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3D FEM ANALYSIS OF GROUND VIBRATION MEASURES FOR MOVING AND STATIONARY TRANSIENT SOURCE

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ABSTRACT

Ground Vibration Measures are often employed to reduce through-soil, road or railway traffic-induced disturbances or ground vibrations caused from machine foundations. This kind of problem is sometimes a major concern in densely populated urban areas situated at soft soil conditions and for structures operating sensitive equipments. In this paper a full three-dimensional (3D) FEM investigation of the effectiveness of vertical, rectangular cross-section, wave barriers (open trenches and concrete walls) in reducing ground vibrations is carried out. The reduction capacity of these measures is also compared with an array of concrete piles or sheet piles, which replaces them. The analysis considers moving and stationary vertical load conditions simulating traffic vibrations and machine foundation vibrations respectively. Ground vibrations caused from a transient source with rather low spectrums predominant frequency, sensitive for the dynamics of the nearby buildings, is considered. A 3D FEM program is formulated employing an implicit direct time integration scheme. Radiation damping, is simulated through transmitting boundaries constructed based on the radiation criterion. Considering different parameters, numerical examples are presented which highlight the reduction capacity of the barriers.

INTRODUCTION

Ground vibrations caused by heavy loaded vehicles, rail traffics or machine foundations have increased considerably during the last years as a result of infrastructure and technological developments leading to several environmental consequences. From some preliminary investigations it is noted that the predominant range of frequency of such type of vibration sources may lay in the interval (5÷50) Hz. The waves propagating at low frequency range can interact with the modes of vibration of the nearby buildings, sometimes approaching resonance conditions, increasing the disturbance. Except considering the vibration source stationary, recently, with the expansion of high-speed passenger train network, concern has been raised about the effect of moving load on wave propagation in the nearby soil. It is thus important to study these phenomena numerically to be able to present engineering solutions, which can reduce ground vibration impact on the environment.

General techniques proposed and used previously and recently can be classified as vertical and horizontal devices considering the position in the ground. As vertical wave barriers open or in-filled trenches, concrete or sheet pile walls and a row of piles, can be classified. Among others these devices were investigated analytically and numerically from the following authors. (Hawwa, 1998) studied the behavior of periodic trenches analytically. (Ahmad et al, 1996) and (Al-Hussaini and Ahmad, 1996) made investigations on active isolation of machine foundations by open and in-filled trenches using boundary element method. (Lee and Its, 1995) investigated surface waves of oblique incidence across deep in-filled trenches. (Fuyuki and Matsumoto, 1980) made a finite-difference analysis of Rayleigh waves scattering at a trench. (Haupt, 1977) employed FEM with an influence-matrix boundary condition concept to investigate isolation of vibrations by concrete core walls. (Aviles and Sanchez-Sesma, 1988) investigated analytically a row of circular piles as ground vibration barrier. A general analytical solution was presented also from (Boroomand and Kaynia, 1991) considering dynamic pile-soil-pile-interaction for vertical piles in homogeneous soil-stratum. A 3D FEM analysis was made lately from (Kellezi and Foged, 2000) for concrete piles of rectangular cross-sections and different dimensions, embedded in halfspace soft soil conditions.

As horizontal wave barriers, wave impeding block techniques can be classified, (Takemiya and Jiang, 1993), (Takemiya and Kellezi, 1998), (Kellezi and Nielsen, 2000).

In general, ground vibration measures have been investigated for stationary load conditions. Attention in this paper is focused on the 3D FEM modeling of the vertical wave barriers with special attention on open trenches, concrete walls and a row of piles or sheet piles which is a cheaper way of constructing the measure in comparison to the two first ones. Moving effect of the load is taken into account simulating vibrations from road or railway traffic. Stationary load is considered as a special case when moving velocity is equal to zero. This corresponds to vibrations caused from machine foundations or from heavy vehicles at a standstill position

A short description of the numerical method formulated and used in this analysis is carried out. The application of moving load in the FEM results in the 3D convection equations of motions. To simulate radiation damping, transmitting boundaries based on the radiation conditions are applied. Dynamic behavior at the soil surface, before and after the measures installation, is given in contour plots, for selected instant of time, and time histories for different components at different locations, considering measures like open trenches, concrete wall and row of sheet piles.

