Tomographic Stone Column Site Characterization Algorithm

Stone columns are used to increase load-bearing capacity and reduce settlement of foundations. Stone columns also improve slope stability and increase the shear strength of a soil. The four major types of stone column construction are vibro-replacement, vibro-displacement, compacted stone columns, and vibro-compaction. There is extensive technical literature available which describes these four construction techniques.

In general terms, in stone column construction a vibrating tool suspended from a crane penetrates to the design depth by means of vibration and of its own weight. Crushed stone is then inserted into the hole. The vibrating probe densifies the soil by breaking down the pores of the surrounding soil. The stone that is inserted into the hole takes the place of the soil and retains pressure on the soil that was created by the vibrating probe. The stone consists of crushed coarse aggregates of various sizes. Stone columns are inserted throughout the area to be improved in a triangular or rectangular grid pattern. The stone column depth depends on the in-situ soil properties.

A very challenging problem is to characterize the in-situ shear wave velocities after the insertion of stone columns. This is due to the resulting very complicated in-situ soil conditions and the correct interpretation of source wave arrivals time. Furthermore, it is mandatory that a proper tomography algorithm is implemented along with raypath refraction. This technical note outlines BCE proposed 2D tomographic stone column imaging algorithm where the unique nature of the stone column site conditions allow for a significant number of *a priori* conditions to be specified which dramatically reduces the optimal solution space for the estimated interval velocities.

Figure 1 illustrates a cross-section of a soil profile where three stone columns have been inserted. The seismic probe and seismic source along with three source wave refracting travel paths have been illustrated. As is shown in Fig. 1, the source waves will travel directly from the source to stone column ***A*** with very small angles of incidence due the relatively high velocity contrast (i.e., $V_2 \gg V_1$, see Technical Notes 7 and 8). The source waves will travel down the stone column refracting into the strengthen medium to be recorded by the seismic probe. The unique site conditions of the stone column ground improvement site allow for several important *a priori* conditions to be specified. This significantly reduces the optimal solution space for the interval velocities (V_1 to V_n) to be estimated.

Tomographic stone column a priori conditions:

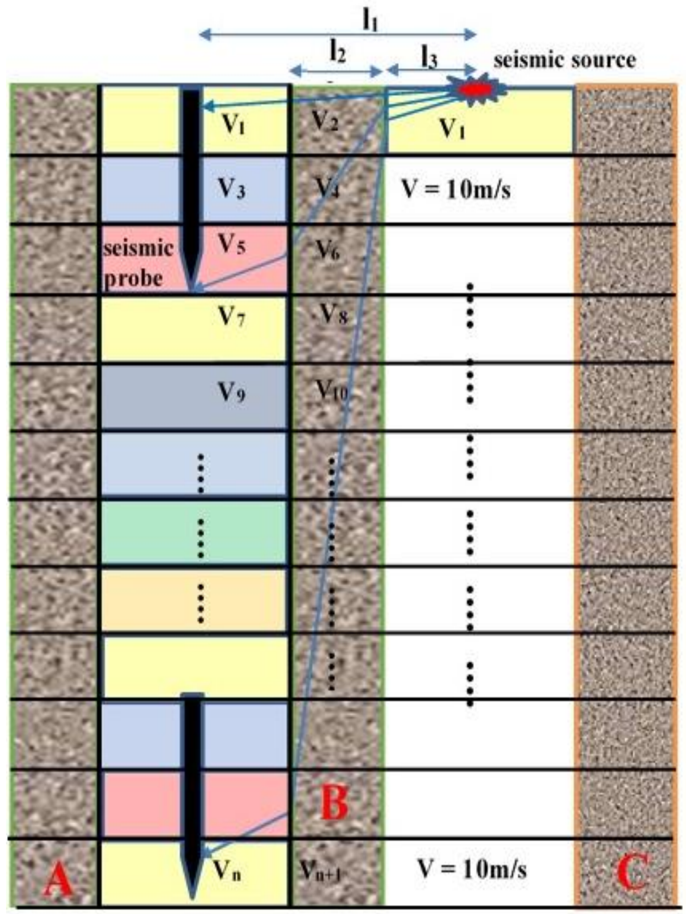

Figure 1. Cross-section of a soil profile where three stone columns have been inserted.

