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A study of the reduction of ground vibrations by an active generator

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ABSTRACT

This paper presents the concept of using an additional generator to prevent ground vibrations. A linear, transversally isotropic three dimensional half-space with the hysteretic damping model, acted upon by a harmonic vertical excitation is assumed. Equations of motion for the transversally isotropic ground model with the absorbing boundary conditions are presented and numerically integrated using FlexPDE software, based on the finite element method. The efficiency of the solution is analysed in terms of reducing the vertical and horizontal components of ground surface vibrations. Results in the form of a dimensionless amplitude reduction factor are presented for four different locations of a generator. The influence of the soil parameters and layers locations on the additional generator's efficiency is investigated. The vibration reduction efficiency in a four-story building is also presented.

1. Introduction, the concept of an additional generator

The aim of this paper is to present an approach for protecting structures from large vibration amplitudes resulting from ground-applied loads. To this end, an additional source of vibration will be applied to the ground surface. The excitation force of an additional generator must be correctly chosen. The main concept is to generate a wave with an opposite displacement direction but similar vibration amplitudes and frequencies to the wave being attenuated. Summing the displacements of these two sources will significantly reduce the vibration.

Generally, approaches for protecting structures from failures caused by seismic, wind or man-induced vibrations can be divided into two groups. The first group ensures excitation resistant structures and joints through the application of passive, active or semi-active vibration mitigation techniques. The second group is based on creating a barrier in the ground to prevent the transmission of the surface wave energy.

Passive control does not require an external power source. This approach includes passive isolation systems, viscoelastic dampers or tuned mass dampers. It is widely used in structural control. Because passive systems are unable to adapt to changing loading conditions, damping forces are not always optimized. This is in contrast to active and semi-active systems, which are able to change their damping characteristics for a better reduction effect. However, these systems require an external power source. The energy requirements for semi-active systems are smaller than those for active systems [1].

In contrast, the concept of vibration screening provides the possibility to control the energy reaching the sensitive zones. Most energy that affects structures nearby is carried by a Rayleigh wave travelling on a ground surface emanating outwards from the vibration source. According to Kramer, in the case of oscillatory loading applied to a ground surface, this is approximately 67% of the total energy [2]. A barrier in the form of a ground discontinuity eliminates the possibility of wave propagation. A vibration attenuation effect is achieved by the proper interception, scattering and diffraction of surface waves. Upon reaching an obstacle, most of the energy of the Rayleigh wave is reflected, but some is transmitted through the barrier and new body waves (P-waves and S-waves) also radiate outward from the obstacle. Different solutions are implemented to achieve wave scattering, including sheet-pile walls, piles [3–5] and in-filled trenches – with water, soft soil, concrete or special materials, such as GeoFoam [6–9]. However, the best results are achieved by the use of so called open trenches [6–8,10,11].

The solution in the form of a ground discontinuity provides the best attenuation effect if the Rayleigh wave is dominant, as in the case when the excitation source is located on a ground surface e.g., man-made ground vibration. Human activities that can generate ground vibrations can be classified as the operation of machines, road and railway traffic, and construction activities [12]. The main construction or demolition activities causing dynamic problems in the vicinity of structures are pile or sheetpile driving, dynamic soil compaction, demolition of structures, rock excavation by explosives, and deep soil compaction by explosives. Pile driving is achieved by impact or vibratory hammers. Both processes generate ground

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vibrations. The shear waves are generated along a pile surface because of friction between the pile and soil particles. The S-waves propagate from contact points to the ground radially on a cylindrical wave front. In addition to the effects around a pile, each impact on a pile creates displacements at the toe of a pile. This generates compression (P-wave) and shear waves (S-wave), which propagate outward from a toe of a pile with spherical wave fronts. Once these waves encounter a ground surface, part of their energy is converted to surface Rayleigh waves, and part is reflected back to the ground [12–14]. Rayleigh waves propagate along a ground surface with two components of amplitude (vertical and horizontal) and a slightly lower velocity than S-waves. The vertical component is dominant in that case. The amplitudes of the Rayleigh wave, which spread out in the cylindrical wave front, are proportional to $1/\sqrt{R}$, where R is the distance from the vibration source.

