Feasibility of MASW (Multi-Channel Analysis of Surface Waves) for Evaluating the Dynamic Properties of Geofoam

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ABSTRACT
Expanded Polystyrene (EPS) - block geofoam has been successfully used in many civil engineering applications such as lightweight fill in roadway embankments over soft ground and in landslide stabilization and repair. Seismic loading can affect both external and internal stability of an embankment containing EPS-block geofoam. The geofoam dynamic parameters required to perform seismic analysis are the shear wave velocity, shear modulus and damping ratios. Currently, these parameters are obtained predominantly from laboratory testing such as resonant column and cyclic triaxial tests. However, laboratory tests are typically performed on small specimens and not on full-size geofoam blocks. Additionally, it is difficult to reproduce the field stresses and strains in conventional dynamic laboratory testing. Techniques such as Spectral Analysis of Surface Waves (SASW) are commonly used in geotechnical practice to measure the shear wave velocity of soils. MASW (Multi-Channel Analysis of Surface Waves) tests were performed on full-size EPS blocks to evaluate the feasibility of using geophysical techniques to measure the dynamic parameters of geofoam for use in seismic analysis. Results of the feasibility study suggest that MASW tests may be a reliable and economical procedure for determining the shear modulus of geofoam blocks.

1. INTRODUCTION

Expanded Polystyrene (EPS) - block geofoam has been successfully used in many civil engineering applications such as lightweight fill in roadway embankments (Stark et al., 2004, Arellano and Stark, 2009) over soft ground and in landslide stabilization and repair (Arellano et al., 2010; 2011b). The National Cooperative Highway Research Program Project 24-11(02), “Guidelines for Geofoam Applications in Slope Stability Projects,” includes a recommended design guideline for the use of EPS-block geofoam in slope stabilization and repair and an overview of the design procedure is included in Arellano et al. (2010; 2011a&b).Figure 1 depicts the major components of an EPS-block geofoam slope system. Seismic loading can affect both external and internal stability of a slope stabilized with EPS-block geofoam. Design for external stability of the overall EPS-block geofoam slope system considers failure mechanisms that involve the existing slope material as well as failure mechanisms that involve both the fill mass and the existing slope material. Failure mechanisms that are considered for external seismic stability analysis include overall slope instability, horizontal sliding of the entire EPS-block geofoam fill mass, overturning of a vertical sided embankment, bearing capacity failure of the existing foundation earth material, and settlement of the existing foundation material. Design for internal stability considers failure mechanisms within the EPS-block geofoam fill mass. Failure mechanisms that are considered for internal seismic stability analysis include horizontal sliding between layers of blocks and/or between the pavement system and upper layer of blocks and load-bearing failure of the EPS blocks.

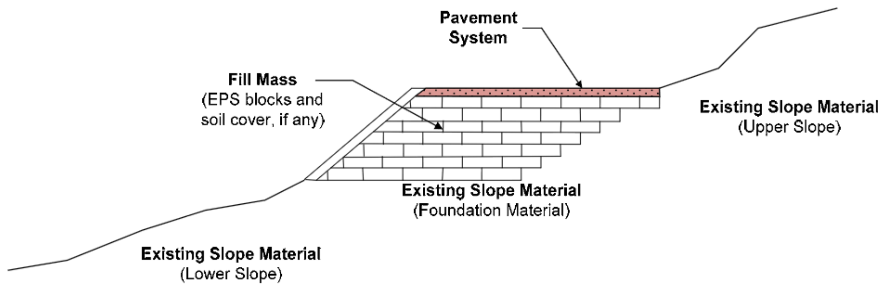


Figure 1. Major components of an EPS-block geofoam slope system (Arellano et al. 2010).

The geofoam dynamic parameters required to perform seismic analysis are the shear wave velocity, shear modulus and damping ratios. Currently, these parameters are obtained predominantly from laboratory testing such as resonant column and cyclic triaxial tests. However, laboratory tests are typically performed on small specimens and not on full-size geofoam blocks. Additionally, it is difficult to reproduce the field stresses and strains in conventional dynamic laboratory testing. Athanasopoulos et al.(1999, 2007), Duskov (1997),Trandafir et al.(2010), Athanasopoulos and Xenaki (2011), Ossa and Romo (2011) performed cyclic triaxial tests and Ossa and Roma (2011), Athanasopoulos and Xenaki (1999, 2011)) performed resonant column tests to measure the dynamic properties on geofoam specimens.