3D FEM ANALYSIS FOR TRANSIENT MOVING LOAD

Several studies have been carried out on the linear dynamic response of continuous pavements subjected to moving loads. (Hardy and Cebon, 1993) developed a linear theory from the well-known convolution integrals considering a moving and stationary frame of reference. (Dieterman and Metrikine, 1997) and (Kim and Roesset, 1998), studied the dynamic response of a beam and a plate respectively, on an elastic foundation, under a constant or time harmonic concentrated force moving at constant speed along the surface. Formulations were developed in the transformed field domains.

In another way the problem was formulated for FEM applications by (Krenk et al, 1999) for transient source of vibrations directly in the time domain. That formulation is further developed here for the 3D case implementing transmitting boundary conditions based on the radiation criterion. The convected equations of motion are given from Eq.1 below

$$\frac{\partial \sigma_{ij}}{\partial x_j} - \rho \frac{\partial^2 u_i}{\partial t^2} + 2V_y \frac{\partial u_i}{\partial x_j \partial t} - V_y^2 \frac{\partial^2 u_i}{\partial x_j \partial x_k} = p(t) \quad (1)$$

σ_{ij} and u_i denote the stress and displacement components respectively, ρ the density of the soil, V_y the velocity of the moving load. The load is supposed to move in the y-direction.

In matrix form equations of motion derive as in Eq. 2 after multiplied by a weight function in the form of a virtual displacement field followed by integration over the volume and using the divergence theorem.

$$\begin{aligned}&[M]\{u_{,tt}\} + ([C] + [C_V] + [C]_\infty + [C_V]_\infty)\{u_{,t}\} + \\ &([K] + [K_V] + [K]_\infty + [K_V]_\infty)\{u\} = \{P(t)\}\end{aligned} \quad (2)$$

[M] and [K] are the usual mass and stiffness matrices for the near field. [C], is material damping matrix taken approximately as Rayleigh damping but function of only stiffness matrices $[C]=\beta([K]+[K]_\infty)$. β, is the so-called Rayleigh damping coefficient related to the modal damping ratio γ of the i-th mode by the relation $\gamma_i = \pi\beta f_i$.

The effect of convection is a nonsymmetrical term containing mixed time and spatial derivatives, which for the element is given by Eq. 3. A symmetrical term, containing the second spatial derivatives, which for the element is given by Eq 4. In these equations Ω denotes the volume field.

$$[c_V] = -2\int_\Omega \left[\bar{N}\right]^T \rho V_y \left[\bar{N}_{,y}\right] d\Omega \quad (3)$$

$$[kv] = -\int_\Omega \left[\bar{N}_{,y}\right]^T \rho V_y^2 \left[\bar{N}_{,y}\right] d\Omega \quad (4)$$

Absorbing BC's formulated based on the radiation criterion are simulated through matrices $[K]_\infty$ and $[C]_\infty$ modeling far field stiffness and radiation damping respectively, The boundary scheme implemented can be considered as doubly asymptotic approximation. It is local in time and space and accurate for low and high frequencies. Eq. 5 and Eq. 6 give the boundary element stiffness and damping matrices. Γ is the boundary surface.

$$[k]_\infty = \int_\Gamma \left[\bar{N}\right]^T [D_K] \left[\bar{N}\right] d\Gamma \quad (5)$$

$$[c]_\infty = \int_\Gamma \left[\bar{N}\right]^T [D_C] \left[\bar{N}\right] d\Gamma \quad (6)$$

$[D_K]$ in Eq.5 is the constitutive matrix for the far field stiffness and $[D_C]$ in Eq.6 for the geometrical or radiation damping, (Kellezi and Takemiya, 2001). These matrices are functions of the density of the soil ρ, shear and Rayleigh wave velocities c_S and c_R, ratio of P- to S wave velocities s, outward unit vectors **n** and **r,** the first normal to the boundary and the second according to the wave direction vector, distance r from the boundary integration point to the source.

Change of the radiation damping and far field stiffness because of the moving load effect is given at the lateral boundary perpendicular to the moving direction by Eq. 7 and Eq. 8 resp.

The matrices in Eq. (2-8) are given in terms of the element shape function matrices, moving velocity and density of the soil.

