Title of paper: **An assessment of the MASW technique incorporating discrete particle modelling**

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Abstract

A Discrete Particle Scheme (DPS) consisting of interacting circular particles is utilised to examine the Multichannel Analysis of Surface Waves (MASW) technique. Synthetic earth models of various complexity are generated using the DPS and analysed by the MASW dispersion and inversion techniques. For normally dispersive cases, dominated by the fundamental mode, the MASW profiles closely match the true synthetic shear wave velocity (V_s) profiles. When tested on a model that contains a low velocity layer, the accuracy is reduced.

MASW field tests at a highly uniform site in Norway (Onsøy) and a site with distinctive layer boundaries in Ireland (Ballinasloe) result in highly repeatable profiles of V_s. Resolution of dispersion curves at low frequencies (<10Hz) is a problem at the Ballinasloe test site, which limits the depth of penetration of the technique. MASW inversion results compare excellently with downhole seismic cone tests at the Onsøy test site and reasonably with a seismic refraction survey at the Ballinasloe site.

Introduction

The use of surface waves for the estimation of shear wave velocity profiles has received considerable attention over the last number of years. The Multichannel Analysis of Surface Waves (MASW) method is one of the more recently developed techniques and makes use of multichannel recording techniques that have similarities to those used in CMP body wave reflection surveys. The MASW method was first introduced in the late 1990's by Park *et al*. (1999) and Xia *et al*. (1999). As with the similar Spectral Analysis of Surface Waves (SASW) method (Nazarian and Stokoe, 1984), the MASW method is concerned with the shallow depths (e.g. < 35m) that are of interest to civil engineers. The most significant difference between the SASW and the MASW techniques, involves the use of multiple receivers with the MASW method (usually 12 to 60) compared to the SASW technique, which is based on a two geophone approach. The MASW technique, when used in conjunction with the software, *Surfseis* (developed by the Kansas Geological Survey), also maximises the signal to noise ratio and is therefore generally seen as an advancement on the SASW approach.

Applications of the method include elastic property determination (Donohue *et al*., 2004 and Foti, 2003), shallow anomaly detection (Park *et al*., 1998a), bedrock mapping (Miller *et al*., 1999), seismic characterization of pavements (Park *et al*., 2001; Ryden *et al*., 2001), stratigraphic layer detection (Harry *et al*., 2005), Poisson's ratio distribution (Ivanov *et al*., 2000a), and seismic characterization of underwater sediments (Park *et al*., 2000; Ivanov *et al*., 2000b, Kaufmann *et al*., 2005).

In order to evaluate the performance of the MASW technique a numerical Discrete Particle Scheme (DPS) developed in the Department of Geology, University

College Dublin by Toomey and Bean (2000) and Toomey (2001) is used. The method is also examined in the field using two well characterised sites.

Discrete Particle Scheme (DPS)

Numerical methods have become increasingly popular in geophysics over the last number of years as a means for investigating seismic wave propagation through complex geological media. These numerical methods (e.g. finite element, finite difference and boundary element), enable geophysicists to study the propagation of seismic waves through highly heterogeneous media, for which analytical solutions to the wave equation must be truncated. The DPS scheme is not based on the wave equation but instead on the underlying physics of wave propagation that occur at the atomic scale (Toomey, 2001). The method uses a particle based approach, where each circular particle represents a unit of the geological media that is to be modelled. The size of each particle is dependant on both the application of the model and the available computational power. The particles interact with one another at their contacts and are free to move in space subject to the constraints imposed by bonds with other particles.

The DPS numerical method allows the user to generate a synthetic earth model consisting of interacting particles. The particles are arranged in a closely packed, isotropic hexagonal configuration (Figure 1), where each particle is assigned a density, diameter and P wave velocity. For a hexagonal lattice the P to S wave ratio is fixed at

1.73 and Poisson's ratio, ν, is 0.25. In order to alter Poisson's ratio a different lattice geometry must be created, which was not possible. However as the sole purpose of using the DPS modelling was to test the MASW technique using synthetic seismograms from known velocity models, the value of ν was considered adequate.

A geophysical experiment is set-up in the model, with a source created (a sinc source with a specified centre frequency) and receivers (geophones) planted in the uppermost layer of particles. In each of the models presented here, 24 geophones were selected (same as for the field experiments detailed below) and the resulting synthetic seismogram was analysed using dispersion curve generation and inversion techniques utilised by the MASW method. As the shear wave velocities of the model were known, the MASW processing techniques were examined to see if they determined their correct values. A number of different models were tested, varying the velocity structure, the number of layers and the layer thickness.

DPS modelling results

Four individual models are presented here of varying complexity. Model 1 is a simple two layer model, Model 2 is a normally dispersive 4 layer model, Model 3 is an irregularly dispersive (i.e. contains a low velocity layer) 4 layer model and Model 4 is a 5 layer model with layers of different thickness.

The particle diameter for each of the models is 0.125m and each model is 840 particles wide (105m) and 798 particles deep (100m). The reason for the large model size is to ensure no reflections from the model sides interfere with the surface wave. There were 24 receivers selected at 1m intervals and the source to receiver offset was 1m. A sinc source with a centre frequency of 30Hz was used for all models detailed here. The density and wave velocities of each model are listed in Table 1 below.

The first DPS model is a simple two layer model. The synthetic seismogram for this model is shown in Figure 2a. The software, Surfseis, was used to select a dispersion curve from the phase velocity frequency spectra, which was generated using a wavefield transformation method (Park *et al*., 1998b). This dispersion image is shown in Figure 2b for the first DPS model. As shown the synthetic data has resulted in a normally dispersive phase velocity – frequency relationship dominated by the fundamental mode Raleigh wave. A dispersion curve was calculated over a frequency range of 14 – 79Hz at 1Hz intervals.

The true V_s profile for this DPS model is shown in Fig. 2c along with the 10 layer inverted MASW profile. 1-D S wave models were estimated by Surfseis using the Levenberg-Marquardt and single value decomposition inversion techniques detailed by Xia *et al*. (1999). A 10 layer inversion model was used in each of the models tested here regardless of how many true layers were present in the DPS model. As shown the MASW produced V_s profile compares well with the true model V_s profile, with an accurate estimate of the upper layer shear wave velocity and detection of the interlayer boundary at close to the true boundary. The halfspace V_s was, however underestimated between 1.5 and 5.7m depth and the inverted V_s appears to 'smooth' over the interlayer boundary. This 'smoothing' and underestimation has been observed previously by O'Neill (2004) and by Safani *et al*. (2005) for a similar two layer model. In this case the smoothing is probably a result of the large velocity contrast between layers.

The second and third DPS models are both comprised of 4-layers of identical thickness. In Model 2 there is an increase in V_s with each deeper layer (i.e. normally dispersive), whereas in Model 3 a low velocity layer (LVL) is present. The velocity of the first layer is greater than that of second layer, which results in an irregularly dispersive profile. The synthetic seismogram and resultant phase velocity frequency spectra from both of these models are shown in Figures 3 (a and c) for Model 2 and Figures 3 (b and d) for Model 3. As shown the presence of a low velocity layer has considerably changed the synthetic seismogram. It is also apparent that higher modes play a significant part in the dispersion curve image of the irregularly dispersive model.

The V_s profiles for both of these DPS Models are shown in Figures 3 (e and f), along with the corresponding inverted MASW profiles. Inverting the dispersion curve of the normally dispersive Model 2 results in a V_s profile that is very similar to the true V_s of the DPS profile. As with Model 1, clear layer boundaries are not detected, although there is a general trend of increasing velocity with depth. The depth of penetration is limited by the clarity of the dispersion image at frequencies lower than 10Hz (see Figure 3c). The inverted MASW profile has slightly overestimated the halfspace by 14.6m/s.

As shown in Figure 3f the LVL is detected however the inverted shear wave velocity of this layer is overestimated by 15m/s. Also the inversion has resulted in a second shallower (non existent) low velocity layer. As this was not detected in the normally dispersive model, this error is clearly present as a result of the true low velocity layer. Below the LVL the velocity of the third layer and the halfspace were measured very accurately.

The fourth model is a normally dispersive 5-layer model where the layer thickness is varied. The first layer is 1.25m thick, the second 1.5m, the third 1.75m and the fourth (lying directly above the halfspace) layer is 2m thick. The synthetic seismogram and resultant dispersion curve image produced for this model are shown in Figures 4a and 4b respectively. As shown the synthetic data has resulted in a normally dispersive phase velocity – frequency relationship dominated by the fundamental mode Raleigh wave. A dispersion curve was calculated over a frequency range of 12.5 – 90.5Hz at 2Hz intervals.

The V_s profile for this DPS Model is shown in Figure 4c along with the corresponding inverted MASW profile. As shown the MASW V_s profile compares well with the true DPS V_s profile. As with previous models the inverted 10 layer V_s profile has not detected clear layer boundaries, although there is a general trend of increasing velocity with depth which corresponds closely with the true DPS model. This may be due to the small differences in the velocities of the individual DPS model layers. The inverted MASW profile slightly underestimated the fourth layer (by 7.9m/s) and overestimated V_s of the halfspace (by 15.7m/s).

Field testing

A number of field tests were carried out to test both the repeatability of the MASW technique and also to provide comparison with other recognised techniques.

The seismic data, at each site was recorded using a RAS-24 seismograph (with 24 geophones) and the corresponding Seistronix software. In both of the sites detailed here a 20lb sledgehammer was used to generate the Raleigh waves which were in turn detected by either 10Hz or 4.5Hz geophones. The field configuration (i.e. geophone spacing and frequency, source to receiver offset) for each of the sites under investigation is detailed in the sections below.

The shear wave velocities (V_s) determined from the MASW method for the Onsøy site are compared with corresponding down-hole seismic CPT (SCPT) data and the Ballinasloe site is compared to a seismic refraction profile.

Onsøy test site, Norway

The Onsøy test site is the main soft clay research site currently used by the Norwegian Geotechnical Institute (NGI). Extensive research work has been carried out on the site since the late 1960's. It is located about 100 km southeast of Oslo, just north of the city of Fredrikstad. The site is underlain by very uniform marine clays of the order of 40 m in thickness and it is described in detail by Lunne *et al*. (2003). Due to the uniformity of the site it was decided to perform five MASW surveys in close proximity to each other in order to investigate the repeatability of the technique. The tests were all parallel and located only 1m apart.

The field set-up for each of the Onsøy profiles consisted of 24 geophones (10 Hz), at 2m intervals collinear with a chosen source location. A number of different source locations were chosen for each profile to determine the optimum acquisition parameters, at source receiver offsets of 0, 2, 4 and 10m (see Park *et al*., 2002). A typical shot record and the corresponding dispersion curve image acquired at Onsøy are shown in Figures 5 a and b respectively. As shown the dispersion curve image is dominated by the fundamental mode Raleigh wave. Even though 10Hz geophones were used, the fundamental mode is observed at a frequency as low as 4Hz, an observation similar to that of Park *et al*. (2002). A dispersion curve was calculated over a frequency range of 4.5 – 25.5Hz at 1Hz intervals.

