INFLUENCE OF GROUND INHOMOGENEITY ON WIND INDUCED GROUND VIBRATIONS

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Abstract

The mechanical behavior of the near surface of the ground (vadose zone, critical zone) is required for many geotechnical applications such as roadway construction, trafficability, foundation design, and agricultural production. The mechanical behavior may also be indirectly related to transport across this critical interface such as; water infiltration and gas flux which are important to hydrological and climate studies.

Mechanical sources for investigating near surface of the ground included high frequency electromechanical sources and loudspeakers. We attempt to exploit the pressure fluctuations produced by wind as a source for investigating near surface soil properties.

In a previous study, the ground was modeled as an elastic homogenous half space and a prediction model was developed for the wind-induced ground motion. However, ground is a layered or inhomogeneous medium and will have a different response due to the surface pressure. In this presentation, we discuss different kinds of theoretical inhomogeneous grounds and their available analytical responses due to a surface load. Furthermore, we use Comsol-Multiphysics®, a commercial finite element package, to simulate a more realistic ground consisting of a layer over a half-space. A new response function is derived by interpolating the Comsol output to substitute in the wind-ground coupling equations. A comparison between the homogeneous and non-homogeneous ground predictions are used to evaluate the importance of layering on wind-induced ground vibrations.

Introduction

Near-surface geophysics focuses on geophysical methods to study properties and layers of the near-surface region of the earth. Seismic field measurement is one of the most common surface-based methods which require a source to generate seismic vibrations. In this paper, we consider wind as a source and investigate ground motion to study near surface ground properties.

Naderyan et al. (2015) utilized the developed theory by Yu et al. (2011) to predict wind pressure at the ground surface based on the wind velocity and then the frequency-dependent correlation of wind noise founded by Shields (2005) to estimate the distribution of wind pressure on the surface. The theory of elasticity for a homogeneous elastic half-space under a quasi-static point load was applied to the predicted wind noise distribution to develop a quasi-static model for wind-induced ground displacements.

A vast amount of literature exists on the calculation of displacements and stresses in a half-space with different types of theoretical inhomogeneity. In this paper, two types of idealizations are considered for inhomogeneity in the ground and the predictions for the surface displacements are used in the wind-ground model. Kassir (1970), Booker et al. (1985) and Oner (1990) considered an idealized elastic half-space in which the shear modulus or Young's modulus increase with a power of depth and Poisson's ratio remains constant. The analytic deformation response of this model due to a vertical surface load is used in the original wind-ground equation and the results are compared with the previous study. Yue et al. (1988), Ernian (1989) and Pan et al. (2007) idealized the ground as a layered half-space made up of elastic layers laying over an elastic isotropic half-space. In order to simplify the modeling process, we consider a single elastic layer over an elastic homogeneous half-space as our layered ground. Since there is no closed form analytic solution for the deformations of our model, a similar finite element model is built in Comsol-Multiphysics®. We apply an interpolation function of the computed data points by Comsol to the wind-ground model. Finally, we compare new and previous results and discuss the capability of the wind-ground measurements in studying near-surface ground.

In this study, we replace the homogeneous half space model with theoretical non-homogeneous models in order to drive the predictions closer to reality. Comparison between the homogeneous and non-homogeneous predictions provides insight into the use of wind induced seismic to study near-surface ground properties.

Wind-Ground Coupling Theory

Naderyan et al. developed a wind-ground coupling theory by combining following theories: the ground (half-space) deformations due to surface loads (Landau and Lifshitz, 1986), the wind pressure spectrum at the ground surface from the measured wind velocity profile (Kraichnan, 1956, Raspet et al., 2008, Yu et al., 2011), and the distribution of sources associated with wind turbulence over the ground surface applied by the wave number-dependent correlation function of the wind noise in the downwind and crosswind directions (Shields, 2005). Combining these theories leads to following equations for the power spectra of the vertical and horizontal components of the wind-induced ground surface displacements due to the vertical pressure (Naderyan et al., 2015).