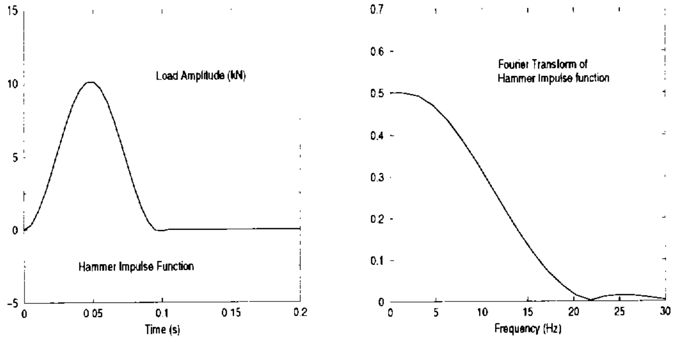
$$[c_V]_\infty = -\int_\Gamma \left[\bar{N}\right]^T n\rho V_y \left[\bar{N}\right] d\Gamma \quad (7)$$

$$[k_V]_\infty = -\int_\Gamma \left[\bar{N}\right]^T n\rho V_y^2 \left[\bar{N}_{,y}\right] d\Gamma \quad (8)$$

A second order correction has also been implemented in the convected equations of motions as the problem is not self-adjoint and Galerkin discretization is approximate. This is based on an alternative version of the Taylor-Galerkin approach for the spatial discretization, (Krenk et al, 1999).

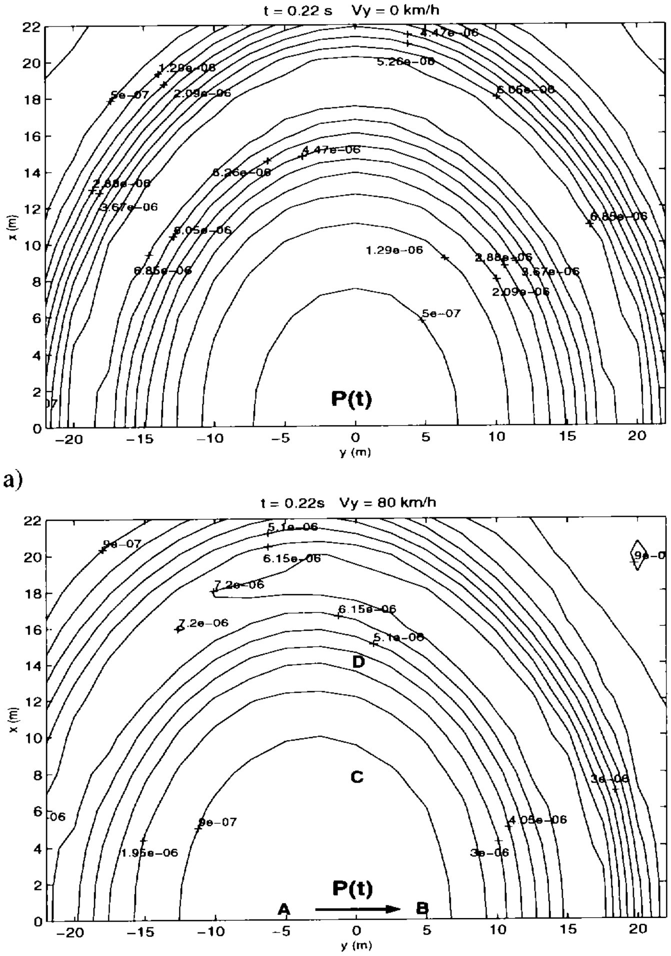
{P} is the load vector, which is supposed to act within the near field at the soil surface {u}, {u,t} and {u,tt} are resp. the system displacement, velocity and acceleration vectors.

Numerical Application



a) b)

Fig. 1 Vibration load. a) Time history. b) Frequency spectrum.



a)

b)

Fig.2 Vertical Displacement at z=0. a) Stationary load. b) Moving load

In the FEM analysis, half of the problem is considered using the symmetry conditions along the y-direction. The transient load which is considered to be a hammer impulse function, see Fig.1, is applied at point (0,0,0) and is supposed to move with velocity V_y=80 km/h or approximately 22.22 m/s. This time function has a wide low frequency content. This frequency range it is found interesting here different from previous analysis, for the reasons mentioned before

Homogeneous halfspace soil conditions are considered with c_S=120m/s, ρ=1800kg/m^3 and ν=0.4, γ=5%. As a matter of fact this is supposed to be the case when a layer of soft soil like fill or till resting on a limestone bedrock, has a depth larger than the critical depth. The 3D FEM Model in Cartesian coordinates covers an area of (-22,22) m in the y-direction and 22m in x-directions. It goes deeply into the halfspace z=22m as well. 8-node isoparametric cubic FE is employed with dimensions dx=dy=dz=λ_S/6=2m. So the model contains 2662 FE's. Transmitting boundaries are implemented at the bottom and the sides of the model at a distance less than two λ_S from the source. To see the moving load effect compared to a stationary load, the vertical displacement component at the soil surface, z=0, is given in Fig. 2 at t=0.22s. This corresponds to the case when the waves are inside the model and vibrations reach the maximum amplitude at the location after the measures. The load amplitude P=40kN is considered. The change in the system behavior when the load is moving in comparison when it is stationary can be noticed by comparing Fig. 2a with Fig. 2b.