The literature of the laboratory test results, indicated above, revealed that the shear modulus of EPS material is sensitive to specimen size. Duskov (1997) performed a series of cyclic uniaxial tests on cylindrical EPS specimens with a diameter of 100 mm and height of 200 mm and with a diameter of 150 mm and height of 300 mm to measure the dynamic modulus of elasticity (E_{dyn}). Dynamic modulus of elasticity is approximately twice the shear modulus based on an assumed Poisson's ratio of zero (Trandafir et al. (2010)). The density of the EPS specimens was 20 kg/m^3. The dynamic modulus of elasticity on the smaller 100 mm diameter specimens ranged between 6.1- 8.3 MPa based on static loads ranging from 15 to 30 kPa and cyclic loads of 30 and 35 kPa. A higher modulus of 9 MPa was obtained on the larger 150 diameter mm specimen based on a test static load of 15 kPa and cyclic load of 30 kPa. Therefore, these laboratory test results indicate that the dynamic modulus of elasticity and corresponding shear modulus is dependent on specimen size.

Athanasopoulos and Xenaki (2011) developed the empirical relationship shown by Equation 1 between the shear modulus (G_0) and density (ρ) of EPS based on the results from unconfined resonant column tests on cylindrical EPS specimens with a diameter of 36 mm and height of 80 mm and with densities ranging from 10 to 30 kg/m^3

$$G_0 = 0.32\rho - 1.4 \quad (1)$$

Equation 1 provides a shear modulus of 6.28 MPa for EPS with density of 24 kg/m^3 which is significantly smaller than the shear modulus of 10.5 MPa measured by Ossa and Roma (2011) based on unconfined resonant column tests on the same EPS density, albeit with a cylindrical specimen with the same diameter but with a larger height of 89 mm. These resonant column tests results also indicate that shear modulus is dependent on the specimen size. Field or laboratory tests on full-size EPS blocks can minimize the effect of specimen size on the measured shear modulus.

Another issue with dynamic laboratory tests is the uncertainty in estimating the field stresses and strains such as estimating the in situ horizontal confining stress to incorporate in conventional dynamic laboratory tests. The confining stress used in dynamic lab tests has an influence on the shear modulus of EPS material. Ossa and Roma (2011) performed a series of resonant column tests on EPS specimens with densities ranging between 24 to 32 kg/m^3 on cylindrical samples with a diameter of 36 mm and a height of 89 mm under confining horizontal stresses of 0, 30, and 60 kPa. A higher shear modulus of 14.5 MPa was obtained under zero confining stress and a lower shear modulus of 12 MPa was obtained under a confining stress of 60 kPa based on test performed on EPS specimens with density of 30 kg/m^3. Test results show that the shear modulus (G_0) decreases as the confining stress increases. Field tests on EPS blocks under actual field embankment configurations eliminate the need to estimate in situ stresses.

In summary, the effect of specimen size and confining stresses on shear modulus values obtained from laboratory tests can be minimized by in situ geophysical tests such as the MASW (Multi-Channel Analysis of Surface Waves) method. Geophysical techniques such as Spectral Analysis of Surface Waves (SASW) and MASW are used in geotechnical practice to measure the shear wave velocity of soils. Utilizing the Geophysical technics to evaluate the properties of different materials such as PCC slab (Bay and Stoke 1990), mortar cement (Cho 2003 and Cho & Lin 2000 & 2005), asphalt pavements (Ryden et al. 2004) have been reported several times. In this paper the feasibility of MASW testing on estimating the shear modulus of full scale EPS blocks are presented herein. A summary of the MASW procedure is subsequently provided followed by a summary of the test results and conclusions from the test.

2. MASW PROCEDURE

MASW is a geophysical test procedure which is typically used to evaluate the small strain shear wave velocity of subsurface soils. The MASW test is performed by placing geophones (typically 24) on the ground surface that record the time histories of propagating waves from an active or passive seismic source located at various distances (offset) from the sensors. Active seismic source waves are generated by hitting the ground at a specified location with a source such as a sledge hammer whereas, passive seismic source waves are generated from random sources such as nearby vehicle traffic.

