Characterizing the vibrator captured ground mass system using finite element analyses

Zhouhong Wei, INOVA Geophysical Equipment Limited, Thomas F. Phillips, Dawson Geophysical Company*

Summary

Vibroseis has become the most widely used method in land data acquisition. When the vibrator baseplate is coupled with the ground, the ground seen by the baseplate is captured and becomes a part of source. Many researchers have developed methods to estimate this captured ground mass system. However, no one gives a quantified geometry of this captured ground mass system. This paper provides a theoretical study using a finite element analysis model to quantify this captured ground mass system. Meanwhile, through the finite element analysis model, the ground roll is visualized.

Introduction

Accurately knowing the vibrator captured ground mass system is vital to the macro model of the very near-surface velocity. In general, if a good coupling is assured between the vibrator baseplate and the ground, this vibrator captured ground mass will completely join with the vibrator baseplate and becomes a part of vibrator source. Usually, a simple mass-spring-damper model (Figure 1) is used to describe this vibrator captured mass system. In this model, Fg represents the vibrator ground force and Xg is the displacement of the ground mass. The parameters of Mg, Kg and Dg represent the mass, stiffness viscosity of the captured ground mass system, respectively.

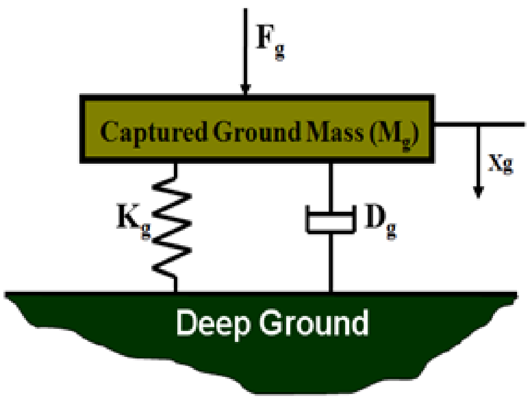

Figure 1. A simple model of the vibrator captured ground mass system.

While vibrator vibrating, the vibrator ground force pushes against this captured ground and the vibrator baseplate feels the ground response to the applied ground force. In other words, at each vibrator shot point, this captured ground system can be seen by the vibrator baseplate and the motion of this system is recorded and embedded in the baseplate acceleration signal. Therefore, the known dynamics of the vibrator (the reaction mass and baseplate accelerations) can be used to estimate underlying ground properties such as the mass, stiffness and viscosity (Safar, 1984; Wei, 2008).

In theory, the displacement of the vibrator captured ground mass will cause the far-field particle displacement. From Fig. 1, a second-order transfer function (equation 1) can be derived. Equation 1 shows that the displacement of the vibrator captured ground mass system is proportional to the filtered vibrator ground force. The filtered vibrator ground force is the output of the vibrator ground force filtered by the captured ground mass system. Additionally, it can be learned from equation 1 that the displacement of the captured ground mass system is very local. It is dependent on local ground properties at each shot point. When the vibrator moves from place to place, these parameters of the captured ground will vary. Therefore, the displacement of the captured ground mass system will vary as well from location to location. Consequently, the far-field ground particle displacement or velocity will become changeable. This is one of reasons why the far-field wavelet is not stable. The other reason, which easily can be seen from equation 1, is the variation of the vibrator ground force.

$$X_g(s) = \frac{F_g}{M_g s^2 + D_g s + K_g} \qquad (1)$$

To understand the vibrator captured ground mass system more accurately, a theoretical study using finite element analyses was performed. The main purpose of this study is to identify the geometries of the vibrator captured ground mass beneath the baseplate.

Finite element analysis model

The finite element analysis model used for dynamic simulation is constructed using the ANSYS Structure software including both static and dynamic analysis packages. This model is illustrated in Figure 2 and is consisted of three parts. The first part is the earth. It was modeled as a hemisphere with a radius of 1,000 m. In addition, absorbing boundaries were included in the form of mode damping and node-to-node damping such that the energy from the vibration would be dissipated properly. The second part is the near source ground. It was modeled as a small hemisphere with a radius of 2 m and embedded in the earth model. Because the earth model is too large, this near source ground model cannot be seen in Fig. 2. Figure 3 illustrates this model. The model size of this ground is chosen to be big enough to contain the captured ground mass. Meanwhile, the shape of hemisphere was

DOI http://dx.doi.org/10.1190/segam2013-0005.1

chosen to ensure that this near source ground would have an even response to the ground force applied. The third part is the vibrator baseplate. This baseplate was simply modeled as a small disc with a length of 0.914 m in radius and a thickness of 17.78 cm. The Young's Modulus, the Poisson's Ratio and the density are three very important parameters used to characterize the material properties. The Texas clay, its Young's Modulus, Poisson's Ratio and density are respectively 1.38 GPa, 0.25 and 1.2 g/cm^3, was assigned to the earth and the near source models. The properties of the structure steel were assigned to the baseplate disc model.