For moving load the ground vibration amplitudes are different in the front and on back of the load. The velocity of wave propagation in the soil will decrease in the moving direction and increase in the opposite direction. This could be imagined as if the load is trying to reach the waves and move away from them respectively

GROUND VIBRATION MEASURES FOR MOVING LOAD

As mentioned before the load is supposed to move in the y-direction, parallel to the barriers, see Fig. 3 where a quarter of the model is shown. In this figure different parameters like trench depth H, distance of the trench from source R and half of the trench length L, are shown

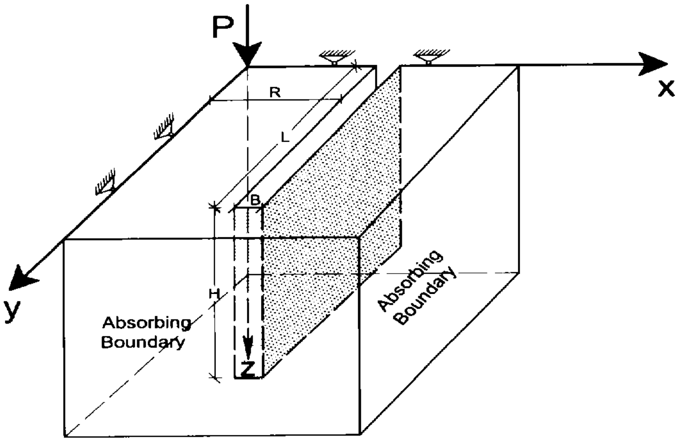


Fig.3 An open trench as ground vibration measure.

In Fig.4a vertical displacement component is given at z=0 when a trench of width $B=0.17=\lambda_S$ and $H=1.5\lambda_S$ is open at a distance $R=0.83\lambda_S$ from the moving load. The length of the trench $2L=3.3\lambda_S$ is chosen recommended from the literature. In Fig.4b the trench is filled with concrete material having Young's Modulus $E=3.1*10^7 kN/m^2$, $\rho=2400 kg/m^3$, $\nu=0.25$ and $\gamma=5\%$.

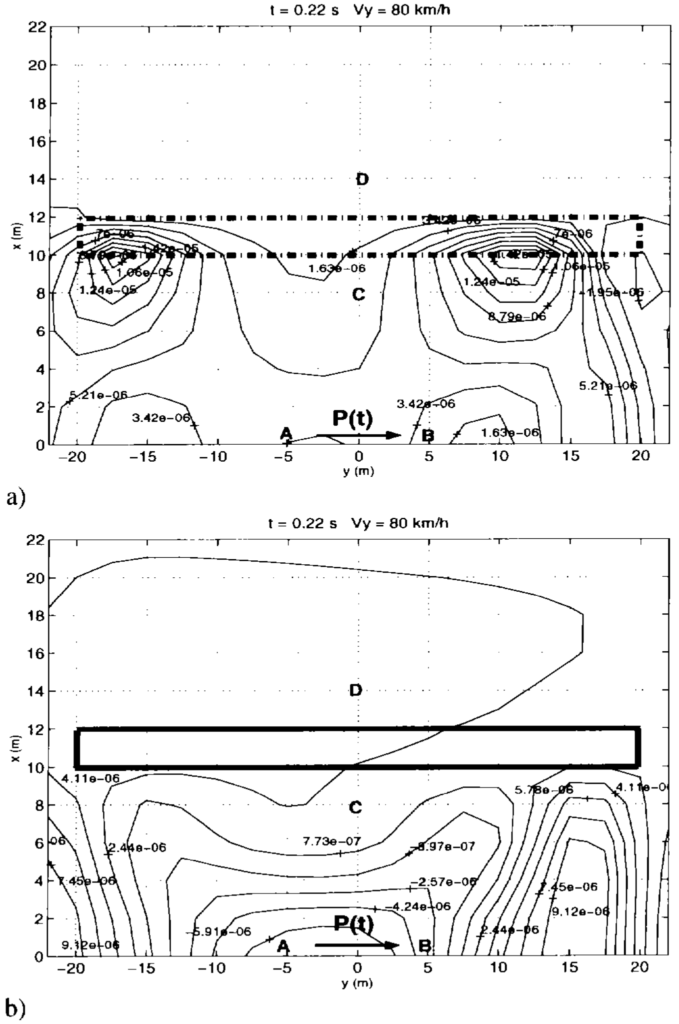


Fig. 4. Vertical Displacement at z=0. a) Open trench. b) Concrete wall. $R=0.83\lambda_S$, $H=1.5\lambda_S$, $L=1.65\lambda_S$, $B=0.17\lambda_S$.

