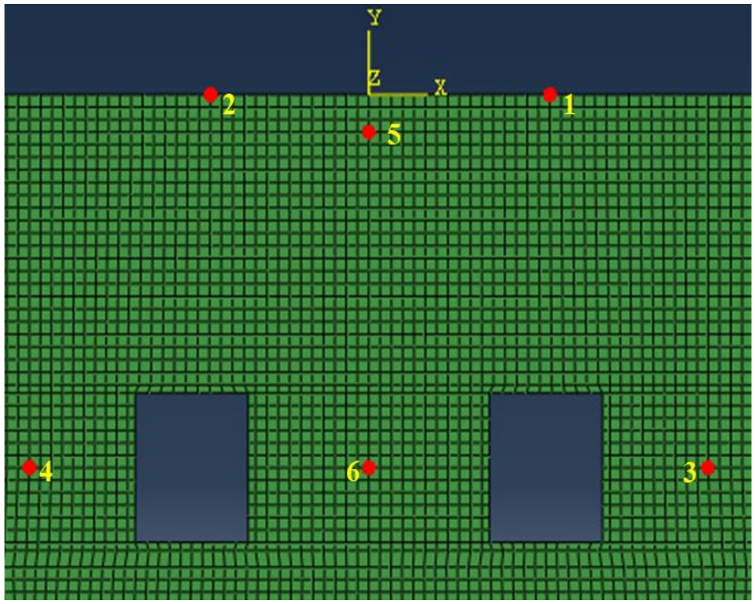
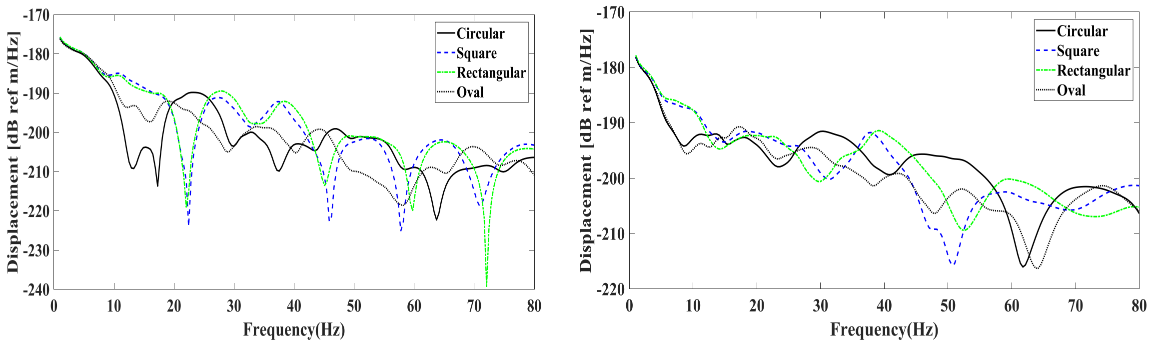


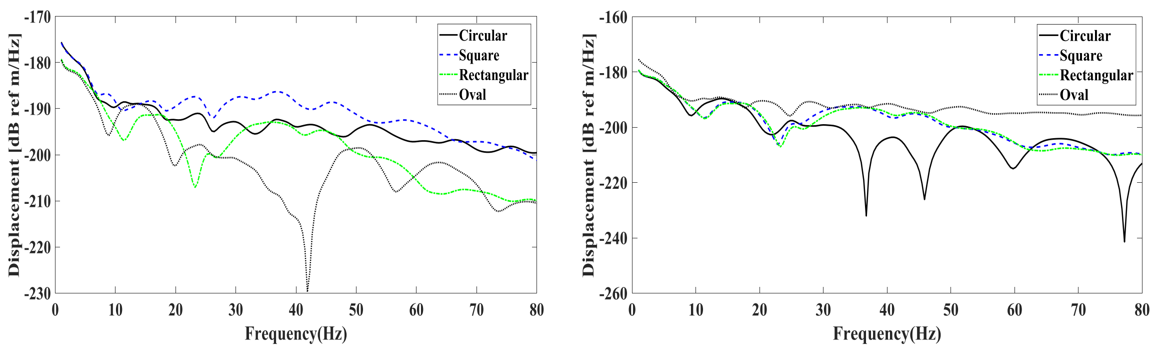
Figure 28 Response point locations (1, 2, 3, 4, 5 and 6) for twin tunnel models in homogenous soil

In Figure 29(a, b) the vibration was measured at two different points on the ground surface, point 1 and point 2. The lines of vibration values for different tunnel shapes are applied above each other at low frequency [1 Hz –10 Hz]. The difference in vibration for different tunnel shapes starts occurring at a higher frequency [20 Hz – 80 Hz] in harmony along the frequency axis. In Figure 29(a, b), the displacement for twin oval tunnels appear to be different from the other tunnel shapes at frequency of [40 Hz]. It is noted that the vibration values at a point near by the source is more that the vibration at a point far away from the source. Figure 30(a, b) presents the vibration at points (0, -1.5) and (1, -15) m, respectively. It seems clear from Figure 30(b) that vibration measurements are diverted for oval twin tunnels at frequency >15Hz when it is compared with other tunnel shapes (circular, square and rectangular) in half-space homogenous soil medium.



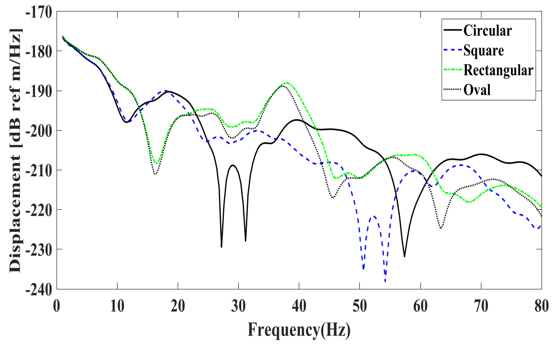
(a) Point (8, 0) m. (b) Point (-8, 0) m.

Figure 29 Displacement response at the points (8,0) m and (-8, 0) m for different twin tunnel shapes in homogenous soil

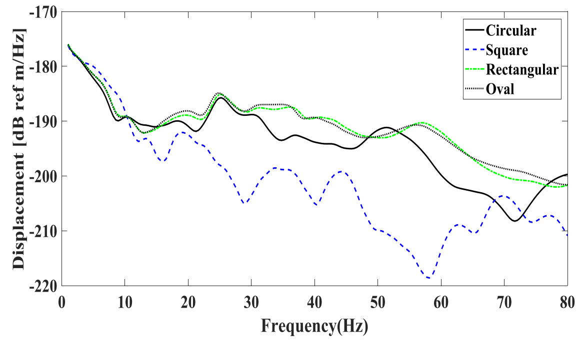


(a) Point (15, -15) m. (b) Point (-15, -15) m.

Figure 30 Displacement response at the points (15, -15) m and (-15, -15) m for different twin tunnel shapes in homogenous soil



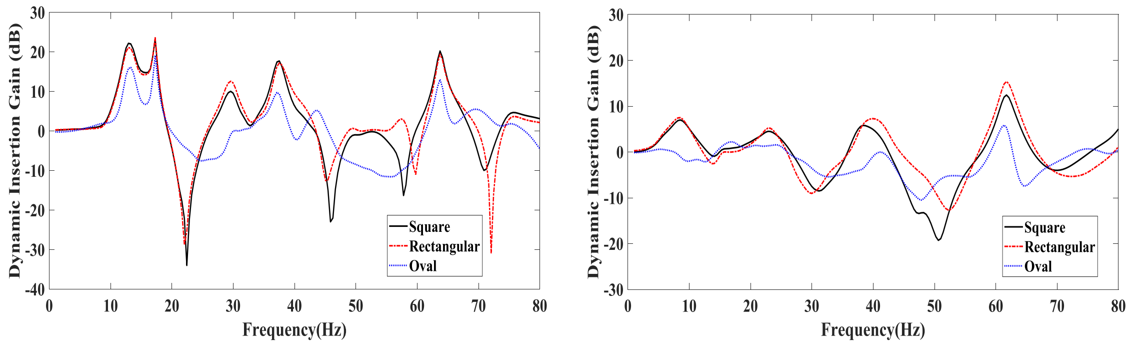
(a) Point (0, -1.5) m.



(b) Point (0, -15) m.

