Implementation of the FMDSMAA Algorithm

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ABSTRACT: One of the most common analysis techniques in dynamic soil analysis is theEquivalent Linear (EL) method. The important parameters required within the EL method are the low-strain shear modulus (G_0), modulus reduction and the equivalent viscous shear damping ratio (η_s). Downhole seismic testing (DST) has proven to be a very accurate tool for estimating low strain shear modulus values as long as source wave raypaths are taken into account in near surface investigations. DST has also been utilized to estimate low-strain interval η_s values. The low-strain DST $\eta_s$estimates provide for a reference of laboratory test such as the Resonant Column Test (RCT). RCT can suffer from various disadvantages such as sample disturbance and sample preparation which can shift the estimated η_s values. The RCT results can be adjusted so that the low strain RCT η_s estimates agree with the low strain in-situ DST η_s estimates. Low strain η_s estimates are also very important for predicting and assessing ground amplification during earthquakes. The most common technique utilized for estimating η_s from DST data sets is the Spectral Ratio Technique (SRT). The SRT incorrectly assumes the DST near surface source waves are traveling along the same travel path and is highly susceptible to measurement noise and any source wave interference. To address the SRT shortcomings BCE has developed a new algorithm referred to as the FMDSMAA technique. The FMDSMAA technique has been described in 2019 with only test bed simulations. This paper outlines the implementation details and enhancements of the FMDSMAA technique for damping ratio estimation from real seismic data acquired during DST.

Keywords: Downhole Seismic Testing (DST); site characterization; absorption estimation; Fermat's principle; dynamic soil analysis (DSA); damping ratio.

1. Introduction

1.1. Background

Downhole Seismic Testing (DST) techniques such as the Seismic Cone Penetration Test (SCPT) have been used extensively for the *in-situ* the estimation of low strain ($<10^{-5}$) shear (*V*s) and compression (*V*p) wave velocities. These velocities are directly related to the various soil elastic constants, such as the Poisson's ratio, shear modulus, bulk modulus and Young's modulus.In Dynamic Soil Analysis (DSA) accuracy in the estimation of these two in-situ velocities is of paramount importance because their values are squared during the calculation of the soil elastic constants[1-4].

Another critical input parameter in DSA is the viscous shear damping ratio (η_s), which allows for the modelling of the stress-deformation response of soils due to imposed shear strains from dynamic loading [6-11]. DST can be used to determine the low strain η_s, which is very important for predicting and assessing ground amplification during earthquakes [12]. The results obtained with DST can also serve as a reference for values derived with theResonant Column Test (RCT).

In a RCT the strain level is increased step-by-step and the damping ratio is measured at each step. The test result is then a relationship between damping ratio and shear strain over a shear strain magnitude of 10^{-5} up to 1 percent. However, a RCT is prone to various disadvantages such as sample disturbance and sample preparation, which can affect the results. This effect can be corrected by adjusting the RCT results so that the low strain RCT η_s estimates agree with the low strain in-situ DST η_s estimates.

Baziw and Verbeek [13] developed a new technique for estimating ηs values from DST seismic data. This new technique is referred to as Forward Modeling Downhill Simplex Method Absorption Analysis (FMDSMAA) and was shownto have numerous advantages over the commonly applied Spectral Ratio Technique (SRT). It utilizes several estimated in-situ parameters (such interval velocities, source wave travel paths, angles of incidence and reflection, density, and source wave amplitudes) when estimating absorption values and the technique takes the soil structure into account as the layer absorption values for up to eight layers are estimated simultaneously along with the geometric spreading exponent. Furthermore, the FMDSMAA technique provides for an error estimate.

Baziw and Verbeek [13] demonstrated the implementation and performance of the FMDSMAA algorithm by considering a challenging test bed example. It was shown that the FMDSMAA algorithm was able to obtain accurate absorption estimates which demonstrated the FMDSMAA's correctness. This paper outlines the implementation details and enhancements of the FMDSMAA technique for damping ratio estimation from real DST seismic data.