To notice the effect of the open trench and concrete wall, Fig.4a and Fig.4b should be compared with Fig.3b, which correspond to the same model but without barrier inclusion. The decrease in the vibration amplitude after measures, at a distance (12÷22) m from the source, can be investigated from the values of the vertical displacement component at the contour plots.

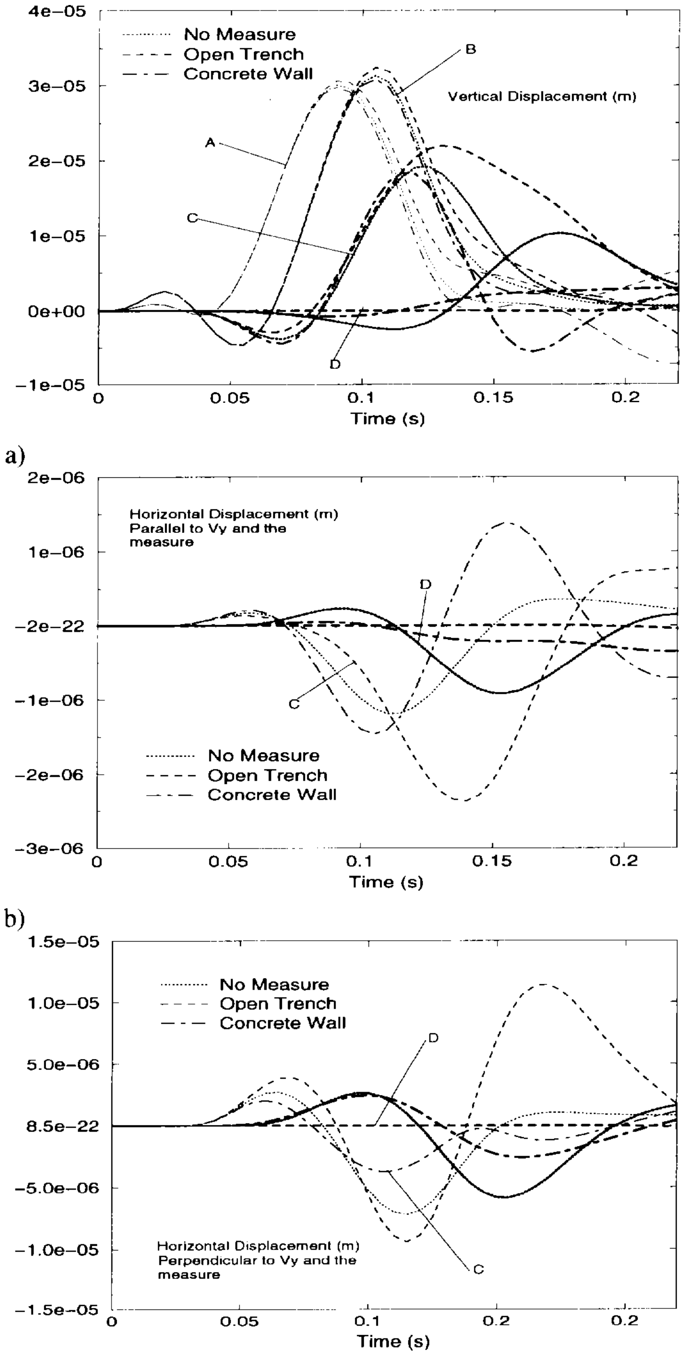


Fig. 5 Dynamic response at the free surface points for V_y=80km/h, $R=0.83\lambda_S$, $H=1.5\lambda_S$, $L=1.65\lambda_S$, $B=0.17\lambda_S$

It seems that the trench designed as above completely reduces the vibrations and the concrete wall of the chosen width gives high ground vibration reduction. The vertical component of vibration is the main focus as vibrations are caused from vertical load. However horizontal x and y-direction components are investigated too. In Fig. 5 the time histories for the vertical and horizontal displacements at the locations A, B, C and D, shown in Fig. 4, are given. These correspond to no measure, open trench and concrete wall measure. From the responses at the locations A and B, Fig.5a it is clear that the waves propagate faster on the back of the load and slower in the front and the amplitudes decrease in the back and increase in the front. From the response at the locations C in front of the measure, the amplification for the three components caused from the open trench is obvious. This is not the case for the concrete wall except for the horizontal component parallel to the wall. From the behavior at location D after the measure there is a 100% amplitude reduction of all components from the trench and about 80% from the concrete wall.

