Wind Induced Ground Motion

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WIND INDUCED GROUND MOTION

A Thesis
submitted in partial fulfillment of requirements
for the degree of Master of Science
in the Department of Physics and Astronomy
The University of Mississippi

by

VAHID NADERYAN

April 2015
ABSTRACT

Wind noise is a problem in seismic surveys and can mask the seismic signals at low frequency. Development of practical solutions to this problem must be based on a good understanding of the mechanism of the wind-ground coupling. This thesis investigates the driving pressure and shear stress perturbations on the ground surface associated with wind-induced ground motions. A prediction of the ground displacements spectra from the measured ground properties and predicted pressure and shear stress at the ground surface is developed. Field measurements are conducted at a site in Marks, MS, having a flat terrain and low ambient seismic noise under windy conditions. Multiple triaxial geophones are deployed at different depths to study the wind-induced ground vibrations as a function of depth and wind velocity. Furthermore, a test experiment including a vertical and a horizontal mass-spring apparatus is designed to exert controlled normal pressure and shear stress to the ground. The match of the predictions and the measurements of the test experiment verify the linear elastic rheology and the quasi-static displacements assumptions of the model. Comparison of the predicted wind induced ground displacements spectra with the measured spectra shows good agreement for the vertical component but a significant underprediction for the horizontal components. The results indicate that the existing shear stress models significantly underestimate the wind shear stress at the ground surface and the amplitude of the fluctuation shear stress must be of the same order of magnitude of the normal pressure. This result might be useful for estimating ground surface shear stress under environmental flows in
studies of soil erosion and sediment transport. Measurement results show that mounting the geophones flush with the ground provides a significant reduction in wind noise on all three components of the geophone. Further reduction in wind noise with depth is small for the depths up to 40 cm.
DEDICATION

This thesis is dedicated to my parents,

Fereydoon Naderyan and Molouk Bazgir
ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisors, Dr. Richard Raspet and Dr. Craig Hickey, for their excellent guidance, immense knowledge, caring, patience, and for providing me with an excellent atmosphere for doing research. I am grateful to their insight and wisdom throughout all of the stages of this work. I am also deeply grateful to Dr. Luca Bombelli, for serving on the thesis committee, and for his strong support and guidance in the past three years. I would also like to express my gratitude to Jeremy Webster, who has given me numerous instructions and help in the past two years.

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CHAPTER 1
INTRODUCTION AND LITERATURE SURVEY

1.1: INTRODUCTION

Wind noise significantly limits seismic measurements and can obscure seismic signals sensed by geophones and other seismic sensors. Wind turbulence over the ground generates pressure and shear stress distributions at the ground surface that result in deformation of the ground. These wind-induced ground deformations are measured by seismic sensors.

The main purpose of this thesis is to develop and gain a quantitative understanding of the coupling between the wind and the ground. Understanding the physics of this coupling phenomenon is necessary for the development of practical solutions to the problem of wind noise on seismic sensors. Current understanding is limited to observational and qualitative conjectures for particular cases. Section 1.2 reviews previous works that study the wind noise interaction with seismic sensors. There is no theory available to predict ground displacements due to the wind coupling. There are no quantitative and testable physical models to calculate displacements in the ground from the measured velocity fluctuations outdoors.

Chapter 2 develops a theory of wind-induced ground displacements. First, the driving pressure perturbations on the ground surface associated with wind-induced ground motions is investigated. Yu (2009) developed a model to predict the power spectrum of wind turbulent pressure fluctuations at the ground surface using the wind velocity spectrum. In this work, Yu’s
model is used to calculate the pressure power spectrum at the ground surface. This model has been verified by measurements of the pressure at the ground surface.

The deformation of the ground associated with the wind derived surface forces are modeled assuming an infinite half-space elastic medium subjected to a distribution of point forces at the surface. This solution, measured ground properties, wind pressure and shear stress at the air-ground interface, and the results for wind noise correlations (Shields, 2005) are employed to predict the displacement amplitudes of the horizontal and vertical ground motions as a function of depth.

Chapter 3 describes the field surveys and data analysis. The measurements were acquired at a site having a flat terrain and low ambient seismic noise under windy conditions. Multiple 3-Component (3-C) geophones were deployed at different depths to study the induced ground displacements as a function of depth.

Chapter 4 presents the results and compares predictions of the power spectrum of the ground displacements to geophone measurements. It will be shown that for the vertical displacement, the prediction and measurement match very well. The model, however, underestimates the horizontal components of the displacement. A controlled test measurement is designed and conducted to verify the ground motion model. The results show that the ground motion measurements can be used to measure the wind shear stress at the surface and indicate that the fluctuating shear stress is much larger than expected. Application of this method indicates that the magnitude of the wind shear stress fluctuations at the rough ground surface must be similar to the pressure spectrum magnitude. To understand the influence of each input parameter on the ground displacements a sensitivity analysis is performed. Chapter 5 discusses the main results and conclusions.
1.2: LITERATURE SURVEY

The effect of wind noise on seismic measurements has been the subject of many investigations. A review of the literature is helpful to gain insight for subsequent research. For convenience, the review will be grouped into four areas: wind noise on geophones, sound-wave noise generated by seismic sources, wind noise on very long period seismograms, and wind noise effects on the horizontal to vertical spectral ratio (HVS)

a) Wind noise on geophones

Most investigations of wind noise on geophones (except Withers, Aster, Young, and Chael, 1996) study the wind noise on the geophones during a seismic survey, and none of them record the geophone data while only wind is blowing in the absence of other seismic sources.

Withers et al. (1996) used a 1500-m cased borehole in New Mexico to study high frequency (1 Hz to 60 Hz) seismic noise characteristics. They deployed a 3-C set of surface sensors along with a vertical borehole seismometer at depths of 5.0, 43.0, and 85.0 m. Their data shows a correlation between wind speed and seismic background noise. The minimum wind speed to increase the seismic background noise was 3.0 m/s at the surface, 3.5 m/s at 43.0 m in depth, and 4.0 m/s at 85 m in depth. Noise was reduced by 20 dB at 43.0 m depth for frequencies greater than 10 Hz. For frequencies from 5 to 15 Hz this reduction increased with frequency from about 0 to 20 dB. Based on their measurements, it was concluded that the signal-to-noise ratio (SNR) can be improved by as much as 20 to 40 dB between 23 and 55 Hz and 10 to 20 dB between 10 and 20 Hz, by deploying at a depth of 43.0 m rather than at the surface. They also conclude that only minor additional reductions occurred between 43.0 and 85.0 m depth. They suggested a 40.0 m deployment depth is adequate for wind noise reduction at similar sites. It should be noted that a large noise reduction was observed at the 5.0 m depth.
Bland and Gallant (2001; 2002) studied the effect of wind noise on 3-C geophones. Geophones were deployed at the surface and at different depths between 5 cm to 50 cm. The seismic recorder was configured to record 512-ms long traces using a sample interval of 0.250 ms. The measurements display higher horizontal wind noise amplitudes than the vertical component on the same geophone. Based on their measurements, the signal to noise ratio (SNR) improves by 3 dB for every 10 cm of geophone depth, and the vertical elements are about 4 dB less sensitive to wind noise than the horizontal elements. For winds from 17.5 km/h to 22.5 km/h (4.86 m/s to 6.25 m/s) it was determined that the SNR improves by 3 dB for every 3 km/h (0.83 m/s) decrease in wind speed. They conclude that one should bury geophones an additional 10 cm for every 3 km/h (0.83 m/s) increase in wind speed.

The experiment was subject to a number of sources of error: The average wind speed was measured over a period of several seconds, while the seismic records were about half a second. Another important source of error was the variation in noise sensitivity from channel to channel in their measurements. Also, they mention very low levels of noise at frequencies below 20 Hz, but this may be because the sensors are 20-Hz geophones with very low gains below 20 Hz.

b) Sound-wave noise generated by seismic source

Air waves generated from seismic sources travel at the speed of sound in air (about 340 m/s). These waves are considered noise on the geophones. Studying this effect is not the subject of the current thesis, but since both wind and sound wave noises are air-associated noise and some similarities exist between them, some papers in the literature of sound-wave noise on geophones are reviewed here. The papers reviewed here do not address the problem of wind noise on geophones, although they study the effect of sound waves generated from seismic sources on the geophone.
Stewart (1998) studied the air blast recorded on 3-C geophones, and on a microphone in proximity to the geophone. The triaxial geophone and microphone both had band pass responses from 2 Hz to 250 Hz. Cross-correlation of the geophone velocity data and the microphone pressure data showed that the geophone and microphone signals are about 180° out of phase. This finding led Stewart to try adding the signals as a means of reducing the air noise on the geophone.

Dey, Stewart, Lines, and Bland (2000) attempt to use microphone recordings to suppress air-wave noise on geophone data. Their study use a seismic line consisting of a series of four-component (3-C 10 Hz geophones and a Panasonic WM-54BT electret condenser microphone with a frequency range of 20 to 16000 Hz) in the Pike’s Peak heavy oil field, Saskatchewan, Canada. The microphone was placed close to the geophone and the data were recorded at a 2-ms sample rate for a total record length of 20 s. A 90° phase mismatch was found between the microphone data and the geophone data. This is in contradiction to the 180° phase mismatch reported by Stewart (1998). As a preliminary investigation they subtracted the signal from the microphone data rotated by + \pi/2 and added the signal by the microphone data rotated by − \pi/2 as an attempt to filter the geophone record. Based on the results it was concluded that this simple subtraction or addition process is not an ideal filter.