$$\begin{aligned}|U_r(k)|^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u_r(r)u_r(r')p_z{}^2(k) \\ \exp(-\alpha\frac{k}{2\pi}|x-x'|)\cos(k|x-x'|)\exp(-\beta\frac{k}{2\pi}|y-y'|)\,dxdx'dydy'\end{aligned} \tag{1a}$$

$$\begin{aligned}|U_z(k)|^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} u_z(r)u_z(r')p_z{}^2(k) \\ \exp(-\alpha\frac{k}{2\pi}|x-x'|)\cos(k|x-x'|)\exp(-\beta\frac{k}{2\pi}|y-y'|)\,dxdx'dydy'\end{aligned} \tag{1b}$$

where U_r and U_z are horizontal and vertical displacements at the observation point of the pressure, k is wind wave number, υ and E are Poisson's ratio and Young's modulus, respectively, (x, y) and (x', y') are coordinates of two random points on the ground surface with respect to the observation point of the pressure, r and r' are $\sqrt{x^2+y^2}$ and $\sqrt{x'^2+y'^2}$ respectively, $p_z{}^2$ is the Power Spectral Density (PSD) of wind pressure on the ground, α and β are two constant numbers based on the wind velocity.

Homogeneous Ground

In the study by Naderyan et al. (2015), the expressions for the ground deformation, is given by Eq. 2. The ground is assumed as a homogeneous linearly elastic medium bounded by an infinite plane on one side (half-space). The vertical and radial surface deformations of the model due to a normal surface load, as a function of radius from a delta function force source are (Landau and Lifshitz, 1986):

$$u_r(r) = \frac{(1+\nu)(1-2\nu)}{2\pi E}\frac{1}{r}F_z \tag{2a}$$

$$u_z(r) = \frac{(1+\nu)(1-\nu)}{\pi E}\frac{1}{r}F_z \tag{2b}$$

where r is the radial distance from the load's center, ν and E are Poisson's ratio and Young's modulus, respectively, and F_z is the vertical force. Eq. 1 can be completed with these expressions and numerically calculated over truncated ranges.

Inhomogeneous Ground

Continuously Increasing Rigidity

Oner (1990) considered an idealized elastic half-space in which the shear modulus increases with an arbitrary power of depth and Poisson's ratio is constant. The horizontal surface displacement of this model due to a vertical point force equals to zero because of zero shear modulus at the surface. The vertical displacement is as follow:

$$G = G_0 z^n \tag{3a}$$

$$u_z = \frac{F_z}{4\pi G_0}\frac{1}{(n+1)r^{(n+1)}} \tag{3b}$$

where G is shear modulus, z is the depth with the positive direction toward the half-space, u_z is the vertical displacement, F_z is the vertical point force, r is the radial distance from the load's center, and the following restrictions apply; 1/3 < n < 2/3 and $n = (1/\nu) - 2$. Fig.1a shows comparison of ground surface deformation predicted using Eq. 3 and Eq. 2 with $G_0 = 10^7$ due to equal vertical loads ($F_z = 100N$). The vertical surface displacements for the homogeneous ground and three different inhomogeneous grounds in which shear modulus increases at different rates as a function of depth are shown in Fig. 1a.

