

Evaluation of Wave Barriers on Ground Vibration Reduction through Numerical Modeling in Abaqus

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Abstract: This paper aims to investigate the train-induced ground vibration and appropriate countermeasures using numerical modeling by Abaqus. First, the effect of appropriate boundary modeling in wave propagation studies is addressed by illustrating the application of non-reflecting boundaries in Abaqus using infinite elements. Second, the propagation of waves in the ground was investigated by applying an impact-type loading. Then, the attenuation of maximum acceleration on the surface ground was compared to the data from geotechnical centrifuge tests conducted at Tokyo Institute of Technology and the theoretical solutions. These comparisons confirmed the reliability of the numerical modeling by Abaqus in this study. Next, the effect of barriers in reduction of ground vibration was investigated by modeling a wave barrier at the transmission path. Three different types of barriers were evaluated considering their stiffness: Concrete wall, improved soil, and EPS. A benchmark model was also analyzed without any mitigation measure to evaluate the effectiveness of the wave barriers. Furthermore, the effects of both geometry (depth and width) and material of barriers on the vibration reduction were examined through a parametric study and the results were verified using the geotechnical centrifuge tests.

Keywords: Ground Vibrations, Wave Barriers, Mitigation Measures

1. Introduction

Rapid development of urban areas requires the development of new railway lines to compensate the growing demand for public transportation; hence care should be taken in planning the new railway lines in the densely populated regions, and mitigation measures should be implemented to reduce the vibration levels. Zerwer et al. (2002) employed Abaqus in finite element modeling of

Rayleigh waves and notified the importance of proper mesh dimensions and damping characteristics in the finite element simulation. They presented equations to calculate the linear Rayleigh damping coefficients (average) with minimum variance within the frequency bandwidth of interest. Hall (2003) also applied the Abaqus in the numerical modeling of train-induced ground vibration studies and reported an acceptable agreement between the numerical simulation and the field measurements. Yang et al. (2003) conducted a parametric study on train-induced wave propagation in soils using finite/infinite element modeling and concluded the mechanism of wave propagation in layered grounds for practical applications. Yang and Hung (1997) also implemented the same finite/infinite scheme to study the effect of wave barriers for the reduction of train-induced ground vibrations. They performed a parametric study on geometrical and material properties of the wave barriers and recommended the optimal values for isolating the train-induced ground vibrations. Moreover, a detailed literature review on the vibration screening methods can be found in Ahmad and Al-Hussaini (1991). However, few works have been carried out to further investigate the effect of wave barrier characteristics, both geometrical and material, to reduce the train-induced ground vibrations using Abaqus in connection with geotechnical centrifuge tests.

In this respect, this research aims to investigate the train-induced ground vibrations and appropriate countermeasures using numerical approach by the dynamic three-dimensional finite element program Abaqus. This software was employed using the supercomputer facilities of Tokyo Institute of Technology called TSUBAME. Considering the high frequency nature of train-induced vibrations, Abaqus/Explicit was employed in this study and the main part of the model was developed in Abaqus/CAE as a visualization tool. Axisymmetric condition was applied to model the ground and a uniform mesh was implemented. In addition, the infinite element was utilized to reproduce the non-reflecting boundaries and prevent the wave reflections. First, the propagation of waves in the ground was investigated by applying an impact-type loading. Then, the attenuation of maximum acceleration on the surface ground was obtained and the results were compared to the data from geotechnical centrifuge tests conducted at Tokyo Institute of Technology (Itoh 2003) and the theoretical solutions (Bornitz 1931). These comparisons confirmed the reliability of the numerical modeling by Abaqus in this study. Second, the effect of barriers in reduction of ground vibration was investigated by modeling a wave barrier at the transmission path. Three different types of barriers were evaluated in this study considering their stiffness: Concrete wall, improved soil, and EPS. A benchmark model was also analyzed without any mitigation measure, and then the models with countermeasures were compared to evaluate their effectiveness.

2. Outline of finite/infinite element modeling in Abaqus

The finite element model in this study consisted of an axisymmetric scheme to reproduce the ground for a more realistic simulation. The finite element part of the model was built using Abaqus/CAE as a visualization tool. Figure 1 displays the finite/infinite element parts of the ground model which the infinite element portion will be further explained in this paper. The dimensions of the model were selected based on the geotechnical centrifuge tests; which were employed for verification, hence the results could be quantitatively compared. In other words, the centrifuge test results (Itoh 2003) were used to validate the present numerical model and confirm

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In wave propagation problems, element dimensions are chosen with respect to the highest frequency and lowest velocity wave (V_R). The use of coarse finite element meshes can result in the filtering of high frequency components whose short wavelengths cannot be modeled by widely spaced nodal points. This can cause underestimation of results. Kuhlemeyer and Lysmer (1973) suggested a maximum element size of one-eighth of the shortest wavelength and we followed this recommendation and selected the element size of 0.25 m considering the Rayleigh wave velocity of the ground ($V_R = 97.89$ m/s) and the highest frequency of input motion (40 Hz). The axisymmetric model, shown in Figure 1, measured 12×17 m² and consisted of 3380 elements and

3498 nodes. The material properties of the ground are tabulated in Table 1 which was selected identical to the geotechnical centrifuge tests (Itoh 2003). The elements comprised of 4-node, linear, axisymmetric, solid, and reduced-integration elements (CAX4R). The ground was a homogenous isotropic elastic medium without any damping at this step. The time increment also must be carefully chosen to maintain numerical stability and accuracy. Numerical instability may cause the solution to diverge if the time increment is too large. Conversely, a very short time increment can cause spurious oscillations (Gibb's phenomenon). The calculation of the time increment depends on the element dimensions which the equations are described in Zerwer et al. (2002). In this study, a maximum time increment (0.0012 sec.) was considered based on the suggestions by Zerwer et al. (2002), though the automatic time incrementation option was activated to select the time increment in all analyses and prevent any numerical instability.