Alcudia and Stewart (2008) presented two cases of microphone applications in seismic explorations. The first case summarizes some preliminary results from a dual-sensor experiment (microphone – 3C geophone) aimed at attenuating some of the ambient noise from the geophone records. A correlation between the air noise recorded by the microphone and the geophone noise is observed. In the second case they introduce some air pressure and ground motion signal relationship results from a dynamite explosion. The cross correlation of the signals suggests that there is a strong negative correlation.
c) **Wind noise on very long period seismograms**

Sorrells (1971) assumed that the wind-induced pressure field is a plane wave which propagates at the speed of the wind and derived a formula for the seismic response of the earth, which is modeled as a homogeneous, isotropic, elastic, half-space. The numerical studies indicate that the vertical displacements generated by these waves can contribute significantly to the long-period noise field. The results show that the seismic disturbances created by plane pressure waves decay rapidly with depth. Pressure waves also create significant tilt noise on long-period horizontal seismograph systems located at or near the surface regardless of the ground type. Tilt is the horizontal derivative of the vertical displacement.

Sorrells, McDonald, Der, and Herrin (1971) experimentally study the local atmospheric pressure field and the seismic noise fields on vertical seismographs in the period range 20 to 100 seconds, both on the surface of the ground and in a mine at a depth of 183 m. They measure and compare the seismograph’s response during calm periods (3.1 m/s), windy periods (7.8 m/s), and also for acoustic waves passing over the ground. They conclude that the earth motions caused by the turbulent atmospheric pressure field can contribute substantially to the seismic noise recorded at the surface in this period range, and most of this noise can be reduced by placing the detector several hundred meters below the surface. The difference between the noise levels recorded at the two depths is approximately 10 dB.

Savino and Rynn (1972) study propagating air waves recorded by vertical seismographs in the period range of 30 s to 375 s. They conclude that the sensitivity of the high-gain seismographs to air waves is the result of the instruments’ response to ground motion statically induced by atmospheric loading rather than to variations in the buoyant force. The method of Sorrells (1971a) was used to calculate the ground displacements and tilts associated with the passage of a plane
wave of air pressure over a homogeneous elastic half-space. A comparison of the calculations with the measurements shows that the atmosphere couples directly to the ground by quasi-static loading.

Sorrells and Goforth (1973) studied low frequency (< 0.1 Hz) earth motion generated by slowly propagating partially organized pressure fields. They assume the homogeneous pressure field is a random process which is stationary in time. The transfer functions relating earth motion and atmospheric pressure variations for poorly correlated fields were very similar to those calculated for plane waves. The correlation studies show that the coherence between pressure variations and ground motion depends on the correlation structure of the atmospheric pressure and the ground response.

Beauduin, Lognonné, Montagner, Cacho, Karczewski, Mornad (1996) investigated the effect of barometric pressure at very low frequency (0.1 mHz to 0.01 Hz) on a seismic vault at two different stations. It was observed that seismic data were strongly correlated to atmospheric pressure data at the first station. However the correlation was lower, but still significant, at the second station. These good correlations were not observed every day and depended on the atmospheric conditions. A transfer function was calculated to minimize the coherence between the observed seismic data and the atmospheric pressure field. The higher the seismic data were correlated to pressure, the better this method removed the atmospheric pressure noise. Consequently, they suggest deployment of microbarometers in the global long-period seismic stations.

Kroner, Jahr, Kuhlmann, and Fischer (2005) studied barometric pressure induced signals on horizontal seismometer and strain meter records for the Moxa observatory by means of finite element (FE) analysis. For modelling, a linear, elastic rheology and a quasi-static approximation
were used. They include the main topographic elements of the observatory surroundings such as hill flanks and a valley in an area of approximately 2.5 km². The gallery in which a long-period STS-1 seismometer and two quartz tube strainmeters were installed was modeled. The influence of a uniform pressure load, the effect of wind-induced pressure, and the passage of pressure fronts were investigated between 0.0002 and 0.0125 Hz. To include wind-induced pressure in the numerical model they assumed that this pressure leads to an additional uniform pressure on all model surfaces. It was shown that all three pressure scenarios can lead to significant tilt and strains affecting the seismometer and strainmeter records.

**d) Horizontal to vertical spectral ratio (HVSR)**

Cara, Giulio, and Rovelli (2003) analyzed the seismic noise recorded by broad-band stations in the middle of and around the Colfiorito plain in a firm site and a soft site in the frequency band 0.1 Hz to 10 Hz. The amplitude of horizontal to vertical spectral ratio (HVSR) and the correlation between long-term variations of seismic noise and amount of precipitation, wind speed, and atmospheric pressure from a meteorological observatory about 35 km away from Colfiorito was studied. It was found that wind speed best matches the low frequency disturbances at both the firm and soft sites. The effect of wind on seismic noise became significant as soon as the wind velocity exceeded 5 m/s.

Mucciarelli, Gallipoli, Giacomo, Nota, and Nino (2005) analyzed the influence of local wind on microtremor measurements. The variation in the horizontal to vertical spectral ratio (HVSR) was studied at a permanent 3-C seismological station under various wind conditions using a 1-Hz seismometer sheltered in a concrete box 1.5 m below the ground surface. If the sensors were well protected from direct wind, the effect of wind speed up to 30 km/h (8.3 m/s) was to increase the amplitude of all the components of seismic noise in the band 0.1 Hz to 10 Hz so that
there were no changes in HVSR. An experiment under controlled condition in a wind room equipped with a laser particle image velocimeter (PIV) was also conducted to analyze the effect of increasing wind speed on geophones wired to an external acquisition unit and an all-in-one unit. The experiment demonstrated that HSVR can be adversely affected by wind interacting with sensors and wires. Numerical modeling was undertaken in which they simulated wind on the sensors by adding random white noise to the sensor components.

e) Summary

The literature survey shows that there is a need for theoretical models for the mechanism of the wind induced ground vibrations. Literature applicable to wind-ground coupling studies is very limited. There is an agreement on using elastic rheology and quasi-static assumptions for ground modeling. There is also an agreement on the significance of the wind coupling effects on the horizontal and vertical seismic sensors and increase of the noise with wind velocity increase. However, there is a wide variation in measurements of the ground displacements as a function of depth of burial and wind velocity. None of the previous works has accounted for the effect of shear stress at the ground surface on the wind-induced ground displacements. This thesis seeks to develop an effective theory to predict ground displacements associated with turbulent wind outdoors, and to introduce experiments to study wind noise on geophones.
2.1: WIND PRESSURE AT THE GROUND SURFACE

To develop a theoretical model for wind-induced ground motions, requires an investigation of the driving forces over the ground surface. Wind turbulence generates pressure and shear stress distributions at the ground surface. In this section, Yu’s (2009) theoretical model for the prediction of the wind pressure at the ground surface is introduced and discussed.

Kraichnan (1956) investigated the relation between turbulent boundary layer flow and pressure fluctuations at a boundary surface. George, Beuther, and Arndt (1984) investigated pressure spectra in a turbulent free shear flow and compared calculations of the turbulence-turbulence interaction pressures and turbulence-mean shear interaction pressures to measurements of the pressure fluctuation spectrum. George et al. (1984) assume that the velocity spectrum follows a one-dimensional von Karman spectrum form. Raspet, Yu, and Webster (2008) found that a slight revision to the von Karman spectrum form provides a good fit to the measured wind turbulence spectrum outdoors.

Yu (2009) used Kraichnan’s mirror flow model of anisotropic turbulence and the spectral model from George et al. (1984) to develop a theory for the prediction of the pressure fluctuation spectrum at the ground surface. Yu, Raspet, Webster, and Abbott (2011) show that the turbulence-shear interaction pressure fluctuation is the dominant source of wind noise at the ground surface,
compared to the turbulence-turbulence interaction pressure fluctuation. They developed a model for the calculation of wind pressure fluctuations at the ground surface from the measured atmospheric turbulence spectra and wind velocity, for level grass covered ground.

In the present study, the longitudinal wind velocity spectrum along the direction of flow is fit to the von Karman spectral form modified by Raspet et al. (2008) as an appropriate turbulence spectrum fit:

\[
F_{11}^{1}(k_1) = \frac{C}{[1 + (k_1 \lambda)^2]^{5/6}},
\]  

(2.1)

where \(C\) and \(\lambda\) are fit parameters. \(k_1\) is the wave number in the direction of flow; \(k_1 = \frac{2\pi f}{U_c}\) (the Taylor frozen turbulence hypothesis), where \(f\) is the measured frequency and \(U_c\) is the convection velocity. Figure 2.1 shows the coordinate system used for wind throughout this thesis. \(x_1\) is the longitudinal direction along the flow, \(x_2\) is the vertical direction and \(x_3\) is the transverse direction.

![Coordinate system for wind.](image)

**Figure 2.1. Coordinate system for wind.**

In the surface layer, the relation between the outdoor wind velocity and height is approximately logarithmic (Panofsky and Dutton, 1984). The mean wind velocity for a logarithmic profile satisfies the form
\[ U_1(x_2) = a \ln \left( \frac{x_2}{x_0} \right), \quad (2.2) \]

where \( a \) is friction velocity \( (u_*) \) divided by the von Karman constant \( (\kappa) \) and \( x_0 \) is the roughness length of the surface. The corresponding mean velocity gradient is

\[ s(x_2) = \begin{cases} 
\frac{a}{x_2}, & x_2 \geq x_0 \\
0, & x_2 < x_0 .
\end{cases} \quad (2.3) \]

The average wind velocity is usually assumed to be zero under the roughness length \( (0 \leq x_2 < x_0) \). Finally, the predicted pressure fluctuations spectrum due to the turbulence-shear interactions at the surface is given by:

\[
|p(0, k_1)|^2 = \frac{440a^2 \rho^2 k_1^2 C \lambda^4}{9\pi} \int_0^\infty \int_0^\infty \frac{dk_2 dk_3}{[1 + (k\lambda)^2]^{17/6}} \\
\times \left[ \int_{x_0}^\infty e^{-kx_2} \sin(k_2 x_2) \frac{x_2}{x_2} dx_2 \times \int_{x_0}^\infty e^{-k'x'_2} \sin(k_2 x'_2) \frac{x'_2}{x'_2} dx'_2 \right], \quad (2.4)
\]

where \( \rho \) is the density of air.

