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A PARAMETRIC STUDY OF BACKFILLED TRENCH FOR REDUCTION OF TBM INDUCED GROUND VIBRATIONS

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Abstract

Wave barriers in the form of backfilled trenches are often installed in the ground to reduce the ground vibrations induced by man-made sources, such as traffic and machine foundations. This type of ground vibration and ground vibrations due to tunnel boring machines (TBMs) can be a major problem in densely populated urban areas and for structures housing sensitive equipment. No previously published research has been found in the literature on the use of backfilled trenches to provide a screen to the vibrations due to TBMs. In this paper the results of a numerical study, using a 3-D finite element model with infinite elements, to investigate the effectiveness of backfilled trenches in reducing the ground surface vibration due to tunnelling activities are presented. The ABAQUS V6.4 finite element software has been used to construct the model and three-dimensional eight-noded linear brick and reduced integration elements are employed for the ground and the tunnel lining. The effects of variations in the geometrical and material properties of the backfilled trench on reducing the ground vibrations have been studied. The findings of this study are that only a thin trench is required to provide an effective wave barrier giving a significant reduction in the vibration velocity, the percentage reduction in the vibration velocity increases with increasing depth of the wave barriers, and softer backfill material yields a better screening effect than stiffer material.

INTRODUCTION

Wave barriers in the form of backfilled trenches are often installed in the ground to reduce the ground vibrations induced by man-made sources such as traffic and machine foundations [1]. Such ground vibrations and ground vibrations due to a tunnel-boring machines (TBMs) can be a major problem in densely populated urban areas and for structures which house sensitive equipment. The environmental effects of vibrations have received considerable attention in recent years owing to the damage they can cause both to buildings and people and in many countries new rules and regulations have been introduced to control vibrations [2]. Therefore, screening of vibrations induced by traffic and construction activities has become an important issue in recent times and it has been shown that it is possible to reduce the ground vibration significantly by placing a suitable wave barrier in the ground [3].

The methods of vibration isolation for soil-structure interaction systems may be classified into two families: active isolation and passive isolation. Active isolation, also known as source isolation, refers to the installation of barriers so close to the wave source that energy transmitted from it can be directly cut off, or to the installation of barriers surrounding the vibration source [4]. Passive isolation, also known as receiver isolation, involves the placing of suitable barriers in the ground before the structure or surrounding the structure [3]. An active isolation barrier can effectively isolate stationary sources of vibration, whereas a passive isolation barrier is effective for a wide variety of wave generating sources, including moving sources. Different kinds of wave barriers, among them open and backfilled trenches are the most common in practical applications as they are most effective and their installation cost is low [5], [6].

In the past few decades, the boundary element method (BEM) has emerged as a very efficient numerical technique for solving a wide class of engineering problems. This method is especially well suited for wave propagation problems in soils involving a semi-infinite domain. A number of researchers have carried out 2-D and 3-D numerical analyses using the BEM to investigate the screening of vibrations by means of open and backfilled trenches and the use of different types of foundations to screen the vibration due to machines [1], [3], [7], [8], [9]. However, the BEM is not well suited for the modelling of irregular geometries. To overcome this problem, several procedures for coupling finite elements with boundary elements or finite elements with infinite elements have been proposed by a number of researchers [6].

It can be observed from the above literature review that a number of researchers have carried out a lot of work on systems to provide isolation from machine foundation or high-speed train induced vibrations. To the best knowledge of the author, no work has been reported in the published geotechnical literature on the screening by backfilled trenches of the ground vibrations due to a TBM. Therefore, an investigation of the performance of backfilled trenches in reducing the ground vibrations due to a TBM is timely. In this paper, numerical studies, using 3-D finite element model coupling with infinite element, are presented which investigate the effectiveness of backfilled trenches, in reducing the ground surface vibrations due to tunnelling activities.