2. FMDSMAA Technique

While Baziw and Verbeek [13] give a more thorough description of the FMDSMAA technique with the advantages over the commonly applied SRT, the main aspects of FMDMSAA algorithm is described in this section. The main advantages of the FMDSMAA technique is that (1) raypaths, which adhere to Fermat's principle, are taken into account, (2) greater soil structure is incorporated into the low strain ηs estimation and (3) the algorithm is applied in the time domain, which makes it less susceptible to measurement noise or source wave interference.

Standard absorption estimation algorithms such as the SRT assume that the absorption value being estimated is based upon source waves traveling along the same travel path(see Fig 1). While this may be the case for crosshole seismic testing, as is obvious from Fig. 2 it is not the case for near surface DST investigations.

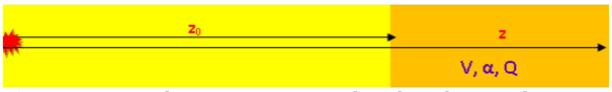

Figure 1. Assumed source wave travel paths when implementing SRT.

In this figure$V_i$and α_i denote the soil interval velocity and absorption ($\eta_s = \alpha\lambda/2\pi$, λ is the source wave‘s wavelength), and it illustrates a near surface DST investigation with a layered soil profile. Consequently the seismic waves will not travel in straight lines, but adhere to Fermat‘s principle to reach to the receiver in the least amount of time.As a result the distance travelled in a certain layer varies with each test depth (e.g. the distance travelled in the top layer at depth Z_5 is minimal compared to the distance traveled in this layer at depth Z_2).

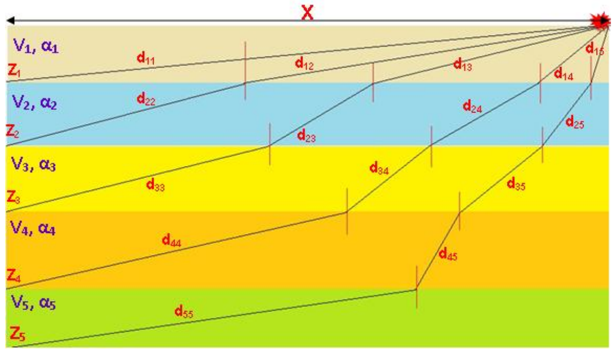

Figure 2. Near surface DST with ray paths in accordance with Fermat’s principle, which are clearly no straight lines.

2.1. FMDSMAA Algorithm Outline

The FMDSMAA algorithm centers around the maximum amplitudes in the recorded seismic traces. These amplitudes at each subsequent DST depth of acquisition are mathematically expressed as follows[13]:

$$A_i = A_0 \prod_{j=1}^{i-1} T_{ji} \left(x_0 / \sum_{j=1}^{i} d_{ji} \right)^n e^{-\left(\alpha_1 (d_{1i} - x_0) + \sum_{j=2}^{i} \alpha_j d_{ji}\right)}, \quad (2)$$

with $j \geq 1,\ i > 1$

In eq. (2), T_{ji}denotes the transmission coefficient moving from layer i to j, dji and $\alpha$are defined in Fig. 2, and A_0 and x_0 define the initial source wave amplitude and offset, respectively. If the ratio of the normalized (either in absolute terms or globally) amplitudesis calculated then the unknown amplitude A_0 drops out of eq. (2).

Using eq. (2), the FMDSMAA technique for estimating shear wave absorption coefficients is then described as follows:

- Utilizing the standard interval velocity FMDSM technique [2-4], obtain estimates of V_i, T_{ij}, and d_{ij}.
- For the depth increments under analysis determine the maximum amplitudes from the recorded amplitudes for each depth increment from the seismic recordings.
- Specify the estimated densities for each depth interval based on the CPT recordings or lab test results.
- Implement FMDSMAA to calculate the synthesized amplitudes with eq. (2) based on assumed absorption coefficients, whereby the RMS difference between the measured and synthesizes amplitude ratios are minimized.

It should be noted that when utilizing the FMDSMAA it is mandatory that the same source energy (e.g., same pendulum hammer height and the same coupling between the source and the ground) is applied throughout the seismic profile when acquiring seismic data.