In MASW testing, the seismic source is chosen based on the survey depth desired. Seismic sources with large impact energy such as the use of heavy weights can be used for deep investigations (Park (2011)). Seismic sources with lower impact energy such as the use of small balls can be used for shallow investigations (Cho and Lin (2005)). An active seismic source consisting of a tennis ball, approximately 6.7 cm (2.64 inch) in diameter, was utilized in testing a full-size EPS block. Forty-eight 4.5 Hz geophones similar to the one shown in Figure 2(a) were placed on top of the 0.96 × 1.22 × 7.32 m (3.17×4× 24 ft) EPS block at 15.24 cm (0.5 ft) intervals as shown in Figure 3. Time histories of propagating waves were collected by dropping the ball used as the active seismic source from a height of approximately 15 cm (5.9 inch) onto the surface of the EPS block at 48 different locations or stations. At each station, the test was repeated five times, i.e., the ball was dropped five times, and for each test, the geophones recorded time histories of propagating waves.

The time histories recorded by the geophones are digitized by Geodes (Figure 2. (b)) and the digitized data is transferred to a portable laptop that contains the Geometric Seismodule Controller software™ package. The time histories of propagating waves were recorded at time intervals of 0.125 milliseconds for a duration of 2 seconds. In order to initiate the start of data collection of each test in the software, one of the following two alternatives must be specified: automatic triggering or manual triggering. In automated triggering, the start of the test is recognized by the software automatically from a trigger which is installed on the head of a sledge hammer that is used as an active seismic source and connected to the laptop computer. In manual triggering, the start of test data collection for each test is manually triggered by the person that is monitoring the data acquisition software in the laptop during the test. Since a tennis ball was used as a seismic source, the automatic triggering was not an option and the manual triggering method was used.

(a) (b)

Figure 2. (a) 4.5 Hz geophone, (b) Geode

One objective of MASW testing is to obtain shear wave velocity profile at various locations along the block length. A shear wave velocity profile is obtained at the centerline of a series of 24 geophones aligned as shown in Figure 3. The centerline of the 24 geophones is called midsection as shown on Figure (3). Shear wave velocity profiles at other locations of the EPS block can be obtained by moving the 24 geophone series to another location along the block length to change the midsection of the 24 geophones and repeating the test. In testing the full-size EPS block, 48 geophones were utilized instead of 24 to incorporate geophones along the full length of the block to minimize the number of tests needed to obtain shear wave velocity profiles throughout the length of the block. Therefore, 48 geophones were utilized instead of 24 to obtain a two- dimensional (2D) image of shear wave velocity of the block by choosing different 24 geophones series combinations having different midsection locations along the block. The use of 48 geophones expedited the time needed to obtain shear wave velocity profile along the block compare to the time needed to obtain shear wave velocity profiles with only 24 geophones because the use of 24 geophones would require physically moving the 24 geophones after each test, which would have damaged the block as well.

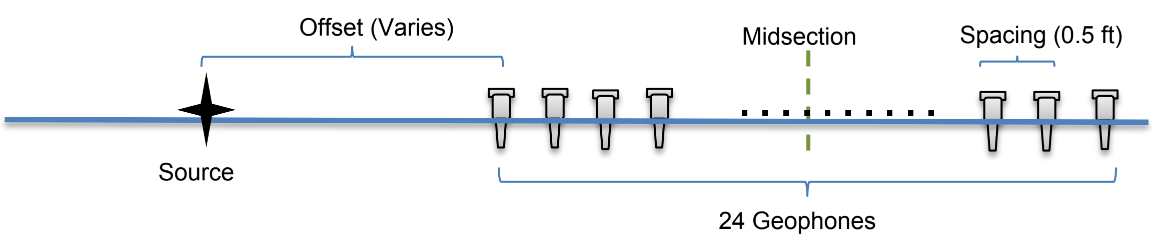


Figure 3. Source-receiver configuration for active MASW test

Noise effects such as vibrations of the data acquisition components and vibrations from random noise sources not related to the specific active seismic source used in the test, can introduce random errors in the test data.

In order to minimize noise from vibration of any data acquisition system components such as the geophone cables, connection cables and Geodes, the data acquisition system is kept away from contact with the EPS block during the tests.