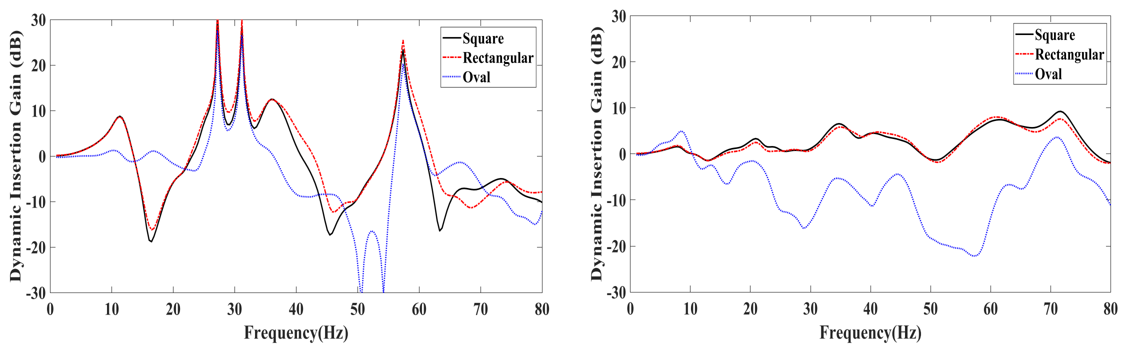
Figure 31 Displacement response at the points (0, -1.5) m and (0, -15) m for different twin tunnel shapes in homogeneous soil

Figures (32, 33) show the displacement response of a square, rectangular or oval twin tunnels by using an equation (9) for insertion gain. The displacement for a circular tunnel shape is taken as a reference. There is a clear difference between the oval twin tunnels and on one hand and the other twin tunnel shapes (circular, square and rectangular) on the other hand. In general, it was observed that changing the tunnel shapes has an influence on the vibration values corresponding to medium and high frequency range [40Hz – 80Hz] for homogenous half-space soil medium.



(a) Point (8, 0) m. (b) Point (-8, 0) m.

Figure 32 Dynamic insertion gain at the points (8, 0) m and (-8, 0) m for different twin tunnel shapes in homogeneous soil



(a) Point (0, -1.5) m. (b) Point (0, -15) m.

Figure 33: Dynamic insertion gain at the points (0, -1.5) m and (0, -15) m for different twin tunnel shapes in homogeneous soil

4.6 Effect of Tunnel Shape in a Multi-layered Half-space

The multi-layered soil medium is modeled by using Abaqus software in 2D. The soil layers have different properties and thickness as shown in Table 12. The single tunnel model geometries in multi-layered soil are shown in Figure 34. The total depth is assumed to be 100 m with width of a 150 m. The underground railway tunnel is modeled at the center of the 2D layered soil medium. The harmonic load is applied at the bottom of the tunnel in y-direction.

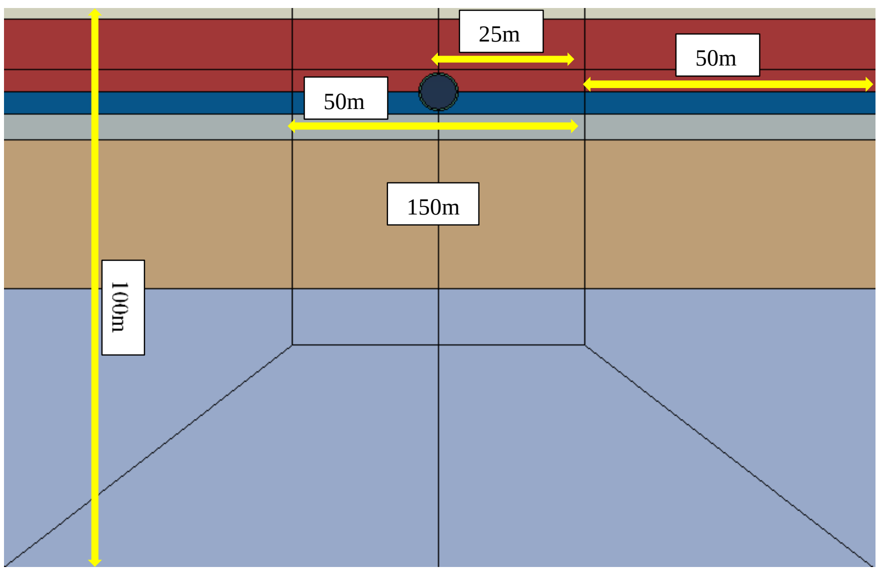


Figure 34 2D FEM model layout for circular tunnel embedded in multi-layered half-space.

4.6.1 Qatar soil descriptions

Qatar soil consists of ground filling on the surface and sedimentary rocks in layers. The ground conditions of Qatar soil used in this research consists of six soil layers. The first layer is called Made Ground and Fill Material with a thickness of 2m. The other five layers are generally Medium strong off white, brown to brown dolomitic limestone (Simsima Limestone).

The surface layer is generally described as fill, although in some cases the soils may be more likely Made Ground, or less commonly, original wadi deposits. Regardless of their origin, the layer is generally described as a fine to medium grained, medium dense to very dense sand with some gravel and cobbles of limestone. In some instances, the Made Ground is underlain by a layer of 'residual soil', which is the complete weathering product of the bedrock limestone. This residual soil is described as a greenish grey silt or sand with sub-angular gravel of limestone.

The Simsima Limestone Formation is encountered as a light brown to grey calcareous to dolomitic limestone with occasional pockets and joints filled with siltstone. The upper part of the Simsima Limestone is weak and more highly weathered. The lower part of the Simsima Limestone is weak to moderately weak and is generally more uniform with small clay filled pockets and close to medium spaced rough undulating sub-horizontal fractures. The Midra Shale Formation comprises attapulgite rich shale and is described as a weathered siltstone, mudstone or shale with close to medium spaced, rough and undulating sub-horizontal fractures.

The Rus Formation has an upper predominantly calcareous sequence and a lower Gypsiferous sequence. The calcareous sequence is described as very weak to medium strong off-white to light brown, grey partially weathered Calcisiltite interbedded with calcarenite and weak to medium strong partially weathered cement-stone with close space. Table 12 provides a summary of Qatar’s soil layers with material properties that are used for multi-layered soil models. The location of layered soil used in this work is shown in Figure 35.

Figure 35 Soil location in Qatar

4.6.2 Damping Properties for Multi-layered Soil Medium

Before conducting the dynamic analysis of multi-layered soil profile, the damping properties for each soil layer needs to be calculated. In Abaqus, the damping properties can be assigned by using the Rayleigh damping coefficients α and β. The damping coefficients α and β are artificial parameters used for computational software convenience to replace actual material damping ratio ξ where, α is the mass-proportional Rayleigh damping factor and β is the stiffness-proportional Rayleigh damping factor. Parameters α and β depend on vibration period T (i.e. frequency f, circular frequency w) and strain, since damping ratio ξ depends on strain. From Shake91, a modified version of Shake for conducting equivalent linear seismic response analyses of horizontally layered soil deposits user manual (Idriss et al. 1993). The Shake91 data analysis, for sample soil layer of Qatar is presented in Table

11. It provides a clear picture about the damping ratio that varies with the strain.

Table 11 Damping ratio for rock (Idriss et al. 1993)

Damping ratio ξ in rock					
For strain ξ (%):	0.0001	0.001	0.01	0.1	1.0
ξ (%):	0.4	0.8	1.5	3.0	4.6

The dynamic characteristics and parameters of soil are depended on the strain level. For soil 1, the damping ratio is taken as 2% as reported by (Ruiz and Rodríguez 2015). The material damping ratio is 3.0% for soil 2, 3, 4 and 5 based on a small strain of 0.1% for soil layers. The available data for Qatar soil is up to a depth of 50 m from the ground surface. The maximum depth of the tunnel is 25 m from the ground surface, therefore, the available soil data up to depth 50 m is enough for modeling the dynamic analysis of underground tunnels. The last layer (soil 6) is primarily located within the infinite element boundary condition. This layer is assumed to be Rus Formation with a damping ratio of 3%. The assumed maximum foundation depth of the nearest building is 25 m. It must be noted that the maximum depth of interest for measuring the displacement response is a depth of 25 m, therefore, the interested point of measuring the vibration is between 0 m to 25 m. To perform a dynamic analysis of the soil with tunnel, it is important to consider damping effects within the analysis. To do that, Rayleigh damping constants α, β for soil 2, 3, 4, 5 and 6 are calculated for the soil media based on the calculations reported in Chapter 3. For soil 1, the Rayleigh damping constants α, β are taken as reported by (Ruiz and Rodríguez 2015) for sand soil.

Table 12 Typical multi-layered soil profile in Qatar.

