Laterally constrained inversion of surface wave data at Najaf city (Iraq)

LATERALLY CONSTRAINED INVERSION OF SURFACE WAVE DATA AT NAJAF CITY (IRAQ)

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ABSTRACT

A case history is reported to outline a possible strategy for the construction of a pseudo-2D model of shear-wave velocity for seismic site response studies. Experimental data have been collected using the Multichannel Analysis of Surface Wave technique (MASW) at six sites in the city of Najaf (Southern Iraq). The sites are aligned along the route of a proposed subway. The dataset has been processed to extract the dispersion curves of each site and then it has been inverted by using a Laterally Constrained Inversion (LCI) algorithm. The initial model for the local search algorithm has been obtained with a preliminary Monte Carlo Inversion (MCI). A priori information from borehole logs and lateral constraints between neighboring 1D models are used to mitigate the non-uniqueness of the solution. The result is a pseudo-2D shear-wave velocity model of the area which is in good agreement with sediment lithology and thicknesses obtained from borehole logs.

Keyword: shear-wave velocity, surface waves, inverse problems, Montecarlo, site characterization

INTRODUCTION

Seismic characterization in terms of shear-wave velocity (V_S) is a prerequisite to evaluate seismic site amplification [1]. Moreover, the shear-wave velocity is directly related to soil stiffness at small strains, a key parameter in soil mechanics and foundation engineering [2]. V_S profiles can be estimated by exploiting the dispersive nature of Rayleigh surface waves in heterogeneous media. Surface Wave Methods (SWM) are based on the solution of an inverse problem; hence they are in general affected by uncertainties, which are associated to measurements and to solution non-uniqueness [3]. Still they present some important advantages such as the non-invasive nature that allows hard-to-sample geo-materials to be characterised in their undisturbed state. Moreover they usually supply a fast and cost-effective way to determine the geometry and small strain stiffness of geologic formations at engineering scale. They also provide a good resolution at shallow depth, as required for geotechnical characterization.

In surface wave analysis, the experimental data are processed to extract the dispersion curve (phase velocity as a function of frequency) which is used for the solution of an inverse problem. Typically the subsoil is modeled as a 1D layered linear elastic medium characterized by four parameters for each layer: Poisson's ratio, S-wave velocity, density, and thickness.

The inverse problem can be solved by using deterministic or stochastic inversion approaches to provide model parameters of the subsoil to a depth that depends on the maximum retrieved wavelength. The surface-wave inverse problem is ill-posed, mix-determined, and strongly nonlinear; hence, it suffers from severe solution non-uniqueness, i.e. different solutions may be equivalent as they equally honour the experimental data [3].

The use of a-priori information may significantly increase the reliability of the final velocity model. A-priori information can be derived from boreholes or other investigation techniques and can be used to define a consistent initial model or to constrain the inversion process [4]. The inversion can be accomplished with many techniques (see [5] for additional references).

In this work, we use the Laterally Constrained Inversion (LCI) algorithm [6, 7] to invert a set of dispersion curves for adjacent sites, in a way that also honors the available a-priori information. The initial model for the local search algorithm is obtained with a preliminary Montecarlo inversion [8]. The inversion strategy is similar to the one proposed by Socco et al. [7] for the analysis of ground roll data along a seismic reflection line. It can be summarised as follows:

1. Estimation of the dispersion curve for each site;
2. Dispersion curve quality evaluation and section of reliable data points;
3. Monte Carlo Inversion (MCI) of the dispersion curves to get the initial model;
4. Laterally Constrained Inversion (LCI) of the dispersion curves to supply a pseudo-2D velocity model.

The surface wave tests have been performed in the city of Najaf (IRAQ) at sites where results from other geotechnical tests are also available. This work is part of a wider project aimed to integrate surface non-invasive geophysical methods with boring and in-site tests to evaluate the geotechnical and mechanical properties of the location of the proposed tunnel of a metro project in the Najaf area. In particular because of the high seismic hazard of the region, a shear-wave velocity model is necessary for studying the seismic response of the tunnel.