In Yu (2009) and Yu et al. (2011), the results of the prediction model were compared to measurements of wind noise on a flush microphone in a surface beneath a foam covering. The theory provided reliable predictions in the low and middle wave number range. At high wave number, the model slightly underestimates the pressure fluctuation level.

In Equations (2.2), (2.3), and (2.4), \( a = \frac{u_*}{\kappa} \), where \( u_* \) is the friction velocity and \( \kappa = 0.41 \) is the von Karman constant. Yu (2009) and Yu et al. (2011) use multiple anemometers at different heights to measure the wind velocity profile and determine the friction velocity. In this thesis only one anemometer is employed, so the velocity profile cannot be directly measured. Instead, the friction velocity is calculated from the measured three-dimensional wind spectrum (Garratt, 1994):
\[ u^4_* = \langle u'_1(t)u'_2(t) \rangle^2 + \langle u'_3(t)u'_2(t) \rangle^2, \]  

(2.5)

where \( u'_1(t), u'_3(t), \) and \( u'_2(t) \), are the fluctuating parts of the velocity components. In order to get \( u'_1(t), u'_3(t), \) and \( u'_2(t) \), the coordinate system is rotated so that in the new reference frame the mean of the vertical component, \( u'_2(t) \), becomes zero. Then Reynolds decomposition yields:

\[
\begin{cases} 
    u_1(t) = U_1 + u'_1(t) \\
    u_3(t) = U_3 + u'_3(t) \\
    u_2(t) = u'_2(t),
\end{cases}
\]  

(2.6)

where \( U_1 \) and \( U_3 \) are the mean values of the horizontal velocity components.

Yu’s prediction for the pressure fluctuation spectrum at the ground surface, Equation (2.4), is used to predict the spectrum of the pressure fluctuations at the ground surface. An ultrasonic research anemometer placed 1.0 meter above the ground surface collected the turbulence spectrum data. The turbulence spectrum data was used to determine the values for the fit parameters, \( C \) and \( \lambda \), by fitting the measured velocity Power Spectral Density (PSD) to Equation (2.1). Finally the roughness length, \( x_0 \), is calculated from Equation (2.2) to be used in the calculations of the pressure fluctuation spectrum, knowing the mean wind velocity, \( U_1(x_2) \), and \( \alpha \). Details of the PSD calculation of the wind velocity measurement and the procedure to obtain \( C \) and \( \lambda \) are explained in Section 3.4.

Spectral data and measured coefficients are used to predict the power spectral density of the pressure fluctuations at the ground surface (Equation (2.4)). More experimental details of these measurements and samples of calculations are described in Chapter 3.
2.2: DEFORMATION IN AN INFINITE ELASTIC HALF-SPACE CAUSED BY A SURFACE POINT FORCE

The deformation of an elastic medium bounded by an infinite plane on one side, i.e., occupying a half-space, due to forces applied to its free surface can be determined. The free surface of the elastic medium is taken as the xy plane, and the medium is in the positive side of the z. The equation of equilibrium of the medium has the form

\[ \nabla(\nabla \cdot \mathbf{u}) + (1 - 2\sigma)\Delta \mathbf{u} = 0, \quad (2.7) \]

where \( \sigma \) is Poisson’s ratio of the medium, and \( \mathbf{u} \) is the 3-component displacement vector. Since the unit outward normal vector is in the negative z direction, the boundary conditions which must be satisfied at the free surface of the medium are

\[ \sigma_{iz} = -P_i, \quad (2.8) \]

where \( \sigma_{iz} \) are components of the stress tensor inside the medium. \( P_i \) are components of the external forces per unit area applied to the surface and are functions of \( x \) and \( y \).

Assuming that the concentrated force \( \mathbf{F} \) is applied to a very small area so it can be regarded as a point and applying the boundary conditions, the resulting equations for the displacements are (Landau and Lifshitz, 1986):

\[
\begin{align*}
\mathbf{u}_x &= \frac{1 + \sigma}{2\pi E} \left\{ \left( \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} \right) \frac{x^2}{r^2} F_x \right. \\
&\quad \left. + \left( \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} xy \right) \frac{xz}{r^3} - \frac{(1 - 2\sigma)x}{r(r + z)} F_z \right\} \\
\mathbf{u}_y &= \frac{1 + \sigma}{2\pi E} \left\{ \left( \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} \right) \frac{y^2}{r^2} F_y \right. \\
&\quad \left. + \left( \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} xy \right) \frac{yz}{r^3} - \frac{(1 - 2\sigma)y}{r(r + z)} F_z \right\} \quad (2.9a)
\end{align*}
\]
\[ u_y = \frac{1 + \sigma}{2\pi E} \left\{ \left( \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} \right) F_x \right. \\
+ \left[ \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{(2r(\sigma r + z) + z^2)}{r^3(r + z)^2} y^2 \right] F_y \right. \\
+ \left[ \frac{yz}{r^3} - \frac{(1 - 2\sigma)y}{r(r + z)} \right] F_z \right\} \] (2.9b)

\[ u_z = \frac{1 + \sigma}{2\pi E} \left\{ \left( \frac{1 - 2\sigma x^2}{r} + \frac{z}{r^3} \right) F_x + \left[ \frac{(1 - 2\sigma)z}{r^2(r + z)} \right] y \right] F_y \\
+ \left[ \frac{2(1 - \sigma)}{r} + \frac{z^2}{r^3} \right] F_x \right\} \] (2.9c)

where \( \sigma \) is Poisson’s ratio, \( E \) is Young’s modulus of the ground, and \( r = \sqrt{(x^2 + y^2 + z^2)} \).

The solutions at the surface given by setting \( z = 0 \) above are of special interest:

\[ u_x = \frac{1 + \sigma}{2\pi E} \left\{ \left( \frac{2(1 - \sigma)}{r} + \frac{2\sigma x^2}{r^3} \right) F_x + \left[ \frac{2\sigma xy}{r^3} \right] F_y + \left[ \frac{(1 - 2\sigma)x}{r^2} \right] F_z \right\} \] (2.10a)

\[ u_y = \frac{1 + \sigma}{2\pi E} \left\{ \left[ \frac{2\sigma xy}{r^3} \right] F_x + \left( \frac{2(1 - \sigma)}{r} + \frac{2\sigma y^2}{r^3} \right) F_y + \left[ \frac{(1 - 2\sigma)y}{r^2} \right] F_z \right\} \] (2.10b)

\[ u_z = \frac{1 + \sigma}{2\pi E} \left\{ \left[ \frac{(1 - 2\sigma)x}{r^2} \right] F_x + \left[ \frac{(1 - 2\sigma)y}{r^2} \right] F_y + \left[ \frac{2(1 - \sigma)}{r} \right] F_z \right\} \] (2.10c)

**2.3: WIND-GROUND COUPLING THEORY**

The prediction of the source distribution over the surface due to wind pressure was introduced in Section 2.1. The theory for the displacements in a half-space infinite elastic medium due to a surface point force was introduced in Section 2.2. These two theories are combined in
this section by means of the turbulence correlation functions of the wind to develop a predictive theoretical model for wind-induced ground displacements.

In this model the ground is modeled as an infinite half-space elastic medium, as described in the previous section. The wind excitation over the ground surface is assumed to be a slowly moving fluctuation of pressure and shear stress. Very little wave energy is induced. Since the accelerations are small, the ground displacements are mainly quasi-static. This is very different from rapidly moving acoustic excitations.

Consider the solutions for the displacement of points in the medium due to a point force $F$ applied to the surface. If the origin is the point where the force is applied, the effect of this force is the same as that of surface stresses given by $P = F\delta(x)\delta(y)$. The solution for any stress distribution $P(x,y)$ can be obtained from the solution for a concentrated point force. If the displacement due to the action of a concentrated force $F$ applied at the origin is

$$u_i = G_{lk}(x,y,z)F_k,$$  \hspace{1cm} (2.11)

then according to Green’s theory the displacements caused by forces $P(x,y)$ is given by the integral

$$u_i = \iint G_{lk}(x-x',y-y',z)P_k(x',y')dx'dy'.$$  \hspace{1cm} (2.12)

Here $G$ is the Green’s tensor for the equations of equilibrium of a semi-infinite elastic medium. From Equations (2.9), for the point of application of the force at $(x, y, 0)$ and the point of observation at $(0, 0, z)$, $G$ has the form:
\[ G(x, y, z) = \left( \frac{1 + \sigma}{2\pi E} \right) x \]  
\[ \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{(2\sigma r + z + z^2)}{r^3(r + z)^2} x^2 \]
\[ \frac{(2\sigma r + z + z^2)}{r^3(r + z)^2} xy \]
\[ \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{(2\sigma r + z + z^2)}{r^3(r + z)^2} y^2 \]
\[ \frac{1}{r} \frac{1}{r^3} (1 - 2\sigma)z \frac{r}{r^3} \]

The PSD of the \( i \) component of the displacement at the point \((0, 0, z)\) due to point forces applied at \((x, y, 0)\) and \((x', y', 0)\) is:

\[ |u_i(0, 0, z, k)|^2 = \langle u_i(x, y, 0, k)u_i^*(x', y', 0, k) \rangle. \]  
\[ (2.14) \]

The angular brackets indicate either a large scale space average or a large scale time average. Therefore, from Equations (2.12) and (2.14):

\[ |u_i(0, 0, z, k)|^2 = \]  
\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{ik}(x, y, z)G_{ik}(x', y', z) (P_k(x, y, k)P_k(x', y', k)) dx dy dx' dy'. \]

Hence, the vertical component of the PSD of the displacement is given by

\[ |u_z(0, 0, z, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 x \]
\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] x \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] x' \langle \tau_x(x, y, k)\tau_x(x', y', k) \rangle \right. \]
\[ + \left. \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] y \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] y' \langle \tau_y(x, y, k)\tau_y(x', y', k) \rangle \right. \]
\[ + \left. \left[ \frac{2(1 - \sigma)}{r} + \frac{z^2}{r^3} \right] \left[ \frac{2(1 - \sigma)}{r'} + \frac{z^2}{r'^3} \right] \langle p_z(x, y, k)p_z(x', y', k) \rangle \right\} \int_0^z \int_0^Z \int_0^Z dx dy dx' dy'. \]
The angular brackets indicate a large-scale space average of the forces over the ground surface. It is assumed that the cross-correlations are negligible (Shields, 2005).