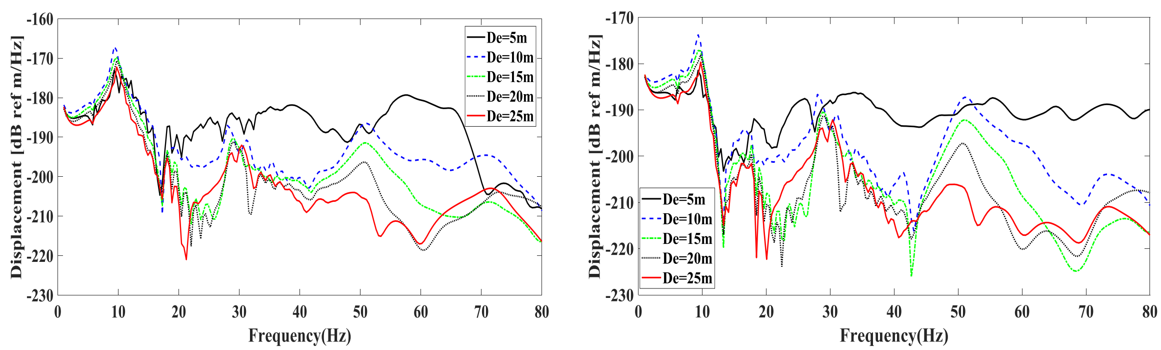
No.	H (m)	E (Pa)	ν	Stata name	ρ (Kg/m3)	ξ (%)	α_R (s^{-1})	β_R (s)
Soil 1	2	1×10^7	0.25	Made ground and superficial deposits	1835.5	2%	0.1244	0.000126
Soil 2	13	1×10^9	0.3	Upper Simsima Limestone	2345.3	3%	2.8380	0.000041
Soil 3	4	2×10^9	0.3	Lower Simsima Limestone	2345.3	3%	13.0442	0.000009
Soil 4	4.5	1.5×10^9	0.3	Midra Shale	2243.4	3%	10.2669	0.000011
Soil 5	26.5	1.5×10^9	0.3	Rus formation	2141.4	3%	1.78448	0.000065
Soil 6	50	1.75×10^9	0.3	Rus formation	2141.4	3%	1.02155	0.000113

4.6.3 Single Tunnel Modeling

The single tunnel is modeled with different shapes at different depths. The tunnel depth is taken from ground surface level to the center point of the tunnel. The depths are taken as 5 m, 10 m 15 m, 20 m and 25 m, respectively. The effect of tunnel depth in multi-layered soil is investigated with regards to the displacement response at different location.

A. Circular Single Tunnel in Multi-layered Soil

It is noted from Figure 36 (a, b) that the vibration decreases when the tunnel depth increases. The vibration from a circular tunnel at the shallow depth of 5 m is the highest value of the compared depths. For a circular tunnel at different depths (5, 10, 15, 20, 25) m, the difference in displacement response at frequency [1 Hz – 18 Hz] is not significant but at high frequency [20 Hz – 70 Hz], the displacement difference is significant.

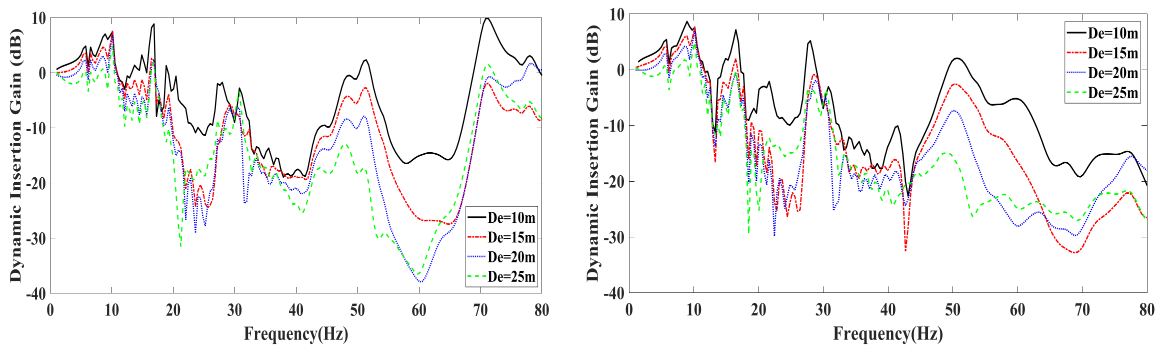


(a) Point (0, 0) m.

(b) Point (0, -1.5) m.

Figure 36 Displacement response at the points (0,0) m and (0, -15) m for circular tunnel at different depths in multi-layered soil

Figure 37 (a, b) shows the results of dynamic insertion gain at different single circular depths at response points (0, 0) m and (0, -1.5) m. The reference displacement response for circular tunnel is taken at a depth of 5 m so the vibration from the tunnel at a depth of 5 m is compared with vibration at depths of 10, 15, 20 and 25 m, there is no clear difference in displacement response at points a and b. It can be seen from Figures (36, 37) that the effects of vibrations have a great effect in small circular tunnel depths at low frequency in multi-layered soil medium.

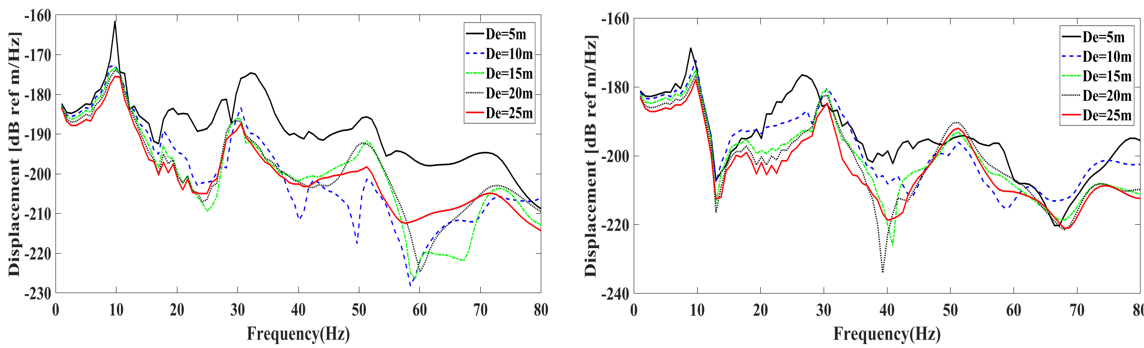


(a) Point (0, 0) m. (b) Point (0, -1.5) m.

Figure 37 Dynamic insertion gain at the points (0, 0) m and (0, -1.5) m for different circular tunnel depths in multi-layered soil

B. Square Single Tunnel in Multi-layered Soil

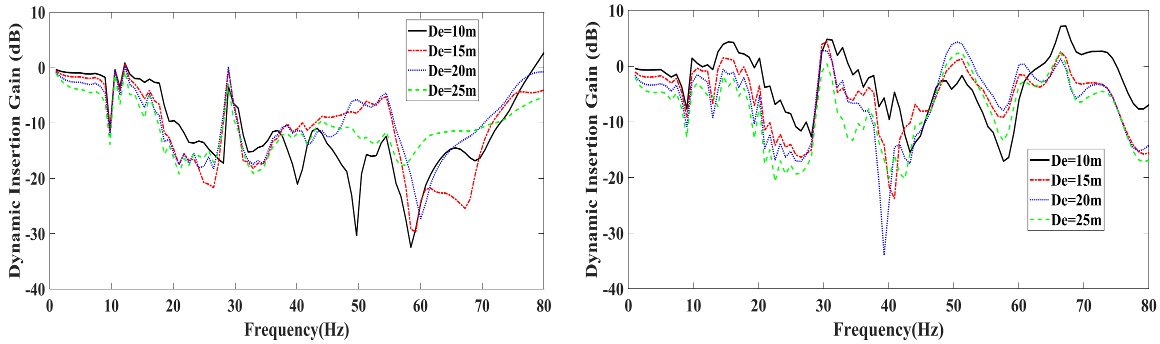
Figure 38(a, b) shows that the vibration varies with the depth for the same tunnel shape. There is a marked difference between the vibration values measured on the surface and inside the multi-soil medium. The reason for this difference is that the vibrations reflect partially on the ground surface since the FEM is in half-space.



(a) Point (10, 0) m.   (b) Point (0, -1.5) m.

Figure 38 Displacement response at the points (10,0) m and (0, -1.5) m for square tunnel at different depths in multi-layered soil

Figure 39 (a, b) shows the results of dynamic insertion gain at different single square depths. The response points are (0, 0) m and (0, -1.5) m. The reference displacement response for a single square tunnel is taken at a depth of 5 m so the vibration from the tunnel at this depth is compared with vibration at depths of 10, 15, 20 and 25 m, respectively. There is no major difference in displacement response at the two different points, a and b. It can be seen from Figures (38, 39) that the effects of vibrations at low frequency region [1 Hz – 20 Hz] have a no effect on depth of single square tunnel in multi-layered soil medium. On the other hand, the vibration at high frequency range [40 Hz – 80 Hz] is affected by the depth of the tunnel.