SITE DESCRIPTION - A-PRIORI INFORMATION

The study area is located at Al Najaf city, which is 160 km southwest of Baghdad city (capital city of Iraq). It extends for about 7.5 km from the central square of the Najaf city to the central square of Al-Kufa town (Long. 44°19′45″ E to 44°23′57″ E; Lat. 32°0′0″ N to 32°1′46″ N; fig. 1).

The study area is located on an unfolded sedimentary plateau, between stable and unstable shelves. The latter represents the Mesopotamian zone. The mean ground level of the area is 50 m above sea level [9]. It is a flat sandy area with inclination less than four degrees toward the east. The sands represent the weathered top layer of Dibdibba sandy formation (Pliocene–Pleistocene). This formation consists of dense to very dense sand beds with thin beds of gravel, silt or clay with gypsum. The thickness of the formation reaches up to 20 m. It is underlain by Injana Formation (Upper Miocene) which is divided into two main units: the upper claystone unit and the lower clastic unit. The first one consists of brown to reddish brown massive, tough claystone. The thickness of this unit reaches 6 m or more in some places. The lower clastic unit consists of alternating clastic rocks (claystone, sandstone and siltstone) or admixtures of these rocks in different ratios. Generally, the claystone and silty claystone or siltstone beds are medium tough to tough, while the sandstones are heterogeneous through cross-bedding. The thickness of this unit reaches up to 25 m [10]. Six boreholes were drilled in this project, from which the local stratigraphy and the depth of water table have been obtained. The underground water table is about 2 m depth. Figure 2 shows the stratigraphic profile.

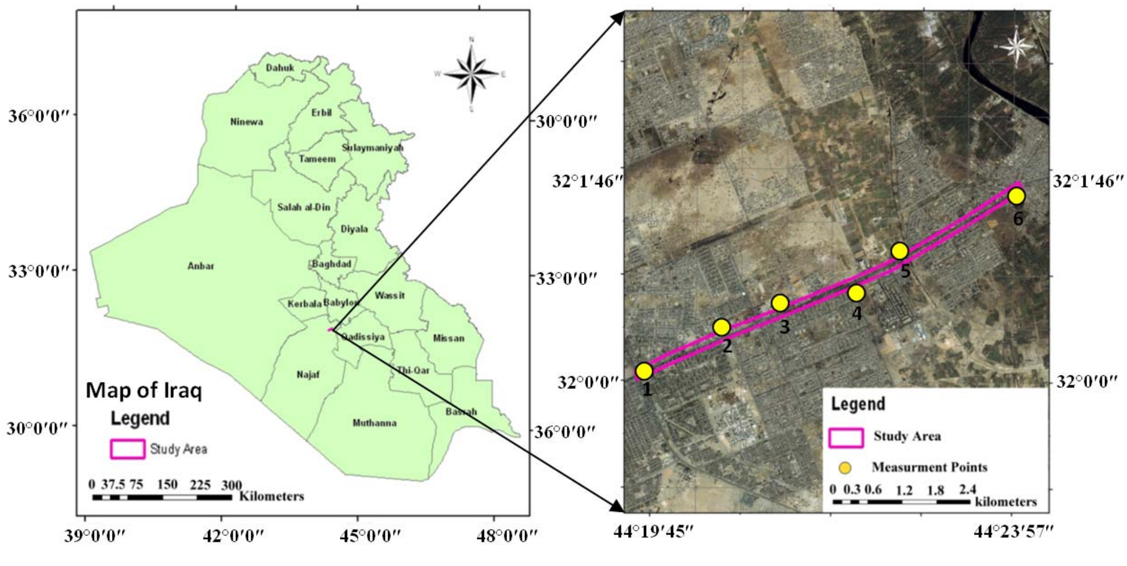


Figure 1. Map of Iraq showing the study area and the position of the testing sites.