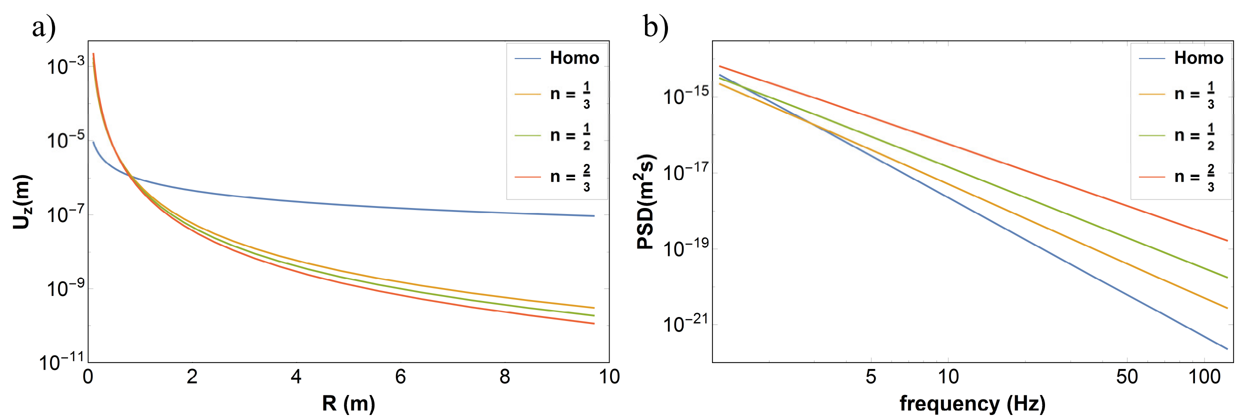

Figure 1: (a) Vertical surface displacements and (b) their power spectral density for homogeneous and inhomogeneous half-space models.

In the nearfield, inhomogeneous models displacements are greater than homogeneous model. It is consistent with the zero value of shear modulus at the surface used in the inhomogeneous model. The surface displacement decreases faster with increasing distance from the source as the power of shear modulus function increases. The deformation of the ground surface are equal for the homogenaous and inhomogeneous models at a distance of 1m corresponding to the depth at which the shear modulus is equal for all of them. The predicted wind driven surface deformation for the homogeneous and inhomogeneous grounds are shown in Fig. 1b. The slope of the lines decreases as the rigidity increases faster with depth. It shows that the influence of gradually changing rigidity with depth is manifested in the slope of the PSD wind coupling results.

Layered Ground

To our knowledge, there is no closed form solution for the deformation response of a layered half-space subjected to a normal static surface load. Therefore, a model simulating an elastic layer over a homogeneous half-space subjected to a vertical static surface load is calculated in Comsol. The soil and source properties are listed in Table 1. Fig. 2a and 3a compare the surface deformations for different top layer thickness. Two homogeneous half-space models are considered; the "Soft-Homo" model having the lower Young's modulus and "Hard-Homo" model having the higher Young's modulus. In Eq. 2, both vertical and horizontal displacements of the homogeneous half spaces (hard and soft) are proportional to $1/r$. Hence, they are parallel with fixed difference (blue and purple lines in Fig. 2a and 3a). For the layered models, the displacements correspond to those of Soft-Homo in the nearfield and to the displacements of Hard-Homo in the far field. The transition occurs at distances closer to the source as the layer thickness decreases.

Table 1: Simulation Parameters

Vertical Force (N)	Load Radius (m)	Young's Modulus (Pa)		Poisson's Ratio	Density (kg/m^3)
		Top Layer	Bottom Half-space		
1000	0.05	0.5×10^8	1×10^8	0.34	2000

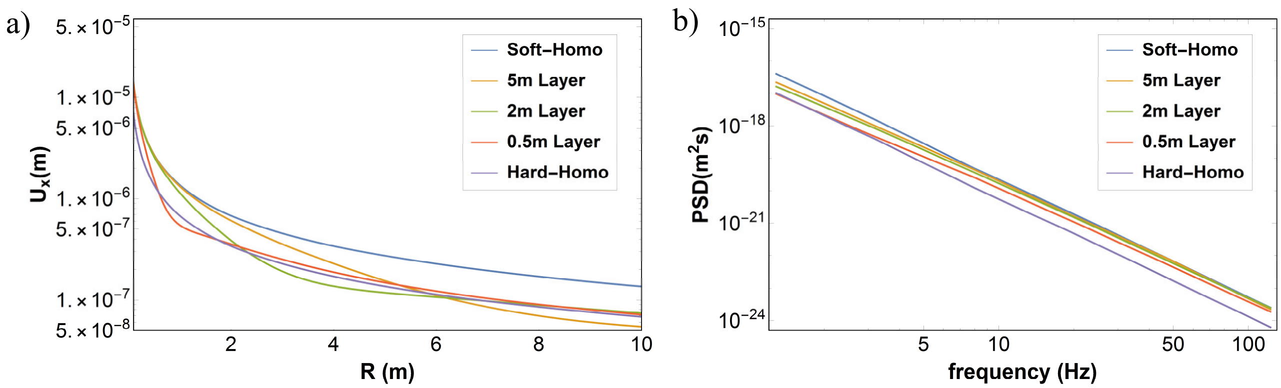

Figure 2: (a) Horizontal surface displacements and (b) their power spectral density for homogeneous and layered half-space models.

