NUMERICAL INVESTIGATION OF UNKNOWN FOUNDATION GEOMETRY USING FULL WAVEFORM INVERSION OF SURFACE WAVES

Siavash Mahvelati, Temple University, Philadelphia, PA

Joseph Thomas Coe, Temple University, Philadelphia, PA

Abstract

As interest in foundation reuse increases, there has been renewed emphasis on methodologies to characterize existing foundations for determination of unknown geometry, material properties, integrity, and load-carrying capacity. Geophysical and non-destructive testing efforts provide an efficient manner by which to evaluate these parameters. Stiffness information from these methods can be used to evaluate foundation geometry as well as load carrying capabilities based on reverse engineering concepts. The use of surface waves as in the Multichannel Analysis of Surface Waves (MASW) method has been largely neglected for this purpose. MASW offers a number of advantages over other seismic methods due to its robustness, speed, and high signal strength. However, lack of case histories means there is limited information regarding the capabilities of MASW for the purposes of foundation evaluation. Recent efforts have highlighted deficiencies in typical MASW inversion analysis when applied for evaluating unknown foundations. The objective of this study was therefore to examine the effectiveness of MASW when applied using a full waveform inversion (FWI) technique for analysis. Numerical testing was performed on a model representing an in-service foundation system. This paper presents the numerical model followed by a discussion of data analysis and interpretation.

Introduction

It has been estimated that there are over 40,000 bridges over water across the United States that lack critical information regarding their foundation system (Collin and Jalinoos, 2014). The missing information may include, but is not limited to, foundation type (i.e., material, shallow versus deep, etc.) and its geometry (i.e., length/width/depth and depth of embedment). There are several issues and concerns that arise from the presence of these bridges. For example, as interest in bridge foundation reuse has increased, such bridges represent a liability if foundation type and load-carrying capacity are not adequately understood. Moreover, it is practically impossible to accurately evaluate the vulnerability of such bridges for scour failure, which led to a policy revision by the Federal Highway Administration (FHWA) in 2009 to label these bridges as “Scour Critical” in the National Bridge Inventory (NBI).

One promising area of recent study has been the evaluation of unknown foundations using seismic Nondestructive Testing (NDT) methods such as Multichannel Analysis of Surface Waves (MASW) (Coe et al., 2016; Nguyen et al., 2016; Mahvelati and Coe, 2017) (Fig. 1). However, results from recent MASW surveys have demonstrated only limited success for unknown foundation evaluation and have also highlighted the complications of solely relying on the interpretation of dispersion images (Coe et al., 2016; Mahvelati and Coe, 2017). Another promising area of study to address this issue is the application of Full Waveform Inversion (FWI) of surface waves. FWI has been successfully implemented in large scale problems on the order of kilometers as in such domain sizes surface waves and body waves become entirely separate, and therefore, dealing with the waveform arrivals involves less complexity (Nguyen et al., 2016). On the other hand, small scale problems (i.e., tens of meters) complicate matters due to the interactions of P/S_V waves, and fewer number of near-surface FWI studies have been carried out (e.g., Gelis et al., 2007; Romdhane et al., 2011; Kallivokas et al., 2013;

Bretaudeau et al., 2013; Nguyen et al., 2016), particularly for anomaly detection. This study presents preliminary results from numerical modeling with FWI aimed at evaluating an unknown foundation.