3. FMDSMAA Implementation Details

The newly developed FMDSMAA technique has been recently implemented on real SCPT data sets, which has allowed the authors to formulate recommended guidelines when processing DST seismic data sets for absorption estimation. A fundamental requirement for carrying out DST absorption analysis is to have a repeatable energy source. In addition, it is important that the source wave amplitudes are recorded that are sufficiently gained to avoid that the amplitudes are “in the weeds” of electrical and ambient noise. Finally, as in all DST post data analysis it is important that the captured seismic traces have good source wave trace metrics [14]. An essential part of the FMDSMAA implementation is to identify seismic traces with either poor trace metrics or nonsensical Peak Particle Accelerations (PPAs) indicative of a nonconstant source energy output (e.g., plate slippage, poor trace quality and\or poor or variable hammer impacts).

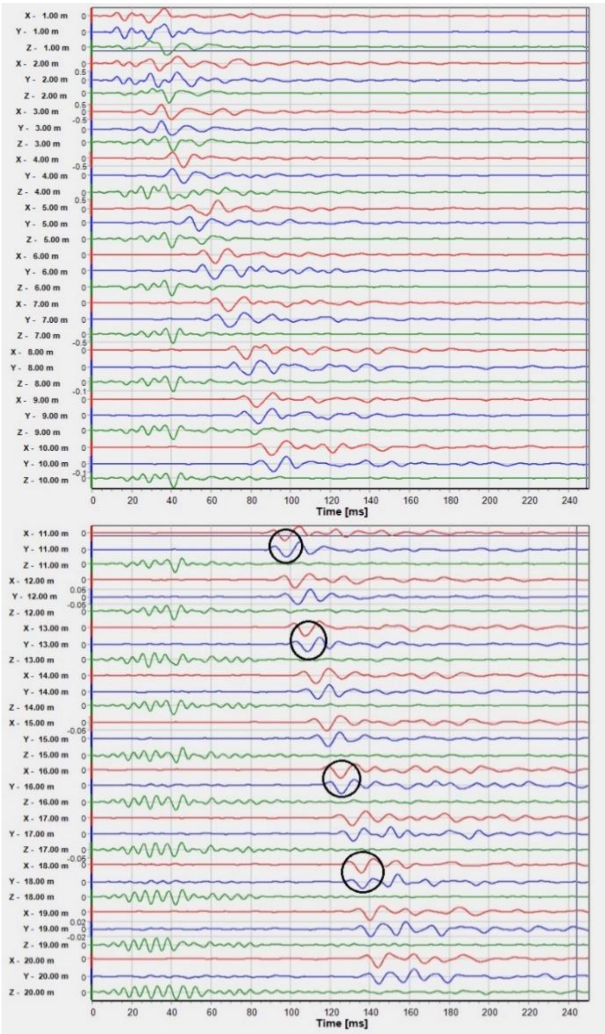

Figure 3. Filtered (200Hz low pass) X, Y and Z components of SCPT data set. Circles identify first trough of the source wave signature

In Fig. 3 a set of minimally filtered (200 Hz low pass filter, the recommended filtration for SH analysis)SCPT seismic traces is shown. A dominant first trough of the source wave signature is identified in some of the filtered traces (denoted by black circles). Since this involves a SH wave analysis the Z component is no longer considered, and the full waveform is determined for each depth and then displayed together with the maximum peak particle acceleration (PPA) for that depth as shown in Fig 4.Traces with PPAs that do not align with the trending value (in this case the traces recorded at 1m, 2m and 5m as identified by black circles) are then dropped from the analysis. It should be noted that these traces also had low trace metrics.

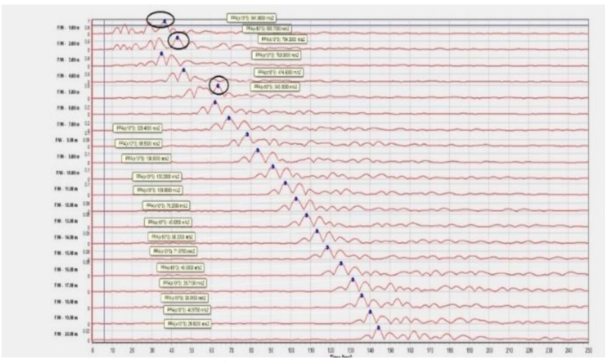

Figure 4. Full waveforms with maximum PPAs illustrated.