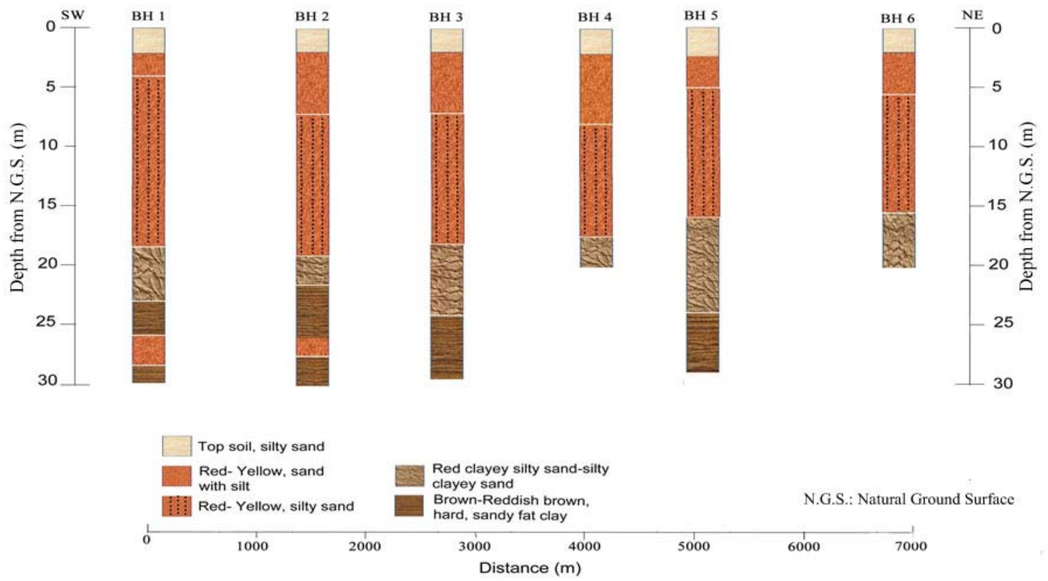


Figure 2. Stratigraphic section of the study area based on both borehole logs and laboratory test results.

SURFACE WAVE ANALYSIS

Multichannel-Analysis-of-Surface-Wave (MASW) survey was conducted at the six sites (fig. 1) by using an ABEM TERRALOC MK6 v2 seismograph and vertical geophones (10 Hz). At each site, along the same seismic line, two different acquisition geometries were adopted: one with 12 receivers and 12.5 m receiver-spacing and the other with 24 receivers and 2 m receiver-spacing, in order to achieve the best resolution for both shallow and deep layers. The two arrays share the same midpoint. Two shot points were used to generate the seismic waves by using a 15 kg sledgehammer as active source with forward and reverse shooting (with a distance between the source and the first geophone equal to the receiver-spacing); the stacking of three shots was used to enhance the signal-to-noise ratio. The signal has been further processed by performing a muting in order to remove the background noise. Near-field effects have been checked with preliminary analyses based on phase versus offset [11] and they appear to be insignificant for the frequencies resolved in this dataset.

The collected seismic records have been processed in the frequency-wavenumber (f-k) domain in order to extract the dispersion curves (the phase velocity of dominant Rayleigh waves as a function of the frequency). The maxima of the f-k spectrum represent the dispersion curve which depends on the characteristics of the site and of the acquisition layout [12]. In the present study, the normally dispersive profile lead to a dominance of fundamental mode over a wide frequency range (Fig. 3).

At the end of the processing stage, the cumulative dispersion curve has been obtained by merging the results from the two linear arrays (12 and 24 channels), in order to widen the frequency range (Fig. 4). Only the data points which were consistently retrieved from the forward and reverse shots have been considered in the inversion.