In order to minimize random ambient noises that typically occur during the day the tests were also performed in the evening. Figure 4 shows the test set up for the full-size EPS22 with measured density of 20.9 kg/m3. The density was obtained from the measured weight of full-size block and the dimensions of the block. EPS 22 is designated by ASTM D6817 – 11.

The analysis used to obtain the shear modulus of the EPS block from the recorded time histories is presented next.

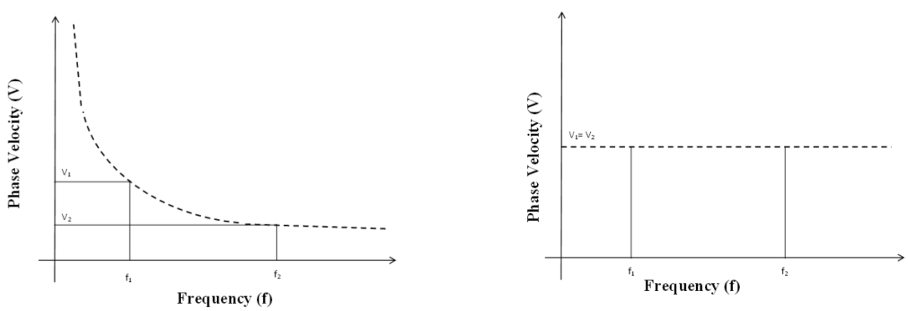
Figure 4. Large scale EPS block under MASW test at the University of Memphis Geotechnical Lab.

3. ANALYSIS

Analysis of MASW data consists of two primary steps:1) dispersion analysis and 2) inversion analysis. An overview of each of these steps is subsequently provided.

3.1 Dispersion Analysis

The purpose of dispersion analysis is to develop a dispersion curve from the time histories recorded by the geophones. A dispersion curve is a plot of phase velocity versus frequency as depicted in Figure 5. Dispersion curves can be dispersive or non-dispersive. In dispersive curves, different frequency components of surface waves travel with different velocity and create a dispersive curve (Figure.5 (a)). For example, in soils, longer wave length (lower frequency (f_1)) penetrates greater depths which is usually in higher densities and therefore travels with higher velocity (V_1> V_2) (Figure 5. (a)). If all the frequency components travel with the same velocity, the dispersion curve will be non-dispersive as a straight line (shown in Figure 5.(b)) (Park(2012)).



(a) (b)

Figure 5. Phase Velocity vs Frequency for (a) dispersive curve, (b) Non- dispersive curve.

As described previously, each geophone records the time history of propagating waves for each test. Therefore, 24 time histories (traces) are recorded for each test. In order to create a dispersion curve for each test, the recorded time histories (set of 24 traces) are transformed to the frequency domain by utilizing the Fast Fourier Transformation (FFT). A band pass filter with desired corner frequencies is used to filter data for each frequency range. The filtered time histories are plotted beside each other in manner where vertical axis represents time and horizontal axis represents the offset at which, each geophone is located. By connecting the normalized peak amplitudes of all traces together, an inclined line can be drawn with a specific slope. It is possible to measure the cumulative values of time history amplitude along the slope. The slope of each line represents a unique velocity by which each frequency is travelling and is called phase velocity. By repeating this procedure for the range of desired frequencies, a contour (dispersion curve) which represents the variation of phase velocity with frequency is generated.

Surfseis software package developed by Kansas Geological Survey is used to generate dispersion curves from the recorded time histories. The test setup configuration details, such as source location, geophone spacing, and number of tests performed at a given seismic source location, are the required software input parameters to generate the dispersion curves. In addition to the provisions previously described to minimize noise effects, the following two additional procedures were also incorporated in the analysis to minimize noise effects:

1) As described previously, at each active seismic source station, the test is repeated 5 times. A dispersion curve is developed for each test repetition at each midsection of a set of 24 geophones and the dispersion curves from the 5 repetitions of the test are stacked (summed) together to obtain a single dispersion curve to minimize noise effect that tends to influence the individual dispersion curves from each individual test.