- There is minimal variation in the stone column interval velocities. This is mathematically quantified by utilizing the Coefficient of Variation (CV) which is defined as the ratio of the standard deviation σ to the mean μ.

  The mean μ_{sc} of the stone column interval velocities is given as

  $$\mu_{SC} = \frac{1}{n}\sum_{i=1}^{n} V_{2*i} \qquad (1)$$

  $n = m/2$ where m is the number of layers or interval velocities to be estimated.

  The unbiased standard deviation σ_{SC} of the stone column interval velocities is given as

  $$\sigma_{SC} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(V_{2*i} - \mu_{SC})^2} \qquad (2)$$

  The unbiased *CV* estimate of the stone column interval velocities is given as

  $$CV = \left(1 + \frac{1}{4n}\right)\frac{\sigma_{SC}}{\mu_{SC}} \qquad (3)$$

  In the 2D stone column tomography algorithm it is required that CV ≤ 0.10.

- The interval velocities in the densified medium are at least 1.3 times smaller than those in the stone columns.

  $$\left[1.3 \times V_{(2*i-1)} \leq \mu_{SC}\right]_{for\ i=1\ to\ n} \qquad (4)$$

- The source waves travel directly from the seismic source to stone column ***A*** with very small angles of incidence. This is due to the relatively high velocity contrast (i.e., $V_2 \gg V_1$, see Technical Notes 7 and 8). This condition is implemented in the Stone Column Tomography Algorithm (SCTA) by setting the interval velocities below the first layer V_1 to $V = 10m/s$.

Stone Column Tomography Algorithm (SCTA) - Test Bed Example

Table 1 below provides the working parameters for a test bed simulation of the SCTA. In this test bed simulation the sensor-source offset is 5m (i.e., l_1 = 5m in Fig. 1), the stone column diameter is 1m (i.e., l_2 = 1m in Fig. 1), and the source-stone column offset is 2m (i.e., l_3 = 2m in Fig. 1). The assumed soil interval velocities (V_1 to V_{11} in Fig. 1) are outlined in column 3 of Table 1. A stone column shear wave velocity of 850 m/s is assumed. The minimum and maximum values set for the stone column interval velocity is 650m/s to 1250m/s.

Figure 2 illustrates the source wave raypaths as the source waves travel through the stone column to the DST receivers. The raypaths are simulated utilizing Fermat's principle. Column 2 outlines the associated arrival times of the source waves as they travel from source to receiver through the stone columns and taking Fermat's principle into account. Column 4 of Table 1 outlines the estimated soil interval velocities if a Straight Ray Assumption (SRA) is implemented. As is evident from the nonsensical SRA results, it is mandatory to utilize a tomography algorithm that implements Fermat's principle when estimating in-situ interval velocities when stone columns are present.

Table 1. ***SCTA*** **Test Bed Example Parameters**

Depth [m]	Arrival Time [ms]	Soil Interval Velocity (V_1 to V_{11} in Fig. 1) [m/s]	SRA Estimated Interval Velocities [m/s]	Percent Difference [%]
2	42.419	100	127.0	11.9
3	33.354	200	-49.2	165.3
4	32.073	260	-446.9	378.2
5	36.207	180	161.6	5.4
6	34.679	250	-483.8	313.9
7	34.676	290	-239957	100.2
8	34.307	365	-2256.2	138.6
9	38.09	220	227.8	1.7
10	40.673	280	342.5	10
11	38.069	350	-346.7	21112.1
12	44.156	150	150.7	0.2