2.1 Selection of appropriate boundary conditions

For most of complicated geometries encountered in practice it is not possible to find closed form solutions and therefore it is necessary to resort to numerical methods such as finite element approach. However, only a finite number of nodal points can be considered in the analysis; thus the numerical methods are not directly applicable to infinite systems. Therefore, a general method through which an infinite system may be approximated by a finite system is a desire. In this respect, Lysmer and Kuhlemeyer (1969) proposed a special viscous boundary to overcome this limitation of numerical methods with an ease application to finite element method. They introduced the viscous boundaries for the analysis of dynamic problems involving infinite continues systems; hence an infinite half space could be successfully modeled as a finite element model (Lysmer and Kuhlemeyer 1969). Abaqus implements the principle of this theory for defining a non-reflecting boundary condition using infinite elements.

Since this study investigates the wave propagation phenomenon in ground, appropriate simulation of infinite boundary conditions should be considered. This section explains how the infinite boundary was applied in this research and demonstrates its advantages. At first, the ground was modeled with the fixed boundary and then, the boundary was improved using the non-reflecting boundary using infinite element option in Abaqus. This section further addresses the advantages of this improvement. In this regard, an impulse type input motion was applied at the center of the ground model (Figure 1) and the propagation of this wave throughout the ground was studied. Figure 2 shows the time histories of accelerations on the ground surface at different distances from the source. As can be seen, introducing the non-reflecting boundaries in the finite element model by applying the infinite elements could significantly enhance the performance of the model through eliminating the reflected waves from the main shock. As is shown, the reflected waves could interrupt the main wave especially near the boundaries where the magnitude of the main shock becomes small, e.g. $d=8.75$ m in Figure 2. Therefore, the results in this section undoubtedly indicate the advantages of the application of non-reflecting boundaries in the wave propagation studies.

Table 1. Material properties of ground (Itoh 2003).

Material	Shear modulus (kN/m ²)	Poisson's ratio	Dry unit weight (kN/m ³)
Soil (Dr=80%)	17.9×10^3	0.23	15.435

2.2 Characteristics of wave propagation in ground model

In this section, it was attempted to establish the reliability of Abaqus in the numerical modeling of wave propagation problems.

The finite element model was same as the previous section (Figure 1) with the non-reflecting boundary condition. An impulse type input motion was applied at the center of the model ground and the propagation of this wave throughout the ground was studied. Figure 3 shows the time histories of acceleration on the ground surface at different distances from the source. The Abaqus/CAE was also employed as a postprocessor to visualize the propagation of waves in the ground, and an example of this visualization is depicted in Figure 4. From this figure, different wave fronts could be understood.

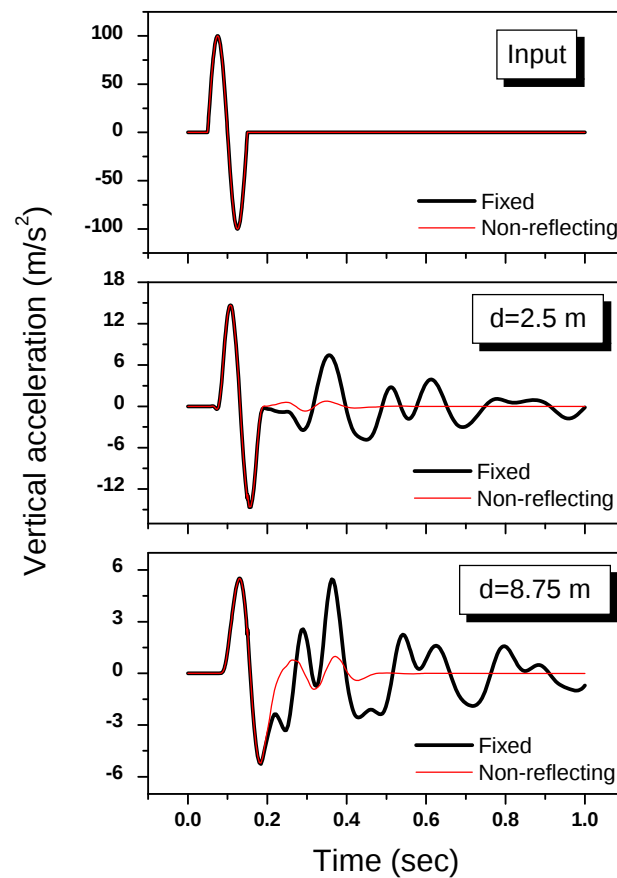


Figure 2. Time histories of acceleration records on ground surface for two boundary conditions (1) Fixed, (2) Non-reflecting.

An example of this process is illustrated in Figure 5 which displays the wave fronts at the time of 0.1 sec. Then, two different wave types were recognized (1) P-wave: compression wave with higher velocity and smaller amplitude, (2) S-wave: shear wave with lower velocity and larger amplitude. Hence, the first disturbance in the propagated wave time history, e.g. Figures 3 and 5, is attributed to the arrival of P wave and the second corresponds to the S wave. This assessment was conducted considering the time history records (Figure 3) and visualized format (Figure 5), and then it was possible to calculate the propagation velocity of abovementioned waves in both theoretical and visualized forms. Theoretical wave velocities were calculated using the material properties in Table 1 and include the shear wave velocity of 106.78 m/s (V_s), the Rayleigh wave velocity of 97.89 m/s (V_R), and the compression wave velocity of 180.33 m/s (V_p). Therefore, a comparison between the two travel distances was made and the results are given in Figure 6. As is shown, there is a strong agreement between these two approaches, confirming the results of Abaqus using the theoretical method.