2) As previously noted, a dispersion curve is obtained at the midsection of a set of 24 geophones for a given offset of the seismic source. Therefore, multiple dispersion curves are obtained at a given midsection location from tests that are performed at various offset locations. For example, Figure 6 provides the various test offset locations and the associated midsection location of a set of 24 geophones located at Station 11.75, which is at the center of the EPS block. Table 2 provides the offset location of each seismic source. Each offset location listed in Table 2 represents a single test. Therefore, as listed in Table 2 and as depicted in Figure 6, 13 different test offset locations are associated with the midsection location at Station 11.75. Therefore, 13 dispersion curves, one for each test offset location, are developed at Station 11.75.

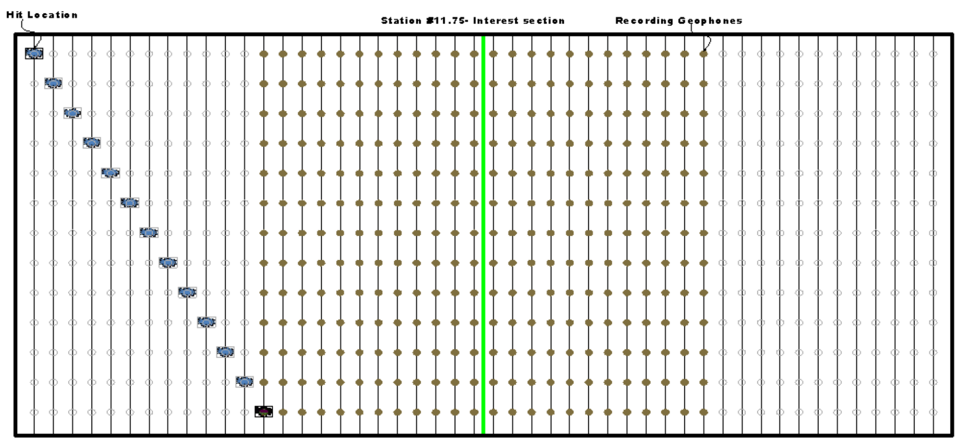


Figure 6. Geophone and test offset used to create a dispersion curve at the middle of EPS block (Station 11.75).

Table.2. Source offset combination for midsection at Station11.75

Source Location (hit) from one edge of block		**Offset from the source as shown in Figure (3)**	
ft	**m**	**ft**	**m**
0.25	0.08	6.00	1.83
0.75	0.23	5.50	1.68
1.25	0.38	5.00	1.52
1.75	0.53	4.50	1.37
2.25	0.69	4.00	1.22
2.75	0.84	3.50	1.07
3.25	0.99	3.00	0.91
3.75	1.14	2.50	0.76
4.25	1.30	2.00	0.61
4.75	1.45	1.50	0.46
5.25	1.60	1.00	0.30
5.75	1.75	0.50	0.15
6.25	1.91	0.00	0.00

Figure 7 shows the total number of dispersion curves after the two previously described procedures were performed. As shown in Figure 7, between 5 to 125 stacked dispersion curves were developed from all the tests performed on the EPS block. The stacked dispersion curves provide improved phase velocity data at various frequencies than the dispersion curves obtained from a single test.

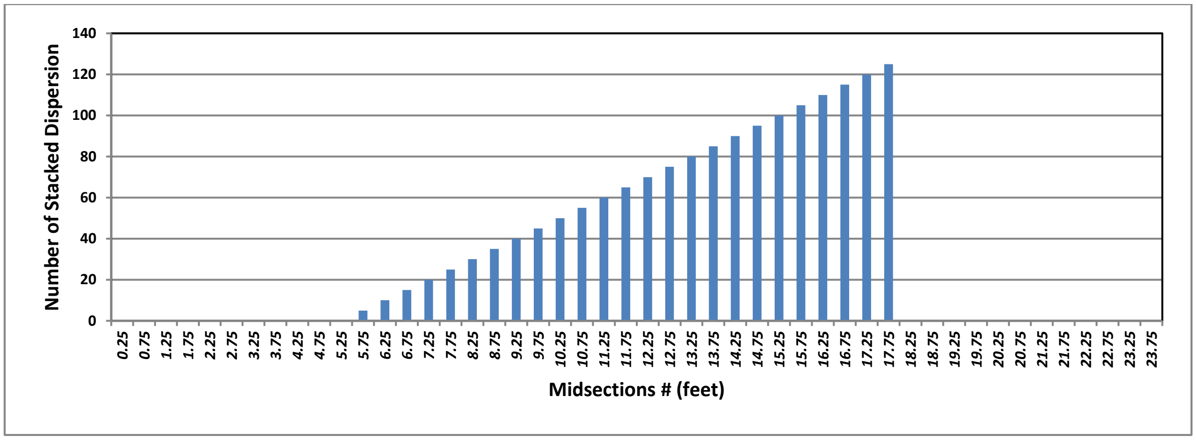


Figure 7. Total Number of stacked dispersion curve after two stacking procedures (step1 and 2) (Graphic fold)

