Dynamic Behavior of a Softer Layer Overlying Hard Soil / Bedrock and Vibration Reduction

Comportement dynamique d'une couche supérieure constituée d’un sol souple recouvrant un sol dur/rocheux, et réduction des vibrations

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ABSTRACT

For new buildings constructed on layered soil conditions and located near heavy traffic or industrial areas, ground vibrations are more and more an issue of concern. Considering different soil conditions the two-layer soil system consisting of a softer layer overlying a stronger one or hard soil is often a realistic approximation for geotechnical engineering design. A numerical investigation on the dynamics of this two-layer soil system is carried out using finite element (FE) method. Transient analysis is applied employing implicit time integration and incorporating an absorbing boundary formulation to simulate radiation damping at infinity. The dynamic stiffness of a single footing resting on this two-layer soil system is also investigated by Echo Models, which represent an alternative to the rigorous approaches. Based on the dynamic of the foundation - two layer soil system interactions the affectivity of the design of a mitigation measure for environment vibration is presented. Numerical examples highlight the efficiency of the method in reducing ground vibrations.

RÉSUMÉ

Pour les bâtiments neufs construits sur des sols stratifiés et situés à proximité d’un trafic routier important ou en zones industrielles, les vibrations au sol sont de plus en plus un sujet de préoccupation. Dans le cas d’une étude sur des états de sols différents, le système de sol à deux couches composé d'un sol souple recouvrant un sol plus ferme ou dur est souvent une approximation réaliste pour toute conception géotechnique. Une investigation numérique sur la dynamique de ce système de sol à deux couches est réalisée à l'aide d’état limite ultime (ELU). Une analyse transitoire est appliquée en employant une intégration temporelle implicite, et en utilisant une formule d’absorption limite pour simuler un amortissement radial à l'infini. La rigidité dynamique d'un simple bloc de fondation reposant sur ce système de sol à deux couches est également étudiée par des modèles Echo qui représentent une alternative aux approches rigoureuses. Sur la base de la dynamique interactive entre le bloc de fondation et le système de sol à deux couches, l'efficacité de la conception d'une mesure d'atténuation des vibrations sur l’environnement est présentée. Des exemples numériques illustrent l'efficacité de la méthode pour réduire les vibrations au sol.

Keywords: Soil dynamic, two-layer soil system, ground vibrations, mitigation measures, Echo Models, finite element (FE) method, time domain, absorbing boundaries.

1 GENERAL INTRODUCTION

The development of modern cities around the world is generally associated with major infrastructure projects, which are often followed by an increased awareness regarding traffic induced vibrations. In different countries in Europe and elsewhere, official regulations are focusing on limiting vibrations, setting up legal limits for acceptable levels.

Under these circumstances there is an increasing demand for better prediction methods regarding ground vibration, particularly for critical soil conditions involving soft soil layers continuing to varying depths and overlying hard soil as shown in figure 1. In addition, better tools for designing mitigation measures, are required.

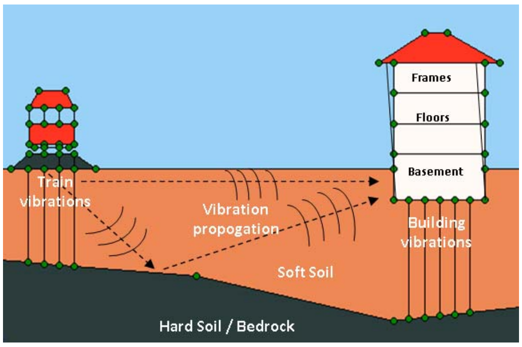

Figure 1 Traffic induced ground vibration in soil conditions consisting of a softer soil overlying hard one.

Low-frequency building vibrations are typical in soft soils while audio frequencies are typical in hard soils. Whole-body vibrations usually consist of frequencies of (2–80) Hz. Soft clayey soils are one of the most problematic cases for whole-body vibration. Usually low vibration frequencies of (5–10) Hz dominate in such soils.

The waves propagating at low frequency can interact with the modes of vibration of the nearby buildings, sometimes approaching resonance conditions.