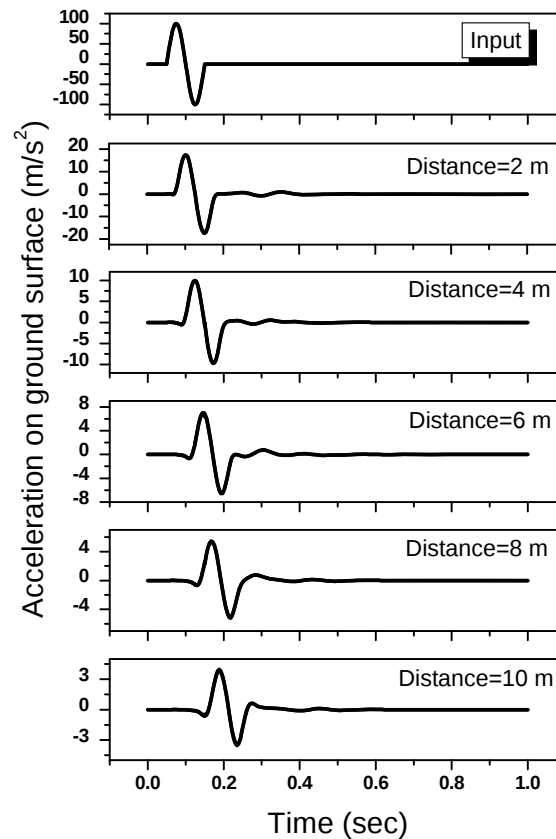


Figure 3. Time histories of acceleration on ground surface at different distances from source.

It is to be noted here that the non-spherical wave fronts, in iso-amplitude plot in Figures 4 and 5, of S and P waves near the ground surface could be attributed to the larger geometrical damping of the body waves near the ground surface which creates smaller amplitude of these waves when approaching the ground surface. While smaller geometrical damping of the Rayleigh wave near the ground surface produces the larger amplitude compared to the body waves. Therefore, the distortion of the body wave fronts near the ground surface would happen.

2.3 Verification of finite element models using centrifuge tests

After confirming the reliability of Abaqus in the wave propagation phenomenon, the finite element model was modified to investigate the train-induced ground vibrations. In this study, geotechnical centrifuge tests were employed to verify the finite element results, and this part explains the procedure we followed. Further information about the centrifuge tests can be found in Itoh (2003).

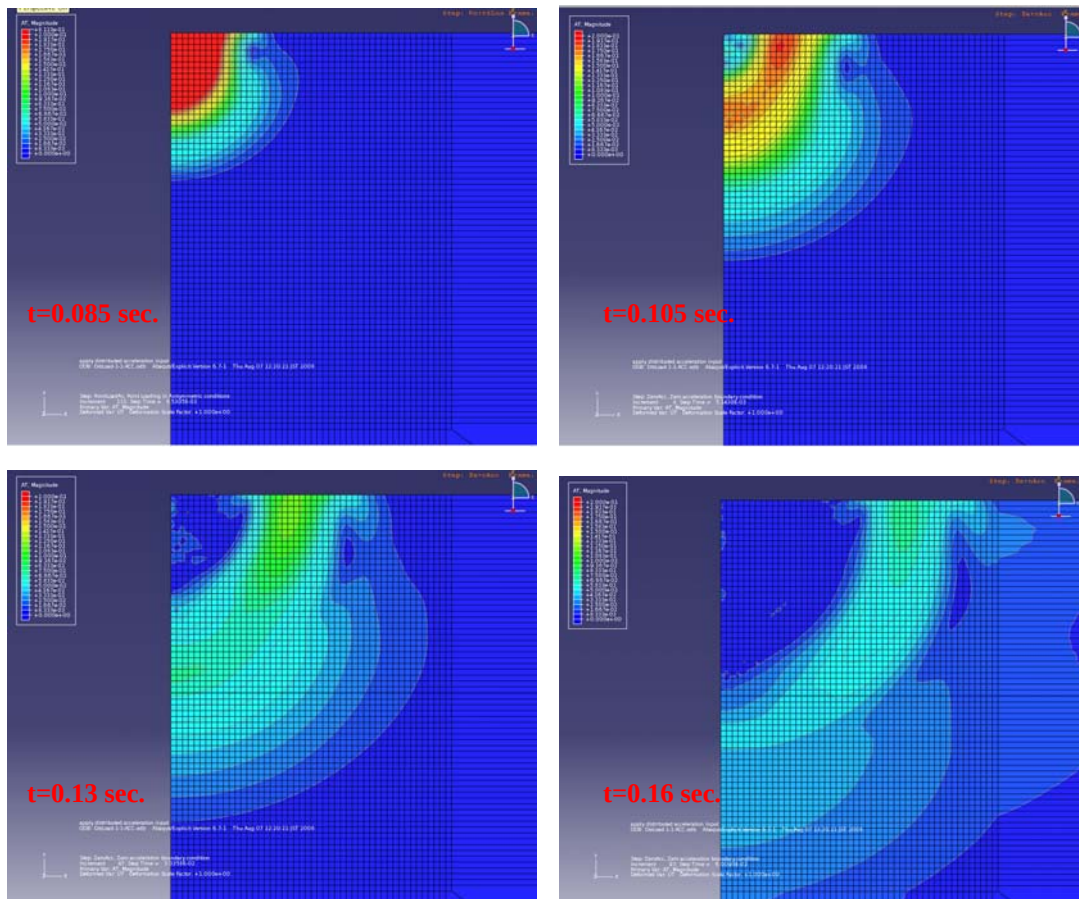


Figure 4. Visualization of wave propagation in ground by Abaqus/CAE at different time steps.