GROUND VIBRATION MEASSURES FOR STATIONARY LOAD

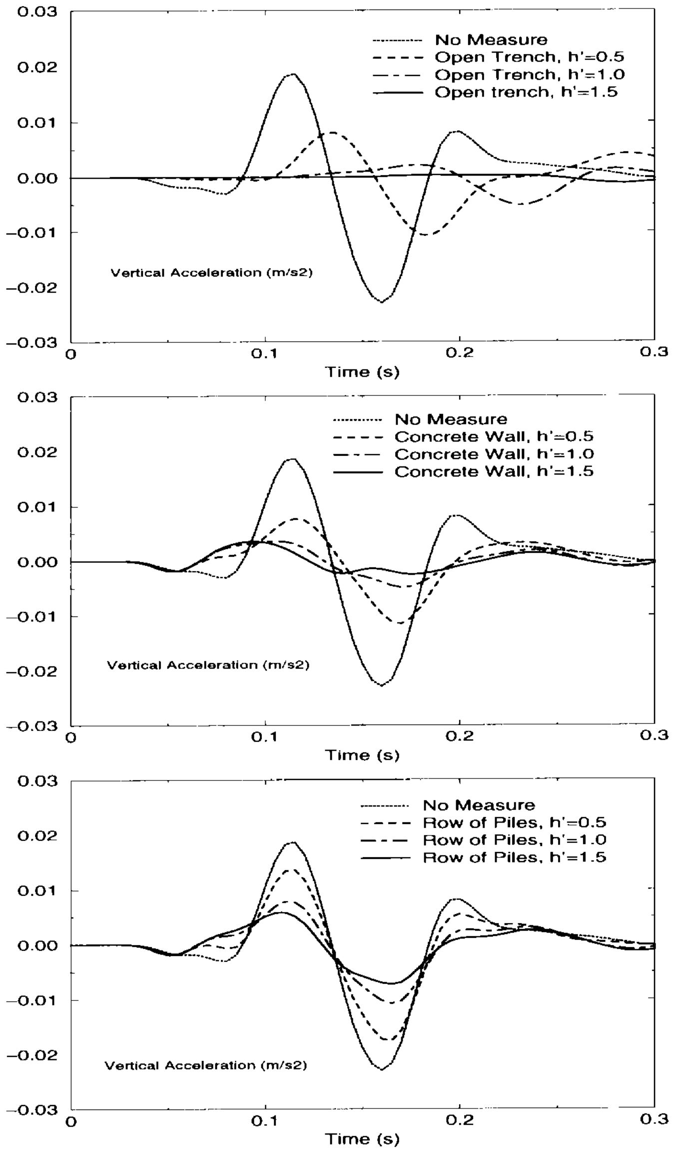
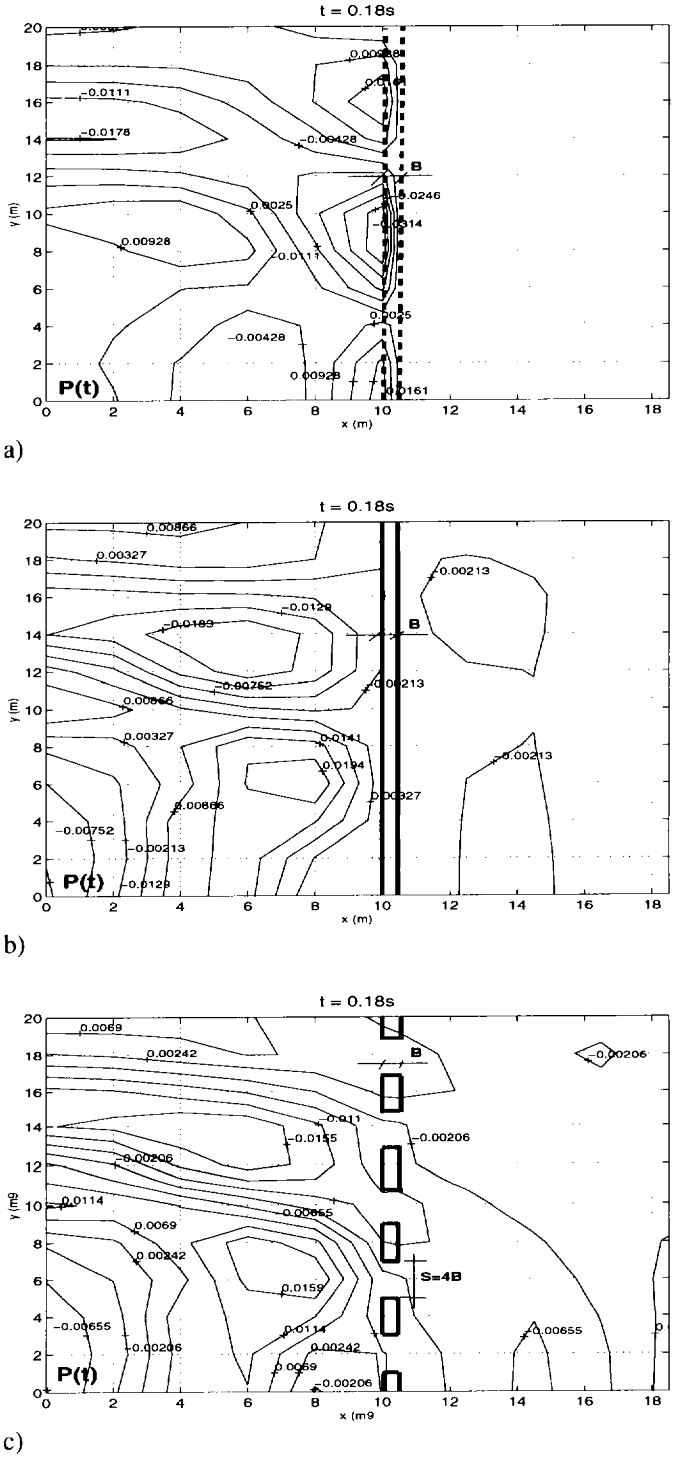