Wind pressure and shear stress at the ground surface are called wall pressure and wall shear stress, respectively. Wind wall pressure is the force component normal to the ground surface, per unit area, as applied by the wind on the ground surface. Wind wall shear stress is force component parallel to the ground surface, per unit area, as applied by the wind on the ground surface. In Equation (2.16) $p_z$, $\tau_x$, and $\tau_y$ are the wind wall pressure, downwind wall shear stress, and crosswind wall shear stress, respectively.

In the model, the corresponding correlation functions, $R_{(x-x',y-y')}$, must be considered in order to have a realistic distribution of the source, wind turbulence, over the ground surface. We assume that:

$$R_{(x-x',y-y')} \approx R_{(x-x')} R_{(y-y')}.$$  

(2.17)

Priestley (1965) experimentally verified that this approximation is reasonably accurate. Hence,

$$|u_z(0, 0, z, k)|^2 = \left( \frac{1 + \sigma}{2 \pi E} \right)^2 \times$$

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] x \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] x' \right\} \tau_x^2(k)$$

$$+ \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] y \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] y' \right\} \tau_y^2(k)$$

$$+ \left[ \frac{2(1 - \sigma)}{r} + \frac{z^2}{r^3} \right] \left[ \frac{2(1 - \sigma)}{r'} + \frac{z^2}{r'^3} \right] p_z^2(k) \right\} R_{(x-x')} R_{(y-y')} \, dx \, dy \, dx' \, dy'.$$

Shields (2005), used a three axis orthogonal pressure sensor array to study wind correlation; one vertical arm and two horizontal arms on the ground aligned in downwind and
crosswind directions. The correlation of the pressure and shear stress is assumed to be the same as the wind correlation, because pressure and shear stress spectra are proportional to the wind velocity spectra. The results for the wind noise correlations are used here as turbulence correlation functions of the wind pressure and shear stresses at the surface.

The wavenumber-dependent correlation function of the wind noise in the downwind direction is

\[ R_{(\text{downwind})} = e^{-\alpha \frac{k}{2\pi} |x-x'| \cos(k|x-x'|)}. \]  

(2.19)

The correlation for the crosswind direction is given by

\[ R_{(\text{crosswind})} = e^{-\beta \frac{k}{2\pi} |y-y'|}. \]  

(2.20)

Shields’ (2005) measurements suggested that \( \alpha \) and \( \beta \) over a range of wind velocities (from 4 to 8 m/s) and atmospheric and environmental conditions are approximately 3.2 and 7.0, respectively. He determined that within experimental error and over the limited range of velocities measured, the correlation is independent of wind velocity and the terrain. In this work, it is assumed that pressure and shear stresses have the same correlation behavior as measured by Shields.

Substituting the correlation functions, Equations (2.19) and (2.20), into Equation (2.18):
\[ |u_z(0, 0, z, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] x \right\} \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] x' \tau_x^2(k)
\]

\[
+ \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] y \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] y' \tau_y^2(k)
\]

\[
+ \left[ \frac{2(1 - \sigma)}{r} + \frac{z^2}{r^3} \right] \left\{ \frac{2(1 - \sigma)}{r'} + \frac{z^2}{r'^3} \right\} p_z^2(k) \cdot \]

\[e^{-\alpha z |x - x'|} \cos(k|x - x'|) e^{-\beta z |y - y'|} \, dx \, dy \, dx' \, dy'. \]

Similarly, for the \( x \) and \( y \) components of the displacement:

\[ |u_x(0, 0, z, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \left[ \frac{2(1 - \sigma)b + z}{r(r + z)} \right] \right\} \left[ \frac{2(1 - \sigma)b' + z}{r'(r' + z)} \right] x \tau_x^2(k)
\]

\[
+ \left[ \frac{2(1 - \sigma)b + z}{r(r + z)} \right] \left[ \frac{2(1 - \sigma)b' + z}{r'(r' + z)} \right] y \tau_y^2(k)
\]

\[
+ \left[ \frac{2(1 - \sigma)b + z}{r(r + z)} \right] \left[ \frac{2(1 - \sigma)b' + z}{r'(r' + z)} \right] x'y' \tau_y^2(k)
\]

\[
+ \left[ \frac{z^2}{r^3} \right] \left[ \frac{z^2}{r'^3} \right] p_z^2(k) \cdot \]

\[e^{-\alpha z |x - x'|} \cos(k|x - x'|) e^{-\beta z |y - y'|} \, dx \, dy \, dx' \, dy'. \]
\[ |u_y(0, 0, z, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{(2r(\sigma r + z) + z^2)}{r^3(r + z)^2} \right\} \left\{ \frac{(2r'(\sigma r' + z) + z^2)}{r'^3(r' + z)^2} \right\} x y x' y' \tau_x^2(k) \]

\[ + \left[ \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} y^2 \right] \left[ \frac{2(1 - \sigma)r' + z}{r'(r' + z)} \right] \tau_y^2(k) \]

\[ + \left[ \frac{y z}{r^3 - r(r + z)} \right] \left[ \frac{y' z}{r'^3 - r'(r' + z)} \right] \left[ \frac{2\sigma x y}{r^3} \right] \left[ \frac{2\sigma x' y'}{r'^3} \right] p_z^2(k) \]

\[ e^{-\frac{\alpha k}{2\pi} |x - x'|} \cos(k|x - x'|) e^{-\frac{\beta k}{2\pi} |y - y'|} \, dx \, dy \, dx' \, dy'. \]

The displacements at the ground surface result from setting \( z = 0 \):

\[ |u_x(0, 0, 0, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{(1 - \sigma)x}{r} + \frac{2\sigma x^2}{r^3} \right\} \left\{ \frac{(1 - \sigma)x'}{r'} + \frac{2\sigma x'^2}{r'^3} \right\} \tau_x^2(k) \]

\[ + \left[ \frac{(1 - 2\sigma)x}{r^2} \right] \left[ \frac{(1 - 2\sigma)x'}{r'^2} \right] p_z^2(k) \]

\[ e^{-\frac{\alpha k}{2\pi} |x - x'|} \cos(k|x - x'|) e^{-\frac{\beta k}{2\pi} |y - y'|} \, dx \, dy \, dx' \, dy'. \]
\[ |u_y (0, 0, 0, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \] (2.22b)

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{2\sigma xy}{r^3} \left[ \frac{2\sigma x'y'}{r'^3} \right] \tau_x^2(k) + \left[ \frac{2(1 - \sigma)}{r} \right] \left[ \frac{2\sigma y'^2}{r'^3} \right] \tau_y^2(k) \right. \]
\[ + \left[ \frac{(1 - 2\sigma)y}{r^2} \right] \left[ \frac{(1 - 2\sigma)y'}{r'^2} \right] p_z^2(k) \right\} \]
\[ e^{-\alpha \frac{k}{2\pi} |x - x'|} \cos(k|x - x'|) \ e^{-\beta \frac{k}{2\pi} |y - y'|} \ dx \ dy \ dx' \ dy'. \]

\[ |u_z (0, 0, 0, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \] (2.22c)

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left\{ \frac{(1 - 2\sigma)x}{r^2} \left[ \frac{(1 - 2\sigma)x'}{r'^2} \right] \tau_x^2(k) + \left[ \frac{(1 - 2\sigma)y}{r^2} \right] \left[ \frac{(1 - 2\sigma)y'}{r'^2} \right] \tau_y^2(k) \right. \]
\[ + \left[ \frac{2(1 - \sigma)}{r} \right] \left[ \frac{2(1 - \sigma)}{r'} \right] p_z^2(k) \right\} \]
\[ e^{-\alpha \frac{k}{2\pi} |x - x'|} \cos(k|x - x'|) \ e^{-\beta \frac{k}{2\pi} |y - y'|} \ dx \ dy \ dx' \ dy'. \]

Yu’s model, Equation (2.4), for normal pressure at the ground surface is used in this work as \( p_z \) in Equations (2.21) and (2.22).

Mathis, Marusic, Chernyshenko, and Hutchins (2013) developed a model for predicting the wall shear stress fluctuations in turbulent boundary layers. However, no predictive model for the wall shear stress fluctuation at the ground rough surface under unsteady wind conditions were found in the literature. The Mathis et al.’s model and other models in the literature are proposed and verified for wall shear stress at smooth surfaces with boundary layer flows. The direct measurement of the wall shear stress fluctuations is largely inaccessible in field measurements.
The fluctuation magnitude of wall shear stress, \( \tau'_{w, rms} \), as reported by the most recent works in the literature (such as Mathis et al., 2013; Orlu and Schlatter, 2011) is

\[
\tau'_{w, rms} \approx 0.4 \langle \tau_w \rangle ,
\]

(2.23)

where the mean wall shear stress is calculated from

\[
\langle \tau_w \rangle = \rho u_*^2 ,
\]

(2.24)

where \( \rho = 1.2 \text{ kg/m}^3 \) is the density of air, and the friction velocity, \( u_* \), is calculated from Equation (2.5). Hence, the \( \tau'_{w, rms} \) will be on the order of 0.04 Pa. This shear stress fluctuation is two order of magnitude smaller than the normal pressure fluctuations predicted from Yu’s model.