An important modification to the numerical model was to consider the material damping. This option was applied to the model in Abaqus using Rayleigh damping coefficients. The Rayleigh damping parameters provide a linear material attenuation (Equation 1).

$$D = \frac{\eta_1}{2\omega} + \frac{\eta_2\omega}{2} \quad (1)$$

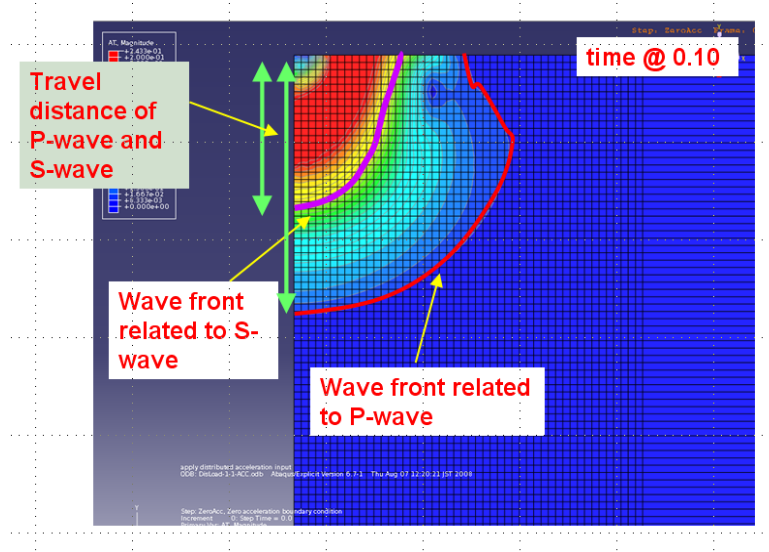


Figure 5. Visualization of wave front propagation in ground by Abaqus/CAE at time of 0.1 sec.

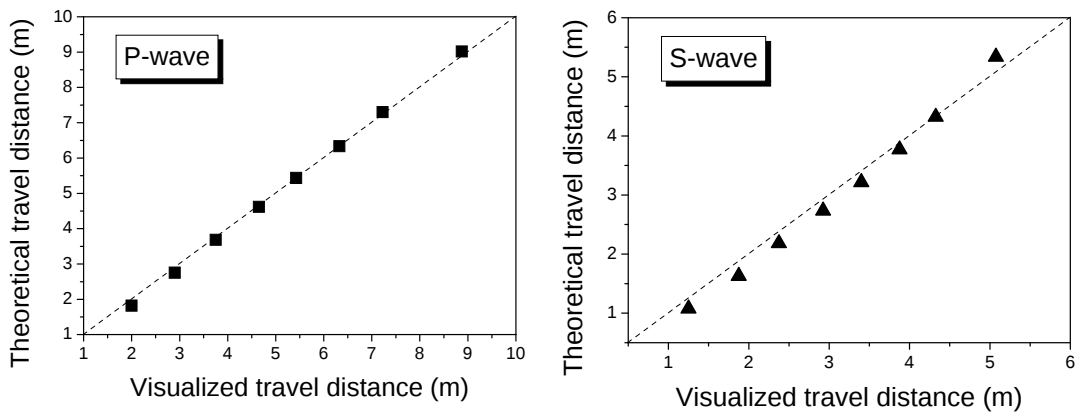


Figure 6. Theoretical and visualized travel distances of wave fronts.

where D is damping ratio, η_1 is mass damping parameter, η_2 is stiffness damping parameter, and ω is circular frequency. In the Rayleigh damping approach, two mass and stiffness constants are defined to produce an average damping ratio within a bounded frequency range while having a minimum variance. This method and the related equations are elaborated in Zerwer et al. (2002). Table 2 provides the damping coefficients for the ground, producing a 5% damping in the specified frequency bandwidth. Another important issue was to consider the increase in the shear modulus of soil with the increase in the depth or overburden pressure. Therefore, the ground was divided into four layers (Figure 7) and each layer was assigned a specified shear modulus to reproduce the real condition of the field.

Table 2. Rayleigh damping coefficients in this study.

Rayleigh damping coefficients		Average damping ratio	Minimum variance for damping	Frequency bandwidth (Hz)
Mass constant	Stiffness constant			
3.4163	0.001124	5%	0.1	1.5 ~ 40

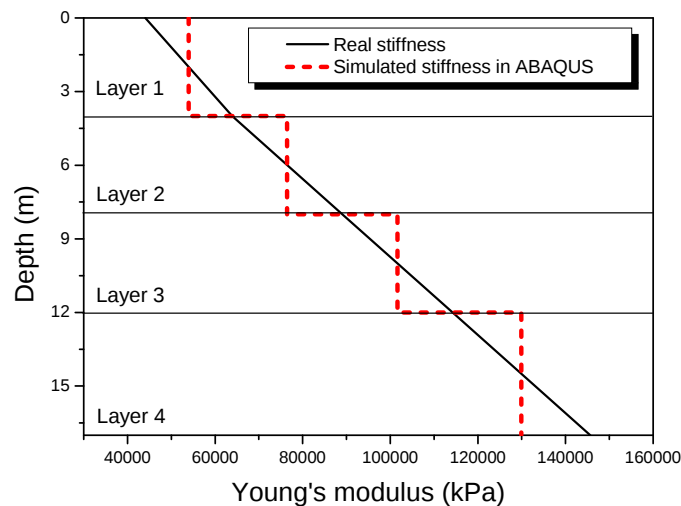


Figure 7. Variation of Young's modulus with depth (Jung 1998).

Since the boundary condition in the centrifuge tests was almost fixed (a rigid box with sponges attached), the boundaries in the finite element model (Figure 1) were changed into a fixed conditions, providing a similar circumstances to the centrifuge tests. Therefore, reflected waves existed in both approach records. The input motion in the finite element model was identical as the centrifuge test, being similar to an impulse type input motion (Figure 8). The frequency of this input motion was 10Hz which is located in the frequency range of train-induced ground vibrations (Yoshioka 2000 and Itoh et al. 2005).

Figure 8 shows an example for the comparison between the finite element model and the centrifuge test. As can be seen, the records on the ground surface at the distance of 1.25 m from the source displays a reasonable agreement especially for the case of first arrival wave which is believed to be free from any reflected wave.

In the next step, the peak values of the first arrival waves were selected to draw the attenuation curves for the surface ground waves. Figure 9 illustrates the comparison between the finite element model and the centrifuge tests, and the results display a reasonable agreement. Moreover, this figure includes the attenuation curve from a theoretical approach. Bornitz (1931) suggested theoretical attenuation curves for both body and surface waves which included geometrical and material damping. It should be noted here that the curved assigned to Bornitz (1931) in Figure 9 indicates the attenuation for the surface waves and demonstrates an acceptable agreement with the finite element and centrifuge results.