Fig. 6 Dynamic response after the measure, at x=12.5m, y=0m, z=0m. R=0.83λ_S, B=0.04λ_S, L=1.65λ_S.

For the frequency range of interest considered in this paper, the open trench and the concrete wall constructed as in the previous section have rather large dimensions considering the width B, which make them expensive for practical purposes. For this reason B=0.04λ_S is chosen in this section for stationary load. The same model as before is considered for V_y=0. As in this case there is symmetry in the x-direction as well, a quarter of the model is investigated. Computations in Fig. 6 are carried out varying the depth h'=H/λ_S of the thin open trench, concrete wall and a row of piles of cross section Bx4B (or a row of sheet 4 piles of cross section BxB) and net spacing S=4B, see Fig. 7c. From Fig. 6 and Fig. 7 we see that an open trench, a concrete wall and a row of concrete sheet piles embedded in homogeneous soil conditions and designed as above, reduce the amplitude of ground vibrations at an amount 100%, 70% and 50% respectively for h'=1.5. This means that an amplitude reduction factor A=0, A=0.3 and A=0.5 or an isolation effectiveness F=1-A=1, F=0.7 and F=0.5 is achieved respectively at that location. This is comparable to previous analysis.



a)

b)

c)

Fig. 7. Vertical acceleration at z=0m. a) Open trench b) Concrete wall c) Row of pile. R=0.83λ_S, B=0.04λ_S, L=1.65λ_S.

For open deep trenches the width does not change the vibration reduction capacity. For the concrete wall, larger the width larger the reduction capacity. When the wall is replaced with a row of concrete piles or sheet piles designed as in Fig. 7c, the reduction capacity drops, however considering the fact that construction work can be reduced and excavation work can be avoided, the profit is large. On the other hand a row of piles can be constructed for high water table levels in the ground which is not the case for an open trench or a concrete wall.

CONCLUSIONS

A full 3D FEM analysis of vertical ground vibration measures with emphasis to open trenches, concrete walls and a row of sheet piles, for moving and stationary transient source of vibrations, is carried out. A 3D FEM program is formulated in Cartesian coordinates for this purpose implementing absorbing BC's to simulate the far field. For nonstationary transient source of vibration, moving velocity is considered much lower than the shear wave velocity of the ground in the range $c_S \approx 6V_y$ giving subsonic conditions. Low frequencies of 10Hz are found interesting different from previous analysis. As convected equations of motion gives nonsymmetrical matrices, a general profile matrix is used for solving the equations of motions.