The absolute value of the PPA for the remaining depths are shown in Table 1, which provides the input for the next step in the selection of the traces that will provide feasible or reasonable absorption estimates. In general terms, it is to be expected that the maximum full waveform PPA gradually decreases with depth. Therefore any traces that do not fit this assumption are dropped; i.e. traces recorded at depths 8m, 13m, 15m, 17m and 19m.

The next step in the process it to specify the densities for remaining depth intervals, based either on known values from soil investigationsor lab tests, or densities based upon the soil classification [5]. For this data set densities for the various layers were estimated from CPT data and interpolation and averaging was implemented.

Finally to complete the input parameters the source wave arrival times for the depth increments under considerationand the frequencyhave to be specified. The latter are is determined by measuring the period duration in the seismic traces as tabulated in Table 2. The other input parameters are then summarized in Table 3.

The FMDSMAA then derives the absorption values by optimizing the difference between the calculated and the the measured values for the normalized maximum PPA values or maximum amplitudes in the seismic traces. To do this a l_1 norm cost function is utilized, which is outlined in eq. (3). In this equation A is the derived amplitude based upon the assumed absorption values, A^m is the measured amplitude, and q is the number of layers or absorption coefficients to be estimated.

$$\min_{\alpha_i}\left\{\sum_{i=1}^{q-1}\left|\frac{A_i}{A_{i+1}}-\frac{A_i^m}{A_{i+1}^m}\right|\right\} \quad (3)$$

It should be noted that the most commonly used norm is the l_2 norm, also known as least squares norm as described in eq. (4).

$$\min_{\alpha_i}\left\{\sum_{i=1}^{q-1}\sqrt{\left(\frac{A_i}{A_{i+1}}\right)^2-\left(\frac{A_i^m}{A_{i+1}^m}\right)^2}\right\} \quad (4)$$

The l_2 norm tends to evenly distribute the error (minimizes the energy) for all error residuals while the l_1 norm has proven to be somewhat better in identifying amplitude outliers within the FMDSMAA.

The initial results of the FMDSMAA are shown in Table 4, but given the relative large error residual for the depth of 7m it was decided to drop the trace at this depth rerun the FMDSMAA with the outcome shown in Table 5. These results reflect a somewhat anomalous absorption value for the interval between 3m and6m. The investigator has then the option of dropping the trace acquired at 4m and rerunning the FMDSMAA. Table 6 outlines the results if that were to happen.

Table 1. Maximum PPA values

Depth [m]	PPA($\times 10^3$) [m/s^2]
933	754.3
4	753
6	340.3
7	320.4
8	86.93
9	136.9
10	130.2
11	106.6
12	76.2
13	45.92
14	58.2
15	71.67
16	45.58
17	39.71
18	39.91
19	40.97
20	25.92

Table 2. Frequency and wavelength values

Depth [m]	Period [ms]	Frequency [Hz]
4	12.1	82.6
9	13.2	75.8
10	13	76.9
12	12.8	78.1
14	11.5	87.0
16	13.1	76.3
18	11.9	84.0
20	11.7	85.5
Average	**12.4**	**80.8**

Table 3. FMDSMAA Input Parameters

Depth [m]	Arrival Time [ms]	Normalized Maximum PPA [m/s^2]	Density [kg/m^3]
3	43.2572	1	1661.4
4	49.1934	0.998378	1726.4
6	65	0.451208	1697.5
7	71.972	0.424793	1763.7
9	86.3344	0.181548	1787.2
10	94.1431	0.172588	1762.8
12	105.7365	0.101014	1823.9
14	116.2743	0.077147	1834.7
16	128.4554	0.060458	1788.7
18	138.8935	0.052917	1624.9
20	147.2301	0.034364	1570.9

4. Comparison with SRT results

To illustrate the advantage over the FMDSMAA over the SRT, the latter was used to calculate the Q value for the depth intervals outlined in Table 4. The results are given in Table 7, and they show non-sensical negative value for Q for various depth intervals. For this would imply that there was an increase in amplitude due toabsorption as the source wave travelled to greater depths. In addition these values do not reflect the input data. In SRT rectangular time windows are applied to the full waveform seismic data under analysis so that spurious time series recordings and measurement noise are minimally incorporated into the spectral ratioanalysis [12].