3. Effect of wave barriers in ground vibration reduction

In this section, the effect of wave barriers as mitigation measures in ground vibration reduction is investigated and results are compared with the geotechnical centrifuge tests. A comprehensive parametric study was conducted on the both geometrical and material properties of barriers which the results are addressed in this section.

In the centrifuge tests, an impact type point loading was applied through a ball-dropping system which details can be found in Itoh (2003) and Itoh et al. (2002). Wave barrier was installed at a distance of 2.25 m from the source to reduce the ground vibrations. A schematic illustration of the wave barrier system is depicted in Figure 10.

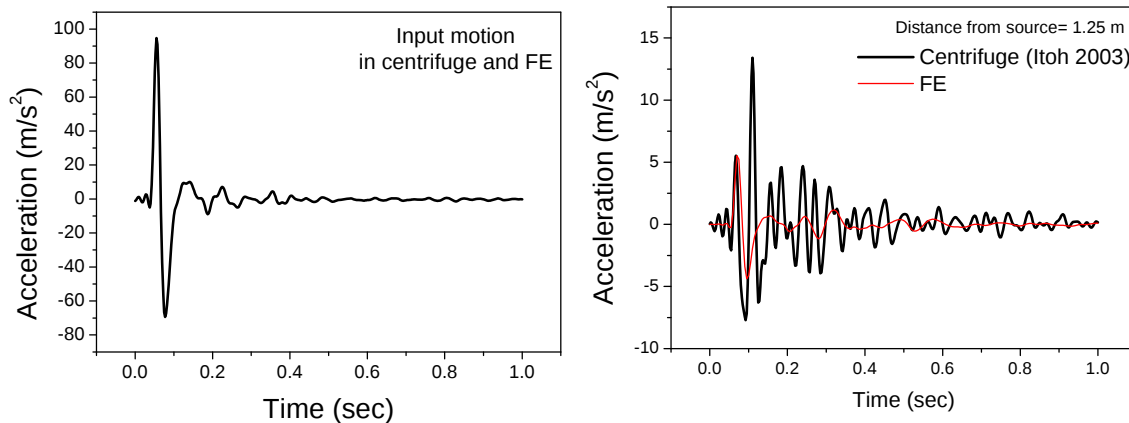


Figure 8. Time histories of input and recorded accelerations in numerical modeling and centrifuge experiment.

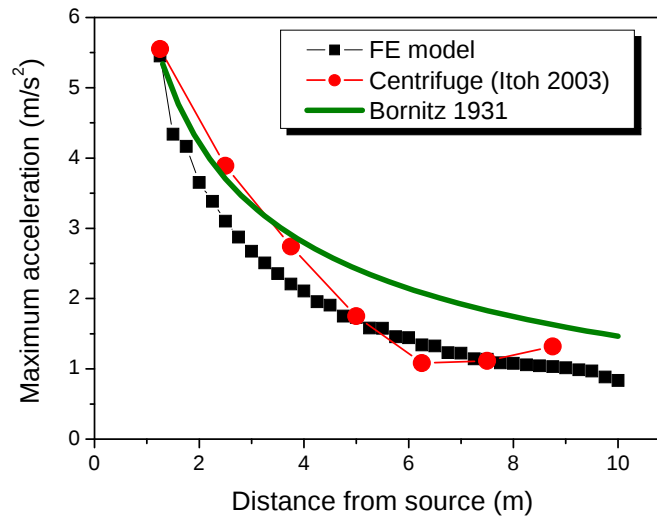


Figure 9. Comparison between attenuation curves for waves on ground surface derived from numerical modeling, centrifuge tests and theoretical method.

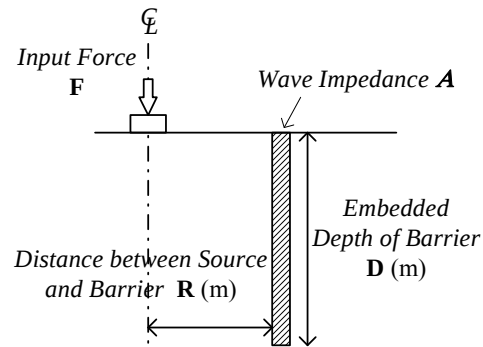


Figure 10. Schematic illustration for wave barriers in geotechnical centrifuge tests (Itoh et al. 2002).

The finite element model was improved in this part by inclusion of non-reflecting boundaries using infinite elements to minimize the wave reflections. Three types of wave barriers were employed in the centrifuge tests including Aluminium, Acryl and Expanded Poly-Styrol (EPS) which stand for concrete wall, improved soil, and EPS itself in the prototype scale (numerical model in Abaqus), respectively. Please refer to Table 3 for their properties. All these barriers were considered at the distance of 2.25 m from the source of vibration, because of the limitations in the centrifuge testing which imposed this restriction, and this study also followed the same

configuration for the uniformity. Please see Figure 11 for the configuration of ground and wave barrier.

Table 3. Material properties of wave barriers (Itoh 2003).

Material	Shear modulus (MN/m ²)	Poisson's ratio	Dry unit weight (kN/m ³)	Damping ratio (%)
Aluminium	25.6×10^3	0.34	26.5	1
Acryl	12.1×10^2	0.35	11.8	1
EPS	11.1×10^{-1}	0.10	0.12	5

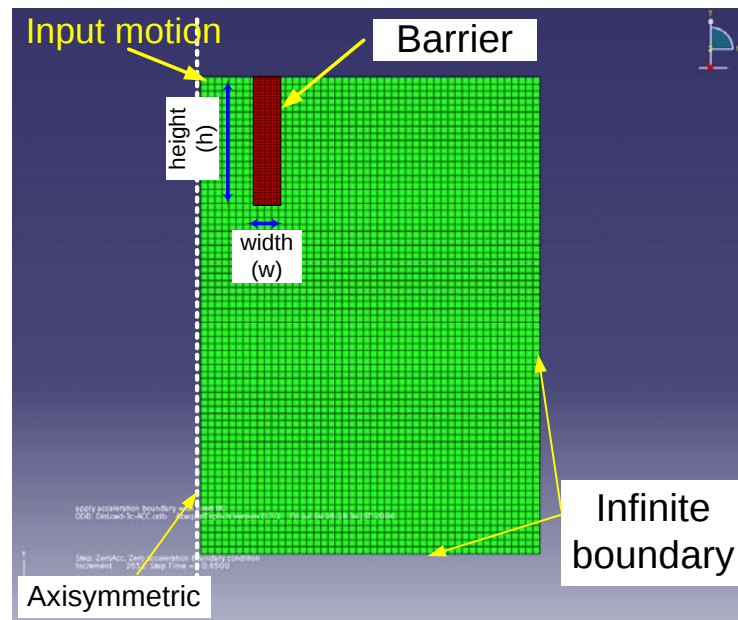


Figure 11. Finite/infinite element model of wave barrier in Abaqus (width=w and height=h).