V_s values inverted for the MASW surveys at Onsøy are presented in Figure 5c, along with down-hole Seismic CPT measurements (Eidsmoen *et al*., 1985). The depth of penetration of the MASW method for all of the profiles was between 14.5m and 16.2m. There is excellent agreement between all of the MASW profiles for this site.

There is also excellent agreement between the MASW profiles and the seismic CPT profiles of V_s, with the MASW profiles generally lying within the variation of the SCPT profiles.

Ballinasloe test site, Ireland

The Ballinasloe test site is located approximately 150km west of Dublin and about 70 km east of Galway, in the midlands of Ireland. Shortly after performing the MASW survey a number of boreholes were drilled at the exact same location, which provides a comparison between the inverted velocities and the subsurface geology. The ground surface at this site is underlain by a shallow organic layer (1.2m) of very soft Peat, which is common to sites in the centre of Ireland. Lying directly below the peat is a layer of uniform soft clay (1.2m - 8m depth), which in turn overlies a layer of dense sand and gravel at a depth of 8m. As three distinctive strata were present at the site it was hoped that the MASW technique could resolve each of the layer boundaries.

Two MASW survey lines were performed for the Ballinasloe site, again to test the repeatability of the survey. The first (MASW 1), consisted of 10Hz geophones at 1m intervals. MASW 2 was performed at the same location as MASW 1 and consisted of 4.5Hz geophones, at 1m intervals. For the first profile, shot records were acquired on opposite sides of the receiver spread (labelled opposite in Fig. 6c).

A number of different source locations were chosen for each profile, to determine the optimum acquisition parameters, at a number of source-receiver offsets between 1m and 10m. An example of seismic data acquired at Ballinasloe is shown in Figure 6a with the corresponding dispersion curve image shown in Figure 6b acquired when using 4.5Hz geophones. As with Onsøy the dispersion curve image is dominated by the fundamental mode Raleigh wave. It was observed that at frequencies lower than 9Hz the dispersion image became unclear and disjointed. As a result the 4.5Hz geophones could resolve frequencies of 7Hz whereas the 10Hz geophones could resolve frequencies no lower than 9Hz. This limited the depth of penetration of the technique at this site.

V_s values inverted for the MASW surveys at Ballinasloe are presented in Figure 6c, along with a seismic refraction shear wave velocity profile performed on the same day and at the same location as the MASW profiles. The field setup for the seismic refraction survey consisted of 12 s-wave receivers, at 3m intervals, with source receiver offsets of 0m, 15m and a mid point shot gather. The depth of penetration of the MASW method when using the 10Hz geophones (profiles MASW 1a and 1b) was 6.7m, whereas when using the 4.5Hz geophones (MASW 2) the depth of penetration was 9.6m.

There is excellent agreement between all of the MASW profiles for this site. The seismic refraction survey compares reasonably well with the MASW profiles although it consistently gives a higher V_s above 5m depth.

As shown in Figure 6c the MASW method detects each of the three layers identified by the subsequently drilled boreholes. It identifies the very low velocity peat layer to a depth of approximately 1.3m, and shows V_s increasing for the soft clay from 66m/s at 1.2m depth, to 162m/s at a depth of 7.7m. Only the survey which employed 4.5Hz geophones was able to detect the layer of dense sand and gravel, which is evidenced by a significant jump in V_s at a depth of 7.7m depth. Interestingly the refraction survey failed to pick up this layer.

Conclusions

The MASW technique was firstly tested numerically using a Discrete Particle Scheme (DPS) by generating synthetic seismic data from a number of synthetic earth models of varying complexity. When tested on normally dispersive models, dominated by the fundamental mode, very accurate V_s profiles were obtained, when compared to the true modelled velocities. Increasing the complexity of these models did not appear to reduce the accuracy of the resulting V_s profiles. For a model with a large velocity contrast it was observed that the inversion resulted in a 'smooth' transition of shear wave velocity between layers rather than a single increase in velocity.

When tested on a model that contained a low velocity layer, the accuracy of the inversion was reduced. Although the inverted MASW V_s profile was quite similar to the actual model profile, and the reversal was detected, a shallower non existent LVL was introduced during the inversion.

Field tested at two sites, the MASW technique was shown to be highly repeatable. At the Ballinasloe test site, however, the depth of penetration was limited due to difficulties in resolving low frequencies, particularly when 10Hz geophones were used. There was excellent agreement between the MASW V_s profiles and the seismic CPT profiles of V_s for Onsøy. V_s determined using the seismic refraction method compared reasonably with the MASW technique at Ballinasloe. The inverted V_s profile for

Ballinasloe clearly detects each of the layer boundaries confirmed by subsequent boreholes.

Although automation is possible using MASW, to achieve confident profiles of V_s it is highly recommended that surface wave data is manually processed. Overall the MASW technique has performed very well and has produced very repeatable and accurate profiles of shear wave velocity.

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Figure and Table Captions

Figure 1 The discrete particle scheme consists of particles arranged in a hexagonal geometry. Each particle is bonded to its six surrounding neighbours.

Figure 2. (a) Synthetic seismogram, (b) dispersion image and (c) inverted MASW V_s profile compared with true $V_{s,}$ for Model 1

Figure 3. (a, b) Synthetic seismograms, (c,d) dispersion image and (e,f) inverted MASW V_s profiles for Model 2 and Model 3

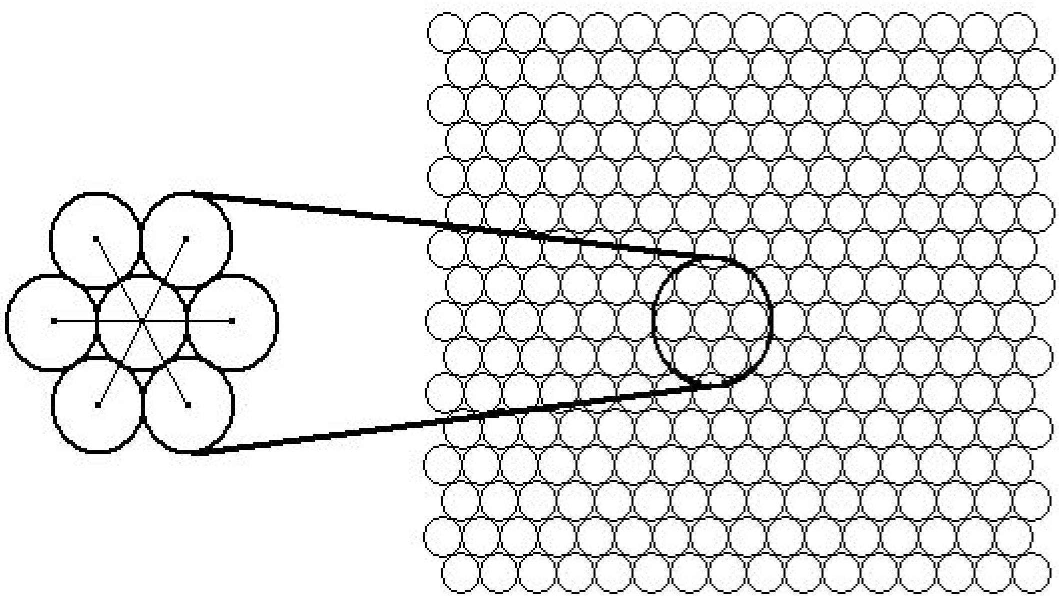
Figure 4. (a) Synthetic seismogram, (b) dispersion image and (c) inverted MASW V_s profile compared with true $V_{s,}$ for Model 4

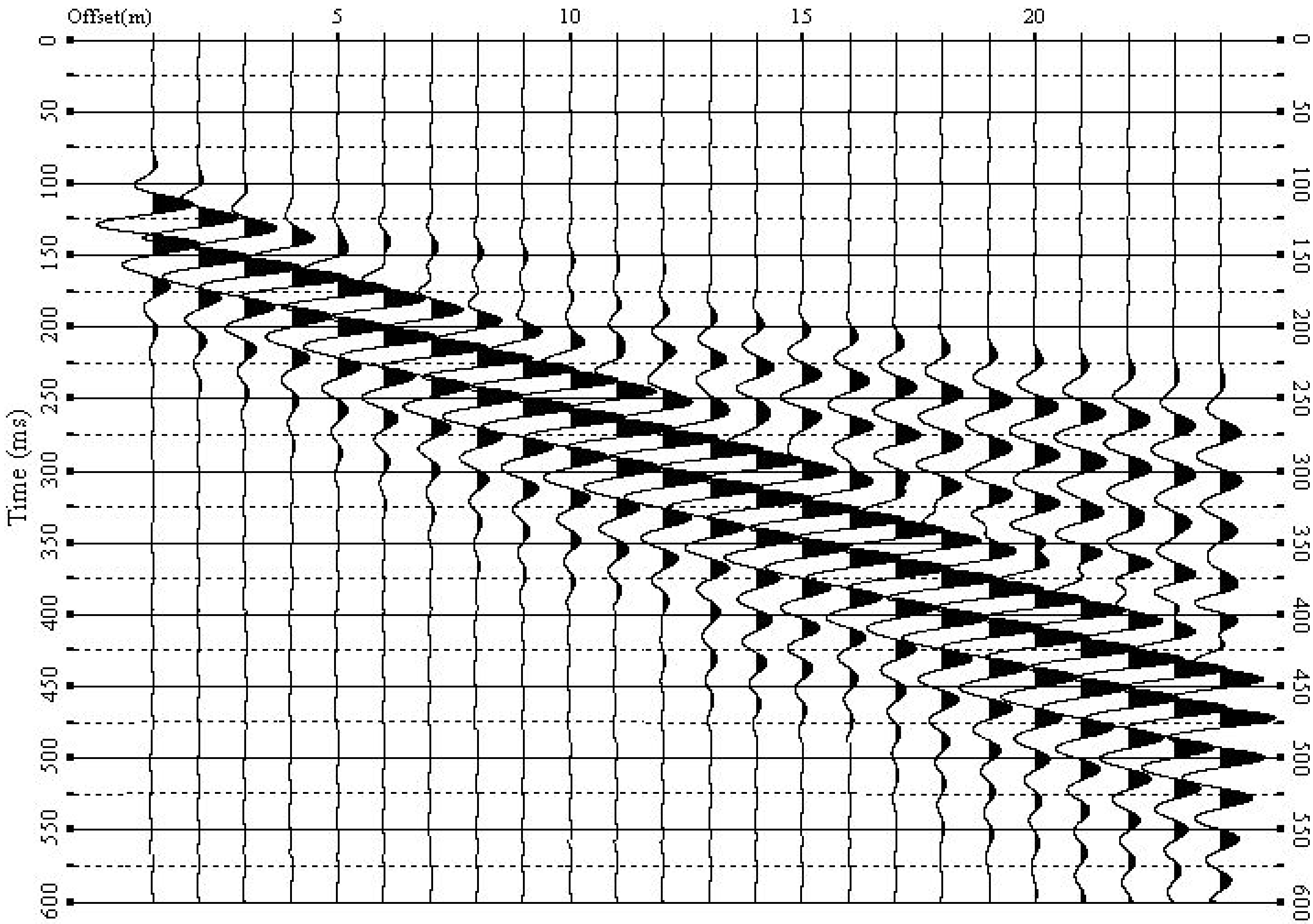
Figure 5. (a) Typical shot record, (b) dispersion image and (c) V_s from MASW compared with down-hole SCPT survey (Eidsmoen *et al*, 1985) from the Onsøy test site