Our calculations show that for wall shear stresses of this magnitude, the contribution of \( \tau_x \) and \( \tau_y \) terms in the ground displacements will be negligible comparing to the contribution of the normal pressure \( p_z \) in Equations (2.21) and (2.22). Therefore, if only the normal pressure terms in Equations (2.21) are considered the ground displacements will be:

\[
|u_x (0, 0, 0, k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times
\]

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[ \frac{1 - 2\sigma}{r^2} \right] \left[ \frac{1 - 2\sigma}{r'^2} \right] p_z^2 (k)
\]

\[
e^{-\alpha \frac{k}{2\pi} |x - x'|} \cos(k|x - x'|) e^{-\beta \frac{k}{2\pi} |y - y'|} dx \, dy \, dx' \, dy'
\]
\[ |u_y(0,0,0,k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[ \frac{(1 - 2\sigma)y}{r^2} \right] \left[ \frac{(1 - 2\sigma)y'}{r'^2} \right] p_z^2(k) \]

\[ e^{-\frac{\alpha}{2\pi} |x - x'|} \cos(k |x - x'|) e^{-\frac{\beta}{2\pi} |y - y'|} \, dx \, dy \, dx' \, dy' \]

\[ |u_z(0,0,0,k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[ \frac{2(1 - \sigma)}{r} \right] \left[ \frac{2(1 - \sigma)}{r'} \right] p_z^2(k) \]

\[ e^{-\frac{\alpha}{2\pi} |x - x'|} \cos(k |x - x'|) e^{-\frac{\beta}{2\pi} |y - y'|} \, dx \, dy \, dx' \, dy'. \]
CHAPTER 3
FIELD MEASUREMENTS

3.1: SITE LOCATION

All measurements were acquired in a agricultural field near Locke Station, MS. The terrain was flat and open around the location of measurements for about 25.0 m to the east and west, 4.0 m to the north, and 10.0 m to the south. Beyond these points, the site consists of mowed grass and harvested fields with a fetch of about 180 m to the west, 600 m to the east, and 1.5 km to the north. The wind often blew from south to north. This field was chosen for several reasons: proximity and ease of access for experimentation, distance from main roads and highways and consequently low seismic ambient noise. Eleven sets of measurements were conducted from 12/19/2013 to 02/07/2015, under different wind conditions. All measurements were performed at times in which there were no farming or other human activities in the vicinity.

The only possible source of induced seismic noise is a wind fence placed 35 m away from the measurements location. Figure 3.1 is an aerial photo from Google Maps that shows the location of the measurements and the fence. The possible influence of the wind fence in the data is described in Section 4.4.
3.2: GROUND TRUTH AND SITE CHARACTERIZATION

A set of standard seismic refraction measurements were performed to provide the ground truth and characterization at the site. These measurements provide the information used to obtain the values of p-wave and s-wave velocities. The measured p-wave and s-wave velocities were 285 ± 5 m/s and 140 ± 5 m/s, respectively. The density of the ground was measured by carefully taking a controlled volume of the soil. The weight of the soil sample was divided by its volume to calculate the density. The density of the ground was measured to be 1995 ± 10 kg/m³.

3.3: EXPERIMENTAL SETUP

3.3.1: ANEMOMETER

Wind velocity measurements were obtained simultaneously with the geophone measurements. A Gill Instrument R3A-100 Ultrasonic Research Anemometer was used to measure the turbulence spectrum data. The anemometer was mounted 1.0 m above the ground surface. The internal sampling rate of the Gill Anemometer is 100 Hz and it can measure down to
0 Hz. The anemometer was connected to a National Instruments AD/DA data acquisition card controlled by a program written in Labview©. Matlab© was used for data post processing. Figure 3.2 shows a photograph of the setup for the Gill Anemometer in the field.

![Figure 3.2. Experimental setup for the anemometer.](image)

### 3.3.2: GEOPHONES

From 12/19/2013 to 10/15/2014, four spiked 3-component GS-32CT, 10-Hz Geospace Geophones with 635-ohm windings were used for the ground vibration measurements. For measurements conducted from 01/07/2015 to 02/07/2015, four spiked 3-component 4.5-Hz, RTC Geophones with 375-ohm windings were used. The two types of geophones are similar in dimensions. Each geophone box contains two perpendicular horizontal and one vertical geophone element. Each geophone has three 7-cm steel spikes on the bottom for coupling to the ground.
Four geophones were planted at the corners of two adjacent equilateral triangles. The spacing between each two geophones was 65 cm; far enough so that wind noise generated by one geophone would not be detectable by adjacent geophones, and close enough so that the wind would not vary greatly over the area of the experiment. The first geophone was planted at the ground surface. The second geophone was mounted flush to the ground surface. The third and fourth geophones were buried at depths of 20 cm and 40 cm, respectively. All the holes were dug with a shovel, and made as small as practical. All the holes were backfilled and covered with the same soil after planting the geophones. The geophones were oriented with the $x$ component approximately along the wind direction, the $y$ component along the horizontal cross-wind direction, and the $z$ component in the vertical direction. Figure 3.3 shows a diagram of the relative location of the geophones and the anemometer with respect to wind direction. In this figure ‘GA’ represents the geophone above the ground, ‘GF’ represents the geophone mounted flush to the ground, and ‘GB1’ and ‘GB2’ represent the geophones buried 20 and 40 cm, respectively. Figure 3.4 shows a photograph the geophone setup in the field.

![Diagram of geophone setup](image)

**Figure 3.3.** Plan view diagram of the relative location of the geophones and the anemometer with respect to wind direction.
Outputs from the geophones were connected to a 24-channel Geometrics Geode seismograph. The first 12 channels were used for the four 3-component geophones. For data acquisition, Geometrics Multiple Geode Operating Software (MGOS) was used to record data from Geode channels to a computer. After acquisition, Matlab© was used to analyze the data.

3.4: ANEMOMETER DATA ANALYSIS

The output data from the anemometer is proportional to the $x_{1m}$, $x_{2m}$, and $x_{3m}$ components of the wind velocity. The $x_{2m}$ and $x_{3m}$ components of the anemometer’s output are multiplied by 8.0, the sensitivity of the Gill anemometer, to convert wind velocities to m/s. The $x_{1m}$ component is multiplied by -8.0 since it is in the opposite direction of the wind direction. The anemometer was placed in such a way that the $x_1$ component approximately faced the wind direction. However,
the direction of the wind varies with time. New coordinates, $x_1$ and $x_3$, are calculated during the analysis to make the mean velocity in the $x_3$ direction equal to zero. Suppose $u_1m(t)$ and $u_3m(t)$ are the time series of the measured $x_1m$ and $x_3m$ components of the wind velocity, and $u_1(t)$ and $u_3(t)$ are the new velocities in the direction of flow and perpendicular to the flow in the horizontal plane. The time average of $u_1m(t)$ and $u_3m(t)$ are noted as $U_1m$ and $U_3m$, respectively. The relations between $u_1(t), u_m(t), u_1m(t)$, and $u_3m(t)$ are:

$$
\theta = \tan^{-1}\left(\frac{U_3m}{U_1m}\right) \quad (3.1)
$$

$$
u_1(t) = u_1m(t) \cos \theta + u_3m(t) \sin \theta \quad (3.2)
$$

$$
u_3(t) = -u_1m(t) \sin \theta + u_3m(t) \cos \theta. \quad (3.3)
$$

The velocity in the vertical direction is unaffected. The mean velocities in the direction of flow and perpendicular to the flow in the horizontal plane are noted as $U_1$ and $U_3$, respectively. But $U_3$ is equal to zero. The convection velocity $U_C$ calculated as $U_C = 0.7 \times U_1$, is used to convert the measured frequency spectrum to a wave-number spectrum (Yu, 2009; Yu et al., 2011). The wind velocity power spectrum is calculated from the fluctuating velocity data from the Gill anemometer. The measured velocity power spectral densities of the Gill device, as a function of wave number, are used in the predictions of the pressure power spectral densities at the ground surface.

The power spectral density (PSD) of the data was generated with a standard periodogram. The time series data are converted from the time domain to the frequency domain using discrete Fourier decomposition of the recorded time series data. A Hamming window was applied to the data before the Fourier transform was calculated. The power spectral densities are normalized so that the root mean square average of the velocity fluctuation is equal to the area under the power
spectral density curve. The root mean squared (RMS) value of the time series data, $f$, is defined by

$$(RMS)^2 = \frac{1}{N^2} \sum_{j=0}^{N-1} |f_j|^2$$

(3.4)

where $N$ is the number of samples. The area under the PSD curve is

$$A_{PSD}(F_k) = \frac{W_d}{N^2} \sum_{k=0}^{N-1} |F_k|^2$$

(3.5)

where the $F_k$s are the binned amplitudes, $W_d$ is the width of the bins in which those amplitudes fall, and $N$ is the number of samples. The output bins are of size 1 and unitless. To keep the area under the PSD curve fixed, when the initial bins are converted to frequency, $W_d$ is multiplied by $\frac{F_N}{N}$, where $F_N$ is the Nyquist frequency, so the amplitudes are divided by $\frac{F_N}{N}$.

The FFT routine is used to produce the wind velocity frequency spectrum from the time series points collected by the anemometer. Then the PSD is calculated as a function of frequency. Finally the PSD is converted from frequency to wave-number space using Taylor’s frozen turbulence hypothesis as below:

$$F_v(k_1) = \frac{U_C}{2\pi} F'_v(f)$$

(3.6)

$$k_1 = \frac{2\pi}{U_C}$$

(3.7)

where $U_C$ is the convection velocity in the direction of flow, and $F'_v(f)$ is the power spectral density of the velocity. Hence, the units of $F'_v(f)$ are $m^2/s$ and those of $F_v(k_1)$ are $m^3/s^2$. 