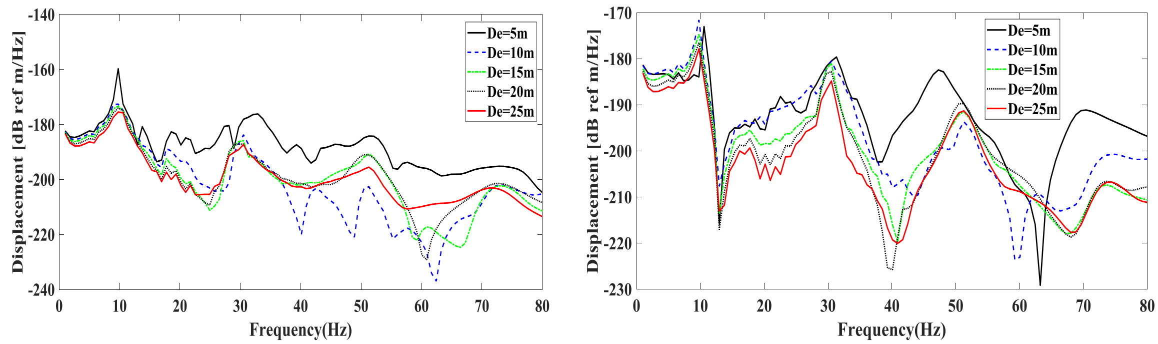


(a) Point (10, 0) m. (b) Point (0, -1.5) m.

Figure 39 Dynamic insertion gain at the points (10, 0) m and (0, -1.5) m for square tunnel at different depths in multi-layered soil

C. Rectangular Single Tunnel in Multi-layered Soil

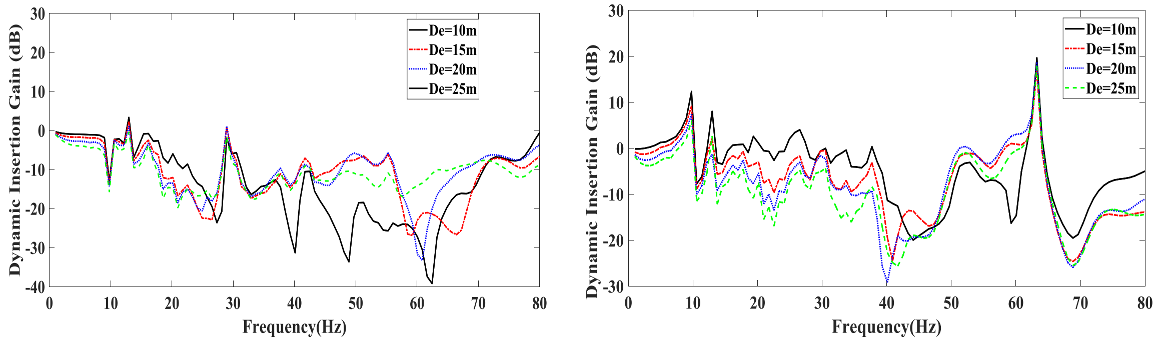
The displacement response for an applied harmonic load at the bottom of single rectangular depth is shown in Figure 40(a, b) at points of (10, 0) m and (0, -1.5) m, respectively. The vibration rate of variance at frequency 10 Hz for point b (0, -1.5) is between -172 to -185 dB_{ref} m/Hz but at frequency 70 Hz, the variance of displacement response at is [-193 to -208 dB_{ref} m/Hz] for the same point of response.



(a) Point (10, 0) m. (b) Point (0, -1.5) m.

Figure 40 Displacement response at the points (10,0) m and (0, -1.5) m for rectangular tunnel at different depths in multi-layered soil

Figure 41(a, b) shows the dynamic insertion gain at different rectangular depths. The response points are (10, 0) m and (0, -1.5) m. The reference displacement response is taken at depth of 5 m. It is noted that the shape of the tunnel at low frequency and with different depths does not play a central role in the vibration generated by the movement of the train inside the tunnel because of the hardness and strength of the rocks layers surrounding the tunnel.

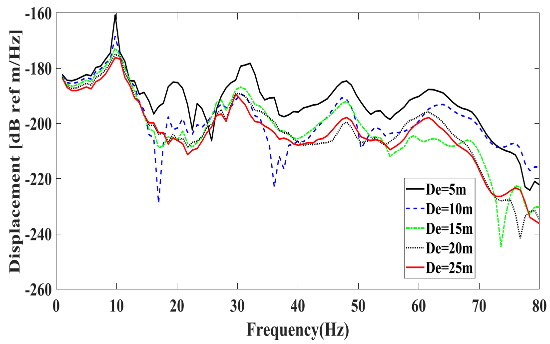


(a) Point (10, 0) m. (b) Point (0, -1.5) m.

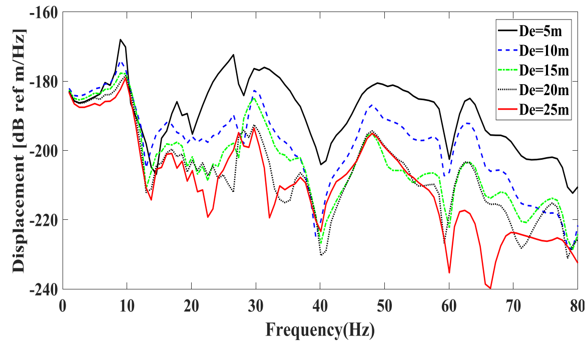
Figure 41 Dynamic insertion gain at the points (10, 0) m and (0, -1.5) m for rectangular single tunnel at different depths in multi-layered soil

D. Oval Single Tunnel in Multi-layered Soil

Figure 42(a, b) exposes the displacement values and the corresponding vibration on the surface (10, 0) m and inside the soil (0, -1.5) m. It was observed that the rate of increase in vibrations is inversely proportional to the depth of the underground oval tunnel. This can be attributed to the fact that whenever the response point is taken far away from the source of vibrations, the transferred energy between the source and the point of interest location is reduced due to damping properties of the tunnel and soil.



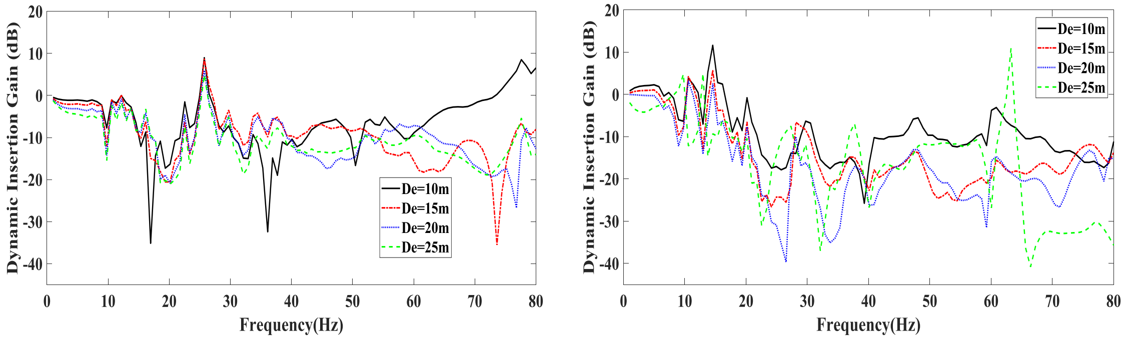
(a) Point (10, 0) m.



(b) Point (0, -1.5) m.

Figure 42 Displacement response at the points (10,0) m and (0, -1.5) m for oval tunnel at different depths in multi-layered soil

Figure 43(a, b) shows the dynamic insertion gain at different oval depths for response points of (10, 0) m and (0, -1.5) m, respectively. The reference displacement response is taken at a depth of 5 m. It can be said that the vibration produced from the oval tunnel at a depth of 25 m is smaller than the vibration generated by the tunnel depth of 5 m at the same response point. The displacement response difference between different oval tunnel depths in multi-layered soil appears clearly at high frequencies [40 Hz – 80 Hz]. It can be explained by the fact that at a higher frequency, the energy of the propagated waves in the soil becomes higher than the energy of the wave at a lower frequency.

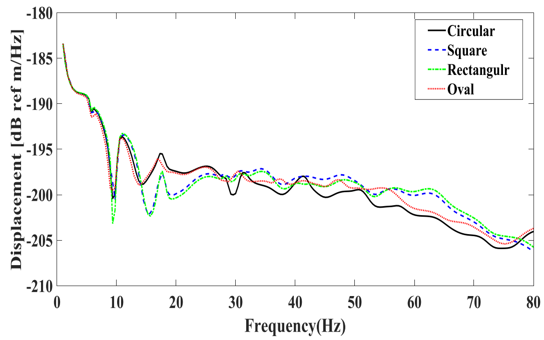


(a) Point (10, 0) m. (b) Point (0, -1.5) m.