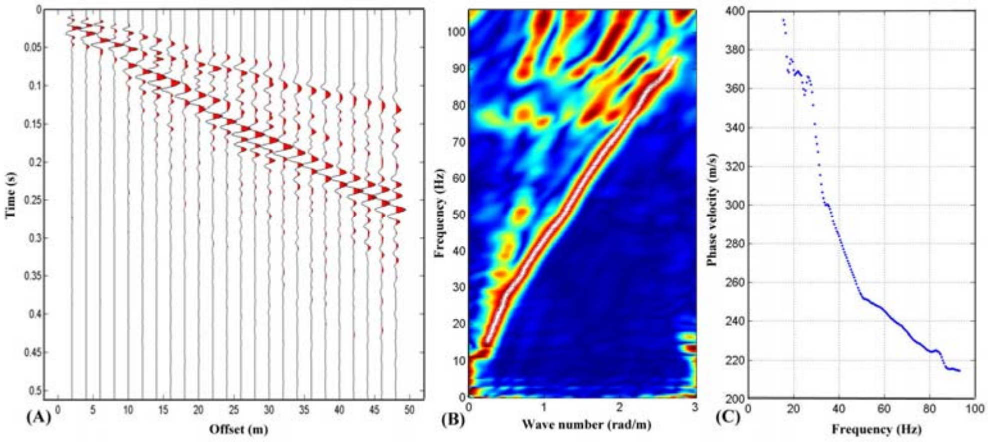


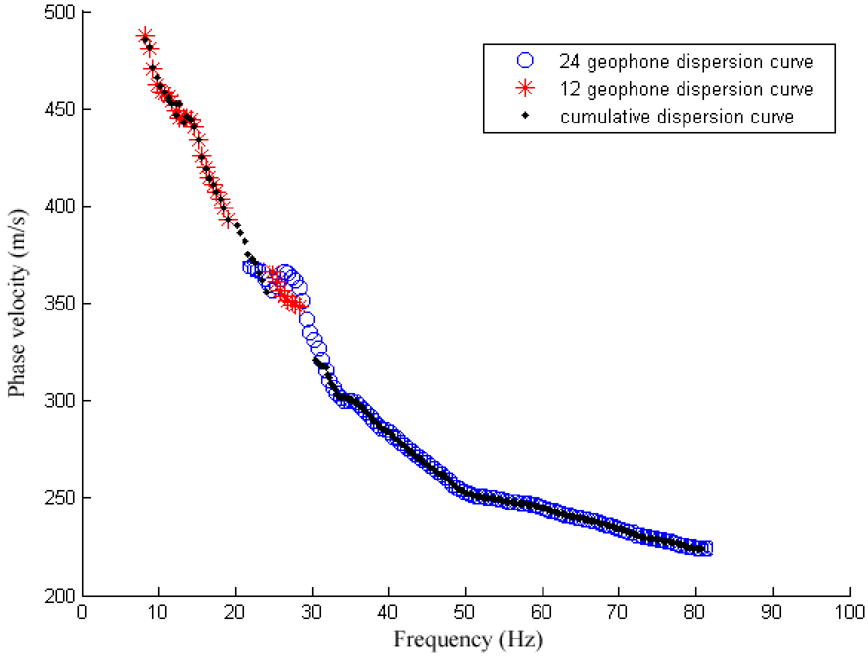
Figure 3. Example of experimental data processing to estimates the dispersion curve from 24 geophones seismic record of Site 1: A) Seismic raw data; B) f-k spectrum; C) dispersion curve.