NUMERICAL MODELLING

Initially 3-D FE analyses were carried out to simulate the magnitudes of the ground vibrations at the surface due to TBM. The accuracy of the model was verified by comparing the measured and predicted vibrations and good agreement was found between these. In this paper, the effectiveness of backfilled trenches as wave barriers for isolating TBM induced ground vibrations has been examined. The FE model is shown in Figure 1. The geometry was idealised by a finite region (Zone I) and by a semi-infinite far field region (Zone II). The ABAQUS V6.4 finite element software was used to construct the model and three-dimensional eight-noded linear brick and reduced integration elements, C3D8R, were employed for the ground and the tunnel lining in Zone I. Reduced-integration elements use fewer integration points in each direction than the fully integrated elements. These reduce the running time, especially in 3-D finite element model analyses. In Zone II, the soils and tunnel lining in the far field that extends to infinity, were modelled by the infinite elements, CIN3D8. In the model, the top layer is brown clay, the middle layer is Dublin boulder clay and the bottom layer is limestone. The dimensions of the finite element model are 132.0m in the transverse direction, 50.0m in the vertical direction and 40m in the direction of the tunnel. The top layer is 2.5m thick, the middle layer is 11m thick and the bottom layer is 36.5m thick. The diameter of the tunnel is 12.0m. The material properties that were used for the different soil layer in the finite element analyses are given in Table 1.

The geometric dimensions of the trench barrier and the properties of the backfill material are shown in Table 2 and Table 3, respectively. As all the dimensions are assumed and the properties of the backfill material have been taken from reference [6]. A series of parametric studies to examine the sensitivity of the vibration predictions to variations in the input parameters of the trench dimensions and the properties of the backfill material have been carried out. Note that when a certain parameter is investigated, the other parameters are kept constant.

By advancing in the ground, the tunnel-boring machine is a vibrating source from which vibrations are transmitted into the ground. Therefore, the vibrations in the ground due to the TBM during boring have been modelled by a dynamic loading system. The finite elements representing the TBM cutter have been loaded by a short triangular pulse. Due to this pulse, waves propagate through the soil and the response at the surface has been predicted. The analyses have been carried out in the time domain. The isolation effects have been calculated using the percentage velocity reduction defined as,

$$\text{Percentage velocity reduction} = \left(1 - \frac{\text{vibration velocity with barrier}}{\text{vibration velocity without barrier}}\right) * 100 \qquad (1)$$

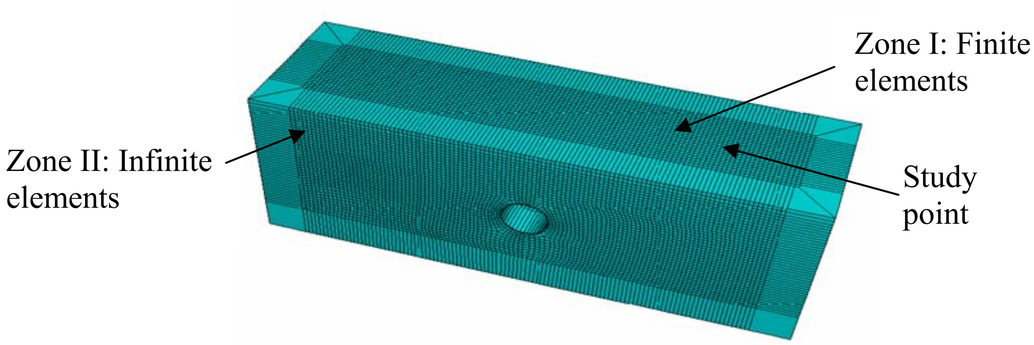

Figure 1– Three-Dimensional FE model

Table 1– Values of soil parameters used in models

Parameter	Top layer, (brown clay)	Dublin boulder clay	Limestone	Concrete	Steel
Density, kg/m^3	2000	2300	2710	2400	7800
Young's modulus, GPa	0.2	1	60	40	200
Poisson's ratio	0.495	0.495	0.25	0.2	0.3
Damping, %	2.85	1.75	1	1	0.5