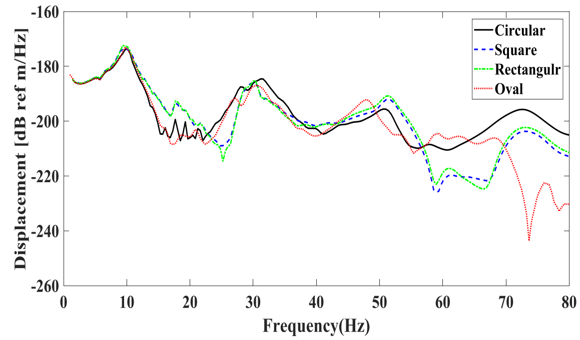
Figure 43 Dynamic insertion gain at the points (10, 0) m and (0, -1.5) m for different oval tunnel depths in multi-layered soil

4.6.4 Comparison between Different Single Tunnel Shapes in Multi-layered Soil

A circular tunnel having an outer diameter of 6.830 m was taken as the reference shape for the compression of displacement response for different tunnel shapes. All tunnel shapes have a cross-section area almost equal to that of the circular tunnel. The tunnel depth measured for the surface to the center of the tunnel was taken as 15 m for all models. The displacement response was measured at ground surface at the point (10, 0) m and inside the soil medium at the point (15, -15) m. Figure 44(a) shows the displacement response for different tunnel shapes at a point inside the soil are close to each other across the entire frequency range. However, at a point located on the surface, there is a notable difference in displacement response at frequencies higher than 50 Hz as shown in Figure 44(b). Therefore, it can be concluded that the effect of changing tunnel shapes in a layered soil medium is more significant across the ground surface and at higher frequencies.



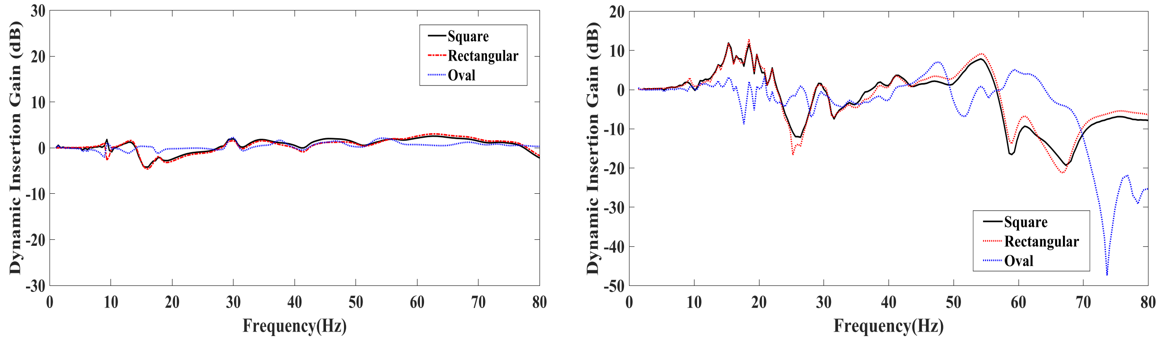
(a) Point (15, -15) m.



(b) Point (10, 0) m.

Figure 44 Displacement response at the points (10,0) m and (15, -15) m for different tunnel shapes in multi-layered soil

Figure 45 shows the dynamic insertion gain at points (15, -15) m and (10, 0) m, resulting from changing the tunnel shape from circular to square, rectangular and oval. The analysis displayed at Figure 45 shows that changing the tunnel shape has a minimal effect on the dynamic response measured at a point inside the soil. However, the response at the surface appears to be significantly affected, especially at frequencies higher than 50 Hz.



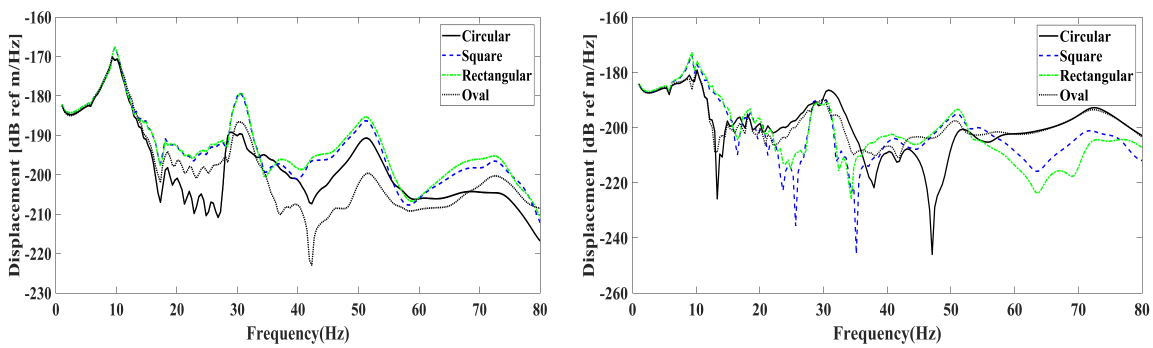
(a) Point (15, -15) m.

(b) Point (10, 0) m.

Figure 45 Dynamic insertion gain at the points (15, -15) m and (10, 0) m for different tunnel shapes in multi-layered soil

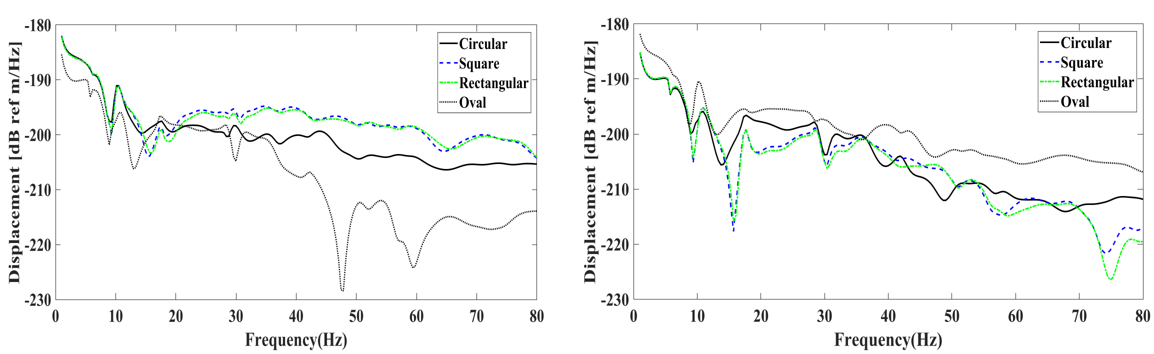
4.6.5 Twin Tunnel Modeling

The 2D FEMs for different twin tunnel shapes (circular, square, rectangular and oval) are made at a depth of 15 m in multi-layered soil in Qatar. The response points for vibration in y-direction are taken at eight different locations. The reason for the selection of these points is due to the presence of the harmonic concentrated load in one of the tunnels and therefore, the resulting vibrations are different on both sides of the tunnel as reported in Figure 46(a, b). Twin tunnels with different shapes have similar displacement response in low frequency [1 Hz – 18 Hz] as shown in Figure 46(a). It is worth mentioning here that whenever the response point is moved away from the source of vibration in the twin tunnel model, the difference between vibrations for different tunnel shapes is increased at a lower frequency as shown in Figure 46(b). In Figure 47(a, b) the displacement for twin tunnels is measured inside the soil on either side of the tunnels (points (15, -15) m and (-15, -15) m). The vibration response at high frequency is higher than the vibration response at low frequency. Figure 48(a) presents the vibration of different tunnel shapes at a point inside the soil (0, -1.5) m. In Figure 48(b), the vibration from oval twin tunnels appears somewhat different from other shapes (circular, square and rectangular). This difference is due mostly to different outer surface lengths that are touching the adjacent soil layer in two directions.