For example, the final dispersion curve from stacking steps for Station 5.75 is shown in Figure 8. This figure shows the variation of phase velocity by frequencies and the shading represents the dominancy of each phase velocity on results. Since EPS material are homogenous material, as described before, the dispersion curve are non-dispersive and show an approximately straight line. As shown in Figure 8, the dispersion curve is nearly horizontal line at frequencies greater than 70 Hz. Figure 9 shows a magnified image of the dispersion curve at frequencies greater than 70 Hz. As shown in Figure 9, the dispersion curve represents a non-dispersive wave with phase velocity constant with frequency as defined by Figure 7(b).

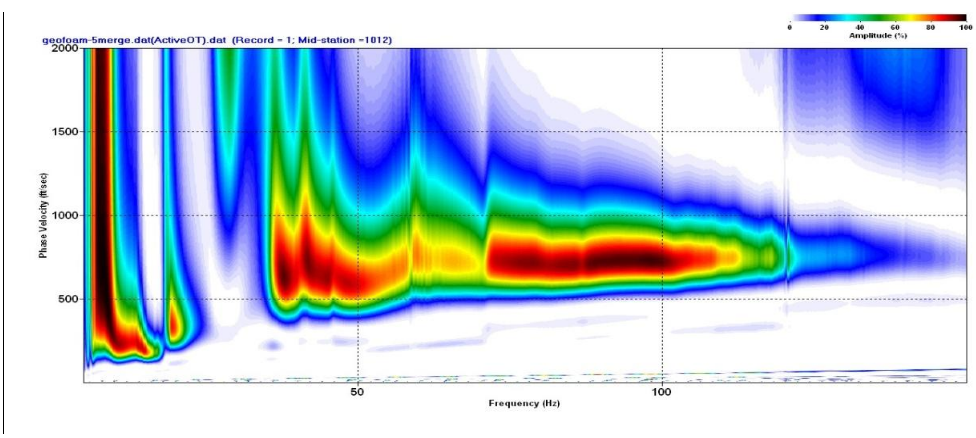


Figure 8. Dispersion curve from Surfseis for station # 5.75.

The phase velocities for various frequencies are obtained from the non-dispersive portion of the dispersion curve by connecting the highest amplitudes in this portion as shown as marked points in Figure 9. Table 3 represents the extracted phase velocities versus frequencies for this section.

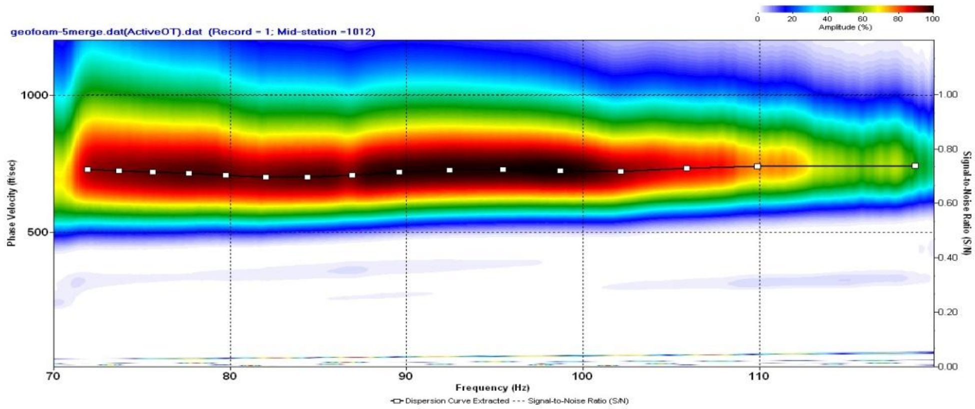


Figure 9. Extracted dispersion curve from Surfseis for station # 5.75.