Different vibration mitigation measures are proposed and applied in the past and recently and an extensive literature is available. After modelling of the ground vibrations by simple conventional models [1] and FE analyses [2]-[4] open or in-filled trenches, concrete or sheet pile walls have been previously investigated analytically and numerically also by [5]-[6].

FE modeling of the ground vibrations and a mitigation measure based on cement injection applied for a soft layer overlying a hard one are presented in this paper.

2 DYNAMIC TIME DOMAIN FE ANALYSIS

For investigating the dynamic behavior of the current two-layer soil system a FE program is developed for soil dynamic analyses. Only vibrations for vertical excitations are considered here.

Direct time integration is implemented to be able to perform harmonic and transient analysis. Material damping in the soil is included in the form of Rayleigh damping. The unbounded infinite soil domain is modeled through transmitting or absorbing boundary conditions.

When σ_{ij} and u_i denote the stress and displacement components respectively, ρ soil density and p(t) the applied time function stress, the elasto-dynamic equations of motion are given as:

$$\frac{\partial \sigma_{ij}}{\partial x_j} - \rho \frac{\partial^2 u_i}{\partial t^2} + p(t) = 0 \qquad (1)$$

When equations (1) are multiplied by a weight function in the form of a virtual displacement field $\bar{u}_i$ followed by integration over the volume and reformulation using the divergence theorem equation (2) is derived.

$$\int_{\Gamma} \bar{u}_i \left(\sigma_{ij} n_j\right) d\Gamma - \int_{\Omega} \left(\bar{\varepsilon}_{ij} \sigma_{ij} + \rho \bar{u} \ddot{u} - \bar{u} p \right) d\Omega = 0 \qquad (2)$$

The stress σ_{ij} at the boundary integral in equation (2) represents the stiffness of the far field and geometrical damping given in vector form in equation (3).

$$\{\sigma\} = [D_K]\{u\} + [D_C]\{u_{,t}\} \qquad (3)$$

The formulation of the absorbing boundaries consists of how the constitutive matrices $[D_K]$ and $[D_C]$ are derived.

For the soil conditions consisting of soft soil overlying hard one, surface waves plays a major role. In context of one-dimensional wave theory a cylindrical wave traveling in the positive x-direction is approximated by equation (4).

$$u_i(x,t)=\frac{1}{\sqrt{x}}f(x-ct) \tag{4}$$

For soil half space model $c=c_R$ for example for the horizontal component of the in-plane motion. From the strength of materials theory [1] the differential equation satisfied from a cylindrical wave front could be as given in equation (5).

$$\frac{1}{c}u_{i,tt}-\frac{1}{x}u_{i,x}-u_{i,xx}=0 \tag{5}$$

This is the equation of motion of a cone with linear area variation. Considering only outgoing waves the boundary differential equations equals

$$\left[\frac{\partial}{\partial t}+\frac{c}{2x}+c\ \frac{\partial}{\partial x}\right]u_i=0 \tag{6}$$

The boundary stress derives as

$$\sigma_i(x,t)=-\left[\frac{\rho c^2}{2x}u_i(x,t)+\rho c\ u_{i,t}(x,t)\right] \tag{7}$$

The linear cones from the boundary location x to infinity are modeled also by a mechanical system, which contains a spring and a damper with frequency independent coefficients.

These models are used as absorbing boundary for surface waves with constitutive stiffness matrices $[D_K]$ and $[D_C]$ derived as

$$[D_K]=\frac{\rho}{r}(n*r)\left\{\frac{1}{2}\left(sc_R^2n_x^2+c_R^2\left(1-n_z^2\right)\right)+c_S^2n_y^2\right\} \tag{8}$$

$$[D_C]=\rho(n*r)\left\{sc_Rn_x^2+c_R\left(1-n_z^2\right)+c_Sn_y^2\right\} \tag{9}$$

In equations (8) and (9) s is the ratio of P- to S wave velocities. Development of the above method in two-dimensional (2D), plane strain, and axisymmetric conditions is presented in [2]-[4].