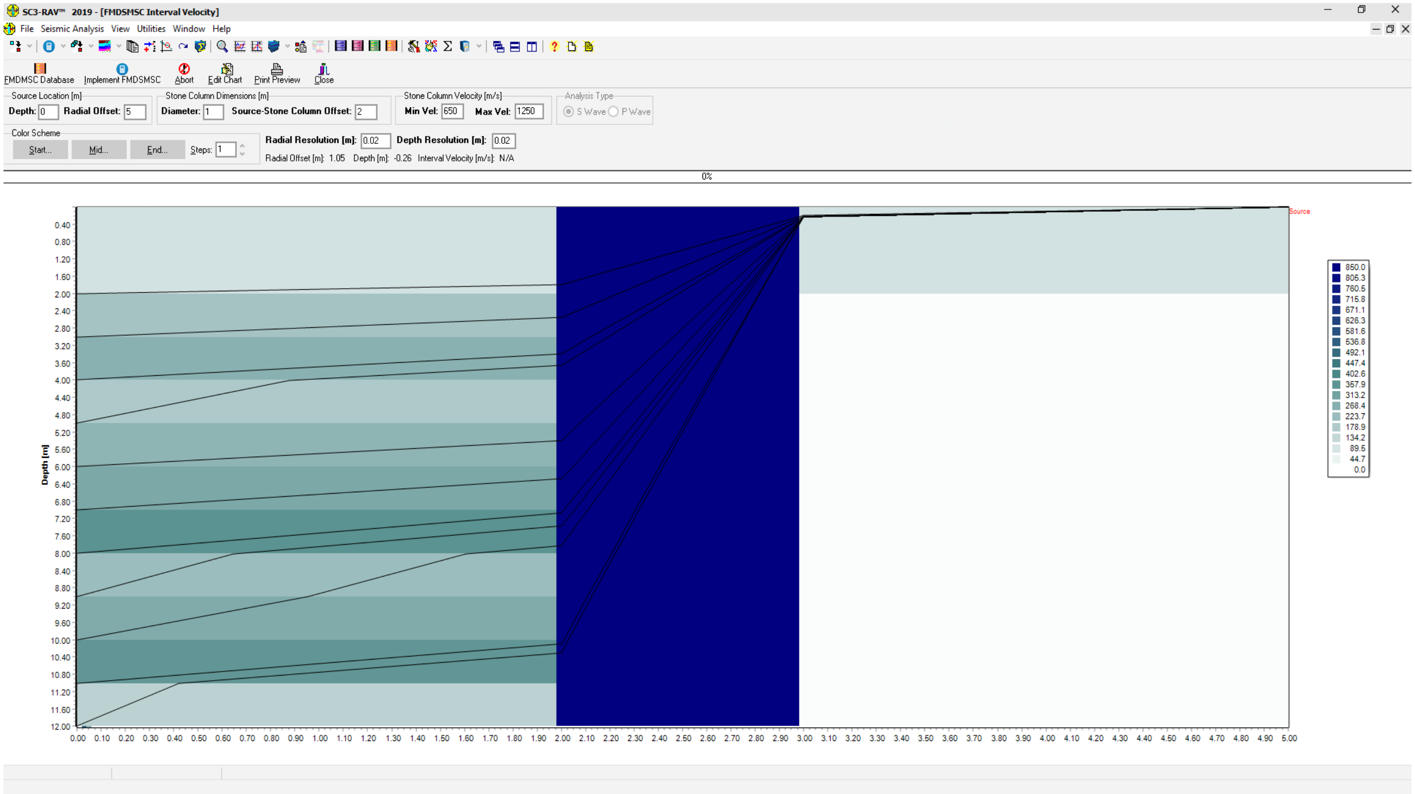

Figure 2. Schematic illustrating the source wave raypaths as the source waves travel through the stone column to the DST receivers and utilizing Fermat's principle.

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