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The method described in Yu (2009) is used to perform a least squares fit to the wind velocity PSD in wave-number space with the von Karman form in Equation (2.1). Since this method was developed for outdoor wind turbulence and level grass-covered ground and it is applicable to the current work. The coefficients $C$ and $\lambda$ are determined by this least-squares fitting for each data set. Figure 3.5 displays an example of the measured longitudinal wind velocity ($u_1(t)$) power spectrum 1.0 m above the ground and its fit. The data used is 02-07-2015 Run 7.

![Figure 3.5](image)

**Figure 3.5.** An example of the measured longitudinal wind velocity ($u_1(t)$) power spectrum and its fit. The data used is 02-07-2015 Run 7.

The average roughness length calculated using the method described in Section 2.1.1 is $x_0 = 0.0056$ m. The measured roughness length is found to be on the order of that listed for open flat terrain with no vegetation roughness length (0.005) (Panofsky and Dutton, 1984). The $a$ is determined as described in Section 2.1. The logarithmic profile model truncated below the roughness length is used to generate the predicted pressure spectra. The predicted pressure spectrum at the ground surface in wave number space is generated by numerically integrating Equation (2.4) using the $C$, $\lambda$, $a$, and $x_0$ parameters.
3.5: GEOPHONE DATA ANALYSIS

Geogiga front end seismic data processing was used to convert the geophone recorded files to ASCII format for Matlab© analysis. The preamp gain on MGOS software was set to 24 dB. The Geode hardware has an internal low-cut filter at 1.75 Hz. The recorded data was multiplied by a descaling factor of $1.6985 \times 10^{-4}$. Then data was divided by 1000 to convert from millivolts to volts.

The power spectra (PSDs) for the ground velocity measured using the geophones were generated following the same procedure as for the wind velocity spectra through windowing, FFT transform, and converting bins to frequency space. The PSDs were calculated for all three components. The PSDs in frequency space are divided by the square of the frequency response function of the geophone to convert from voltage ($V^2 s$) to velocity ($\frac{m^2}{s^2} s$). Figures 3.6 and 3.7 show the frequency responses of the 10-Hz and 4.5-Hz geophones, respectively. The PSDs are divided by $(2\pi f)^2$ to convert from velocity ($\frac{m^2}{s^2} s$) to displacement (m2s). These PSDs of the ground displacements of geophone components are used to compare to the predicted PSDs.

![Figure 3.6. Frequency response curve for 10-Hz geophone.](image-url)
Figure 3.7. Frequency response curve for 4.5-Hz geophone.

Figure 3.8 displays an example of the measured power spectrum of three components of a geophone at the ground surface during a windy day. The mean wind velocity was 6.6 m/s for this measurement. The data used is 02-07-2015 Run07.

Figure 3.8. An example of the measured power spectrum of three components of a geophone planted on the ground surface during a windy day. The data used is 02-07-2015 Run07.
CHAPTER 4
RESULTS AND DISCUSSION

4.1: MEASURED WIND INDUCED GROUND DEFORMATION

In this section, the wind noise for each component of the ground deformation is investigated. For each geophone, the $x$ component is aligned with the approximate wind direction. The $y$ component is horizontal perpendicular to $x$, and the $z$ component is vertical. Figure 4.1 displays the power spectra of the $x$, $y$, and $z$ components of the geophone placed on the ground. Figure 4.2 displays the power spectra of three components of the geophone mounted flush to the ground surface. Figures 4.3 and 4.4 display the power spectra of three components of the geophones buried 20 cm and 40 cm under the ground, respectively. The mean wind velocity was 6.6 m/s in this measurement. The data used is 02-07-2015 Run07.
Figure 4.1. Three components of the wind-induced displacement PSDs for the geophone on the ground surface.

Figure 4.2. Three components of the wind-induced displacement PSDs for the geophone mounted flush to the ground surface.
Figure 4.3. Three components of the wind-induced displacement PSDs for the geophone buried 20 cm.

Figure 4.4. Three components of the wind-induced displacement PSDs for the geophone buried 40 cm.

The horizontal components of the displacements are larger than the vertical component for the geophone at the ground surface (Figure 4.1). The direct interaction of the wind with the geophone shakes it more in the horizontal directions. The displacement on the $x$ component of the geophone, along the wind direction, is larger than the cross wind horizontal component, $y$. 
because it is exposed to the wind direction. Figures 4.2, 4.3, and 4.4 show that for the buried geophones the three components of the displacements are at the same level.

4.2: WIND VELOCITY EFFECT

The spectral levels under high and low wind conditions verify that the observed displacements are due to the wind. Figure 4.5 displays a comparison between the displacements at high wind velocity (7.1 m/s), medium wind velocity (4.8 m/s), and low wind velocity (2.2 m/s) for the geophone at the ground surface. Figure 4.6 displays the displacements on the geophone mounted flush to the ground, and Figures 4.7 and 4.8 display data for the geophones buried at 20 cm and 40 cm, respectively. Unwanted noise peaks at 60 Hz, 120 Hz, and 180 Hz on the low wind velocity data are due to electrical interferences. The data used for high wind velocity (7.1 m/s) is 04-10-2014 Run09, for medium wind velocity (4.8 m/s) is 07-08-2014 Run08, and for high wind velocity (2.2 m/s) is 03-13-2014 Run14.

![Figure 4.5. Displacements at different wind velocities for the ground surface geophone.](image-url)
Figure 4.6. Displacements at different wind velocities for the flush mounted geophone.

Figure 4.7. Displacements at different wind velocities for the geophone buried at 20 cm.
Figure 4.8. Displacements at different wind velocities for the geophone buried at 40 cm.

The results show a large difference in all three components of the displacements due to high wind velocity and low wind velocity. As shown in Figure 4.8, even for the geophone buried at 40 cm, the differences in the displacements are large. This assures that what is measured is actually the wind effect on the geophones. The mechanism and structure stay the same for high wind and low wind velocities, but the displacement amplitudes are bigger for higher wind velocity.

4.3: THE DEPTH EFFECT

To investigate whether the wind noise can be reduced by burying the geophones, the effect of depth on the reduction of the displacements on each component is studied. Figure 4.9 displays the displacements of the horizontal in-line components, $x$, of the geophone at the ground surface, the geophone mounted flush to the ground, and the geophones buried at 20 cm and 40 cm. Figures 4.10 and 4.11 displays the data for the horizontal cross-line, $y$, and the vertical, $z$, components of the geophones. The mean wind velocity for this measurement was 6.6 m/s. The data used is 02-07-2015 Run07.
Figure 4.9. The effect of depth on the horizontal in-line component of the displacement.

Figure 4.10. The effect of depth on the horizontal cross-line component of the displacement.
Burying the geophone drastically reduces the amount of noise on all three components of the geophone, since it eliminates the direct interaction of wind with the geophone case. Noise reduction afforded by deeper burial of the geophone beyond the flush mounted was small.

4.4: COMPARISON OF MEASUREMENTS AND PREDICTIONS

The 3-C geophones were used to measure the ground vibrations in three directions. Simultaneously, the wind velocity spectrum was measured with a 3D sonic anemometer above the ground. The measured wind velocity spectrum was used to calculate the normal pressure at the ground surface. The power spectrum of the normal pressure at the ground surface was calculated using Equation (2.4). The predicted normal pressure power spectrum, the wind correlation functions, as well as the measured ground parameters were used (Equation (2.25)) to predict the power spectra of the three components of the ground displacements.

Figure 4.12 displays predicted and measured ground displacement spectra for three components of the geophone mounted flush to the ground, i.e. $z = 0$. The mean wind velocity
for this measurement was 6.3 m/s and the measured coefficients to predict the pressure at the
ground surface were $C = 1.99$, $\lambda = 2.68$, and $a = 1.66$. The data used is 02-07-2015 Run08.

![Figure 4.12. The measured and predicted displacements for a wind speed of 6.3 m/s.](image)

As shown in Figure 4.12, the measurements and the predictions for the vertical component
of the displacement match very well, but the horizontal displacements are underpredicted. The
bumps in the spectra at low frequencies (from 6 to 13 Hz) may be due to seismic motions produced
by the interaction of the wind with the nearby wind fence. Since these bumps increase with wind
velocity, we speculate that as the wind shakes the fence, it induces vibrations into the ground which
are sensed by the geophones.

It is well known that there are important differences between the turbulent flow behavior
in indoor wind tunnels over a smooth surface and outdoor wind fluctuations over a rough ground
surface. In the fluctuations of the pressure and shear stresses at the ground surface the roughness
characteristics of the ground play an important role. Also wall pressure and wall shear stress under
steady wind is different from the turbulent wind outdoors.
The disagreement in the predicted and measured horizontal components, casts doubt on the validity of the existing predictive models for the amplitude of wall shear stress fluctuations for field measurements over ground rough surface. To investigate the role of wall shear stress fluctuations on the ground displacements, the shear stress terms in Equations (2.22) must be considered. Before discussing this further, it is helpful to design a test experiment to check the validity of the proposed theoretical model describing the ground’s quasi-static displacements.

4.5: TEST EXPERIMENT; CONTROLLED PRESSURE AND SHEAR STRESS TO THE GROUND

The predicted horizontal displacements are significantly smaller than the measured horizontal components of the ground displacements. In this section a test experiment with controlled pressure and shear stress exerted on the ground surface was conducted. The ground model of the proposed theoretical model can be tested by applying known and controlled horizontal and vertical forces to the ground surface.