3 EXAMPLE – SOFT LAYER OVERLYING HARD SOIL

The dynamic of this two-layer soil system consisting of a softer layer overlying hard soil is investigated in this section. The effect of the thickness of the softer layer on the dynamic response at the soil surface is elaborated. The soil properties for the relatively soft layer are chosen such as c_s=200 m/s, ρ=2000 kg/m^3 and Poisson's ratio ν=0.33. The depth of the layer *d* is increased with 6 m starting with 4m.

A harmonic pulse is chosen with frequency *f=10 Hz.* This means that S-wavelengths with $\chi_s=20\ m$ will propagate in the top layer. FE mesh is constructed by choosing the element size 1/10 of χ_s which has proven to be a good approximation for isoparametric elements.

In the *z*-direction, Neumann boundaries are placed at the bottom of the model and transmitting boundaries, as described in the next section, on the side at a distance of one χ_s.

The displacement response at a distance from the dynamic source is shown in figure 2, as time histories. Computations are carried out without any material damping for the soil to investigate only radiation damping effect. Then 5% material damping was inserted to see its role at the resonance conditions.

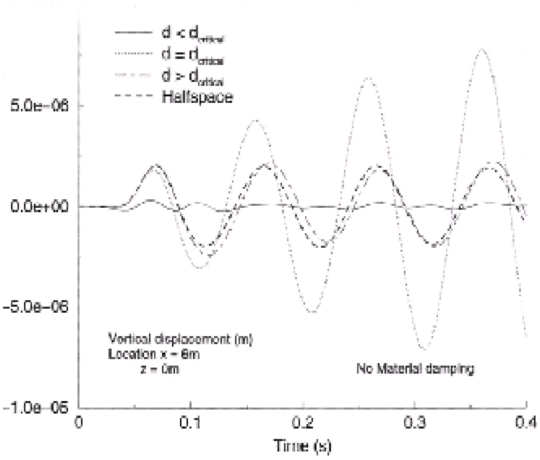

Figure 2 Vertical displacement amplitudes at the top layer surface, 6m distance from the harmonic source.

Material damping for the near field is included as a function of the mass and the stiffness matrices and for the far field only as a function of the stiffness.

To interpret the results in figure 2, the eigenfrequencies of the layer for vertical vibrations must be defined as $\omega_{i,v}=2\pi c_p\,(2i-1)/4d$. The critical depth, $d_{critical,}$ corresponds to the value of the fundamental frequency of the softer layer equal to the frequency of the load. In this example this value is $d=d_{critical}\ =\ 10\ m$. So for $d=4\ m<d_{critical}$ there is almost no vibration, no wave propagation in the softer layer. For resonance conditions the increase of the displacement amplitudes is shown in figure 2. For $d=16\ m>d_{critical}$ the response approaches that for halfspace conditions.

4 ECHO ANALYSIS

After investigating the dynamic behavior of a soft layer overlying a hard one, the dynamic characteristics of rigid mass-less circular footing supported on it are elaborated.

In this case the static stiffness increases for vertical load to: $K_v=4\mu r_o(1+1.3r_o/d)/(1-\nu)$ *where* K_v is the static stiffness for the homogeneous half-space footing-soil system, μ is the Shear Modulus of the soil, r_0 the radius of the circular footing. This results in an increase of the fundamental frequency of the footing-soil system making the total system stiffer.

In addition, the dynamic stiffness is strongly frequency dependent. However, the most important effect is the existence of a cut-off frequency below which radiation of energy does not take place and the soil effect on the damping of the total system is only through material damping.

These findings can also be confirmed by Echo Models described in [1] and [2]. A wave pattern is postulated, which incorporates, in addition to the decay of the wave amplitudes propagating away from the source, also the reflections at hard soil interface and on the free surface.

The dynamic stiffness coefficients for the mass-less circular footing are derived for vertical vibrations, as function of the non-dimensional frequency $a_0=\omega r_0/c_s$ *and* given in figure 3 for different ratios $m=d/r_o$.

The reason for these computations is to demonstrate that the damping coefficients are negligible till a value of a_0 that depends on the depth of the layer, and become appreciable over that value. For example the damping coefficient is negligible for $a_0\approx 2,\ 3,\ 6$ respectively, for decreasing m from 1.5, 1.0, to 0.5.