3.1 Parametric study

The effects of both geometrical and material properties of wave barriers were investigated in this study through a parametric study, and the details are elaborated in this section. From material point of view, as mentioned before, three different barriers were studied including Aluminium, Acryl and EPS which stand for stiff to soft materials. It is to be noted here that these materials correspond to concrete wall, improved soil and EPS in the prototype scale, respectively. In respect to the geometrical characteristics, four different barrier heights were considered in the models ($h=2.5, 5, 10, 15$ m) as well as three different widths ($w=0.25, 0.5, 1$ m).

Figure 12 displays the time histories of the vertical accelerations on the ground surface of a model with the Aluminium barrier which had the configuration of width= 0.5 m and height= 10 m. As can be seen, the amplitude of the acceleration decreased as the distance from the source increased.

Furthermore, a benchmark model was run without any mitigation measure, providing an appropriate reference for the comparison. Figure 13 shows the attenuation curves of the maximum vertical acceleration on the ground surface for different barriers in addition to the benchmark model. As can be seen, all the barriers reduced the ground vibration in comparison with the benchmark model except the EPS barrier at the area between the source and the barrier and on the barrier itself. Figure 13 indicates that EPS barrier magnifies the ground vibration at the area near to the barrier, while beyond the barrier it performs likewise other barriers and reduces the ground vibration. It should be mentioned here that the some amplifications of the ground vibration near the EPS barrier has been observed during a series of field tests which further information can be found in Itoh (2003).

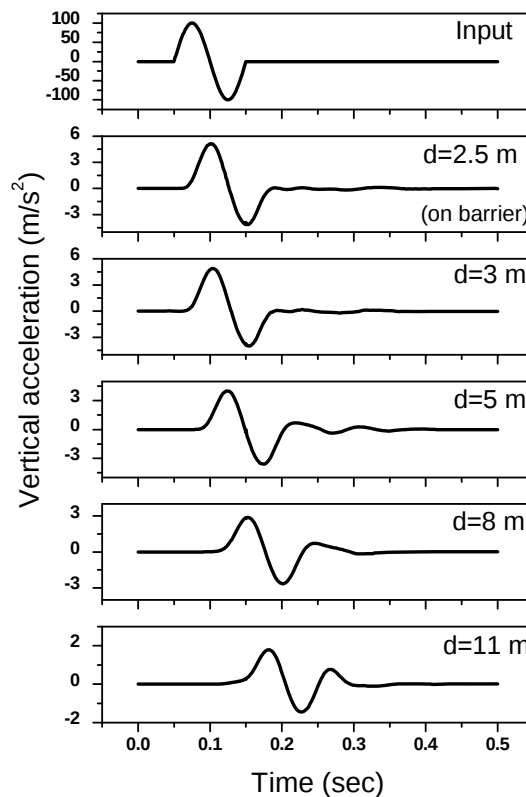


Figure 12 Time histories of acceleration on ground surface at different distances from the source – model with Aluminium barrier (w=0.5 m and h=10 m).

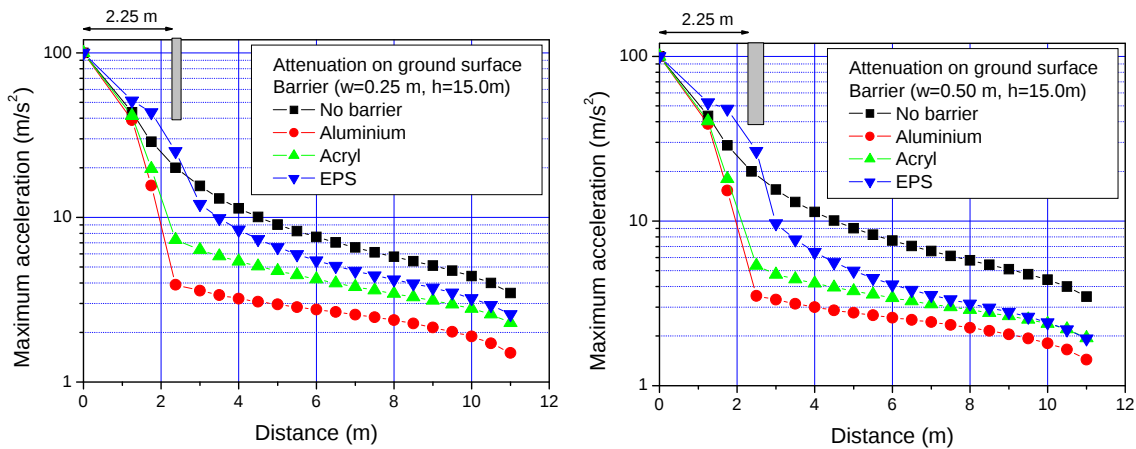


Figure 13. Effect of material on attenuation curves for deep depth barriers.

Furthermore, Figure 13 provides the evidence that in deep barriers, i.e. 10 m here, stiff materials would more significantly reduce the ground vibration compared to the soft materials. As is shown, this observation was consistent for two different barrier widths. In addition, this behavior was investigated for the shallow depth barriers as well and some results are presented in Figure 14. As can be seen, the results exhibit little differences for dissimilar materials, though the softer barrier, i.e. EPS here, showed a better performance in vibration reduction.