Figure 6. (a) Typical shot record, (b) dispersion image and (c) V_s from MASW compared with seismic refraction survey from Ballinasloe test site

Table 1. Input parameters for DPS models, where V_p, V_s are the P wave and S wave velocities, and ρ = density

		Thickness (m)	V_s (m/s)	V_p (m/s)	ρ (kg/m^3)
Model 1	Layer 1	1.5	115.6	200	1850
	Halfspace	∞	289	500	2100
Model 2	Layer 1	3	144	250	1900
	Layer 2	3	173	300	1950
	Layer 3	3	202	350	2000
	Halfspace	∞	231	400	2000
Model 3	Layer 1	3	144	250	1900
	Layer 2	3	115.6	200	1850
	Layer 3	3	173	300	1950
	Halfspace	∞	231	400	2000
Model 4	Layer1	1.25	115.6	200	1850
	Layer2	1.5	144	250	1900
	Layer3	1.75	173	300	1950
	Layer4	2	202	350	2000
	Halfspace	∞	231	400	2000

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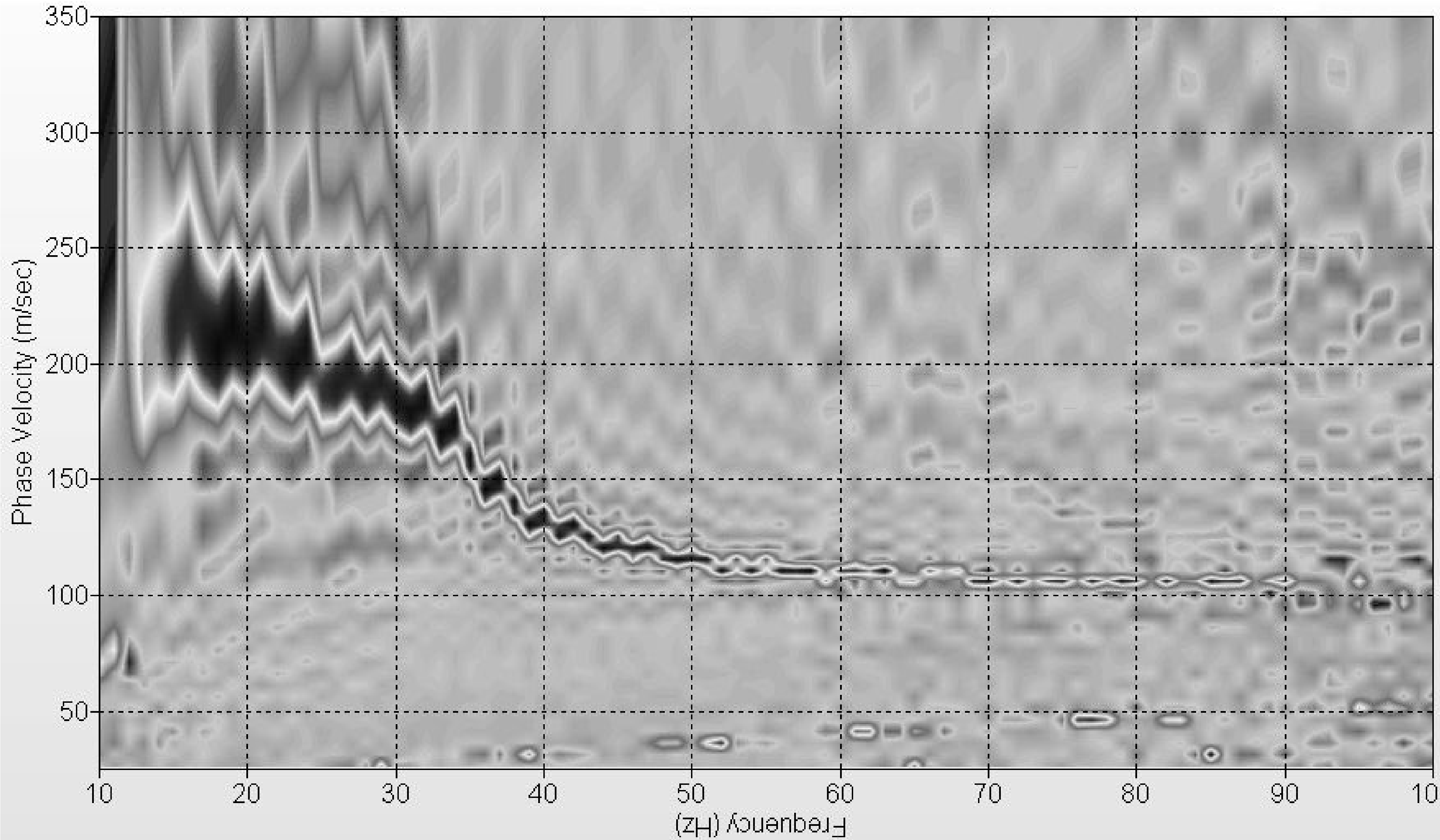
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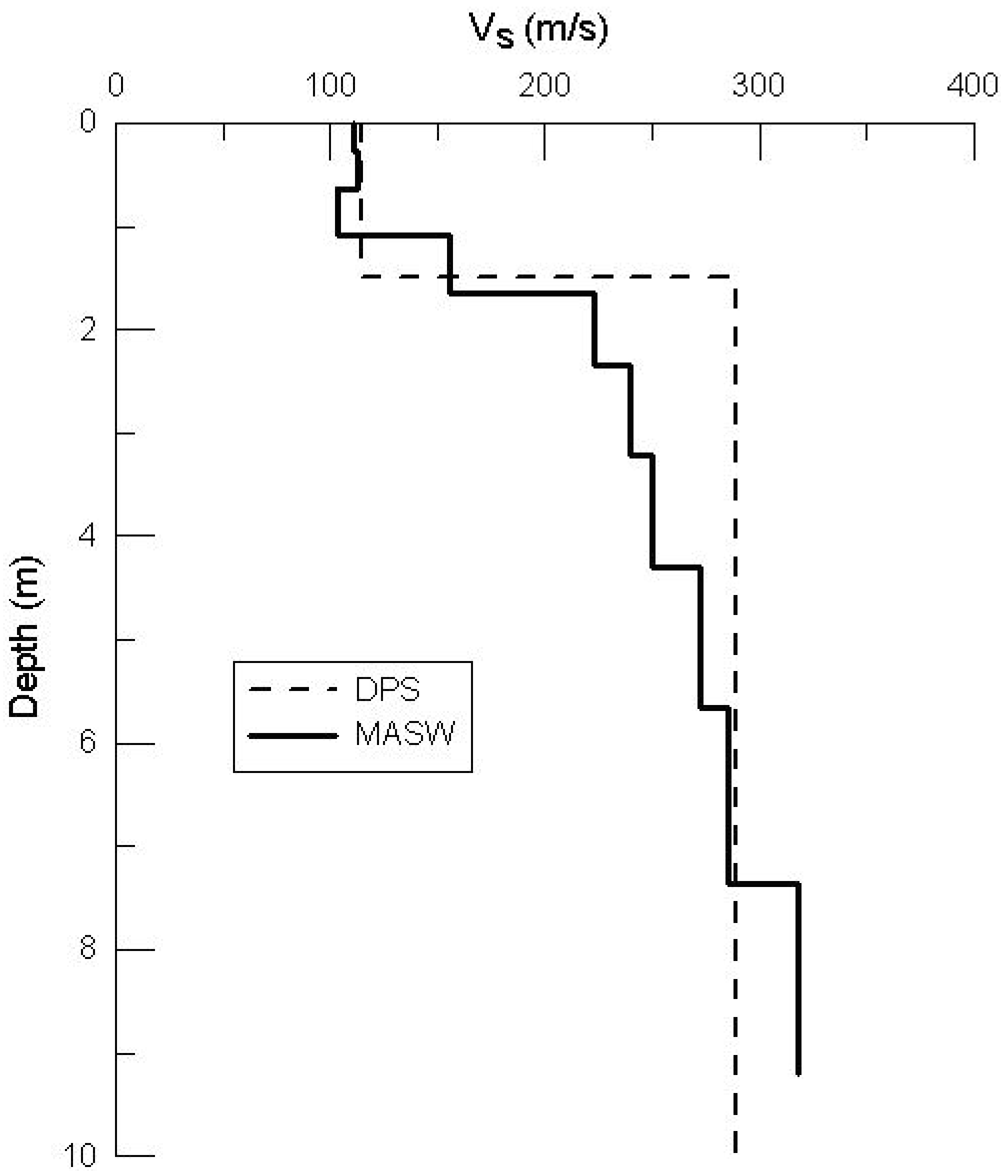
100
Frequency (Hz)