INVERSION

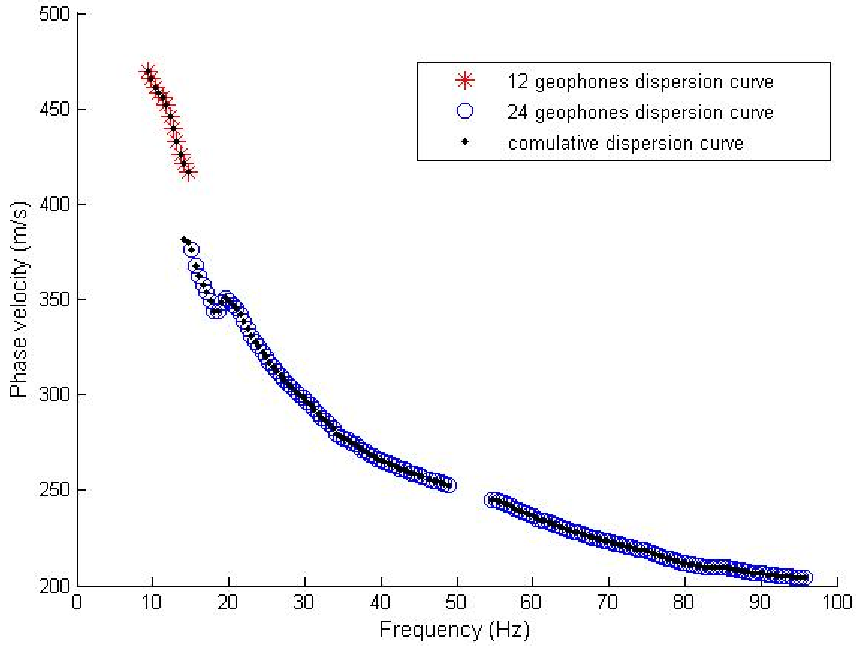
Inversion of experimental data has been implemented as a two step procedure. The best fitting V_S profiles obtained by preliminary Monte Carlo inversions (MCI) [8] were used as initial model for the Laterally Constrained inversion (LCI) [13, 7]. Both inversion algorithms use the Haskell – Thomson forward modelling [14, 15]. The unknown parameters are the shear-wave velocity and the thickness of the layers. The densities and the Poisson's ratio of the layers are assumed a-priori known on the basis of available information, since the dispersion curves are poorly sensitive to their variations. In particular the values of density range between 1800 to 2000 (Kg/m^3) as measured by laboratory tests. The values of Poisson's ratio have been assumed equal to 0.3 for shallow dry sediments and 0.48 for saturated sediments below the water table. Stratigraphic information from borehole logs has been used in the laterally constrained inversion to mitigate solution non-uniqueness.

Monte Carlo inversion (MCI)

Monte Carlo inversion (MCI) is implemented through an efficient algorithm, in which the space of model parameters is randomly explored and the theoretical dispersion curves associated with each of several possible shear-wave velocity profiles are compared to the experimental dispersion curve [8]. After defining the number of layers and the upper and lower starting values for each model parameter (shear-wave velocity and thickness of each layer) MCI generates a set of random models and calculate the associated theoretical dispersion curves. The latter are shifted as close as possible to the experimental dispersion curve by using scale properties of surface waves (if a scaling factor is applied to a shear-wave velocity model, the theoretical dispersion curve is scaled accordingly [16, 17]). With this procedure, the global distance between the experimental and theoretical curves is automatically reduced and each randomly-generated model moves as close as possible to the solution [8].
In our case, the model parameters (S-wave velocities and layer thicknesses) space has been bounded according to the a priori information and it has been sampled with a population of 100000 random profiles. Nevertheless, for the proposed algorithm, the a-priori boundaries are fictitious as the solution can be found in any position of the model parameters space [8].



(A)



(B)

Figure 4. Cumulative dispersion curve of Rayleigh surface wave obtained merging the resulting dispersion curves of the 12- and 24-channel arrays for Site 1: (A) Forward shot; (B) Reverse shot.

A group of equivalent shear-wave velocity profiles has been selected according to a statistical test on the relative misfit between theoretical and experimental dispersion curves, accounting also for uncertainties in the latter [8]. The set of profiles can therefore be assumed as a representation of the solution non-uniqueness for the specific dataset. Figure 5 shows the result obtained by MCI for Site 1, using a representation based on the relative misfit. The darkest colour always corresponds to the model having the lowest misfit with reference to the experimental dispersion curve. The same colour is used to represent each shear wave velocity model and its associated theoretical dispersion curve.