The vibration isolation problem is usually solved by numerical methods, such as finite element methods in connection with non-reflecting boundaries [15–17] or boundary element methods, which automatically satisfy the radiation condition in infinity [5–8,18,19]. In the presented paper, the first approach is used to solve the problem of wave propagation, resulting from ground-applied loads using non-homogenous ground conditions. This paper describes a concept for vibration-mitigation techniques with the potential to reduce the amplitudes of ground vibration by applying an additional vibration source. From the perspective of energy requirements, the proposed solution of an additional generator is similar to active systems applied to structures, but it does not interfere with the structure. Rather it attenuates a vibration amplitude before a wave reaches a structure, which makes the solution similar to ground barriers. However, the approach is easier, less expensive and faster to implement than the two aforementioned methods. It is also portable and can be used repeatedly in different places and situations.

2. Equations of motion for a transversally isotropic medium with hysteretic damping

To assume a correct model for a soil medium, the strains must be estimated. For a relatively large strain (shear strain exceeding 10^{-4}) a two-phase elastic-plastic soil medium model based on the Biot theorem is necessary [20]. In the presented example, the maximum value of observed shear strains does not exceed $5{\bullet}10^{-5}$, so the elastic one-phase model is sufficient. The same model is typically assumed in similar investigations considering wave mitigation techniques [3,4,10,16].

Let us consider stresses acting on a soil element with side measurements dx, dy, dz. The sum of the forces acting in the x-, y- and z-directions, including damping forces, gives the differential equation of motion for the soil medium [21]

$$\sum P_x = 0:\ \frac{\partial\sigma_x}{\partial x} + \frac{\partial\tau_{yx}}{\partial y} + \frac{\partial\tau_{zx}}{\partial z} + tr\cdot\frac{\partial\sigma_x}{\partial t\partial x} + tr\cdot\frac{\partial\tau_{yx}}{\partial t\partial y} + tr\cdot\frac{\partial\tau_{zx}}{\partial t\partial z} = \rho\frac{\partial^2 u}{\partial t^2}$$
$$\sum P_y = 0:\ \frac{\partial\tau_{xy}}{\partial x} + \frac{\partial\sigma_y}{\partial y} + \frac{\partial\tau_{zy}}{\partial z} + tr\cdot\frac{\partial\tau_{xy}}{\partial t\partial x} + tr\cdot\frac{\partial\sigma_y}{\partial t\partial y} + tr\cdot\frac{\partial\tau_{zy}}{\partial t\partial z} = \rho\frac{\partial^2 v}{\partial t^2}$$
$$\sum P_z = 0:\ \frac{\partial\tau_{xz}}{\partial x} + \frac{\partial\tau_{yz}}{\partial y} + \frac{\partial\sigma_z}{\partial z} + tr\cdot\frac{\partial\tau_{xz}}{\partial t\partial x} + tr\cdot\frac{\partial\tau_{yz}}{\partial t\partial y} + tr\cdot\frac{\partial\sigma_z}{\partial t\partial z} = \rho\frac{\partial^2 w}{\partial t^2} \quad (1)$$

where u, v and w are the components of displacement in the x-, y- and z-directions, respectively; ρ is the soil density; σ_x, σ_y, σ_z, $\tau_{xy}=\tau_{yx}$, $\tau_{xz}=\tau_{zx}$, $\tau_{yz}=\tau_{zy}$ are normal and shear elastic stresses, respectively; and tr is the relaxation time, which is inversely proportional to the excitation frequency $tr = 2\xi/\omega$. The relations for strains in terms of displacements are assumed as: $\varepsilon_x=\partial u/\partial x$, $\varepsilon_y=\partial v/\partial y$, $\varepsilon_z=\partial w/\partial z$, $\gamma_{xy}=\partial v/\partial x + \partial u/\partial y$, $\gamma_{xz}=\partial w/\partial x + \partial u/\partial z$, $\gamma_{yz}=\partial w/\partial y + \partial v/\partial z$. For an elastic transversally isotropic material with a horizontal plane of isotropy, the elastic strain stress relationship can be presented as follows [22]:

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0\\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{55} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{bmatrix}, \quad (2)$$

where $C_{11}=1/E_x$, $C_{12}=-\nu_x/E_x$, $C_{13}=-\nu_z/E_z$, $C_{33}=1/E_z$, $C_{55}=1/G_{xz}$, and $C_{66}=2(1+\nu_x)/E_x$. E_x, $E_y=E_x$ are the Young's moduli in the x- and y-directions, respectively, in the plane of isotropy. E_z is the Young's modulus in the z-direction, in the plane perpendicular to the plane of isotropy. Similarly ν_x, $\nu_y=\nu_x$ and ν_z are the Poisson ratios in the plane of isotropy and in the plane perpendicular to the plane of isotropy, respectively. G_{xz} is the shear modulus in the plane perpendicular to the plane of isotropy.

3. Finite element model and absorbing boundary conditions

To avoid wave reflection at the boundary, the absorbing viscous boundary conditions are assumed following Lysmer and Kuhlemeyer [23]. The normal (σ_x) and shear (τ_{xy}, τ_{xz}) stress components for virtual dampers "fixed" to the right (along coordinate $x=70$ m in Fig. 1) and left (along coordinate $x=0$ in Fig. 1) boundaries are given by the formula

$$\sigma_x=a\rho V_x\dot{u},\quad \tau_{xy}=b\rho V_{xy}\dot{v},\quad \tau_{xz}=b\rho V_{xz}\dot{w}, \quad (3)$$

where ρ is the mass density, $\dot{u}$, $\dot{v}$ and $\dot{w}$ are velocities in the x-, y- and z-directions respectively, a and b are parameters introduced to improve the wave absorption at the boundaries in the normal and tangential directions, respectively. Research findings indicate that $a = 1$ and $b = 0.25$ can yield reasonable absorption at the boundary [16,17]. These values are also assumed in this study. V_x denotes the P-wave velocity, and V_{xy}, V_{xz} denote the S-wave velocities. The notation V_{ij} indicates propagation in the i-direction, whereas the polarization is in the j-direction. The explanation of the wave propagation phenomenon by different types of anisotropy including determination of wave velocities is omitted here, as it is widely discussed in the literature [22,24]. The velocities in the plane of isotropy of the transversally isotropic medium are defined as $V_x=V_y=\sqrt{C_{11}/\rho}$, $V_{yz}=\sqrt{C_{55}/\rho}, V_{xz}=\sqrt{C_{55}/\rho}$, and $V_{xy}=V_{yx}=\sqrt{C_{66}/\rho}$, [22,24]. In the plane perpendicular to the plane of isotropy the velocities can be calculated from the following formulas: $V_z=\sqrt{C_{33}/\rho}$, $V_{zy}=\sqrt{C_{55}/\rho}$, and $V_{zx}=\sqrt{C_{55}/\rho}$.

The normal (σ_y) and shear (τ_{yx}, τ_{yz}) stress components in the virtual dampers "fixed" to the near and far edges of the analysed domain (along coordinates $y=0$ and $y=70$ m, see Fig. 1) are expressed as

$$\sigma_y=a\rho V_y\dot{v},\quad \tau_{yx}=b\rho V_{yx}\dot{u},\quad \tau_{yz}=b\rho V_{yz}\dot{w} \quad (4)$$

For the bottom boundary ($z=-35$ m) damping forces are described by the formulas

$$\sigma_z=a\rho V_z\dot{w},\quad \tau_{zx}=b\rho V_{zx}\dot{u},\quad \tau_{zy}=b\rho V_{zy}\dot{v} \quad (5)$$

Additionally, both displacement components are assumed to be zero at the bottom edge of the investigated region.

The vibration source in the form of periodic load ($P_1(t)$ in Fig. 1) is located in the middle of the region considered ($x=35$ m, $y=35$ m, $z=0$)

$$P_1(t)=A\sin(2\pi f\cdot t)\cdot\left(H(t-t_b)-H(t-t_e)\right), \quad (6)$$

where A is the amplitude of the excitation, f is the excitation