V_S (m/s)
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6
8
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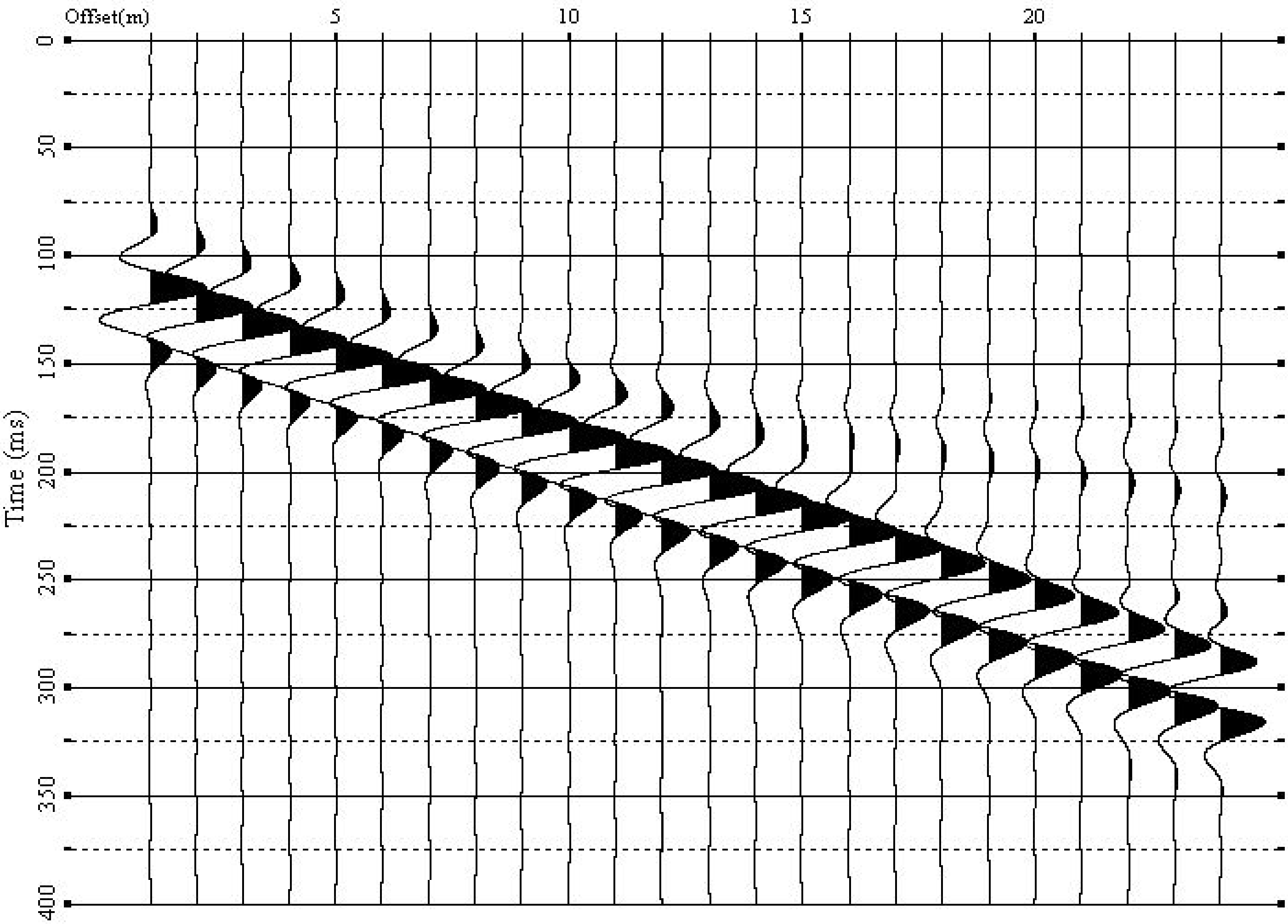
Depth (m)
DPS
MASW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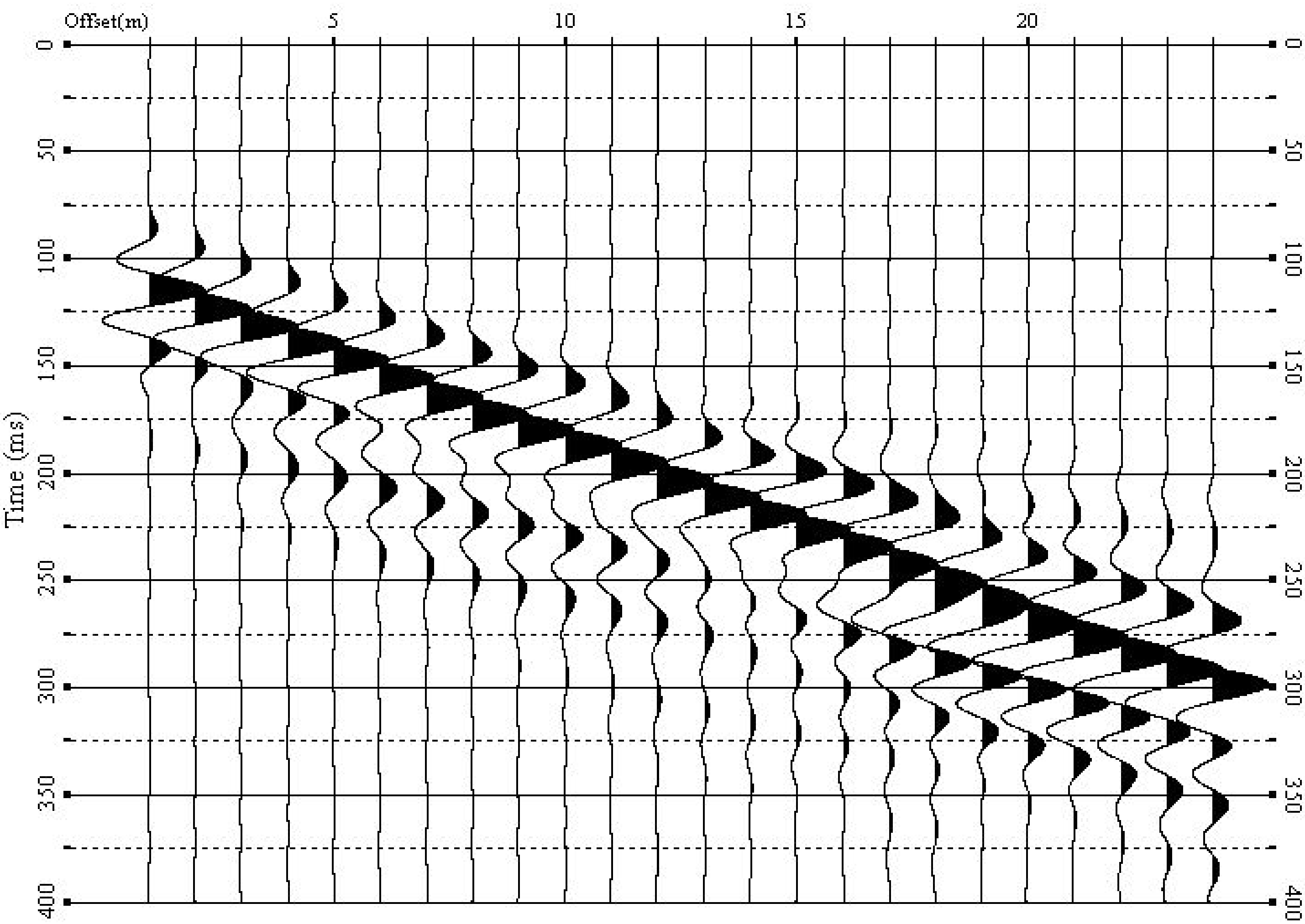