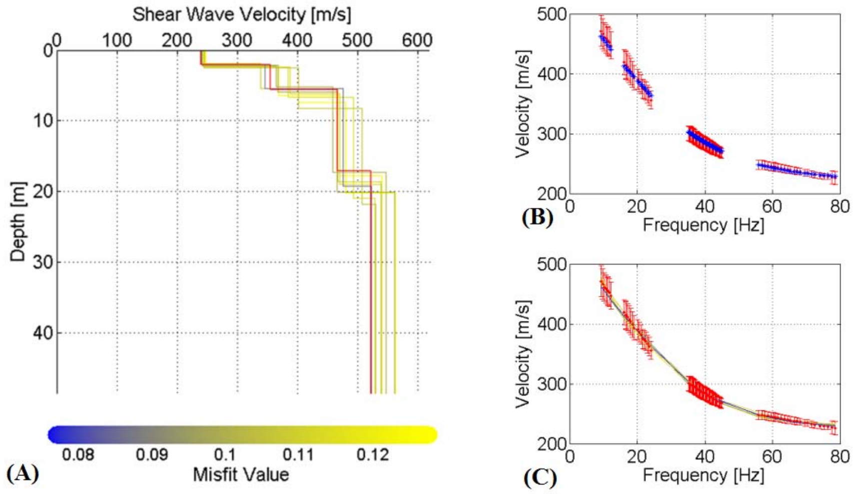


Figure 5. MCI results for Site 1: (A) Vs profiles (red = best fitting profile); (B) comparison between the experimental dispersion curve and the theoretical dispersion curve for the best-fitting Vs profile; (C) comparison between the experimental dispersion curve (the errorbars are the standard deviation of phase velocity) and dispersion curves for the group of selected Vs profiles.

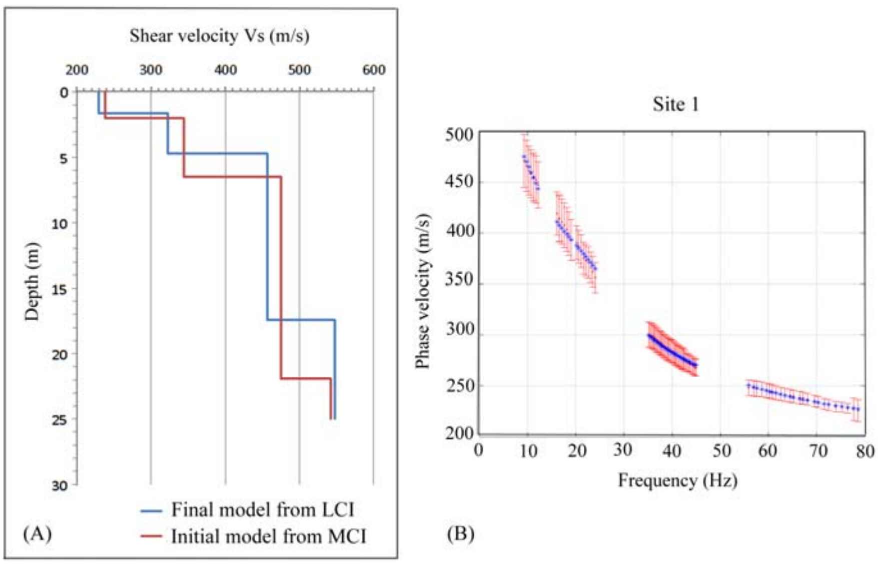


Figure 6. LCI results for Site 1: A) Vs profiles for both final model resulting from LCI and initial model based on MCI results and borehole logs; B) best fitting dispersion curve for LCI.

Laterally Constrained Inversion (LCI)

Laterally Constrained Inversion (LCI) is a deterministic inversion process in which each 1D model is linked to its neighbours with a lateral constraint to provide a single pseudo-2D model. The constraints, which could be weak or strong according to the a-priori information available for the site, act by allowing only a limited variation of each model parameter between two neighboring 1D models [6]. Constraints and any a priori available information (e.g., from drilling) can be introduced into the inversion algorithm in order to mitigate the solution non-uniqueness. The final models balance all the input data (experimental data, constraints and a-priori information). Information from one model spreads to the neighbouring models through the lateral constraints. The model parameters which are not sufficiently constrained by the available experimental data are controlled by the lateral constraints. The result represents an intermediate step between 1D and 2D/3D model reconstructions.
The initial model which we adopted for LCI was a three-layer over half-space with shear-wave velocities based on the results obtained from MCI, while the initial thicknesses were derived from the available boreholes logs. The strength of the constraints was fixed after some preliminary analyses. The strongest constraint for which experimental data are still honoured has been selected.
The results of the LCI inversion for Site 1 are compared to the corresponding initial model in figure 6a. The final model still present a good fitting between the experimental and theoretical dispersion curves (Fig. 6b), but it is considered to be more reliable because it is more consistent with its neighbour models. All the Vs profiles obtained with LCI are represented in figure 7. Figure 8 shows the smooth and consistent pseudo 2D S-wave velocity model of the study area for both final model obtained by LCI (8a) and initial model obtained by MCI (8b).
The LCI results are well correlated to the stratigraphic information available for the study area (Fig. 2), especially with reference to the position of the interface with the stiffer underlying formation (Upper claystone unit of Injana formation). Figure 9 reports the shear-wave velocity profile superimposed on the stratigraphic log for Site 1.