From these investigations it can be concluded that if the layer depth is decreased, the interval from zero to the characteristic frequency is increased. The angular frequency ω, which belongs to the characteristic value of $a_0=\omega r_0/c_s$ is called cut-off frequency and here is denoted by ω_c.The cut-off frequency coincides with the top layer fundamental frequency.

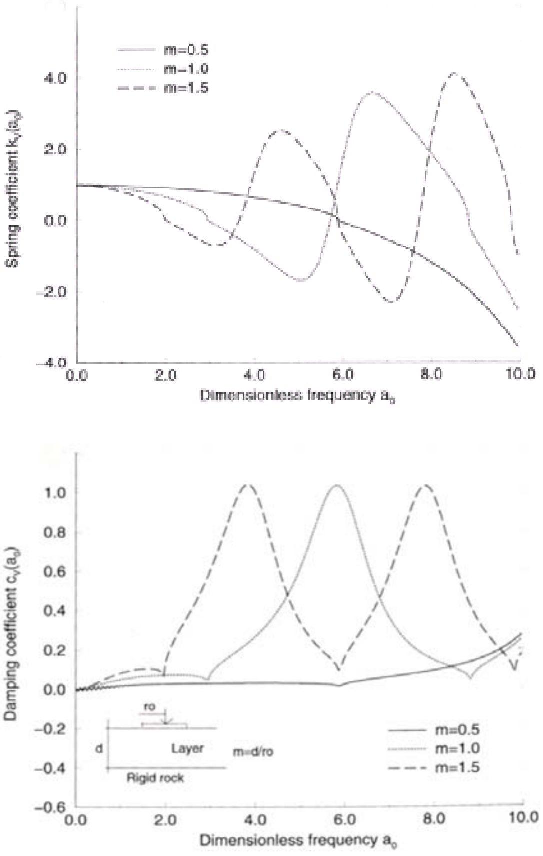

Figure 3 Dynamic vertical stiffness coefficients (spring and damping) for disk on a layer, v=0.33

5 INJECTION VIBRATION MEASURE

Based on the above analyses it is clear that vibration at the soil surface depends on the soft layer thickness, its material properties and the frequency content of the dynamic source.

These investigations led [7] to the idea of developing a new device to reduce ground vibrations, by artificially changing the wave propagation in the top layer. They produced a virtual rigid base at an appropriate depth less than $d_{critical}$, It was concluded that this measure was better engineering practice than trenches.

The application of the above concept for pile foundations is modified by [8] with a new arrangement called wave impeding block (WIB) or H-WIB for transient loading, which can be constructed simply as a variant of the soil improvement techniques.

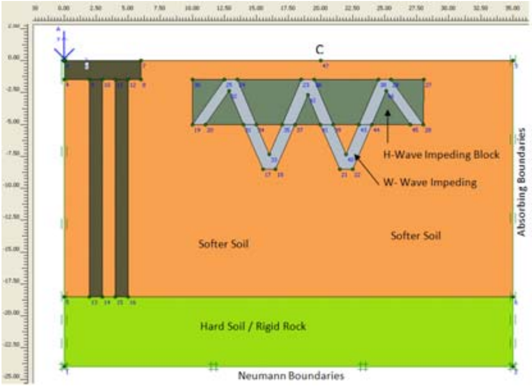

Figure 4 FE Model Geometry with W-WIB

As a type of WIB device, which combines the horizontal and vertical effects of the solid wave barriers, a new configuration measure denoted W-WIB is proposed for the pile foundation. The FE model geometry is given in figure 4. To take into account three-dimensional (3D) effects, an axisymmetric formulation for the model is considered acceptable when the effect on the surrounding environment is investigated.

The soil properties for the relatively soft layer are chosen such as c_s=150 m/s, ρ=1800 kg/m^3 and Poisson's ratio ν=0.45. For the H-WIB and W-WIB c_s=1000 m/s, ρ=1800 kg/m^3 ν=0.3. The hard soil and the pile foundation are assumed as concrete material.