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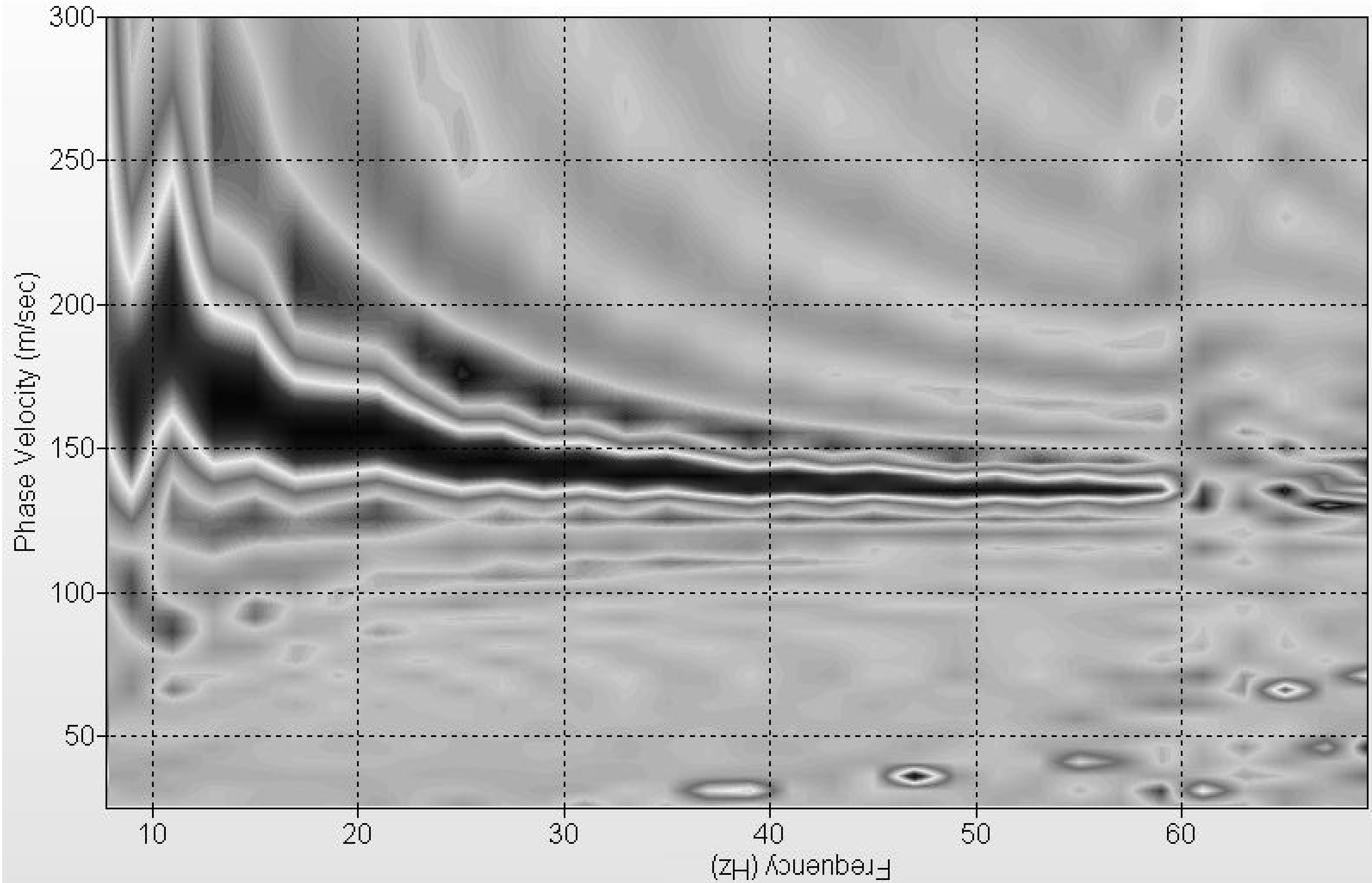
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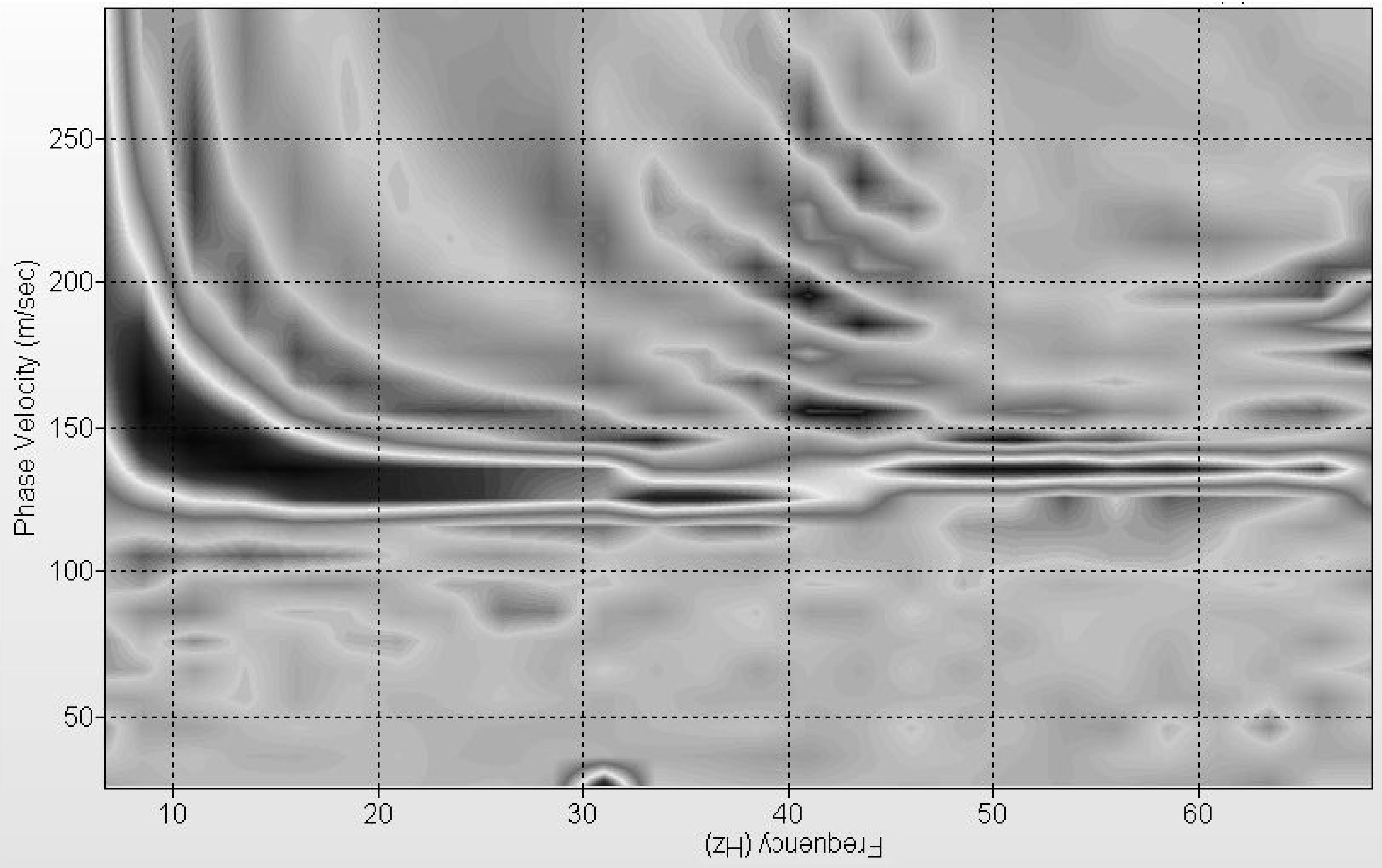
Frequency (Hz)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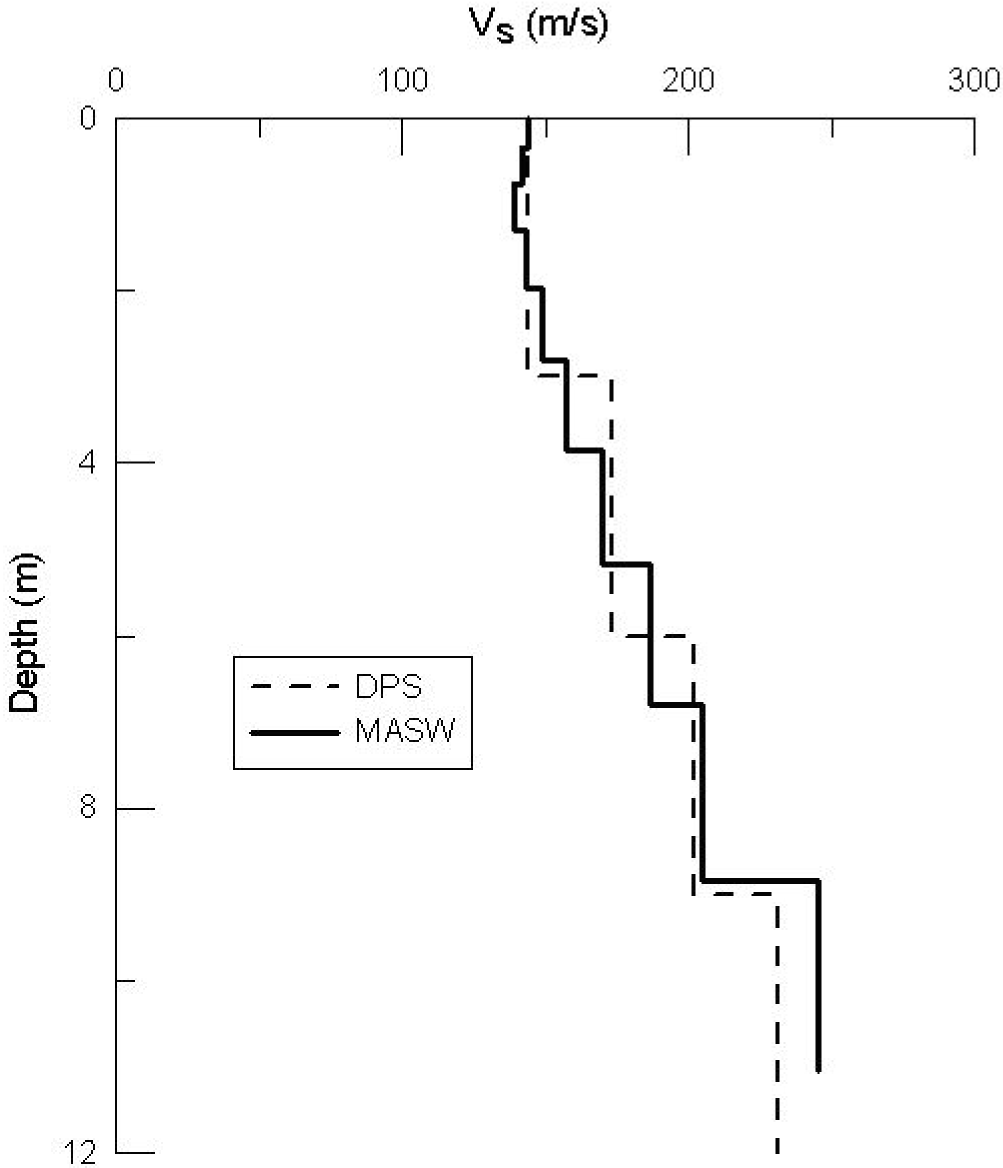
Frequency (Hz)