Table 2– Geometric parameters of the trench barrier

Parameter	Assumed values (m)
Depth of trench below ground surface (D)	2.5, 5.0, 10, 13.5, 18, 24 and 30
Location of trench from the study zone (L)	0.0, 3.0, 6.0, 9.0, 12, and 15
Width of the backfilled trench (W)	1.5, 3.0 and 4.5

Table 3– Material properties of the backfill

Material	Density, kg/m^3	Shear wave velocity, m/s	Poisson's ratio
Backfill	1200, 1600 and 2000	30, 60, and 90	0.25, 0.33 and 0.45

PARAMETRIC STUDIES OF BACK FILLED TRENCH

In this study, the analyses have been performed assuming that the trench barrier is filled with a bentonite-soil mixture, which is softer than the natural soil. The advantage of a backfilled trench is that one can achieve larger trench depths with no need for permanent lateral supports of the vertical sides [6].

The analyses were carried out for trenches with different depths D and widths W, for different distances, L, of the trenches from the study point and for different damping ratios (ξ), densities (ρ), Poisson's ratios (υ) and impedance ratios (IR) of the backfill material.

Effect of the Normalized Depth and Location of the Trench

The effects on the amplitude of the vibration velocity of the depth D of the backfilled trench and the horizontal distance L of the backfilled trench from study point have been investigated. Figures 2 and 3 show the influence of D and L, normalised with respect to the maximum values of 30m and 15m respectively, on the % reduction in vibration velocity in the case of a trench backfilled with a bentonite-soil mixture with a density, ρ_b = 1200 kg/m^3 and shear wave velocity, v_b = 30 m/s and in soil having ρ_s = 2000 kg/m^3 and v_s = 180 m/s. Using these values in Equation 2, the impedance ratio is calculated as IR = 0.1, which indicates a very soft backfill material.

Examining the graphs in Figures 2 and 3, it is evident that the depth of the trench D and the distance of the trench from the study point, L both have important effects on the reduction in vibration velocity. It can be observed that the achieved reduction in vibration velocity increases with increasing depth of the trench D, while it decreases with increasing L.

Based on these findings, it can state that the depth of the backfilled trench and the location of backfilled trench with respect to the study zone are important parameters with regard to the reduction of vibration velocity.

Effect of the Width of the Trench

For the purpose of the investigation, it was assumed that the width of the backfilled trench varies between 1.5m and 4.5m. In Figure 4, the reduction in the vibration velocity for different values of the trench width, normalised with respect to the 4.5m, is shown. It can be observed that, for all vibration velocities, the width of the trench has very little effect on the percentage reduction in the vibration velocity. The reductions of the vibration velocity are 40%, 41% and 44.2% for trench widths of 1.5m, 3.0m and 4.5m respectively. This implies that only a thin trench is required to provide a wave barrier giving a significant reduction in the vibration velocity.

Effect of the Poisson's Ratio of the Backfill Material

The effect of the values of the Poisson's ratio of the backfill material in the trench on the reduction in vibration velocity has been examined using the same model. The depth of the trench was 10.0m. The results obtained from numerical analyses when varying the Poisson's ratio are shown in Figure 5. Reductions in the vibration velocity of 40%, 40% and 39% were obtained for Poisson's ratios of 0.25, 0.33 and 0.45 respectively. It is concluded, therefore, that variations in Poisson's ratio have virtually no influence on the vibrations.

Effect of the Damping Ratio of the Backfill Material

Damping is the property of material to absorb vibration energy. The ratio between the damping of the material to the critical damping is called damping ratio, ξ, where critical damping is the smallest amount of damping required to prevent any oscillation occurring in the vibration system. To investigate the effects of the damping ratio of the backfill material on the effectiveness of the backfilled trench for vibration screening, it has been assumed that the damping ratio varies between 2% and 8%. The depth of the trench was 5.0m. Figure 6 shows the computed vibration reduction at the study point when changing the damping ratio of the backfill material. As can be seen, the percentage velocity reduction remains nearly constant at the measuring point as the damping ratio is changed. The reduction in the vibration velocity is 13.68% for damping ratios of 2%, 5% and 8%. Since the velocity reduction is unaffected by the damping ratio, the effect of damping can be neglected.