The wind-driven deformation of the ground are shown in Fig. 2b and 3b. An interpolation function based on finite number of points of the lines in Fig. 2a and Fig. 3a are used in order to generate a numerical response function of radial distance from the source. The response functions are substituted in the wind-ground equations (Eq.1) and numerically calculated. At low frequencies, the 2-layered models behavior is closer to a homogeneous half space with properties of the bottom layer. As the frequency increases, the layered model become closer to a homogeneous half space with properties of the top layer. It is losing sensitivity to the harder bottom half space. This transition takes place at lower frequencies for the thicker top layers. This observation agrees with the general behavior of Rayleigh waves where, the longer wavelengths penetrate deeper and are sensitive to deeper properties of the ground whereas, shorter wavelengths represent more shallow surface properties.

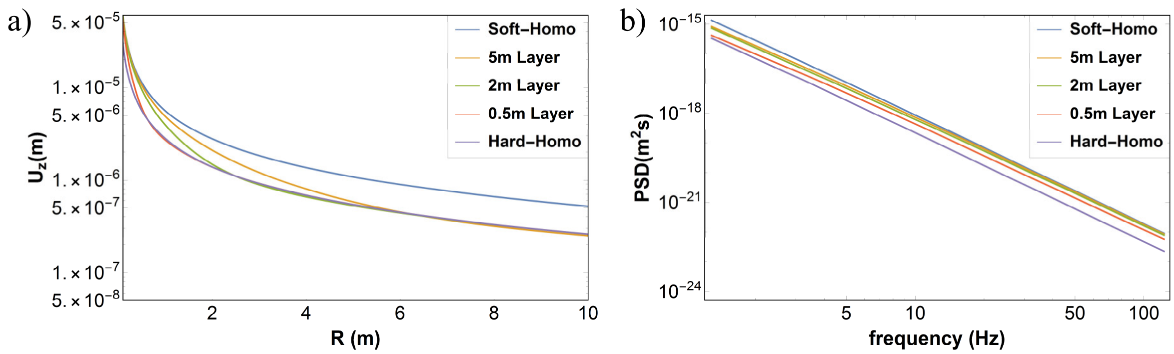

Figure 3: (a) Vertical surface displacements and (b) their power spectral density for homogeneous and layered half-space models.

Conclusion

The wind-ground theory propose a theoretical model in order to transfer the driving pressure perturbations on the ground surface to the ground vibrations. In the previous study, the ground was modeled as an elastic homogeneous half-space. This paper investigate the same theory for inhomogeneous grounds modeled by two common types of idealization for the ground inhomogeneity. First, we consider a ground with gradually increasing shear modulus. A theoretical prediction for this type of inhomogeneity by Oner is used instead of the elastic response of the homogeneous half-space in original wind ground equations. The influence of this change can be seen on the rate of change of PSDs with frequency. The PSD of the displacements decreases slower with frequency as the rigidity increases faster with depth.

Next type of theoretical inhomogeneity is modeled in Comsol by a soft elastic layer over a harder half space in terms of Young's modulus. The displacements of the simulation due to a vertical surface load at a series of points on a radial line are used to find an appropriate response function because a closed form function is needed in the wind-ground equations. The simulation results show a transient behavior from the response of the half space with top layer properties in the nearfield to the response of the half space with bottom layer properties in the far field. This transition occurs at closer distance to the source for thinner top layers. The wind-induced layered ground motion predictions behave similar to a half space built of bottom layer material at low frequencies and converge to the behavior of a half space built of top layer material at high frequencies. The rate of this transition or the slope of the lines relative to frequency can be used as an implication of the top layer thickness.

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