V_S (m/s)
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8
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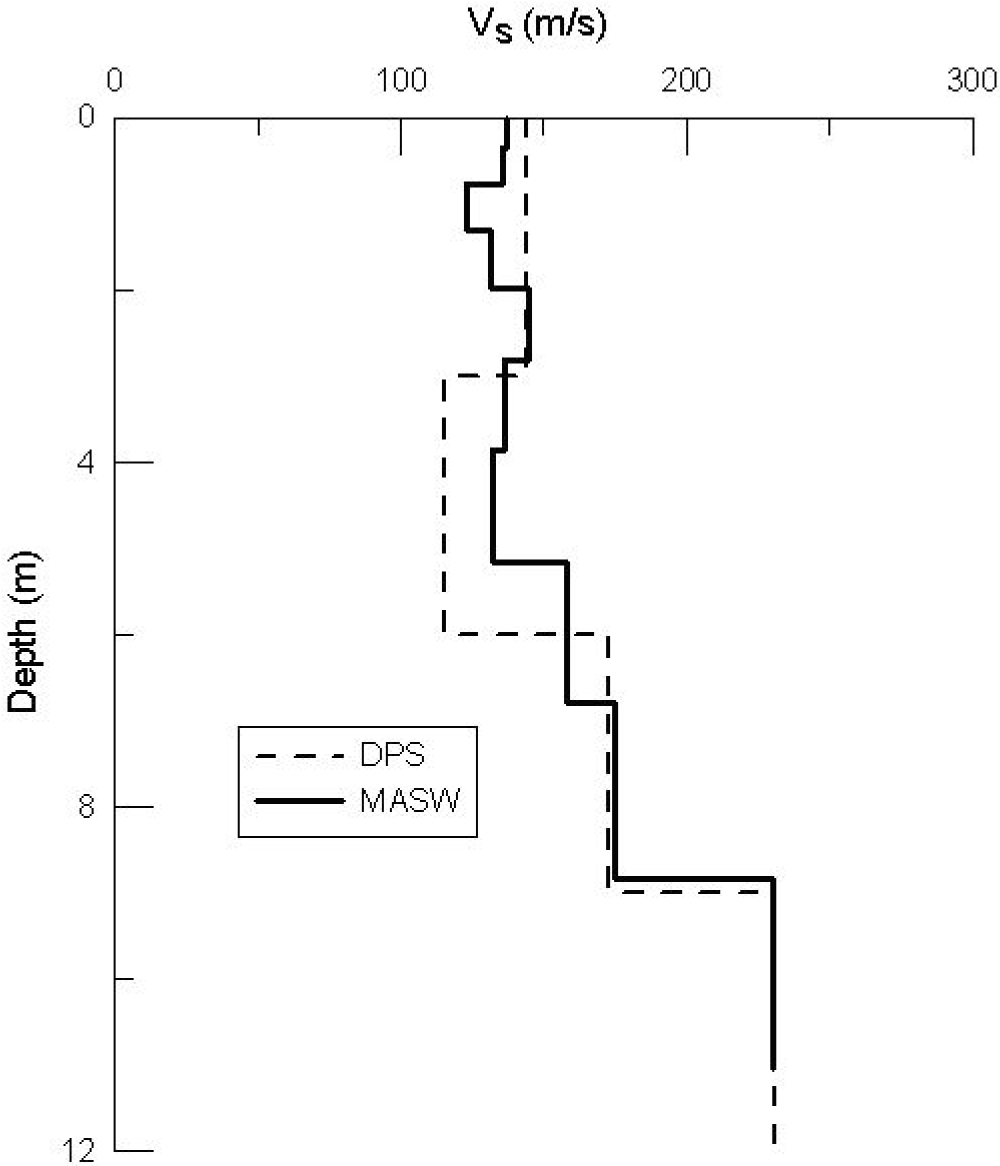
Depth (m)
DPS
MASW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8
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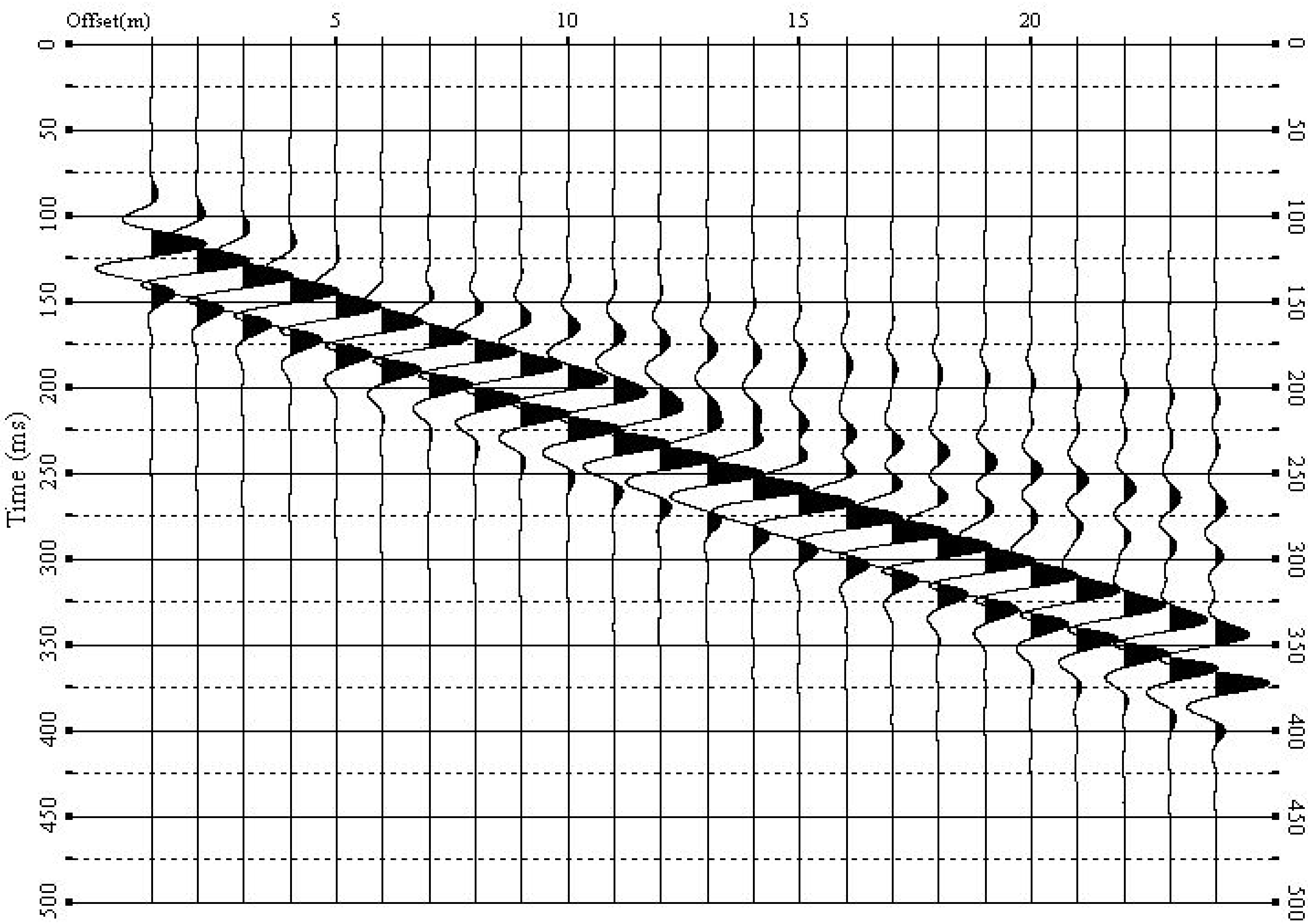
Depth (m)
DPS
MASW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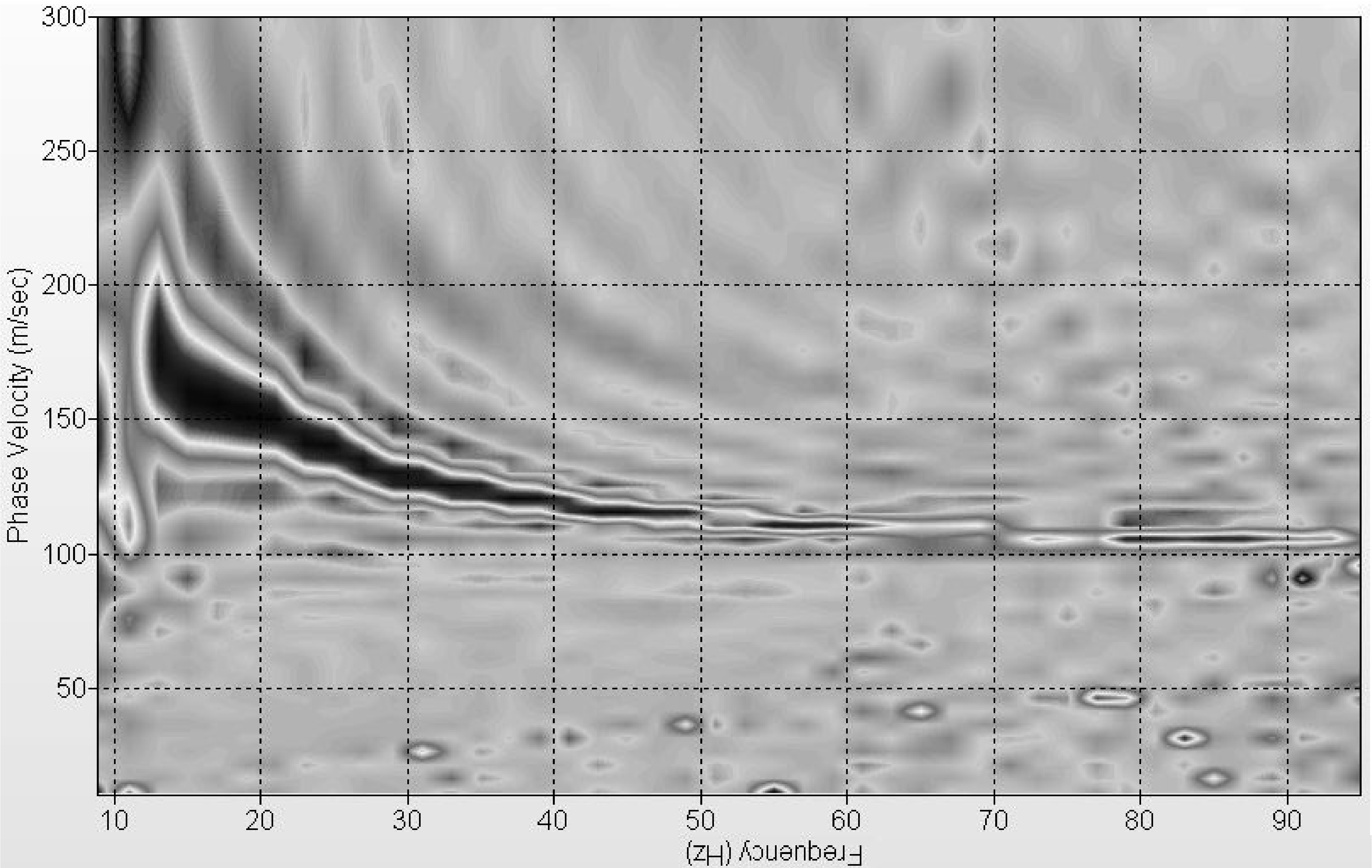