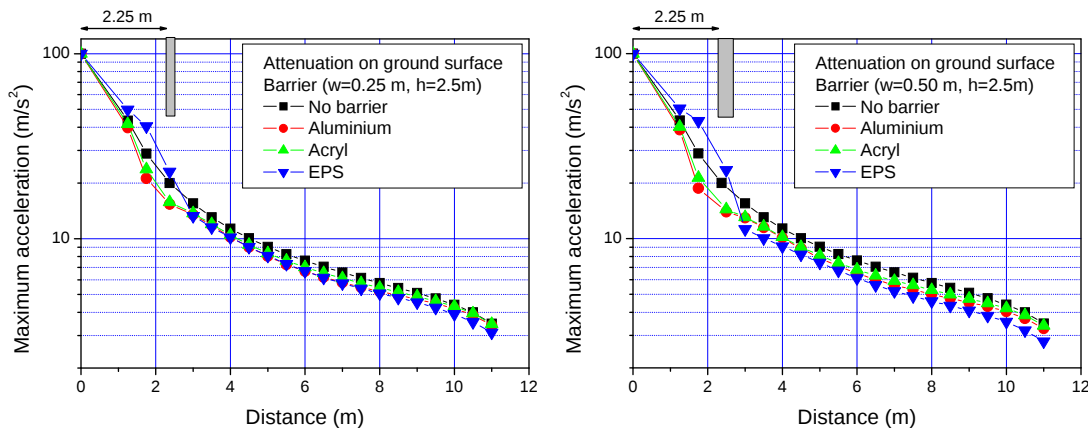


Figure 14. Effect of material on attenuation curves for shallow depth barriers.

Then, the effect of barrier depth was investigate by running the analysis with different barrier depths, and Figure 15 displays two examples of the results for the case of Aluminium and EPS barriers. The results in Figure 15 imply that increasing the depth could effectively enhance the performance of a stiff barrier, i.e. Aluminium here, while this parameter showed a little effect on the soft barrier, i.e. EPS. Hence, deeper depth in the stiff barriers would mean a better performance in the ground vibration reduction.

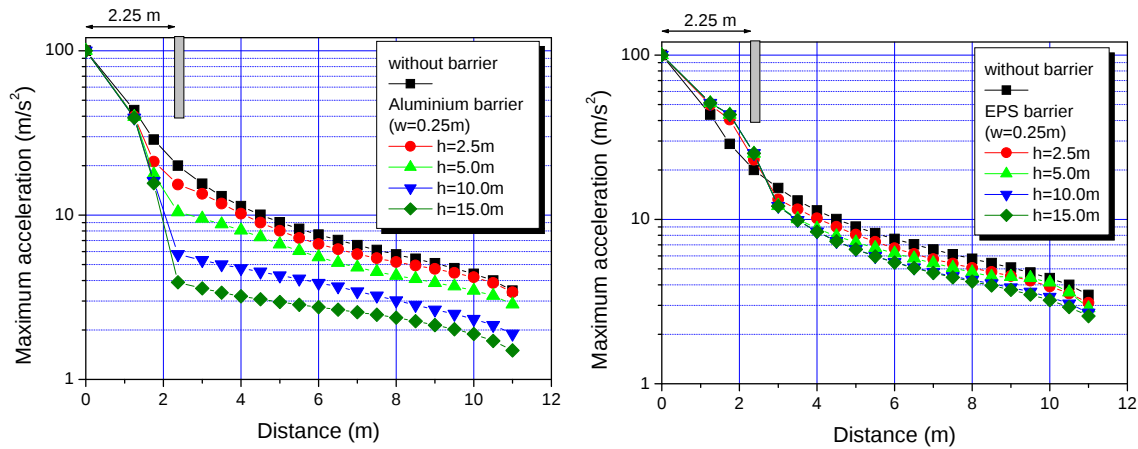


Figure 15. Effect of barrier depth on attenuation curves of Aluminium and EPS barriers.

Next, the effect of barrier width on the vibration reduction was evaluated by conducting the analysis with different widths, and Figure 16 depicts the results for the case of stiff barrier, i.e. Aluminium. Figure 16 reveals that increasing the width of stiff barriers has little effect to improve its performance, while this parameter exhibited an important consequence on the soft barrier, i.e. EPS in Figure 17. Hence, the thicker width in the soft barriers would result in a better performance in the ground vibration reduction.

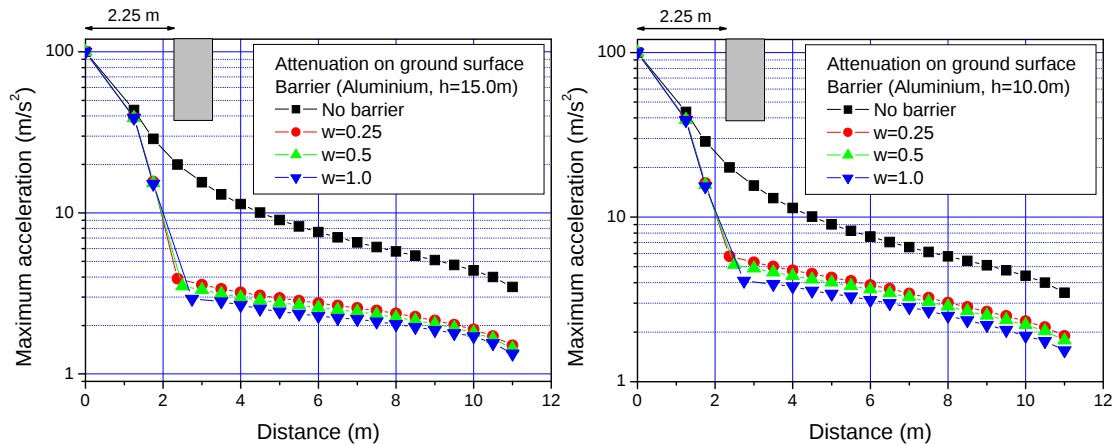


Figure 16. Effect of barrier width on attenuation curves of stiff barrier (Aluminium).