This procedure is repeated for all the sections between 1.75 m (5.75 ft) and 5.41 m (17.75 ft) of EPS blocks. The dispersion curves for each station are stacked (summed) together and a combined dispersion curve for each station is used to extract the phase velocity and their corresponding frequencies.

Table 3. Extracted dispersion results.

Frequency (HZ)	Phase Velocity	
	(m/sec)	(ft/sec)
72.56	216.15	709.16
74.50	216.58	710.55
76.54	215.14	705.84
78.70	213.15	699.31
80.99	211.28	693.18
83.41	210.13	689.41
85.98	211.23	693.02
88.72	214.52	703.80
91.64	217.54	713.70
94.75	218.80	717.85
98.08	217.65	714.07
101.66	216.61	710.65
105.50	219.49	720.10
109.65	221.78	727.61
119.01	223.21	732.32

3.2 Inversion Analysis

Inversion analysis is a procedure to find the shear wave velocity profile from the experimental dispersion curves. In general the inversion is an iterative process to find a shear wave velocity profile for the experimental dispersion curve with the minimum error between theoretical dispersion curve of inverted velocity profile and experimental . In this research since the dispersion curves show a nearly straight line, the iteration to find a profile velocity is not required and the results can be estimated from the available equations related to propagating waves in homogenous media. The relationship between phase velocity (surface wave velocity (V_R)) and shear wave velocity (V_S) can be estimated from Equations (3&4) (Bay and Stokoe (1990)):

$$V_s = \frac{1+v}{0.862+1.14v} V_R \quad (3)$$

For Poisson’s ratio (v) between 0.1 and 0.3, shear wave velocity can be approximated by:

$$V_s = 1.11 V_R \quad (4)$$

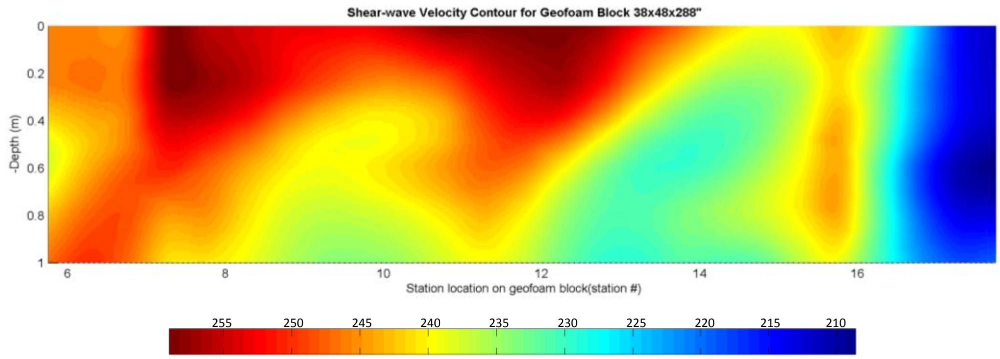


Figure 10. 2-D Shear wave velocity profile of EPS block (m/sec)

Phase velocity is converted to shear wave velocity for all the tested sections of EPS block by utilizing the Equation 4. Figure 10 depicts a 2D shear wave velocity variation within EPS block (between 1.75 m (5.75 ft) and 5.41 m (17.75 ft) of EPS blocks). This plot shows the variation of shear wave velocity by depth of EPS blocks. As shown in Figure 10, the shear wave velocity obtained from the inversion analysis varies within the block. The shear wave velocity should be the same throughout a homogenous material. However, density variations occur with a full size EPS block because of the molding process (Stark et al. 2004), which can contribute to variations in shear wave velocity within the block.

A second factor that can contribute to the variation of shear wave velocity within the block is the used inversion technics which is just based on equations related to Rayleigh wave propagation in homogeneous media. Further works to improve the inversion analysis such as utilizing the Lamb waves (Ryden et al., 2003) is recommended.