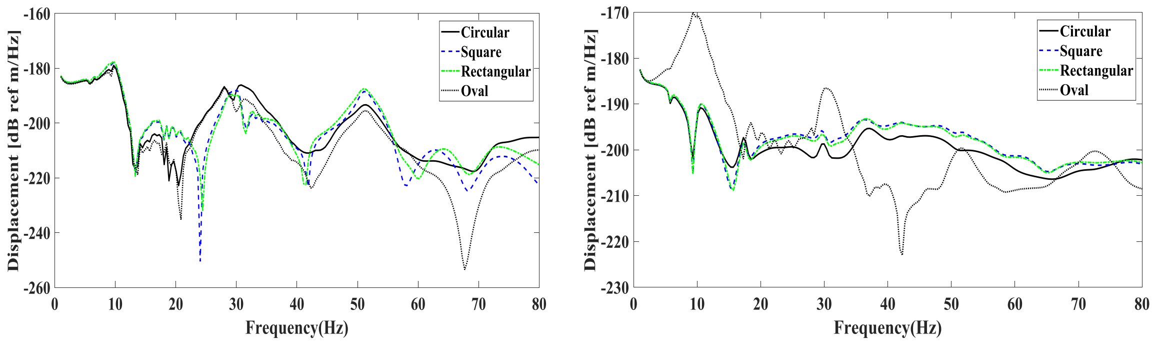
(a) Point (8, 0) m.   (b) Point (-8, 0) m.

Figure 46: Displacement response at the points (8,0) m and (-8, 0) m for different twin tunnel shapes in multi-layered soil



(a) Point (15, -15) m.   (b) Point (-15, -15) m.

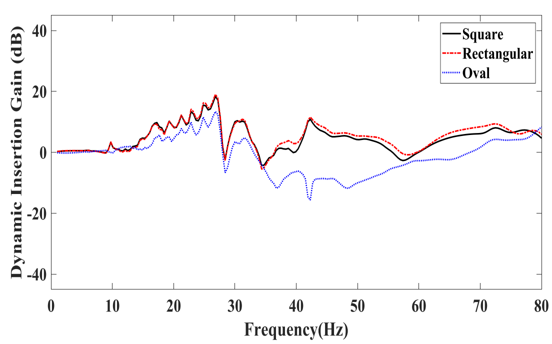
Figure 47: Displacement response at the points (15, -15) m and (10, 0) m for different twin tunnel shapes in multi-layered soil



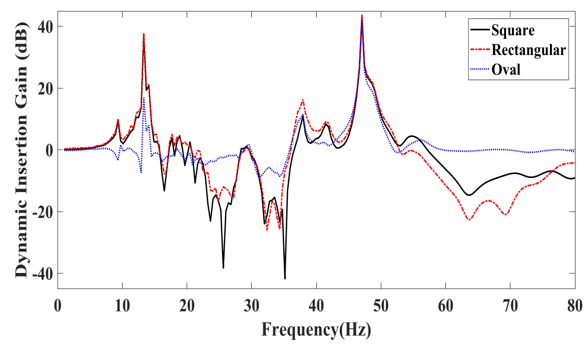
(a) Point (0, -1.5) m. (b) Point (0, -15) m.

Figure 48: Displacement response at the points (15, -15) m and (10, 0) m for different twin tunnel shapes in multi-layered soil

Figures (49-51) shows the dynamic insertion gain at points (8, 0) m, (-8, 0) m which results from changing the twin tunnel shape from circular to square, rectangular and oval. The twin circular tunnel is used as a reference shape. In figure 49(a), the difference in vibration appears in twin oval tunnels from other tunnel shapes at high frequency [35 Hz – 55 Hz]. There is no such difference in vibration for different twin tunnel shapes at a response point located on the ground surface under low frequency range [1 Hz to 10 Hz] as indicated in Figure 49(a, b). There seems to be a difference between the vibration from the twin oval tunnel and other tunnel shapes (square and rectangular) due to difference in geometry as shown in Figures (50b, 51b). The analysis displayed in Figures (50a, 51a) show that changing the twin tunnel shapes influence the dynamic response measured at a point inside the soil in medium to high frequency.

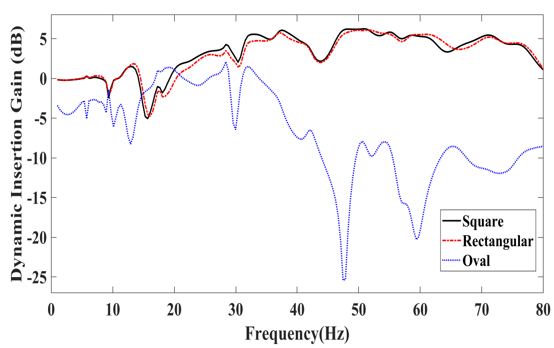


(a) Point (8, 0) m.

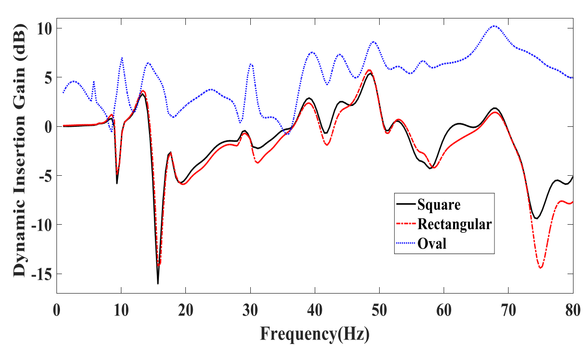


(b) Point (-8, 0) m.

Figure 49: Dynamic insertion gain at the points (8,0) m and (-8, 0) m for different twin tunnel shapes in multi-layered soil

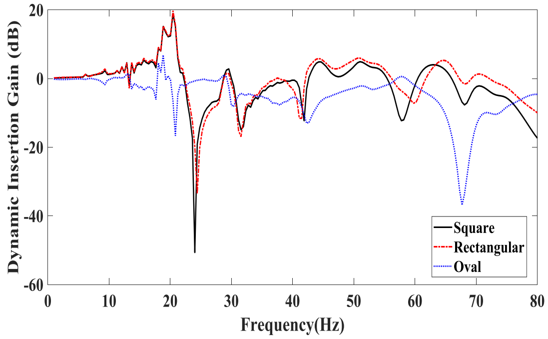


(a) Point (15, -15) m.

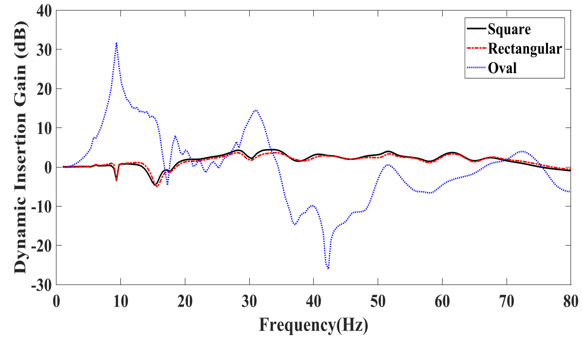


(b) Point (-15, -15) m.

Figure 50: Dynamic insertion gain at the points (15, -15) m and (-15, -15) m for different tunnel shapes in multi-layered soil



(a) Point (0, -1.5) m.



(b) Point (0, -15) m.

Figure 51: Dynamic insertion gain at the points (0, -1.5) m and (0, -15) m for different tunnel shapes in multi-layered soil

In general, changing the tunnel shapes has an influence on vibration measurement in y-direction at high frequency range for a response point located on the ground surface.

4.7 Conclusion for the Effect of Tunnel Shapes on Ground-Borne Vibration

FEMs for single and twin tunnels embedded in homogenous or multi-layered half-space were developed to investigate the vibration against different tunnel shapes. In homogenous soil, changing the single tunnel shape influences the dynamic response measured at a point inside the soil for frequencies between 25 Hz to 70Hz. However, the response at the surface appears not to be affected significantly by tunnel shapes because insertion gain lines are consistent in most of the points. Changing single tunnel shape has an influence on the vibration values corresponding to medium and high frequency range [40Hz – 80Hz] for homogenous half-space soil medium.

The displacement response has a great effect in small depth of circular tunnel at low frequency in multi-layered soil medium. There is a marked difference between vibration values measured on the surface and inside the multi-soil medium. The reason for this difference is the vibrations are reflected partially on the ground surface since the FEM is in half-space. Vibrations at low frequency region [1 Hz – 20 Hz] have no effect in the depth of single square tunnel in multi-layered soil medium. On the other hand, the vibration at high frequency range [40 Hz – 80 Hz] is affected by the depth of the tunnel. The rate of increasing in vibrations is inversely proportional to the depth of the underground tunnel. This can be explained by the fact that whenever the response point is taken far away from the source of vibration, the transferred energy between the source and the point of interest location is reduced due to damping properties of the tunnel and soil. The displacement response difference between different oval tunnel depths in multi-layered soil appears clearly at high frequency [40 Hz – 80 Hz]. It can be explained by the fact that at higher frequency, the energy of the propagated waves in the soil becomes higher than the energy of the wave at low frequency.