Table 4. First attempt FMDSMAAAbsorption Estimates (estimated geometric spreading coefficient = 1.017)

Depth [m]	Interval Velocity [m/s]	Wavelength (λ) [m]	Absorption* (α) [1/m]	Q [1/ Np]	Damping (η) [% Np]	Amplitude Ratio Residual
3	87.4	1.08	0.96953	3	16.67	N/A
4	118.8	1.47	0.05707	37.45	1.34	0.00122
6	111.1	1.38	0.30563	7.45	6.71	0.000699
7	130.2	1.61	0.0488	39.99	1.25	0.143
9	131.1	1.62	0.31643	6.13	8.16	6.95E-05
10	123.5	1.53	0.05465	37.57	1.33	0.0516
12	165.3	2.05	0.04444	34.48	1.45	0.0818
14	183.6	2.27	0.04444	31.14	1.61	0.0101
16	161.2	2	0.06637	23.67	2.11	0.0456
18	188.5	2.33	0.04444	30.34	1.65	0.0811
20	235.6	2.92	0.05431	19.81	2.52	0.0858

***The minimum and maximum allowed Q values are 3 and 40, respectively.**

Table 5. Second attempt FMDSMAA Absorption Estimates (estimated geometric spreading coefficient = 0.96)

Depth [m]	Density (ρ) [kg/m^3]	Interval Velocity [m/s]	Wavelength (λ) [m]	Absorption* (α) [1/m]	Q [1/ Np]	Damping (η) [% Np]	Amplitude Ratio Residual
3	1661.4	87.4	1.08	0.96872	3	16.67	N/A
4	1726.4	118.8	1.47	0.09443	22.63	2.21	0.0344
6	1697.5	111.1	1.38	0.31896	7.14	7	1.57E-06
9	1779.4	130.8	1.62	0.18388	10.55	4.74	0.000397
10	1762.8	123.5	1.53	0.09199	22.32	2.24	0.0818
12	1823.9	165.3	2.05	0.11243	13.63	3.67	0.000775
14	1834.7	183.6	2.27	0.04333	31.94	1.57	0.000147
16	1788.7	161.2	2	0.09443	16.63	3.01	0.00712
18	1624.9	188.5	2.33	0.04329	31.15	1.61	0.0712
20	1570.9	235.6	2.92	0.05291	20.33	2.46	0.0901

***The minimum and maximum allowed Q values are 3 and 40, respectively.**

Table 6. Third attempt FMDSMAA Absorption Estimates (estimated geometric spreading coefficient = 0.963)

Depth[m]	Density (ρ) [kg/m^3]	Interval Velocity [m/s]	Wavelength (λ) [m]	Absorption* (α) [1/m]	Q [1/ Np]	Damping (η) [% Np]	Amplitude Ratio Residual
3	1661.4	87.4	1.08	0.26934	10.8	4.63	N/A
6	1707.2	113.6	1.41	0.09869	22.58	2.21	5.91E-05
9	1779.4	130.8	1.62	0.16045	12.09	4.14	0.000577
10	1762.8	123.5	1.53	0.08548	24.02	2.08	0.086
12	1823.9	165.3	2.05	0.10408	14.72	3.4	1.66E-05
14	1834.7	183.6	2.27	0.03836	36.08	1.39	1.44E-05
16	1788.7	161.2	2	0.09659	16.26	3.08	1.68E-06
18	1624.9	188.5	2.33	0.03835	35.16	1.42	0.0675
20	1570.9	235.6	2.92	0.04687	22.95	2.18	0.101

***The minimum and maximum allowed Q values are 3 and 40, respectively.**

The rectangular time window has an amplitude of 1.0 within a time span between t_1 and t_2. Start time t_1 is defined as the time location when moving back in time one zero crossing from the time index of the maximum pulse. End time t_2 is defined as the time location when moving forward in time two zero crossing from the time index of the maximum pulse.