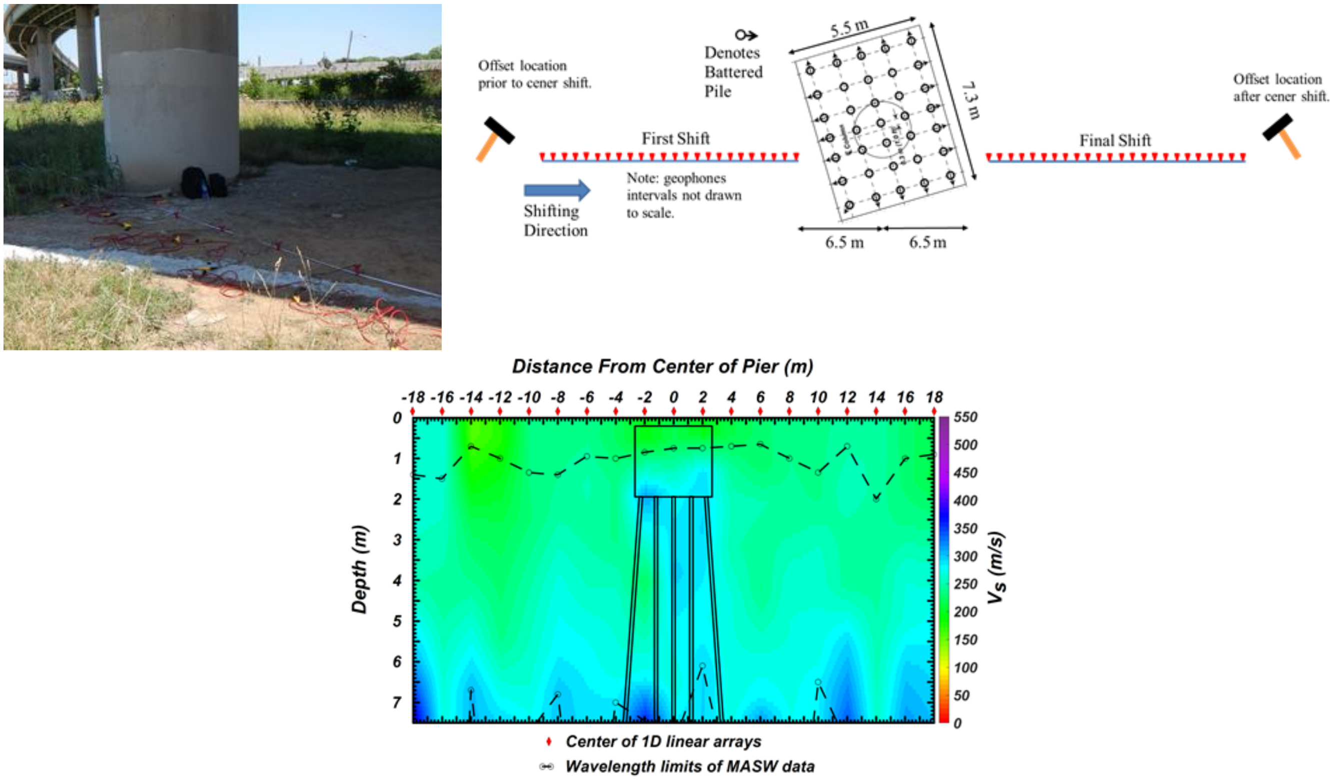

Figure 1: MASW testing to evaluate an unknown foundation: [top] layout and schematic [bottom] results from 2D MASW testing (Mahvelati and Coe 2017).

Full Waveform Inversion

FWI, initially proposed by Tarantola (1984), is a high-resolution seismic imaging method to generate velocity models by minimizing the differences between sets of observed and synthetic waveforms. In this method, synthetic waveforms from a “start” model are initially computed using a finite difference or finite element method scheme. Then, the differences between the observed and synthetic waveforms are determined using a misfit function. Several misfit functions exist in the literature [see Bozdag et al. (2011) for a summary]. Based on the differences, the starting model is updated, and this process is repeated until a convergence criterion is met. It is also necessary for the starting model to be close to the true model. Otherwise, the model updates could converge to local minima that are most likely far from the reality of the subsurface, or cycle-skipping may occur (Virieux and Operto, 2009; Borisov et al., 2016; Datta and Sen, 2016).

The FWI research code SeisFlows (Modrak et al., 2016) was used in the present study. The workflow script can be linked to several forward modeling solvers, including the two dimensional viscoelastic wave propagation code SPECFEM2D that uses a high-order piecewise polynomial approximation of the weak formulation of the wave equations (Tromp et al., 2008). Our main goal in this study is to determine the extent with which a FWI scheme could locate the anomaly associated with the unknown foundation under an ideal scenario (i.e., no free surface). Therefore, in the synthetic simulation, we did not introduce the free surface at the top boundary and all the four boundaries were subjected to Perfectly Matched Layers (PML). This necessitated the placement of the receivers at nodes located one element below the ground surface (Fig. 2). As recommended by Gelis et al. (2007), these changes reduce the complexity introduced by the top boundary and stabilized the model during FWI. The other change employed was that the V_s and V_p of the foundation were reduced to 500 m/s and 1000 m/s, respectively, in order to avoid becoming trapped in local minima expected when large contrasts exist in geobodies (Brandsberg-Dahl et al., 2017). There was less concern with accurately modeling the true stiffness properties of the foundation itself relative to the surrounding soils. The medium was discretized with a 0.5 m x 0.5 m grid size. A line of 30 sources (50-Hz Ricker wavelet) and receivers were located above the reference foundation. The start model was a homogenous soil profile with the same properties as those of the soil in the true model (Fig. 2).

Results and Discussion

Figure 3 presents the subsurface model obtained based on FWI after 10 iterations. These results suggest a buried anomaly at approximately 4.5 m below the surface with dimensions of approximately 6.0 m x 1.5 m. These results agree reasonably well with the 5.0 m depth and true foundation dimensions of 5.0 m x 2.0 m. Given the parameters that were input for the concrete stiffness, it was not expected that the predicted velocities after FWI would be accurate. However, they were quite low (approximately 285 m/s and 555 m/s for V_s and V_p, respectively) relative to the true velocity model. This can be explained by the low values in the starting model (i.e., uniform soil model with V_s = 200 m/s and V_p = 400 m/s). The inversion process was submitted to 6 cores of a laptop and the 10 iterations took 17 hours to be completed. Moreover, although this example was completed on a single computer, the inversion of more complex models with finer meshes will exponentially increase computational efforts. Such efforts would likely be necessary for complex foundation geometries, larger stiffness contrasts within the model, and more realistic soil stratigraphy. This highlights that accurate estimation of stiffness may be time prohibitive unless a more accurate starting model is selected, which may be difficult without a-priori information. Nevertheless, comparing the FWI results to those obtained with a dispersion-based MASW approach (e.g., Coe et al., 2016; Mahvelati and Coe, 2017) demonstrates that FWI provides far better insight about the subsurface and any existing anomalous features such as unknown foundations.