Changing the tunnel shape has a minimal effect on the dynamic response measured at a point inside the soil for multi-layered soil in 2D plane strain case for the cases considered. The response at the surface appears to be significantly affected by tunnel shape especially at frequencies higher than 50 Hz. There is no such difference in vibration for a different twin tunnel shapes at a response point located on the ground surface under low frequency range [1 Hz to 10 Hz] in multi-layered soil. In general, changing the tunnel shapes have an influence on vibration measurement in y-direction at high frequency range for a response point located on the ground surface. It can be concluded that the effect of changing tunnel shape in a layered soil medium is more significant across the ground surface and at higher frequencies.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

Ground-borne vibration response from underground railway tunnels was researched by using Finite Element package. To perform this research, a FE model was first conducted in 2D dimensions for a free circular tunnel with an applied harmonic load at bottom level of the tunnel. The natural frequency values at different mode shapes were measured. Based on similar principles, a 3D dynamic analysis model was then developed for a free circular tunnel with harmonic line load applied at the bottom line of the tunnel to compare the results found in 3D with the 2D model. After that was done, the results found for 2D & 3D single tunnel were compared against the literature of this research. The results for 2D and 3D FEMs were found to be matched with the literature. A verification 2D model using Abaqus was performed for a single circular tunnel embedded in homogenous soil to verify the model with the literature. The results of the analysis in the verification work were in line with the literature.

Single tunnel models with different tunnel shapes (circular, square, rectangular and oval) were studied against the displacement response values in homogenous half-space soil. The results show that the vibration response for different tunnel shapes with same tunnel depth and same material properties are affected by tunnel shapes. The twin tunnels FEM with a horizontal clear distance of 10 m was developed to study the influence of twin tunnels in different shapes on ground-borne vibration. The model shows that at lower frequencies [1 Hz – 10 Hz], the tunnel shape does not significantly affect the vibration response values on the grade level. At higher frequencies [20 Hz – 80 Hz], the vibration is affected by twin tunnels in different shapes.

A FEM for a single tunnel with different shapes (circular, square, rectangular and oval) is modeled in the multi-layered soil of Qatar. The five soil layers were assumed in the model in 2D dimensions with thicknesses of 2 m, 13 m, 4 m, 4.5 m and 26.5 m, respectively. The tunnel shapes and its depth factors were examined against the displacement response at different points in the model. The results show that the displacement response decreases with increases of the tunnel depth regardless of the shape of the tunnel. The difference in vibration at low frequencies [1 Hz – 18Hz] is not significant for the same single tunnel shape at different tunnel depths. At frequencies [20 Hz – 80 Hz], the vibration response for different single tunnel shapes is significantly different at different tunnel depths. The displacement responses for different tunnel shapes (circular, square, rectangular and oval) at a point located in the soil are almost similar across the entire frequency range. However, at a point located at grade level, there is a notable difference in displacement response at frequencies higher than 50 Hz. Therefore, it can be concluded that the effect of changing tunnel shapes in a layered soil is more significant at grade level and at higher frequencies.

The 2D FEM for different twin tunnel shapes (circular, square, rectangular and oval) were developed using Abaqus. The tunnel is modeled at a depth of 15 m in multi-layered soil of Qatar. A harmonic concentrated load is in one of the twin tunnels and therefore the resulting vibrations were different on both sides of the tunnel. Twin tunnels with different shapes have similar displacement response in low frequency [1 Hz – 18 Hz]. The vibration from oval twin tunnels appears somewhat different from other shapes (circular, square and rectangular). This difference is due mostly to section stiffness. A difference in vibration appears for twin oval tunnel from other tunnel shapes at high frequency [35 Hz – 55 Hz]. However, there is no such difference in vibration for different twin tunnel shapes at a response point located on the ground surface under low frequency [1 Hz to 10 Hz]. Under frequency [30 Hz – 80 Hz], the dynamic analysis shows that changing the twin tunnel shapes influences the vibration response measured at a point located in multi-layered soil medium.

5.2 Future Work

Future work in this field is still required to thoroughly study the ground-borne vibration from underground railway tunnels. All the work presented needs to be made and investigated in 3D FEM for homogenous and multi-layered soil properties of Qatar. More research to be performed on the effects of surface vibration due to trains at grade and the traffic which needs to be added in the model to analyze ground-borne vibration from underground railways tunnel. Another research area can be the effect of different twin tunnels depths with different horizontal and vertical alignments which can be addressed in 2D and 3D dimensions. The effect of tunnel numbers (3, 4, 5, …) in the horizontal or vertical alignment on ground borne vibration is required to be studied in 2D or 3D dimensions. Another area of research can be done is dynamic modeling for tunnels in multi-layered soil medium and the foundations of existing structures that are located inside the ground surface. The tunnel segments effect also needs to be investigated on vibration response.

REFERENCES

Andersen, L. & C. J. C. Jones (2006) Coupled boundary and finite element analysis of vibration from railway tunnels—a comparison of two- and three-dimensional models. *Journal of Sound and Vibration,* 293**,** 611-625.

Auersch, L. 2015a. Force and ground vibration reduction of railway tracks with elastic elements. 2246-2258. Journal of Vibration and Control.

--- (2015b) Force and ground vibration reduction of railway tracks with elastic elements. *JVC/Journal of Vibration and Control,* 21**,** 2246-2258.

BS6841. 1987. Guide to measurement and evaluation of human exposure to whole body mechanical vibration and repeated shock.

Clot, A., R. Arcos, J. Romeu & T. Pàmies (2016) Dynamic response of a double-deck circular tunnel embedded in a full-space. *Tunnelling and Underground Space Technology,* 59**,** 146-156.

Connolly, D. P., G. Kouroussis, O. Laghrouche, C. L. Ho & M. C. Forde. 2015. Benchmarking railway vibrations – Track, vehicle, ground and building effects. 64-81. Construction and Building Materials.

Coulier, P., G. Lombaert & G. Degrande (2014) The influence of source-receiver interaction on the numerical prediction of railway induced vibrations. *Journal of Sound and Vibration,* 333**,** 2520-2538.

Dai, F., D. J. Thompson, Y. Zhu & X. Liu (2016) Vibration properties of slab track installed on a viaduct. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* 230**,** 235-252.

Degen, K. G., W. Behr & H. P. Grütz (2006) Investigations and results concerning railway-induced ground-borne vibrations in Germany. *Journal of Sound and Vibration,* 293**,** 865-872.

Degrande, G., G. D. Roeck, P. V. D. Broeck & D. Smeulders (1998) Wave propagation in layered dry, saturated and unsaturated poroelastic media. *International Journal of Solids and Structures,* 35**,** 4753-4778.

Fields, J. M. (1979) Railway noise and vibration annoyance in residential areas. *Journal of Sound and Vibration,* 66**,** 445-458.

Forrest, J. A. & H. E. M. Hunt (2006a) A three-dimensional tunnel model for calculation of train-induced ground vibration. *Journal of Sound and Vibration,* 294**,** 678-705.

--- (2006b) Ground vibration generated by trains in underground tunnels. *Journal of Sound and Vibration,* 294**,** 706-736.

Galvín, P., E. Moliner, A. Romero & M. D. Martínez-Rodrigo. 2017. Investigation of the dynamic response and effect of soil properties of Arroyo Bracea II bridge in Madrid-Sevilla High-Speed railway line through experimental analyses. In *Procedia Engineering*, 3021-3026.

Ganesan, N. & T. C. Ramesh (1992) Free vibration analysis of composite railway wheels. *Journal of Sound and Vibration,* 153**,** 113-124.

Gardien, W. & H. G. Stuit (2003) Modelling of soil vibrations from railway tunnels. *Journal of Sound and Vibration,* 267**,** 605-619.

Gupta, S., W. F. Liu, G. Degrande, G. Lombaert & W. N. Liu (2008) Prediction of vibrations induced by underground railway traffic in Beijing. *Journal of Sound and Vibration,* 310**,** 608-630.

Hamad, W. I., H. E. M. Hunt, J. P. Talbot, M. F. M. Hussein & D. J. Thompson. 2015. The dynamic interaction of twin tunnels embedded in a homogeneous half-space. In *COMPDYN 2015 - 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 120-132.

Hanson, C. E., D. A. Towers & L. D. Meister. 2006. Transit noise and vibration impact assessment.

Hunt, H. E. M. & M. F. M. Hussein. 2008. Ground-Borne Vibration Transmission from Road and Rail Systems: Prediction and Control. In *Handbook of Noise and Vibration Control*, 1458-1469.

Hussein, M. & H. Hunt. 2006a. Modelling of floating-slab tracks with continuous slabs under oscillating moving loads. 37-54. Cambridge, UK: Journal of Sound and Vibration.

Hussein, M., H. Hunt, K. Kuo, P. A. Costa & J. o. Barbosa. 2015. The use of sub-modelling technique to calculate vibration in buildings from underground railways. 303-314. Journal of Rail and

Rapid Transit.