Phase Velocity (m/sec)
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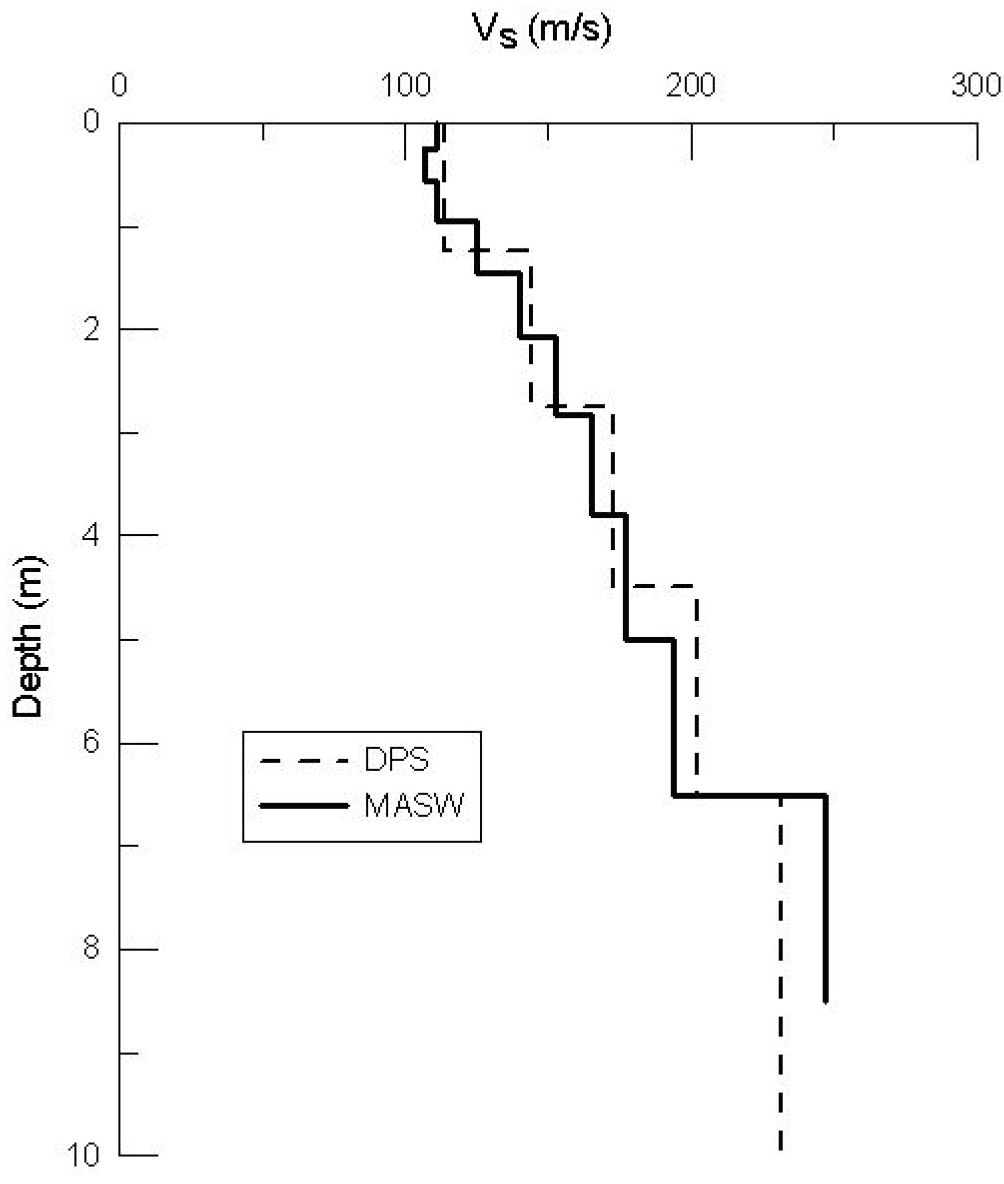
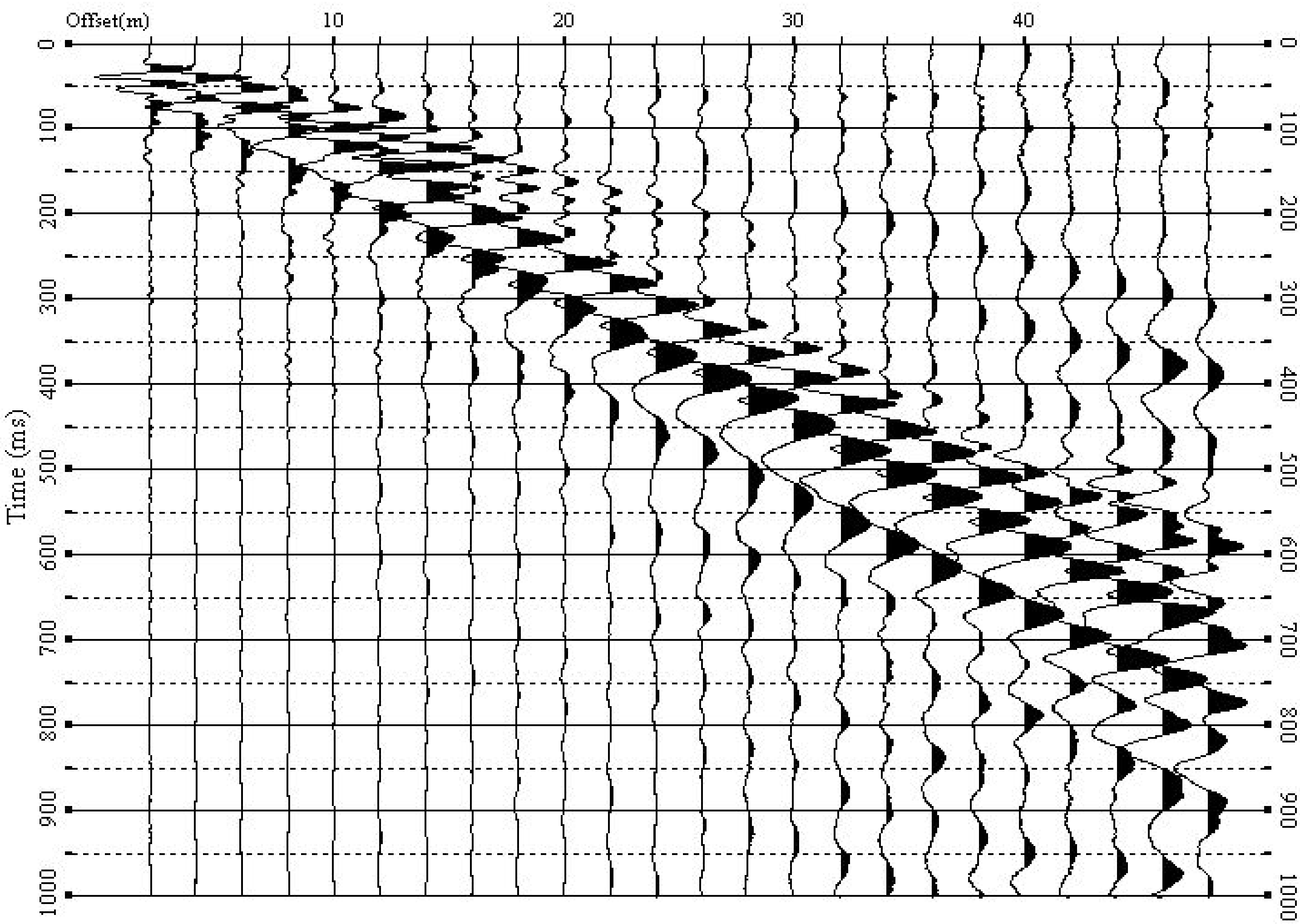
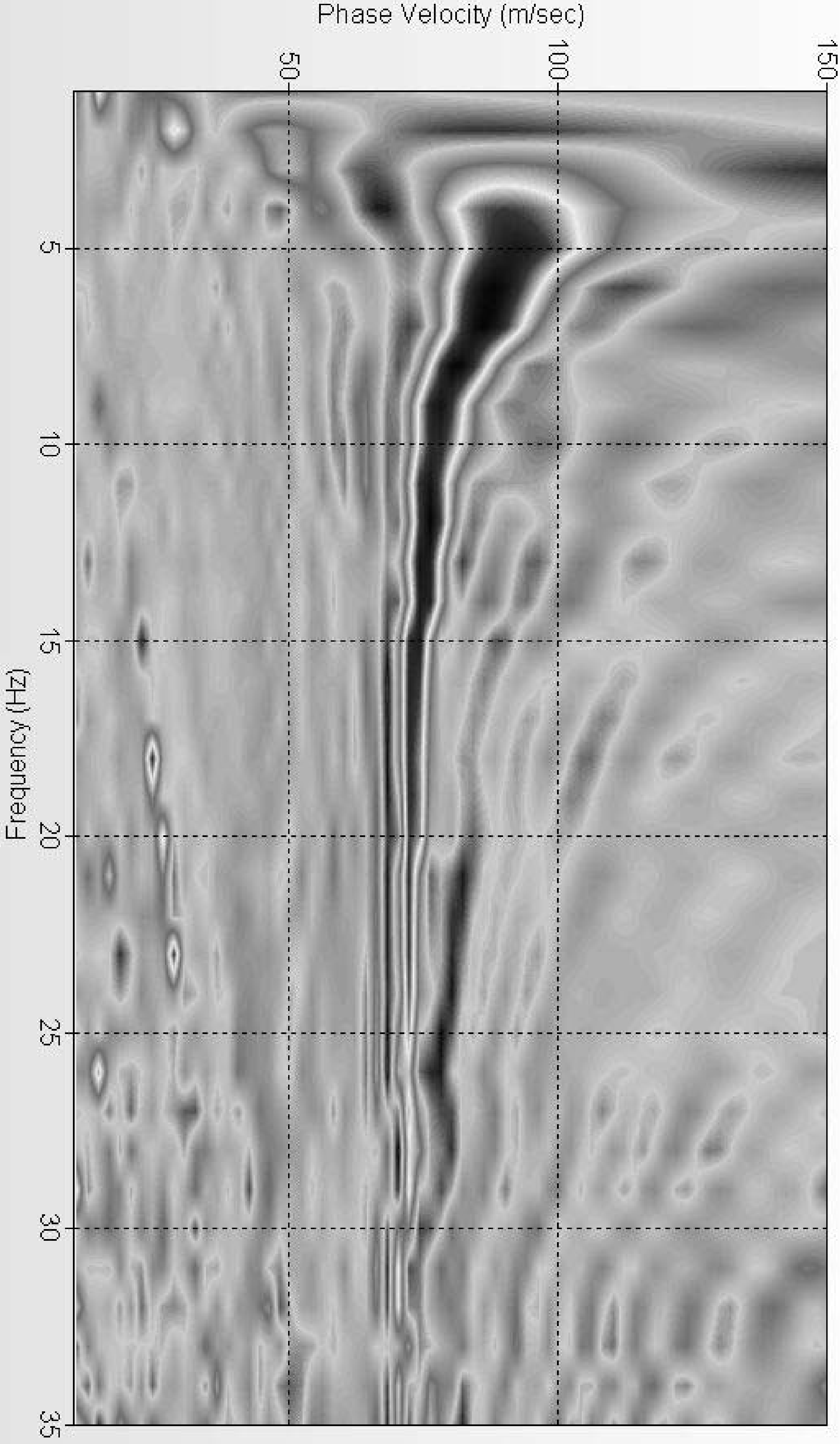
90
Frequency (Hz)