The vertical and horizontal mass-spring apparati built to apply controlled normal and tangential forces are shown in Figures 4.13 and 4.14. In both apparati, a 0.304-kg mass was attached between two identical springs. If the mass is moved from its initial equilibrium position and released it will vibrate at the resonance frequency of the system. The force due to this vibration will be exerted to the ground under the plate.
Figure 4.13 Vertical mass-spring apparatus to exert controlled normal pressure to the ground.

Figure 4.14 Horizontal mass-spring apparatus to exert controlled shear stress to the ground.
The measured resonance frequency for both systems was \( f = 12.33 \) Hz. This frequency can be altered by changing the mass or springs. The mass between the springs was \( m = 0.304 \) kg and the mass of each spring was \( m_s = 0.232 \) kg. So the effective mass of the system is given by

\[
m_{\text{eff}} = m + \frac{1}{3} \times 2 \times m_s = 0.458 \text{ kg.} \tag{4.1}
\]

The force due to the mass-spring system vibration is given by

\[
F = m_{\text{eff}} x \omega^2, \tag{4.2}
\]

where \( x \) is the amplitude of the mass displacement, and \( \omega = 2\pi f \) is the angular frequency of the vibration. Normal pressure, for vertical spring, and tangential stress, for horizontal spring, are calculated from

\[
P = \frac{F}{A}, \tag{4.3}
\]

where \( A \) is the surface area of the plate. For the vertical spring \( A_{\text{vert}} = 0.2116 \text{ m}^2 \) and for the horizontal spring \( A_{\text{hor}} = 0.135 \text{ m}^2 \).

The experiment was conducted on a very calm, non-windy day, at the same site where the wind-ground measurements were conducted. A 3-C geophone was buried 1.0 cm below the surface of the ground and the spring apparatus plate was placed on the ground centered on the geophone. Then the mass-spring was excited to vibrate and the geophone recorded the motion of the soil. The recording length was 30 seconds to allow for large enough vibration (i.e. force) before damping. To measure the amplitude of vibration, a fixed scale was placed behind the vibrating mass and a video was recorded with a high-speed camera. The average amplitude of vibration was assumed as the value of \( x \).
To predict the displacements associated with the vertical spring apparatus above the ground, the modified form of Equations (2.21) can be used as follows

\[
|u_x (0, 0, z, k)|^2 = \left(\frac{1 + \sigma}{2 \pi E}\right)^2 \times (4.4a)
\]

\[
\int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \left[\frac{xy}{r^3} - \frac{(1 - 2\sigma)x}{r(r + z)}\right] \left[\frac{x'z'}{r'^3} - \frac{(1 - 2\sigma)x'}{r'(r' + z)}\right] p_z^2(k) \, dx \, dy \, dx' \, dy'
\]

\[
|u_y (0, 0, z, k)|^2 = \left(\frac{1 + \sigma}{2 \pi E}\right)^2 \times (4.4b)
\]

\[
\int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \left[\frac{yz}{r^3} - \frac{(1 - 2\sigma)y}{r(r + z)}\right] \left[\frac{y'z'}{r'^3} - \frac{(1 - 2\sigma)y'}{r'(r' + z)}\right] p_z^2(k) \, dx \, dy \, dx' \, dy'
\]

\[
|u_z (0, 0, z, k)|^2 = \left(\frac{1 + \sigma}{2 \pi E}\right)^2 \times (4.4c)
\]

\[
\int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \left[\frac{2(1 - \sigma)}{r^3} + \frac{z^2}{r^3}\right] \left[\frac{2(1 - \sigma)}{r'^3} + \frac{z'^2}{r'^3}\right] p_z^2(k) \, dx \, dy \, dx' \, dy'
\]

where \(x_0 = 0.45 \text{ m}\) and \(y_0 = 0.45 \text{ m}\) are the dimensions of the vertical plate and \(P_z\) is the pressure due to the spring-mass system calculated from Equation (4.3). Here the correlation functions are set to one, because the pressure is uniform over the plate, and the integration is over the surface of the plate only. Also, since only normal pressure is exerted, the horizontal stresses, \(\tau_x\) and \(\tau_y\), are set equal to zero.

Similarly, the displacements for the horizontal spring apparatus aligned with the \(x\) component of the geophone, and the geophone placed in the middle of the plate is given by
$$|u_x (0, 0, z, k)|^2 = \left(\frac{1 + \sigma}{2\pi E}\right)^2 \times$$ (4.5a) 

$$\int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \left[ \frac{2(1 - \sigma)r + z}{r(r + z)} + \frac{(2r(\sigma r + z) + z^2)}{r^3(r + z)^2} x^2 \right] \left[ \frac{2(1 - \sigma)r' + z}{r'(r' + z)} + \frac{(2r'(\sigma r' + z) + z^2)}{r'^3(r' + z)^2} x'^2 \right] \tau_x^2(k) \, dx \, dy \, dx' \, dy'$$

$$|u_y (0, 0, z, k)|^2 = \left(\frac{1 + \sigma}{2\pi E}\right)^2 \times$$ (4.5b) 

$$\int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \left[ \frac{2r(\sigma r + z) + z^2}{r^3(r + z)^2} xy \right] \left[ \frac{2r'(\sigma r' + z) + z^2}{r'^3(r' + z)^2} x'y' \right] \tau_x^2(k) \, dx \, dy \, dx' \, dy'$$

$$|u_z (0, 0, z, k)|^2 = \left(\frac{1 + \sigma}{2\pi E}\right)^2 \times$$ (4.5c) 

$$\int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \int_{-x_0/2}^{x_0/2} \int_{-y_0/2}^{y_0/2} \left[ \frac{1 - 2\sigma}{r(r + z)} + \frac{z}{r^3} \right] \left[ \frac{1 - 2\sigma}{r'(r' + z)} + \frac{z}{r'^3} \right] x' \tau_x^2(k) \, dx \, dy \, dx' \, dy',$$

where $x_0 = 0.17$ m and $y_0 = 0.69$ m are the dimensions of the horizontal plate and $\tau_x$ is the stress due to the spring-mass system calculated from Equation (4.3). Here, since only shear stress aligned with the $x$ direction is exerted, the normal pressure, $P_z$, and the horizontal stress in the $y$ direction, $\tau_y$, are set equal to zero.

Tables (1) and (2) show the results of the calculations and measurements for the vertical and horizontal systems, respectively. The estimated error is $\pm 5.0 \times 10^{-10}$ m.
Table 1. Results of the vertical mass-spring measurement.

<table>
<thead>
<tr>
<th>Component</th>
<th>Prediction (m)</th>
<th>Measurement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_x$</td>
<td>$3.0 \times 10^{-9}$</td>
<td>$2.6 \times 10^{-9}$</td>
</tr>
<tr>
<td>$U_y$</td>
<td>$3.0 \times 10^{-9}$</td>
<td>$2.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>$U_z$</td>
<td>$8.5 \times 10^{-7}$</td>
<td>$8.1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Table 2. Results of the horizontal mass-spring measurement.

<table>
<thead>
<tr>
<th>Component</th>
<th>Prediction (m)</th>
<th>Measurement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_x$</td>
<td>$4.7 \times 10^{-7}$</td>
<td>$4.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>$U_y$</td>
<td>$2.6 \times 10^{-9}$</td>
<td>$1.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>$U_z$</td>
<td>$2.4 \times 10^{-9}$</td>
<td>$2.1 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

The reasonable match between the predictions and measurements for the ground displacements, as shown in Tables (1) and (2), verifies the predictive theoretical model for the ground deformation. This verification confirms that the linear elastic rheology is appropriate for this model. It was observed that having only a vertical force on the ground surface produces much larger vertical displacements than horizontal displacements. Similarly, having only a tangential
shear force on the ground produces mainly horizontal displacements in the direction of the tangential force.

4.6: GROUND DISPLACEMENT MEASUREMENT AS A NEW TOOL FOR WIND WALL SHEAR STRESS MEASUREMENT

The measured ground properties, $G$, and the predicted pressure, $P$, have been used to predict ground displacements, $U$, in Equation (2.12). The test experiment actually verifies the ground part of the theoretical model, using known driving forces. Therefore, an inverse approach can be used to measure the driving forces, $P$, from the measured $G$ and $U$. It was shown in the previous sections that for the buried geophones, the three components of the wind-induced displacements are almost at the same level. The predicted displacement for the vertical component agreed with the measured displacement. However, for the horizontal components the predictions underestimated the displacements.

Equations (2.22), indicate that the measured horizontal ground displacement levels in Figure 4.12, must be due to fluctuating shear stress at the rough ground surface much larger than predicted by current wall shear stress models for the smooth wall and steady wind conditions. Indeed, the fluctuating wind shear stress at the ground surface must be of the same order of magnitude as the wind normal pressure to produce the measured levels.

Figure 4.15 displays the comparison of the predicted and measured ground displacements if the wall shear stresses ($\tau_x$ and $\tau_y$) are set equal to the normal pressure ($P_z$) in Equations (2.22). The mean wind velocity for this measurement was 6.3 m/s. The data used is 02-07-2015 Run08.
Figure 4.15. The measured and predicted displacements using the new estimate of wall shear stress.