Effect of the Density of the Backfill Material

The effect of variations in the density of the backfill material on the effectiveness of the backfilled trench on vibration screening has also been investigated. The effects of changing the density of the backfill material, plotted as the ratio of the density of the backfill material, ρ_b, to the top layer soil density, ρ_s, are shown in Figure 7. While the density of the backfill can be adjusted by controlling the consistency of the bentonite-soil mixture, the margin for varying the mass density is rather narrow in practice; therefore, the value of ratio only ranges from 0.6 to 1.0 in the present analysis. The depth of the trench was 10.0m. As can be seen from the results plotted in Figure 7, variations in the density of the backfill material have very little effect on the vibration reduction, as the percentage velocity reduction is approximately constant with changes in the density ratio.

Effect of the Shear Modulus Ratio (G_b/G_s) of the Backfill Material

G_b and G_s are the shear moduli of the backfill material in the trench and the top layer soil, respectively. In order to relate the shear modulus ratio G_b/G_s to a more practical parameter, the impedance ratio (IR), used by geotechnical engineers for determining whether a barrier is soft or hard has been adopted. The impedance ratio is the ratio between the mass density times the shear wave velocity of the backfill material and the original soil [4], [6] and is expressed as follows:

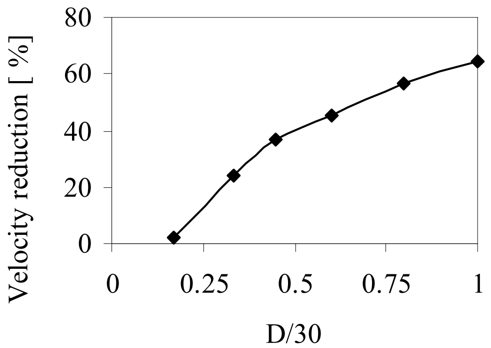

Figure 2 – Effect of normalised trench depth

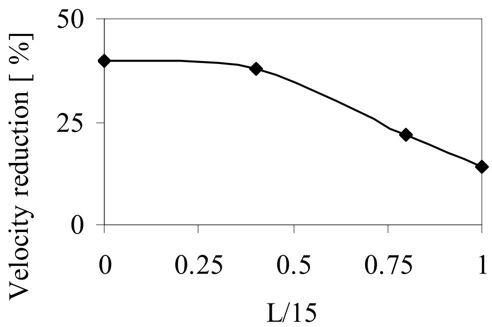

Figure 3 – Effect of normalised distance

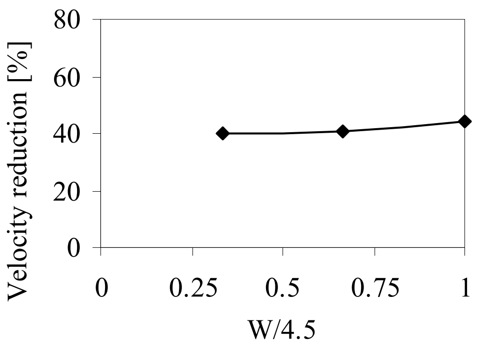

Figure 4 – Effect of normalised trench width

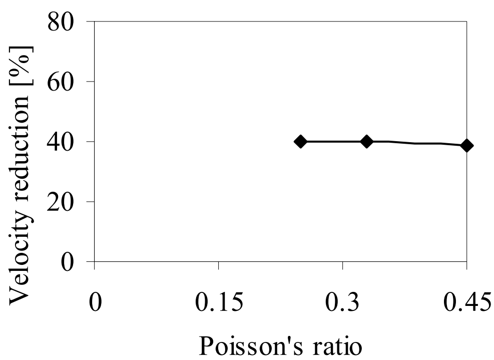

Figure 5 – Effect of the Poisson's ratio (v)

$$IR = \rho_b v_b / \rho_s v_s \quad (2)$$

where ρ_b and ρ_s denote the mass densities of the backfill material and the soil, respectively and v_b and v_s are the shear wave velocities of the two materials. Values of IR<1 mean that the trench barrier is softer than the surrounding soil and visa versa.