Ricker impulse load is chosen for computation as an impulse, which gives fixed frequency predominance. This is because the vibration of high speed traffics is of limited frequency-band. The loading parameters are chosen T_p=0.1 s and t_s=0.1 s as a short period motion. The predominant frequency should be above the softer layer first vertical eigenfrequency.

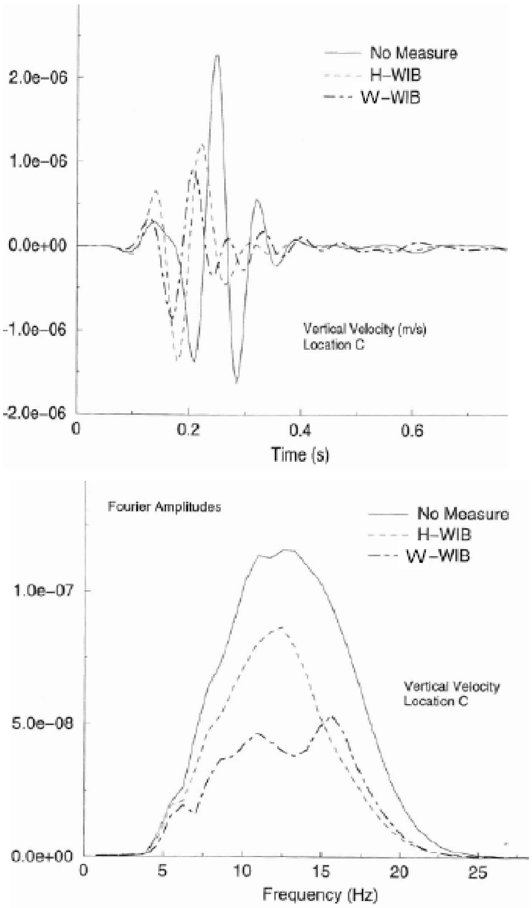

Figure 5 Dynamic vertical response at location C with no measure, H-WIB and deep-W-WIB.

The FE model is applied to three different cases: with no measure, with a horizontal measure H-WIB and the new measure denoted W-WIB.

The width of the H-WIB is determined based on the wave motion in the layered soil, more than one R-wavelength, and the depth is determined 1.5 m from the surface, much less than $d_{critical}$ and as small as possible to reduce the excavation work. As the reinforcement technique for constructing W-WIB consists of injecting cement-milk with blows, which will compact the soil around, its modeling as in figure 4 is found to be an acceptable approximation.

The vertical response is the main focus as the measures are designed to damp this component. W-WIB efficiency is obvious from the time variation of velocity and the Fourier amplitudes given in figure 5. The Fourier spectrum shows which frequencies are damped more indicating the predominant frequency of the travelling waves as well as the cut-off frequency determined from the current 2-layer soil system.

It is investigated that installing a W-WIB shape next to the foundation leads to vibration reduction for the nearby soil surface especially in the surface just above it and at larger distances. It is very important to note that there is no amplification near the dynamic source. The transient responses of ground surface vibration and the Fourier spectrums demonstrate the modified wave propagating characteristics due to the presence of the W-WIB in these aspects: amplitude reduction, time shifting, and decrease of period.

For engineering practice, to reduce ground-born vibrations, the depth of the top of the W-WIB has to be less than 20% of the $d_{critical}$. The material for W-WIB is recommended to be more than 6 times stiffer than the surrounding soil and possibly arranged as in figure 4. The practical way of constructing these measures is related to the technologies of ground reinforcement.

6 CONCLUSION

Conventional and numerical analyses carried out in this paper show that dynamic analysis of sites which can be approximated as a 2-layer system with a softer layer overlying a hard one or a rigid base, are very important in designing machine foundations, bridges and train viaducts foundations, rested or embedded in them.

When the depth of the soft soil layer is less than the critical depth defined above, there is no wave propagation in the layer so there is no vibration in the ground surface. Such a location is optimal to place a vibrating foundation. Employing Echo Models for dynamic analysis of shallow foundations seems to be attractive for the detailed engineering design.

When disturbing ground vibrations already exists, (the depth of the soft layer is larger than the critical depth) methods for reducing them should be considered. The proposed device W-WIB, utilizing the cut-off frequency, seems to exhibit good vibration reduction capacity.

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