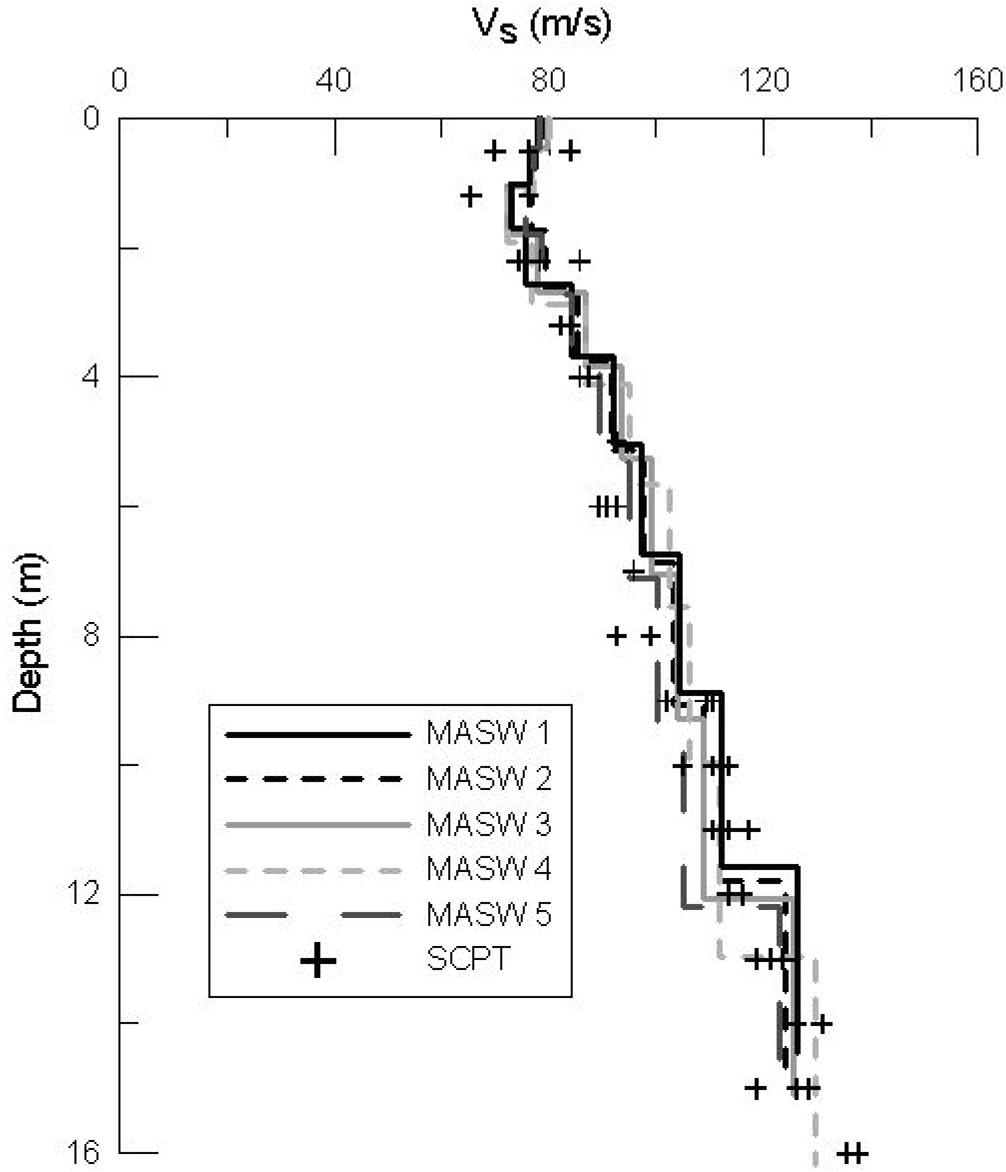


Vs (m/s)
0
100
200
300
0
2
4
6
8
10
Depth (m)
DPS
MASW

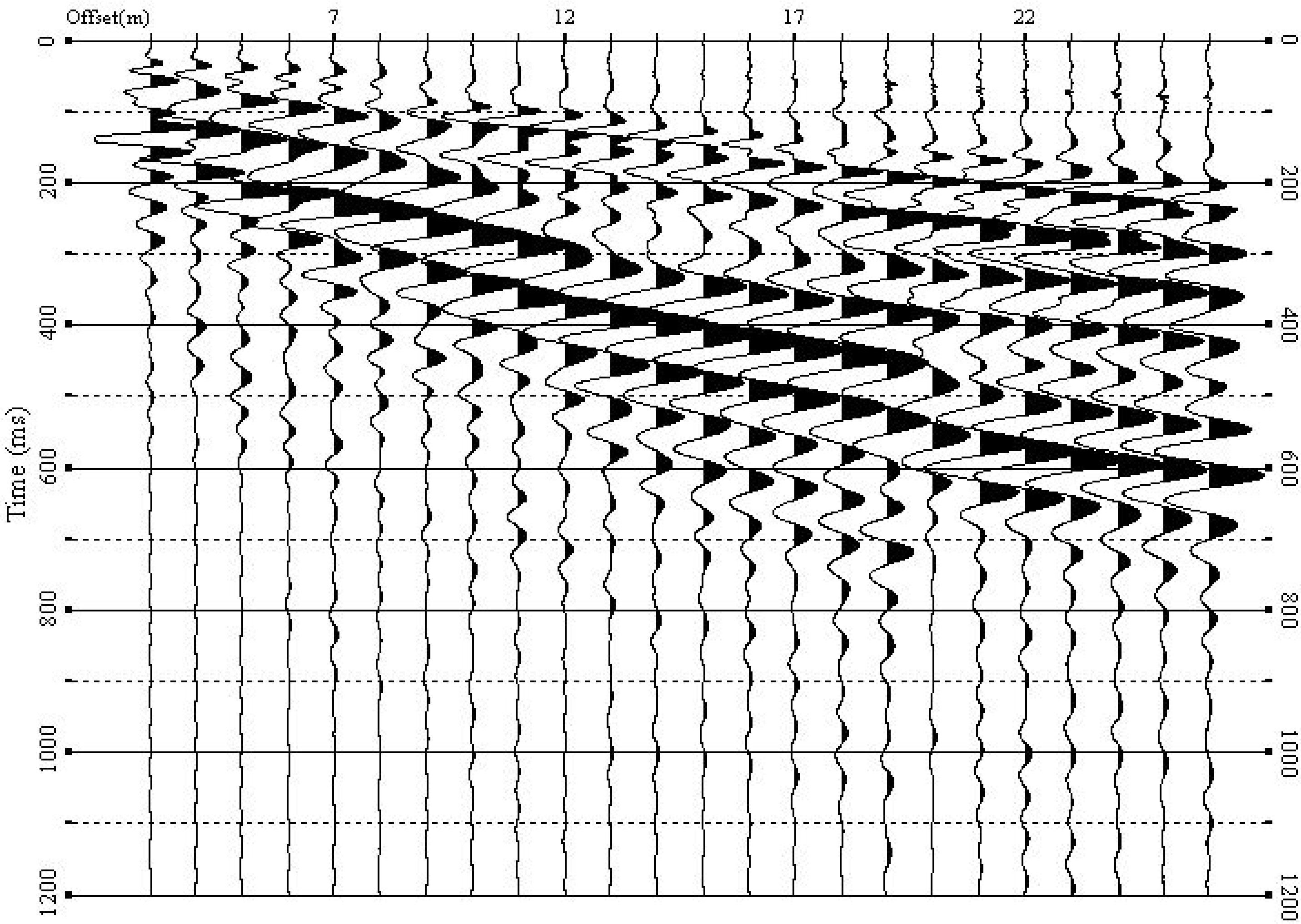

Offset(m)
10
20
30
40
Time (ms)
0
100
200
300
400
500
600
700
800
900
1000

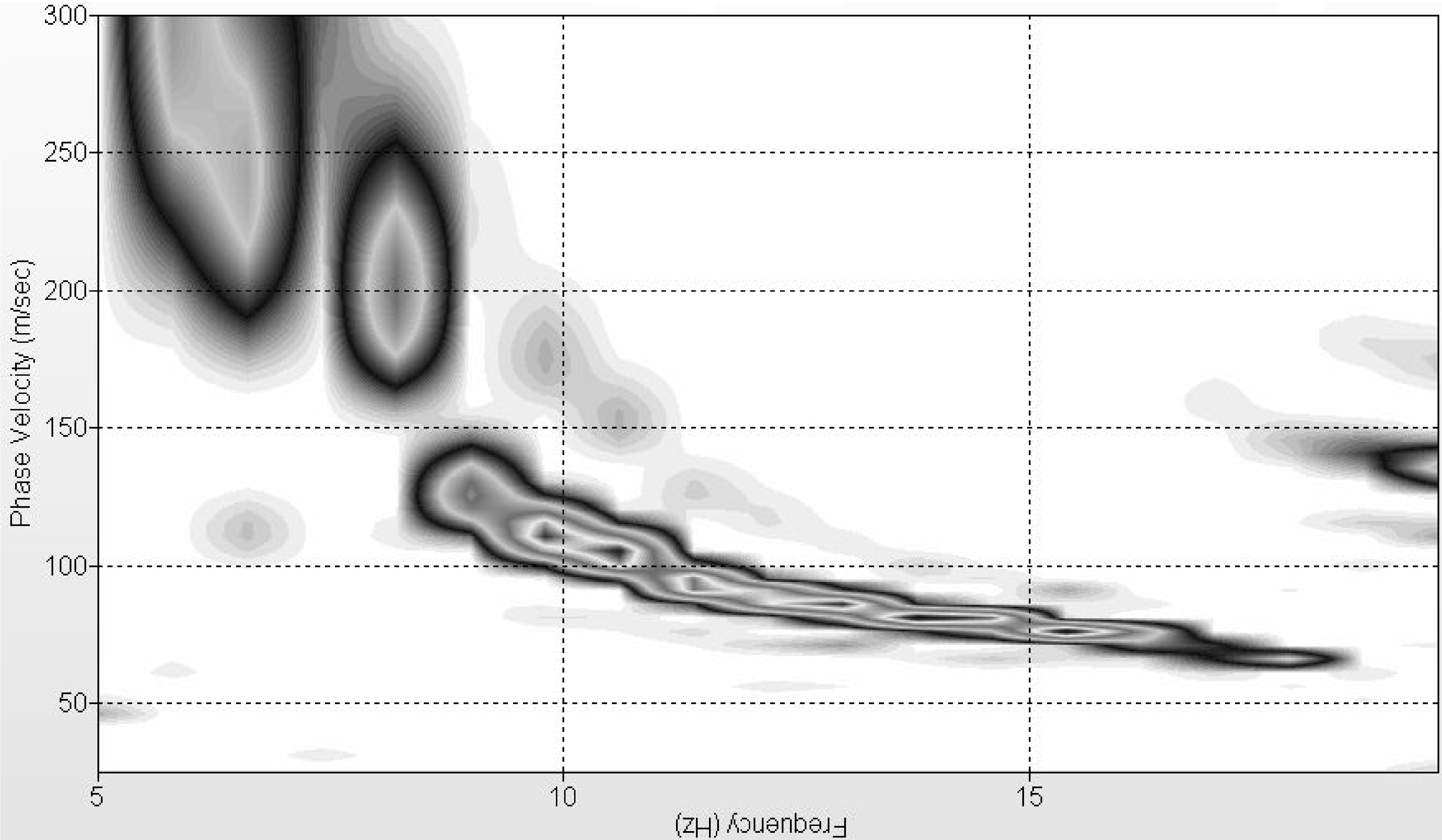


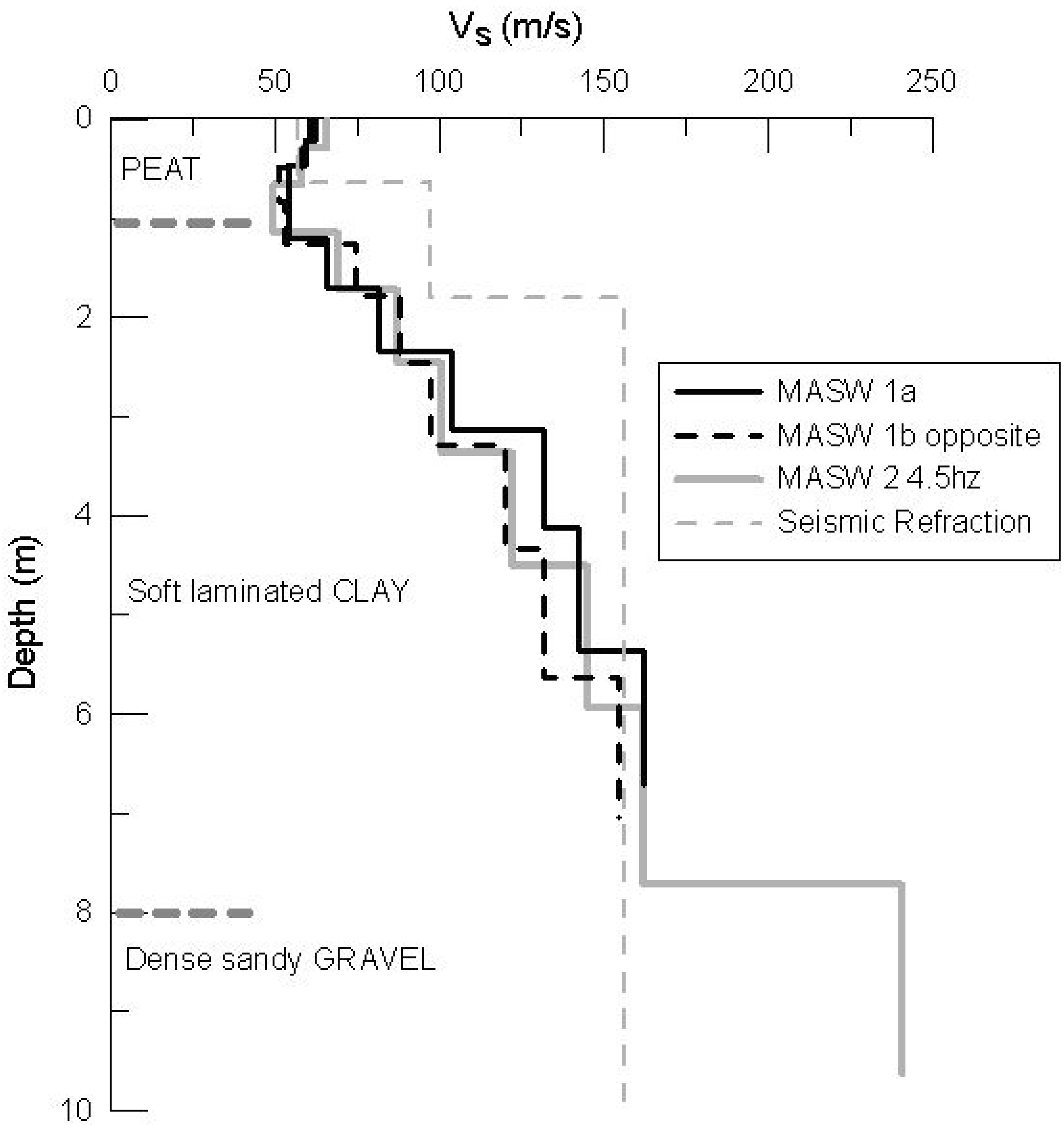
Phase Velocity (m/sec)
50
100
150
Frequency (Hz)
5
10
15
20
25
30
35



Vs (m/s)
0
40
80
120
160
0
4
8
12
16
Depth (m)
MASW 1
MASW 2
MASW 3
MASW 4
MASW 5
SCPT


Offset(m)
7
12
17
22
Time (ms)
0
200
400
600
800
1000
1200


Phase Velocity (m/sec)
300
250
200
150
100
50
5
10
15
Frequency (Hz)



Vs (m/s)
0
50
100
150
200
250
0
2
4
6
8
10
Depth (m)
PEAT
Soft laminated CLAY
Dense sandy GRAVEL
MASW 1a
MASW 1b opposite
MASW 2 4.5hz
Seismic Refraction