When investigating the effect of the shear modulus ratio, the Young's modulus was used instead of the shear modulus. The Young's modulus of the backfill material was considered to be variable while the Young's modulus of the different soil layers was kept constant of the values shown in Table 1. The density and shear wave velocity values given in Table 3 were used to calculate the Young's modulus using Equation (3) and the IR values using Equation (2). The IR values were found to be between 0.1 and 0.3. The depth of the trench was 10m. The percentage velocity reduction verses the impedance ratio IR is presented in Figure 8. It can be observed from Figure 8 that the percentage velocity reduction decreased with increasing IR, indicating that the softer backfill material, which has a lower IR value, is more effective in reducing TBM induced ground vibrations.

$$E_b = 2\rho_b v_b^2(1+\nu_b) \quad (3)$$

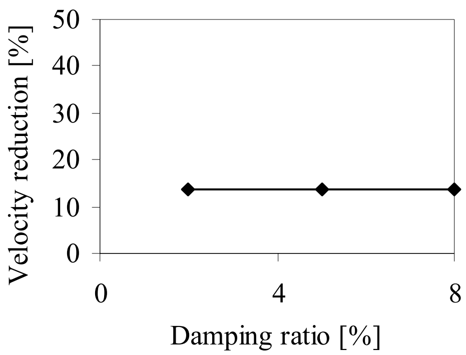

Figure 6 – Effect of damping ratio (ξ)

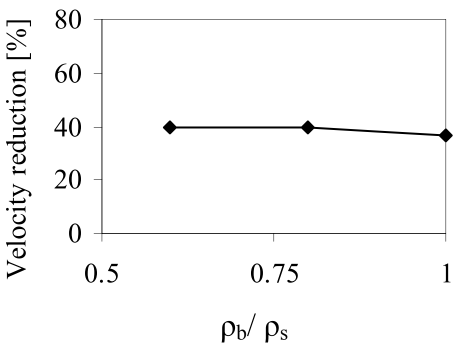

Figure 7 – Effect of normalised density

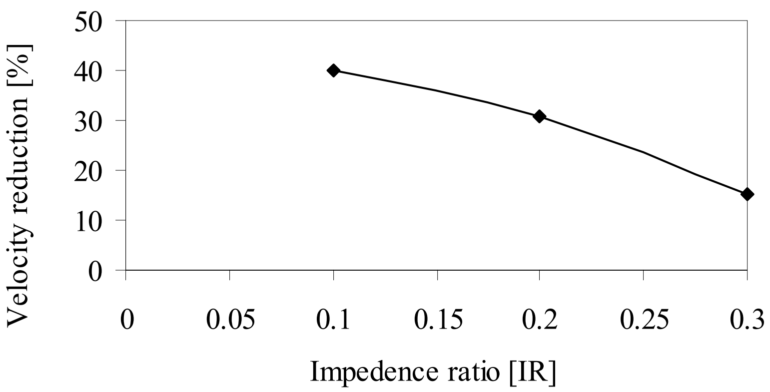

Figure 8 – Effect of the impedance ratio

CONCLUSIONS

The screening of TBM induced ground vibrations by means of a backfilled trench in layered soil between the TBM and the point of interest has been studied using 3-D finite elements coupled with infinite elements. The influences of various parameters such as the trench depth, width, location, Poisson's ratio, density, damping ratio and impedance ratio of the backfill material in the barrier have been investigated. The important observations may be summarized as follows:

- TBM induced ground vibrations can be reduced significantly by means of even thin backfilled trenches.
- Increasing the distance between a trench and the study point decreases its reduction effect due to the propagation of waves below the trench, making the screening effect less significant.
- The width of the backfilled trench, and the damping ratio, density and Poisson's ratio of the backfill material has no any significant effects on the reduction of the ground vibrations.
- Increasing the impedance ratio IR of the backfill material decreases its reduction effects; i.e. a backfill material that is soft with respect to the surrounding soil, generally performs better than a stiffer material.

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