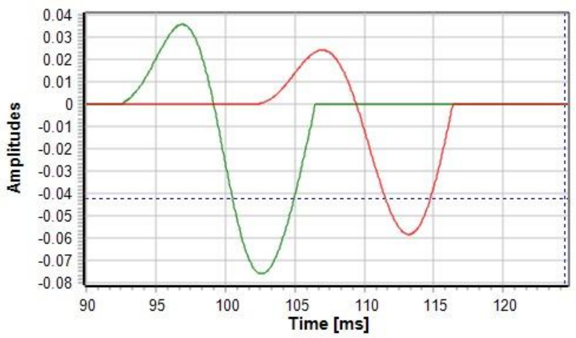

Figure 5. Absolute value full waveforms of the traces acquired at 12 m and 14 m with PPAs shown

Figure 5illustrates the filtered data sets with the rectangular window applied for the traces acquired at the depth of 12m (green trace) and 14m(red trace). Although there is the expected decrease in amplitude, the SRT gives a significant negative Q value as shown in Table 7.

Table 7. 3SRT Estimates for Q

Depth Interval [m]	Q [1/ Np]
3 to 4	-16.8
4 to 6	36.79
6 to 9	1.91
9 to 10	-23.1
10 to 12	45.15
12 to 14	-1.47
14 to 16	1.95
16 to 18	-3.7
18 to 20	17.6

Comparison with Literature Results

To illustrate that the results shown in Table 7 are realistic, the CPT results were used to generate reference values. It is obvious that the generated results fall well within the ranges suggested by these reference values.

Table 8. Field measurements of soil damping (after Stewart & Campanella, 1993)

Soil Type	Damping η (%)
Sand	6
Silt	2.5
Alluvium (sand and clay)	12(<25m);3.5(>25m)
Sandy	5
Clayey	1.7
Fine Sand	1.7
Bay mud	2.5
Clay	4-7
Sand (P-wave)	2-3

Table 9. Comparison derived results with literature results

Depth[m]	CPTU Type Soil Estimate	Calculated FMDSMAA Damping (η) [% Np]	Damping (η) based upon Table 8 [% Np]
0 to 3	Sands	4.63	1.7-6
3 to 6	Clays-clay to silty clay / Sands	2.21	1.7- 6
6 to 9	Clays-clay to silty clay / Sands	4.14	1.7-6
9 to 10	Clays-clay to silty clay / Sands	2.08	1.7- 6
10 to 12	Sands	3.40	1.7- 6
12 to 14	Sands	1.39	1.7- 6
14 to 16	Clays-clay to silty clay / Sands	3.08	1.7- 6
16 to 18	Clays-clay to silty clay / Sands	1.42	1.7- 6
18 to 20	Clays-clay to silty clay	2.18	1.7-6

Conclusions

In 2019 the FMDSMAA technique was introduced as an alternative to the SRT for estimating the viscous shear damping ratio (η_s). At that time the algorithm was demonstrated through test bed data, but in this paper actual downhole seismic testing data were used to demonstrate the functionality of this technique. The paper also highlights the criticality in the FMDSMAA implementation of identifying erroneous full waveform amplitudes.The center part of the FMDSMAA technique is the amplitude of the recorded seismic wave and therefore it is essential that all recorded traces are generated with the same input energy and that the amplitudes are reviewed to remove traces that reflect either non-sensical amplitudes or amplitudes that do not align with the trend.

The paper once again shows that the FMDSMAA technique has significant advantages over the commonly applied Spectral Ratio Technique (SRT). Apart from the previously identified advantages over the SRT (i.e. it is carried out in the time domain and takes into account actual source wave travel paths and soil structure) this paper illustrates how the SRT can result in non-sensical damping values by comparing the results of both techniques with the same input data. Finally the FMDSMAA technique provides an automatic error assessment by comparing the residual between the calculated amplitude and the measured amplitude. This feature provides the user with important feedback on the reliability of the generated results.

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