4.7: CONTRIBUTION OF DRIVING FORCE COMPONENTS TO EACH COMPONENT OF THE DISPLACEMENTS

Since linear elastic rheology is used, the loading effects due to different components of the driving force were superimposed (Equations (2.21) and (2.22)). However, the contribution of each component of the driving forces to each component of the displacements in Equations (2.22) is investigated in this section. $\tau_x$ and $\tau_y$ are set equal to $P_z$, in this investigation so that the contributions will be comparable. In the following figures, the contribution of the terms including $\tau_x$, $\tau_y$, and $P_z$ in the $x$ component of displacement are denoted by ‘$U_{x_x}$’, ‘$U_{x_y}$’, and ‘$U_{x_z}$’, respectively. The contribution of the terms including $\tau_x$, $\tau_y$, and $P_z$ in the $y$ component of displacement are denoted by either ‘$U_{y_x}$’, ‘$U_{y_y}$’, and ‘$U_{y_z}$’, respectively. The contribution of the terms including $\tau_x$, $\tau_y$, and $P_z$ in the $z$ component of displacement are denoted by ‘$U_{z_x}$’, ‘$U_{z_y}$’, and ‘$U_{z_z}$’, respectively.
Figure 4.16 displays the contribution of each term to the $x$ component of the displacement, Equation (2.22a). Figure 4.17 displays the contribution of each term to the $y$ component of the displacement, Equation (2.22b). Figure 4.18 displays the contribution of each term to the $z$ component of the displacement, Equation (2.22c).

![Figure 4.16](image1.png)

**Figure 4.16.** Contribution of each term to the $x$ component of the displacement.

![Figure 4.17](image2.png)

**Figure 4.17.** Contribution of each term to the $y$ component of the displacement.
Figure 4.18. Contribution of each term to the z component of the displacement.

Figures above show that the \(x\), \(y\), and \(z\) components of the displacements are dominated by the ‘\(U_{x,x}\)’, ‘\(U_{y,y}\)’, and ‘\(U_{z,z}\)’ terms, respectively. This means that a one-directional force on the surface is expected to mainly induce a motion in its own direction. Consequently, if \(\tau_x\), \(\tau_y\), and \(p_z\) are in the same order of magnitude the Equations (2.22) are approximated by:

\[
|u_x(0,0,0,k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times
\]

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[ \frac{2(1 - \sigma) + 2\sigma x^2}{r} + \frac{2(1 - \sigma) + 2\sigma x'^2}{r'} \right] \tau_x^2(k) e^{-\alpha k|y-y'| / 2\pi} \cos(\beta k|y-y'|) \, dx \, dy \, dx' \, dy'
\]

\[
|u_y(0,0,0,k)|^2 = \left( \frac{1 + \sigma}{2\pi E} \right)^2 \times
\]

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[ \frac{2(1 - \sigma) + 2\sigma y^2}{r} + \frac{2(1 - \sigma) + 2\sigma y'^2}{r'} \right] \tau_y^2(k) e^{-\alpha k|y-y'| / 2\pi} \cos(\beta k|y-y'|) \, dx \, dy \, dx' \, dy'
\]
\[ |u_z(0,0,k)|^2 = \left(\frac{1 + \sigma}{2\pi E} \right)^2 \times \]

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left[ \frac{2(1 - \sigma)}{r} \right] \left[ \frac{2(1 - \sigma)}{r'} \right] p_z^2(k) \]

\[
ee^{-\frac{\alpha k}{2\pi|x-x'|}} \cos(k|x-x'|) e^{-\frac{\beta k}{2\pi|y-y'|}} \ dx \ dy \ dx' \ dy'
\]

**4.8: VARIATION OF MODEL PARAMETERS**

It is important to understand the contributions from different parameters to the displacement spectrum prediction. The sensitivity of calculated displacements to each parameter is investigated by changing one parameter value, calculating the new response, and comparing the new displacement curve to that obtained with the 'base' parameter set. Compressional velocity \(V_p\) and shear velocity \(V_s\), are varied both above and below their base values. The effect of the source area integration as a function of frequency to determine the effective source area for each frequency range is also investigated in this section. In the following figures, changes in a base parameter value are denoted by either ‘up#’ or ‘dn#’ where # represents the percent increase (up) or decrease (dn) in the base parameter value. The data used in this section is 02-07-2015 Run 8. The average wind speed was 6.2 m/s during this run.

**a) Compressional velocity \(V_p\)**

The relations for Poisson’s ratio \(\sigma\) and Young’s modulus \(E\) in terms of compressional velocity \(V_p\) and shear velocity \(V_s\) are given by

\[
\sigma = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}
\]
\[ E = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \] 

The base value of Poisson’s ratio \((\sigma)\) is 0.34. To maintain reasonable values for Poisson’s ratio \((\sigma)\), the compressional velocity \((V_p)\), is varied 20% both above and below its base value. The base compressional velocity is 285 m/s, so the compressional velocity 20% above the base is 342 m/s, corresponding to \(\sigma = 0.40\), and 20% below the base is 228 m/s, corresponding to \(\sigma = 0.19\).

Figures 4.19 and 4.20 display the effect of changing the compressional velocity on the power spectra of the vertical and horizontal ground displacements due to wind, respectively. Since the two horizontal components were similarly affected, only the \(x\) component is displayed. An increase in compressional velocity \((V_p)\), by 20% leads to a decrease in the magnitude of the power spectra of the horizontal displacements of roughly 16% and of the vertical displacement of roughly 20%. Decreasing the compressional velocity \((V_p)\), by 20% leads to an increase of roughly 42% for the vertical displacements and 35% for the horizontal displacement.
Figure 4.19. Influence of compressional velocity on the vertical component of the wind-induced ground displacement.

Figure 4.20. Influence of compressional velocity on the horizontal component of the wind-induced ground displacement.

b) Shear velocity \( (V_s) \)

To maintain reasonable values for Poisson’s ratio (\( \sigma \)), the shear velocity \( (V_s) \) is varied 20% both above and below its base value. The base shear velocity is 140 m/s, so the shear velocity
20% above the base is 168 m/s, corresponding to $\sigma = 0.23$, and 20% below the base is 112 m/s, corresponding to $\sigma = 0.41$.

Figures 4.21 and 4.22 display the effect of changing shear velocity on the power spectra of the ground displacements due to wind. Since the two horizontal components were similarly affected, only the $x$ component is displayed. An increase in shear velocity ($V_s$), by 20% leads to a decrease in the magnitude of power spectra of the vertical displacement of roughly 38% and of the horizontal displacements of roughly 40%. Decreasing the shear velocity ($V_s$), by 20% leads to an increase of roughly 88% for the vertical displacement and 100% for the horizontal displacements.

![Figure 4.21](image)

**Figure 4.21.** Influence of shear velocity on the vertical component of the wind-induced ground displacements.
c) **Source area**

In the theoretical model the source is integrated over the entire ground surface area up to infinity. It is worthwhile to investigate the effect of the source area integration as a function of frequency to determine the effective source area for each frequency range. In this section the integration over smaller radii is computed to investigate the sensitivity of the model to the source area. Figure 4.23 displays the effect of the radius of integration area in the displacement power spectra for radii of 10 centimeters, 1 meter, and 10 meters. The results for the vertical component (z) of the displacement are shown in Figure 4.23, the horizontal components (x and y) are at the same level.
Figure 4.23. Influence of integration area on the wind-induced ground displacements.

Larger wavelengths, corresponding to lower frequencies, cover larger surface area. Hence, as Figure 4.23 displays, at lower frequencies the displacements are sensitive to the wind pressure load over larger areas. At short wavelengths (high frequency), the ground displacements are dominated by the pressure load over a smaller surface area surrounding the observation point. The displacement for frequencies above 10 Hz is determined by wind over a region of roughly 0.1 m in radius. For frequencies of about 1 Hz it is determined by wind over a region of roughly 1 m in radius. At very low frequencies, (~ 0.1 Hz), the displacement is determined by wind over a region of roughly 10 m in radius.
CHAPTER 5

CONCLUSIONS

This thesis provides predictions of three components of the ground displacements induced by wind noise fluctuations over the ground surface. The theoretical model transfers the driving pressure and shear stress perturbations on the ground surface to the ground vibrations. The measurements show that all three components of the displacement are about the same magnitude. The predictions are in good agreement for the vertical ground displacements. However, the horizontal ground displacements are significantly underpredicted. Comparison of the predictions and the measurements shows that the existing wall shear stress models significantly underpredict the amplitude of the fluctuating shear stress on the ground. The results indicate that the wall shear stress must be of the same order of magnitude of the normal pressure on the ground surface.

The existing wall shear stress models were developed and calibrated for turbulent boundary layer flow over smooth walls. The discrepancy between these results and the existing wall shear stress predictive models are likely due to roughness effects of the ground surface and unsteadiness of turbulent wind outdoors. Further work is necessary to develop a model for fluctuating wall shear stress to account for roughness effect and other additional effects of turbulent outdoor flows.

An experimental setup was introduced to measure ground displacements under controlled pure normal and tangential forces to the ground surface. This experiment verified the linear elastic rheology and the quasi-static displacements assumptions for the ground model. With this calibration, the measured seismic displacements can be used to determine the amplitude of the
wind shear stress at the ground surface associated with wind induced forces. This result can have important implications in prediction of the wall shear stress in environmental studies such as erosion studies and sediment transport studies.

The effect of the burial depth and wind velocity on the displacements has shown that the wind noise on the geophone above the ground is mainly dominated by the direct interaction of the wind with the geophone box. The wind noise increases by roughly 8 dB for an increase of 1 m/s in wind velocity. Mounting the geophone flush to the ground provides roughly 20-25 dB reduction in wind noise. However, only a very small additional reduction in wind noise with deeper burial (down to 40 cm) is realized.
BIBLIOGRAPHY


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VITA

Vahid Naderyan was born in April of 1989 in Kermanshah, Iran. He received his high-school diploma and pre-university certificate from the National Organization for Development of Exceptional Talents (NODET), Kermanshah, Iran in May of 2007. He continued his education at Isfahan University of Technology (IUT) in Isfahan, Iran, where he received a Bachelor of Science in Physics in May of 2012. He was accepted into the graduate program in Physics at the University of Mississippi in August 2012. He won the 1st place prize at the graduate school’s Three Minute Thesis (3MT®) competition for presentation of his thesis research in November of 2014. Vahid has accepted a summer research internship position with Knowles Corporation for summer 2015 in Itasca, Illinois.