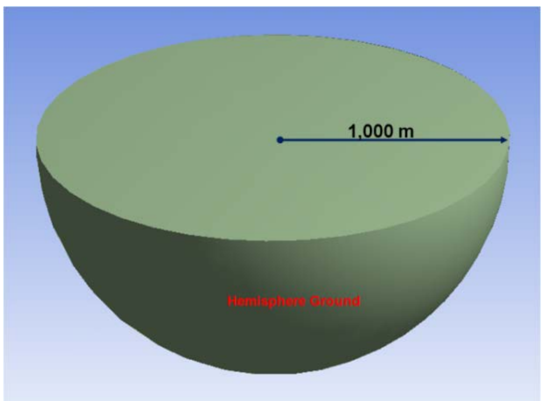

Figure 2. The finite element analysis model.

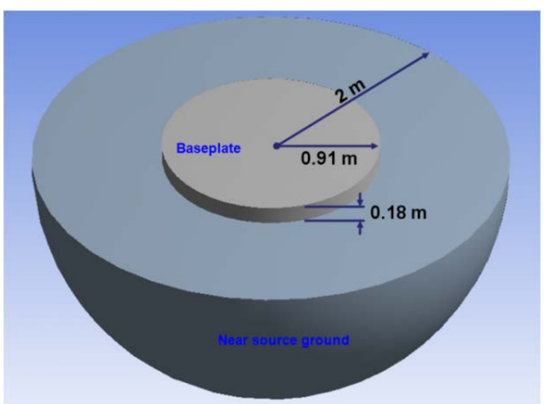

Figure 3. The finite element analysis model of the vibrator baseplate and the near source ground.

Simulation results

The deformation distribution in near source ground including the top surface is simulated as the vibrator baseplate moves up and down. Knowledge of the deformation distribution in ground allows the geometries of the captured ground to be visualized and estimated. For this study, a two-cycle sine wave at 10 Hz with a force level of 133,440 N was distributed uniformly on the circular baseplate.

Figure 4 illustrates the deformation or displacement of the vibrator baseplate (Fig. 4a) and the near source ground (Fig. 4b) when the ground force pushes the baseplate at its peak amplitude. In Fig. 4, the red color represents the maximum deformation while the light green color represents the minimum deformation. Fig. 4a shows that the vibrator baseplate achieves an even deformation of approximately 0.044 mm. This is because the vibrator ground force was evenly applied to the baseplate and the baseplate is well coupled with the near source ground. Fig. 4b shows the deformation distribution of a cross-section of the near source ground hemisphere. In this plot, the red color area means that this portion of the near source ground moves at the same displacement as the baseplate.

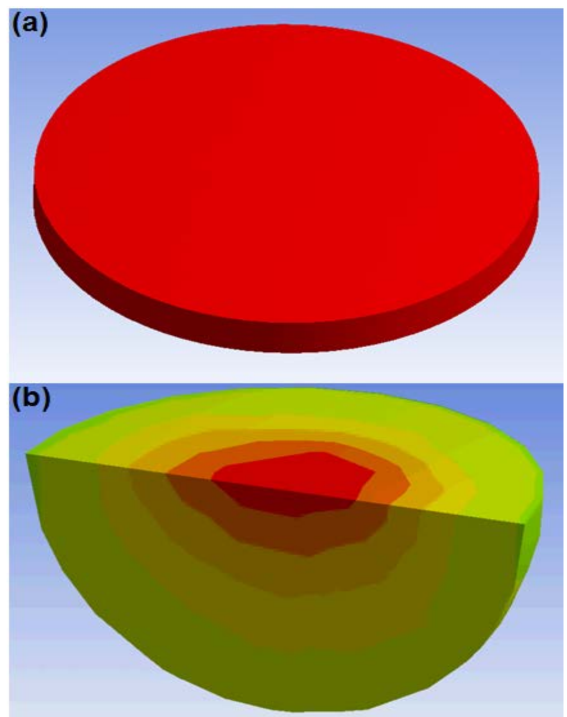

Figure 4. The deformation of the baseplate and the near source ground, (a) the baseplate, and (b) the near source ground.