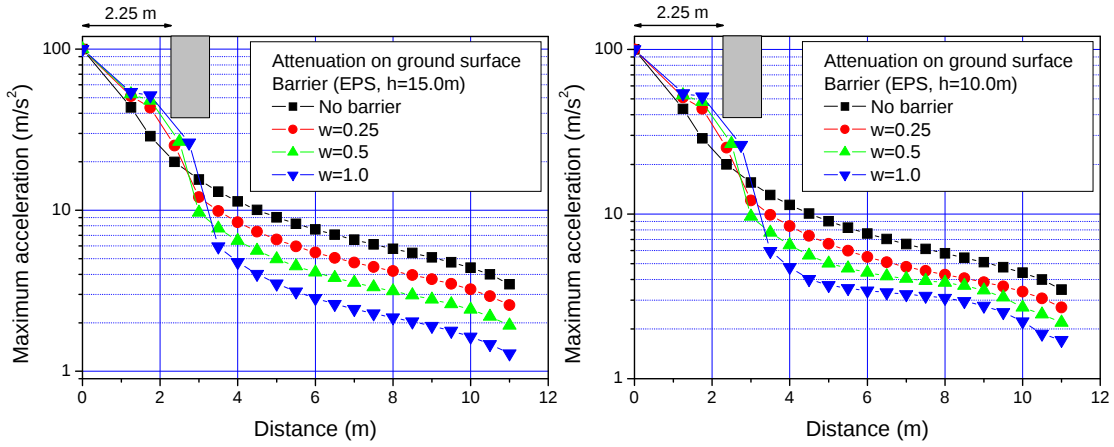


Figure 17. Effect of barrier width on attenuation curves of soft barrier (EPS).

3.2 Verification of numerical results using centrifuge tests

Although the validity and reliability of Abaqus in the numerical modeling of wave propagation was established in the Section 2.3, authors tried to verify the results of finite/infinite element modeling of wave barriers using the geotechnical centrifuge tests. In this regard, a parameter called Reduction Factor (R.F.) was introduced in this study to provide a quantitative comparison between the Abaqus and the centrifuge tests, since amplitude of the input motion in the centrifuge tests was not constant. This parameter represents the efficiency of a barrier in the ground vibration reduction as follows:

$$R.F. = \frac{(A_w - A_m)}{A_w} \times 100 \quad (2)$$

where R.F. is the reduction factor (%), A_w is maximum ground acceleration without any mitigation measure, and A_m is maximum ground acceleration with a vibration countermeasure. The positive R.F. represents effective vibration mitigation, while a negative value stands for vibration amplification. Figure 18 presents an example of this verification by giving an example for the case of Aluminium barrier.

The comparison in Figure 18 demonstrates an acceptable agreement between these two approaches. In other words, Figure 18 again confirms the validity and reliability of the finite/infinite element modeling in Abaqus for the studies related to the train-induced ground vibration and the mitigation measures. Moreover, it is to be noted here that some negative R.F. values near the boundary in the centrifuge test could be accounted for the wave reflection phenomenon as a result of the rigid side of experimental container.

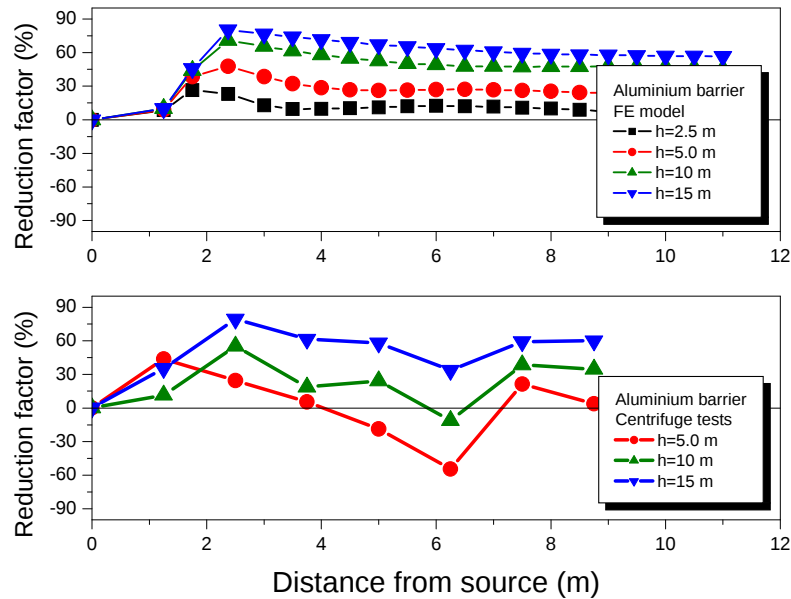


Figure 18. Comparison between numerical results from Abaqus and geotechnical centrifuge tests (Itoh 2003) for case of Aluminium barrier (width=0.25 m).

4. Summary and conclusions

In this study, finite/infinite element modeling of the train-induced ground vibration was conducted using Abaqus and the following conclusions are drawn:

- Advantages of the application of non-reflecting boundary condition to simulate infinite medium in Abaqus were exhibited. While, the rigid boundary conditions in the centrifuge tests imposed the reflected waves in the acceleration records.
- Reliability and validity of the present finite/infinite element model in Abaqus was confirmed using the geotechnical centrifuge tests.
- Wave barriers as the mitigation measures were employed and their efficiency in the ground vibration reduction was investigated in detail.
- It was shown that increasing the depth is an effective tool in enhancing the performance of stiff barriers, while this solution would result in insignificant outcome for the case of soft barriers.

- Stiffer materials provide a more effective vibration countermeasure than soft ones for the deep barriers.
- Effect of width was found to be noticeable for the case of soft barriers, while this parameter had little impact on stiff barriers.
- Reasonable agreement was observed between the mitigation experiments in centrifuge and the results from Abaqus which enables us to consider the Abaqus as a reliable measure for this type of studies.

5. Acknowledgement

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