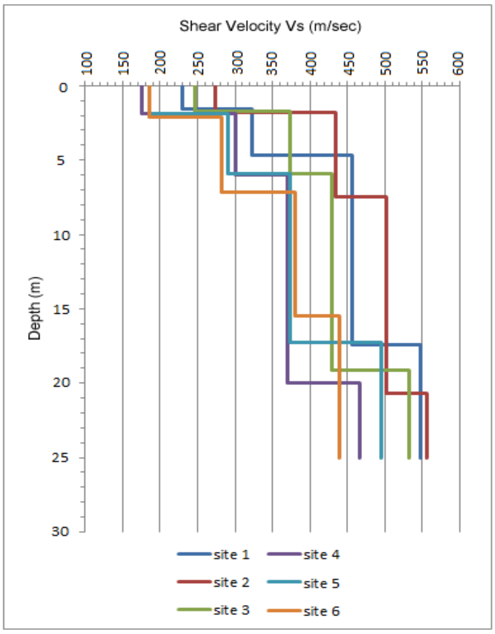
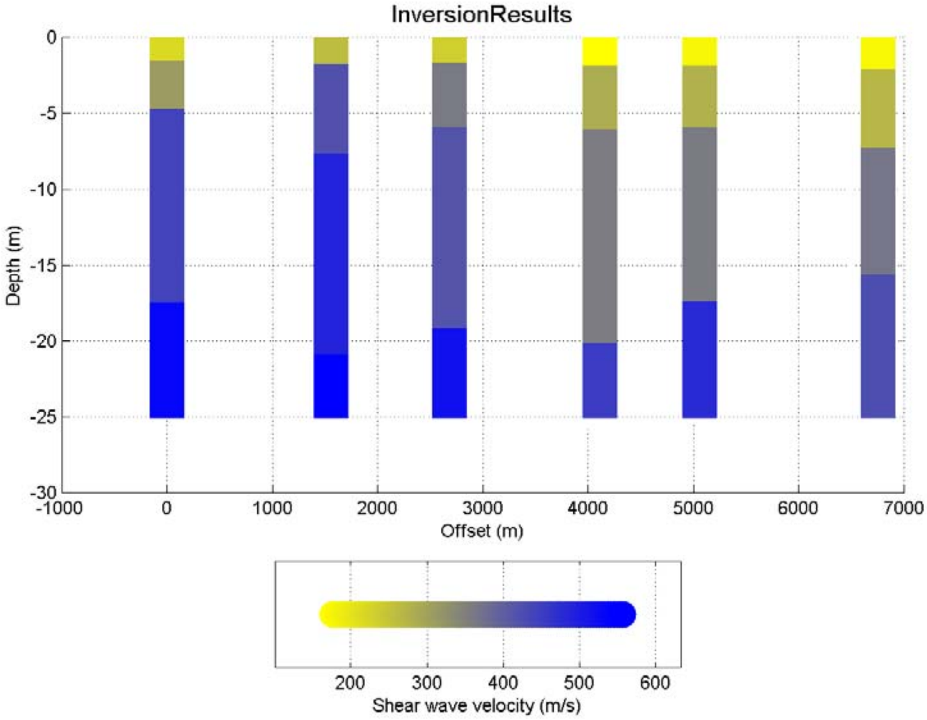
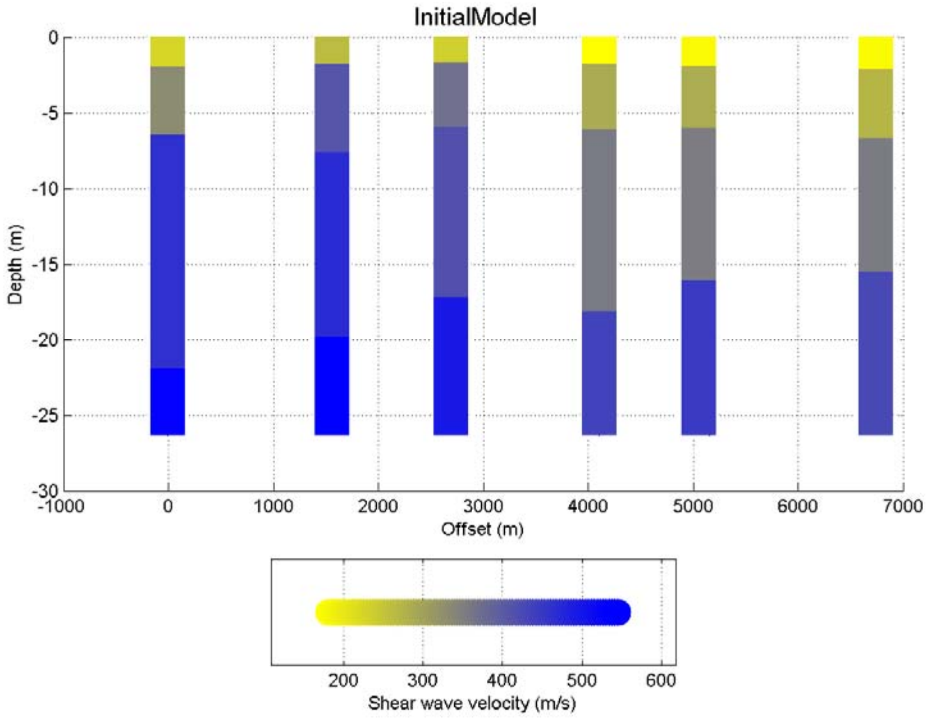