Figure 5 is a detail illustration of Fig. 4b. The top plot shows the top view of the deformation distribution on the surface of the near source ground; the bottom plot shows the front view of the cross-section deformation distribution of the near source ground. The deformation shown in orange-red color is approximately 10% less than that of the red color. If a 10% deformation tolerance is allowed, the

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geometries of the vibrator captured ground mass will be identified and it is look like a spherical cap with a base radius of 1.0 m and the base height of 0.9 m. Therefore, the lumped mass in this volume can be calculated as 2154 Kg with a 1.2-g/cm^3 Texas clay density. If the volume indicated with pure red color is counted, its shape also looks like a spherical cap. The radius of the base of the cap is approximately 0.67 m, and the height of the cap is approximately 0.29 m. The lumped mass in this volume will be approximately 294 Kg.

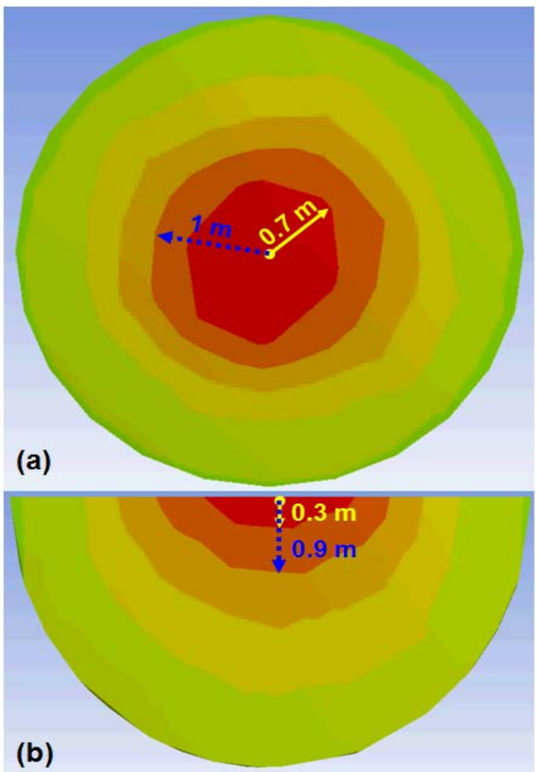

Figure 5. The deformation of the near source ground, (a) the top view, and (b) the front view.

Figure 6 demonstrates an example of the maximum stress and deformation of the captured ground. The top graph shows the wiggle trace of the maximum stress under the applied ground force; the bottom graph shows the corresponding deformation of the captured ground mass. The wiggle trace of the captured ground mass deformation is calculated when the 10% deformation tolerance is taken into account. It is obvious that at 10 Hz the deformation curve and the stress curve are kept well in phase. A slight distortion occurs at the first peak on both stress and deformation curves. However, this distortion disappears in the following peaks. The reason to cause this is unclear. Additionally, the ground stiffness can be calculated using the data shown in Fig. 6. According to Hook's law, the stiffness of an elastic body is equal to the applied force divided by the maximum deformation. Therefore, the stiffness of the captured ground system is 5.5×10^8 N/m. There is no damping (viscosity) in the captured ground because the damping is applied to the outside boundary of the earth in this finite element analysis model. With these values of the mass of the captured ground, the ground stiffness and the ground viscosity, the model shown in Fig. 1 can be quantified.