Hussein, M. F. M., S. François, M. Schevenels, H. E. M. Hunt, J. P. Talbot & G. Degrande (2014) The fictitious force method for efficient calculation of vibration from a tunnel embedded in a multi-layered half-space. *Journal of Sound and Vibration,* 333**,** 6996-7018.

Hussein, M. F. M. & H. E. M. Hunt. 2003. An insertion loss model for evaluating the performance of floating-slab track for underground railway tunnels. In *Proceedings of the Tenth International Congress on Sound and Vibration*, 419-

426.

--- (2006b) A power flow method for evaluating vibration from underground railways. *Journal of Sound and Vibration,* 293**,** 667-679.

--- (2007) A numerical model for calculating vibration from a railway tunnel embedded in a full-space. *Journal of Sound and Vibration,* 305**,** 401-431.

--- (2009) A numerical model for calculating vibration due to a harmonic moving load on a floating-slab track with discontinuous slabs in an underground railway tunnel. *Journal of Sound and Vibration,* 321**,** 363-374.

Idriss, I. M., J. I. Sun, D. University of California, M. Center for Geotechnical, L. Building and Fire Research & D. Structures. 1993. *User's manual for SHAKE91 : a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits*. Davis, Calif.: Center for Geotechnical Modeling, Dept. of Civil and Environmental Engineering, University of California, Davis.

Jones, S. & H. Hunt (2011) Voids at the tunnel–soil interface for calculation of ground vibration from underground railways. *Journal of Sound and Vibration,* 330**,** 245-270.

--- (2012) Predicting surface vibration from underground railways through inhomogeneous soil. *Journal of Sound and Vibration,* 331**,** 2055-2069.

Karlström, A. & A. Boström (2006) An analytical model for train-induced ground vibrations from railways. *Journal of Sound and Vibration,* 292**,** 221-241.

Koroma, S. G., D. J. Thompson, M. F. M. Hussein & E. Ntotsios (2017) A mixed space-time and wavenumber-frequency domain procedure for modelling ground vibration from surface railway tracks. *Journal of Sound and Vibration,* 400**,** 508-532.

Kostovasilis, D., D. J. Thompson & M. F. M. Hussein (2017) A semi-analytical beam model for the vibration of railway tracks. *Journal of Sound and Vibration,* 393**,** 321-337.

Kurze, U. J. (1996) TOOLS FOR MEASURING, PREDICTING AND REDUCING THE ENVIRONMENTAL IMPACT FROM RAILWAY NOISE AND VIBRATION. *Journal of Sound and Vibration,* 193**,** 237-251.

Lin, Q. & V. Krylov. 1999. Effect of Tunnel Diameter on Ground Vibrations Generated by Underground Trains. 17-25. Nottingham NG1 4BU, UK.

Lin, Q. & V. V. Krylov (2000) Effect of tunnel diameter on ground vibrations generated by underground trains. *Journal of Low Frequency Noise Vibration and Active Control,* 19**,** 17-25.

Liu, G. R. & S. S. Quek Jerry (2003) A non-reflecting boundary for analyzing wave propagation using the finite element method. *Finite Elements in Analysis and Design,* 39**,** 403-417.

Lombaert, G., G. Degrande, J. Kogut & S. François (2006) The experimental validation of a numerical model for the prediction of railway induced vibrations. *Journal of Sound and Vibration,* 297**,** 512-535.

Lopes, P., J. F. Ruiz, P. Alves Costa, L. Medina Rodríguez & A. S. Cardoso (2016) Vibrations inside buildings due to subway railway traffic. Experimental validation of a comprehensive prediction model. *Science of the Total Environment,* 568**,** 1333-1343.

Maheshwari, B. K., K. Z. Truman, P. L. Gould & M. H. El Naggar (2005) Three-dimensional nonlinear seismic analysis of single piles using finite element model: Effects of plasticity of soil. *International Journal of Geomechanics,* 5**,** 35-44.

Melke, J. (1988) Noise and vibration from underground railway lines: Proposals for a prediction procedure. *Journal of Sound and Vibration,* 120**,** 391-406.

Melke, J. & S. Kramer (1983) Diagnostic methods in the control of railway noise and vibration. *Journal of Sound and Vibration,* 87**,** 377-386.

Ntotsios, E., D. Thompson & M. Hussein (2017) The effect of track load correlation on ground-borne vibration from railways. *Journal of Sound and Vibration,* 402**,** 142-163.

Ono, K. & M. Yamada (1989) Analysis of railway track vibration. *Journal of Sound and Vibration,* 130**,** 269-297.

Paneiro, G., F. O. Durão, M. Costa e Silva & P. Falcão Neves. 2015. Prediction of ground vibration amplitudes due to urban railway traffic using quantitative and qualitative field data. 1-13. Transportation Research Part D.

Park, J., S. Ahn, J. Kim, H.-I. Koh & J. Park. 2016. Direct determination of dynamic properties of railway tracks for flexural vibrations. 14-21. South Korea: European Journal of Mechanics A-Solids.

Ruiz, J. F. & L. M. Rodríguez (2015) Application of an advanced soil constitutive model to the study of railway vibrations in tunnels through 2D numerical models: A real case in Madrid (Spain). *Revista de la Construccion,* 14**,** 55-63.

Sheng, X., C. J. C. Jones & M. Petyt (1999) GROUND VIBRATION GENERATED BY A LOAD MOVING ALONG A RAILWAY TRACK. *Journal of Sound and*

Vibration, 228**,** 129-156.

Sheng, X., C. J. C. Jones & D. J. Thompson (2003) Ground vibration generated by a harmonic load moving in a circular tunnel in a layered ground. *Journal of Low Frequency Noise Vibration and Active Control,* 22**,** 83-96.

Sica, G., E. Peris, J. S. Woodcock, A. T. Moorhouse & D. C. Waddington. 2013. Design of measurement methodology for the evaluation of human exposure to vibration in residential environments. 461-471. Salford, United Kingdom: Science of the Total Environment.

Stypuła, K. (2014) Vibrations Caused by Train Passages in Underground Tunnel Compared to Vibrations from Ground Surface Transportation-Some Results of Investigations. *Archives of Civil Engineering,* 60**,** 269-286.

Tetsuya, H., T. Yano & Y. Murakami. 2016. Annoyance due to railway noise before and after the opening of the Kyushu Shinkansen Line. 173-180. Applied Acoustics.

Triepaischajonsak1, N., D. J. Thompson, C. J. C. Jones, J. Ryue & J. A. Priest. 2010. Ground vibration from trains: experimental parameter characterization and validation of a numerical model. 140-153.

Triepaischajonsak, N., D. J. Thompson, C. J. C. Jones, J. Ryue & J. A. Priest (2011) Ground vibration from trains: Experimental parameter characterization and validation of a numerical model. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* 225**,** 140-153.

Volberg, G. (1983) Propagation of ground vibrations near railway tracks. *Journal of Sound and Vibration,* 87**,** 371-376.

Wilson, G. P., H. J. Saurenman & J. T. Nelson (1983) Control of ground-borne noise and vibration. *Journal of Sound and Vibration,* 87**,** 339-350.

Wu, T. X. & D. J. Thompson (2001) VIBRATION ANALYSIS OF RAILWAY TRACK WITH MULTIPLE WHEELS ON THE RAIL. *Journal of Sound and Vibration,* 239**,** 69-97.

Xin, T. & L. Gao (2011) Reducing slab track vibration into bridge using elastic materials in high speed railway. *Journal of Sound and Vibration,* 330**,** 2237-2248.

Xu, Q., Z. Xiao, T. Liu, P. Lou & X. Song (2015) Comparison of 2D and 3D prediction models for environmental vibration induced by underground railway with two types of tracks. *Computers and Geotechnics,* 68**,** 169-183.

Yuan, Z., A. Boström & Y. Cai (2017) Benchmark solution for vibrations from a moving point source in a tunnel embedded in a half-space. *Journal of Sound and Vibration,* 387**,** 177-193.

Yuan, Z., Z. Cao, A. Boström & Y. Cai (2018) The influence of pore-fluid in the soil on ground vibrations from a tunnel embedded in a layered half-space. *Journal of Sound and Vibration,* 419**,** 227-248.

Zhou, X. L., J. H. Wang & L. F. Jiang (2009) Dynamic response of a pair of elliptic tunnels embedded in a poroelastic medium. *Journal of Sound and Vibration,* 325**,** 816-834.

Öhrström, E. (1997) EFFECTS OF EXPOSURE TO RAILWAY NOISE—A Comparison Between Areas With And Without Vibration. *Journal of Sound and Vibration,* 205**,** 555-560.