Figure 7. LCI inversion results of 1D Vs profiles for all site.



(A)



(B)

Figure 8. Resulting pseudo 2D S-wave velocity model of the study area: A) Final model obtained with LCI; B) Initial model based on the results of MCI and borehole logs.

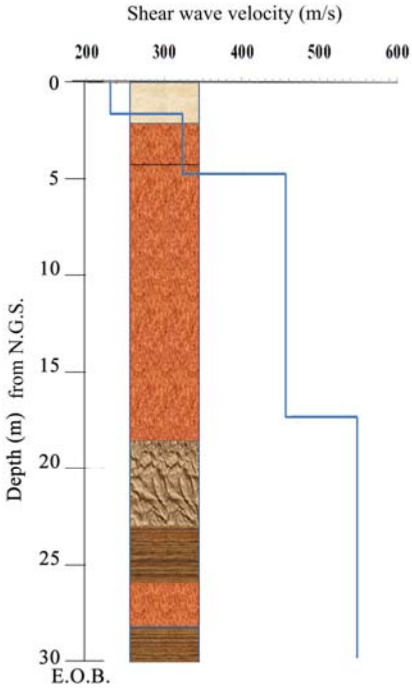


Figure 9. Final Vs profile of Site 1 against sediment lithology from the borehole log.

DISCUSSION AND CONCLUSIONS

The aim of the work was the use of Surface Wave Analysis to determine the shear-wave velocity profile of the proposed site for Metro project in Najaf city (Iraq).
Multichannel Analysis of Surface Wave (MASW) technique was used at six sites along the proposed route of the project. Data were collected with different acquisition geometries in order to improve the resolution and depth of investigation.
A preliminary Monte Carlo Inversion (MCI) has been used to provide a consistent initial 1D S-wave velocity model at each site. The dispersion curves have been then inverted simultaneously by Laterally Constrained Inversion (LCI) which accounts for lateral variations. The obtained result is a pseudo 2D S-wave velocity model, which is in good agreement with the boreholes information (thicknesses and lithology) available for this site.

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