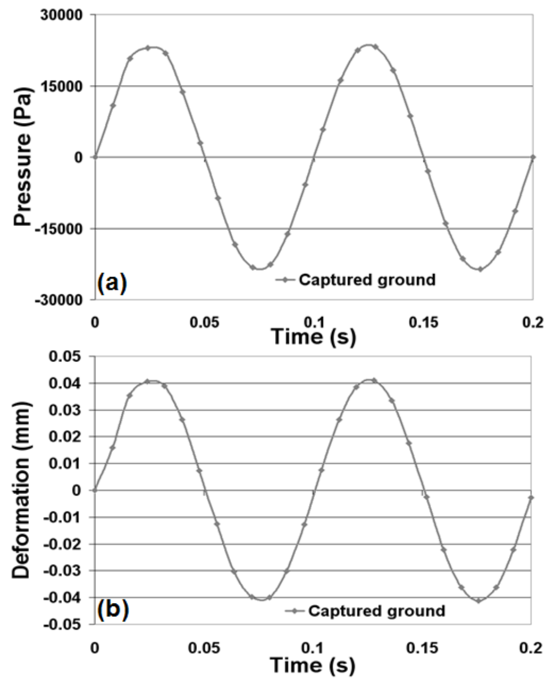

Figure 6. The vibrator shakes at 10 Hz with a force of 133,440 N, (a) the maxium stress under the applied ground force, and (b) the corresponding deformation of the captured ground mass.

Table 1 summarizes important parameters of the captured ground. From this table, it can be learned that the size or geometries of the captured ground mass is dependent on the deformation tolerance comparing to the maximum deformation is given. In general, the captured ground mass becomes large in volume as the tolerance of the deformation increases. Meanwhile, it can be seen from this table that the stiffness is relatively kept as a constant. There is no significant change in magnitude. Of course, the resonant frequency decreases as the mass of the captured ground increases. Keep in mind, in this study a full coupling between the baseplate and the near source ground was ensured.

DOI http://dx.doi.org/10.1190/segam2013-0005.1

Table 1. Parameters of the captured ground

Colors \ Parameters	Volume (m^3)	Mass (Kg)	Stress (Pa)	Deformation (mm)	Stiffness (N/m)	ω_n (Hz)
Red	0.245	294	30000	0.0443	7.1×10^8	247
Orange Red	1.795	2154	22000	0.04	5.5×10^8	80
Yellow Red	3.617	4341	19028	0.031	6.1×10^8	60
Yellow	8.5	10289	14857	0.022	6.7×10^8	41
Yellow Green	15.5	18626	10652	0.0157	6.78×10^8	30
Lawn Green	16.7	20096	6584	0.0095	`6.9×10^8	29.5

Ground roll

Ground roll presents a serious data quality problem for many land seismic surveys as it generally exhibits both long wavelength and high amplitude. With finite element analysis model, ground roll can be simulated and visualized. Figure 7 serves as an example to visualize the ground roll propagation. It does not provide any quantification on ground roll. Fig.7a shows the ground roll produced by a 10-Hz force and Fig.7b shows the ground roll produced when a 60-Hz force is used to shake the ground.

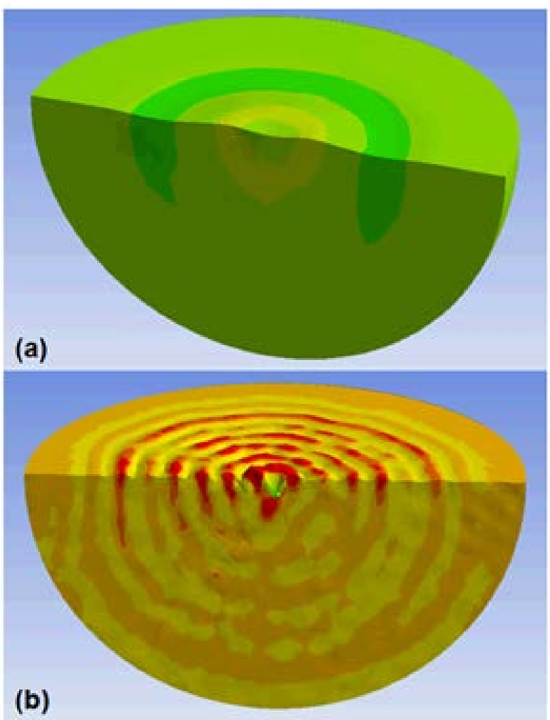

Figure 7. The illustration of the ground roll, (a) at 10 Hz, and (b) at 60 Hz.

Conclusions

Using the finite element analysis model provides a way to theoretically quantify the geometry of the vibrator captured ground mass system. With understanding the properties of the ground near the vibrator, the correct source signature can be estimated from equation 1. Additionally, the finite element simulation can be used to visually demonstrate the ground roll.

DOI http://dx.doi.org/10.1190/segam2013-0005.1

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EDITED REFERENCES

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