Conclusions

Bridges with unknown foundations present a major challenge to the safety and vitality of this nation’s infrastructure. Several techniques, including MASW, have been utilized by researchers and practitioners to characterize these foundations to varying degrees of success. The MASW method using a traditional dispersion-based approach has shown some limitations when dealing with relatively small subsurface anomalies. Due to major developments in high performance computing in recent years, FWI has received increasing attention as a way of addressing some of the weaknesses in a dispersion-based surface wave approach. This paper presented results from an FWI analysis performed to evaluate a buried foundation. The FWI proved quite robust and capable of identifying an unknown foundation which agreed well with the true dimensions. Future efforts can address the idealizations implemented in the model and explore the sensitivity of the results across multiple foundation geometries. These efforts would prove beneficial as they would model more realistic field conditions and better characterize the circumstances where an FWI approach is vital to evaluate unknown foundations.

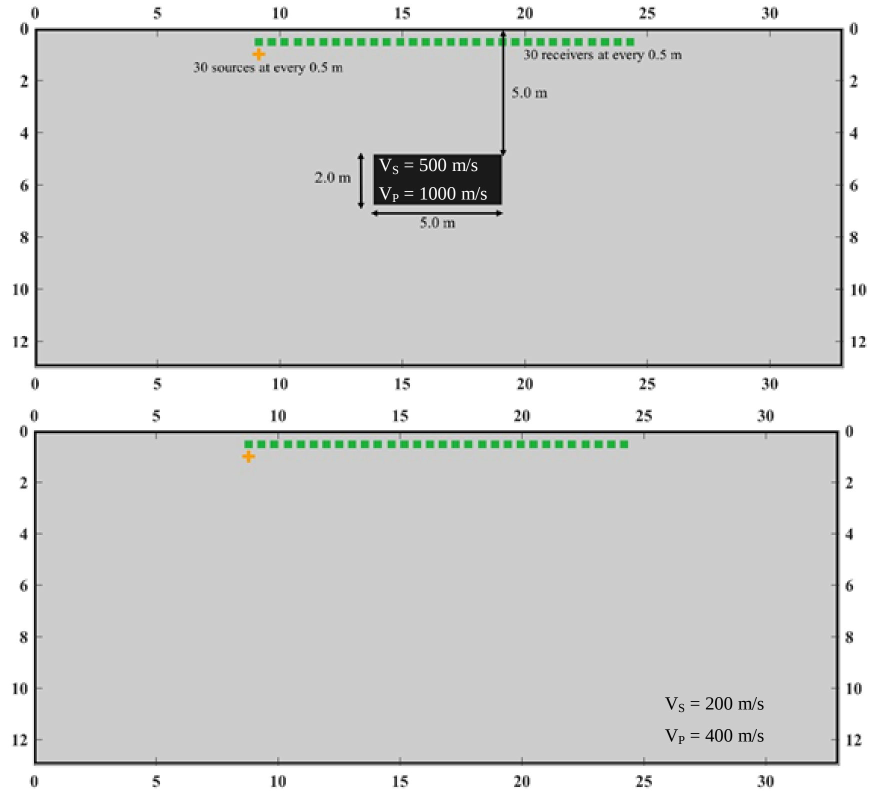

Figure 2: [top] True velocity model [bottom] start model in FWI (dimensions in meters)

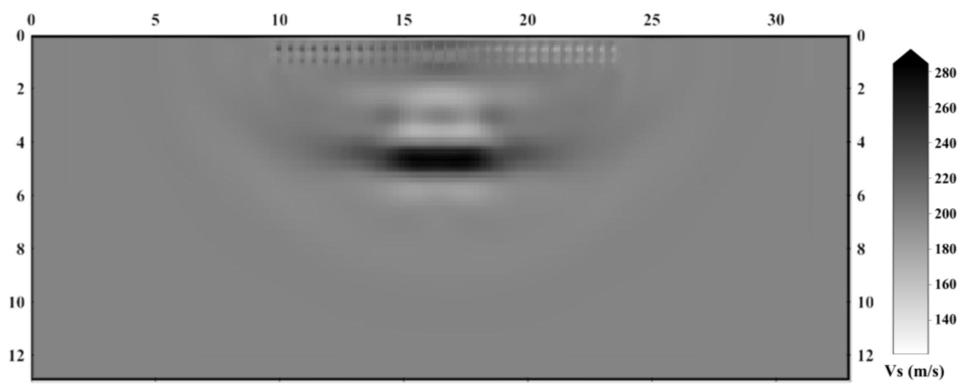

Figure 3: Output subsurface model from FWI (dimensions in meters)

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