From numerical analysis of open trenches it seams that they are very good measures for moving and stationary load and their width is not an important parameter. A concrete wall can be a good vibration reduction measure as well. The width of the wall effects its reduction capacity. However a row of piles or sheet piles could be a more efficient device for this purpose. From a parametric study the depth H of the measures plays a very important role in the dynamic behavior of all the devices.

For the frequency interval and soil stiffness considered an open trench can give maximum reduction of 100%. A concrete wall gives about (70÷80)% and a dashed wall or a pile row will give about 50% ground vibration reduction.

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REFRENCES

Ahmad, S., T.M. Al-Hussaini and K.L. Fishman, [1996]. "Investigation on Active Isolation of Machine Foundations by Open Trenches", Journal of Geotechn. Eng. 122(6), 454-461.

Al-Hussaini T.M. and S. Ahmad, [1996]. "Active Isolation of Machine Foundations by In-filled Trenches Barriers", Journal of Geotech. Engrg.. Vol. 122(4), 288-294.

Aviles, J., and F.J. Sanchez-Sesma, [1988]. "Foundation Isolation from Vibration Using Piles as Barriers", Journal of Engrg. Mechanics, Vol. 114(11), 1854-1870.

Boroomand, B., and A.M. Kaynia, [1991]. "Vibration Isolation by an Array of Piles", Soil Dyn. and Earthq. Engrg. Ed IBF, Comp. Mech. Publicat. Elsevier Appl. Sc. 683-691.

Dietrman, H.A., and A.V. Metrikine, [1997]. "Steady-State Displacements of a Beam on an Elastic Halfspace due to Uniformly Moving Constant Load", European Journal of Mech. Series A, Solids, Vol.16, 295-306.

Fuyuki, M. and Y. Matsumoto, [1980]. "Finite Difference Analysis of Rayleigh Wave Scattering at a Trench", Bulletin of Seism. Society of America, Vol. 70(6), 2051-2069.

Hardy, M.S.A, and D. Cebon, [1993]. "Response of Continuous Pavements to Moving Dynamic Loads", Journal of Engrg. Mech. Vol. 119, 1762-1780.

Haupt W., [1977]. "Isolation of Vibration by Concrete Core Walls", Proc. of the 9th Inter. Conf. In Soil Mech. and Found. Engrg. Japans Soc. of Soil Mech. Found. Eng. Vol. 12, 251-256.

Hawwa A. Muhammad, [1998]. "Vibration Isolation of Machine Foundations by Periodic Trenches", Journal of Engrg. Mech. Vol. 124(4), 422-427.

Lee, S.L. and E.N. Its, [1995]. "Surface Waves of Oblique Incidence Across Deep In-filled Trenches", Journal of Engrg. Mech. Vol. 12(3), 482-486.

Kellezi, L. and H. Takemiya, [2001]. "An Effective Local Absorbing Boundary for 3D FEM Time Domain Analyses", 4th Intern. Conf. on Recent Adv. on Geot. Earthq. Engrg. and Soil Dyn. San Diego, (to appear)

Kellezi, L. and N. Foged, [2000]. "FEM Analysis of a Row of Concrete Piles as Vibration Barrier for Stationary and Moving Load", 53rd Canadian Geotech. Conf. Montreal (to appear).

Kellezi, L. and L.O. Nielsen, [2000]. "Dynamic Behaviour of a Soil Stratum and Vibration Reduction", 13th Nordic Geotech. Conf, Helsinki, Proceed.

Kim, S.M., and J.M., Roesset, [1998]. "Moving Loads on a Plate on Elastic Foundation", J. of Eng. Mech. Vol. 124, 1010-1017.

Krenk, S., L. Kellezi, S.R.K. Nielsen, P.H. Kirkegaard, [1999]. "Finite Elements and Transmitting Boundary Conditions for Moving Loads", 4th European Conf. on Structural Dynamics, Eurodyn'99, Prague, Proc. Vol. 1, 447-452.

Takemiya H. and J. Jiang, [1993]. "Wave Impeding Effect of Buried Rigid Block and Response Reduction of Dynamically Excited Pile Foundations", Structural Engrg. /Earthq. Engrg. Vol. 10(3), 149-156.

Takemiya, H. and L. Kellezi, [1998]. "Paraseismic Behaviour of Wave Impeding Block (WIB) Measured for Ground Vibration Reduction", 10th Japan Earthquake Eng. Symposium, Yokohama, E3-13, 1879-1884.