Shear modulus of material, under the small strain condition, can be calculated from the shear wave velocity from the Equation 5:

$$G = \rho V_s^2 \qquad (5)$$

where,

V_s is the shear wave velocity and ρ is the density of EPS material. Measured shear wave velocities were used to calculate the shear modulus at all the section between 1.75 m (5.75 ft) and 5.41 m (17.75 ft) of EPS block by utilizing the Equation (5). Results show a shear modulus with a range of 10 to 13 MPa (1450 to1885 psi) and an average of 12.2 MPa (1770 psi). This measured shear modulus is in the range of the shear modulus measured by Ossa and Roma (2011) from resonant column tests (10 to 16 Mpa (1450 to 2320 psi) for EPS material with density range of 24 to 32 kg/m^3 (1.5 to 2 lb/ft^3)) but is far from the results from resonant column tests reported by Athanasopoulos and Xenaki (2011) (2 to 8 Mpa (290 to 1160 psi) for EPS material with density range of 10 to 30 kg/m^3 (0.6 to 1.9 lb/ft^3)). Table 4 provides an example of calculated shear wave velocity and shear modulus at the section 5.75 with 1.75m (5.75 ft) distance from the one edge of EPS block. Results show an average shear wave velocity of 240 m/sec (787 ft/sec) and shear modulus of 11.81 MPa.

Table 4. Shear wave velocity and Shear modulus at station #5.75

Frequency (HZ)	Phase Velocity		Shear Wave Velocity		Shear Modulus, G	
	(m/sec)	(ft/sec)	(m/sec)	(ft/sec)	MPa	Psi
72.56	216.15	709.16	239.93	787.16	11.80	1711.81
74.50	216.58	710.55	240.40	788.71	11.85	1718.55
76.54	215.14	705.84	238.81	783.48	11.69	1695.84
78.70	213.15	699.31	236.60	776.24	11.48	1664.61
80.99	211.28	693.18	234.52	769.43	11.28	1635.55
83.41	210.13	689.41	233.25	765.24	11.15	1617.79
85.98	211.23	693.02	234.47	769.25	11.27	1634.80
88.72	214.52	703.80	238.11	781.21	11.62	1686.03
91.64	217.54	713.70	241.46	792.20	11.95	1733.81
94.75	218.80	717.85	242.87	796.81	12.09	1754.05
98.08	217.65	714.07	241.59	792.62	11.97	1735.61
101.66	216.61	710.65	240.43	788.82	11.85	1719.03
105.50	219.49	720.10	243.63	799.31	12.17	1765.03
109.65	221.78	727.61	246.17	807.65	12.42	1802.09
119.01	223.21	732.32	247.76	812.87	12.59	1825.46

4. CONCLUSIONS

Performance evaluation of EPS embankments under dynamic loading, such as earthquake analysis of slope stabilized with EPS blocks, depends on their dynamic properties. Shear modulus and shear wave velocity are geofoam dynamic parameters required to perform seismic analysis. Understanding the behavior of EPS material under dynamic loading is a key issue in the seismic design of EPS embankments. This paper proposes the use of the MASW method to evaluate the large scale dynamic properties of EPS material. Results show an average shear modulus of 12.2 Mpa (1770 psi) for the EPS 22 with the measured density of 20.9 kg/m^3 (1.3 lb/ft^3).

The shear modulus measured by the MASW test shows a higher value than the reported results for EPS blocks with densities close to the tested block (20.9 kg/m^3 (1.3 lb/ft^3)). However, the MASW result is still in the range of the shear modulus measured by Ossa and Roma (2011) from resonant column tests (10 to 16 Mpa (1450 to 2320 psi) for EPS material with density range of 24 to 32 kg/m^3 (1.5 to 2 lb/ft^3)). MASW results vary greatly from the shear modulus reported by Athanasopoulos and Xenaki (2011) measured by resonant column tests (2 to 8 Mpa (290 to 1160 psi) for EPS material with density range of 10 to 30 kg/m^3 (0.6 to 1.9 lb/ft^3)). Further investigation by performing the resonant column test on the tested EPS block in this research is in progress.

This method can be extended to be performed on projects with EPS blocks in the field to measure the dynamic properties of the EPS material under the in-situ condition (confining and vertical pressure). Utilizing the MASW method in evaluating the dynamic properties of EPS material can provide the following potential advantages: (1) eliminate the effect of the small scale sample size on the results, (2) provide a capability to test EPS material under in-situ condition (3) provide an image of integrity of EPS blocks (4) utilize fast and economically procedures.

ACKNOWLEDGEMENTS

The authors would like to give their sincere thanks to Drew Foam Companies and Mr. Charles Tyner for providing the EPS block to The University of Memphis.

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