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Design of Deep Soil Mixing Columns for Mitigation of Heave

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DESIGN OF DEEP SOIL MIXING COLUMNS FOR MITIGATION OF HEAVE

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Design of Deep Soil Mixing Columns for Mitigation of Heave

Theoretical Formulation:

The present design of Deep Soil Mixing (DSM) columns in expansive soils is based on the heave prediction model originally proposed by Fredlund and Rahardjo (1993) and later revised by Rao et al. (1988). This model was evaluated as a part of the TxDOT Research Project 0-5179. The model for predicting the heave of the expansive subsoil was based on the variation of swell pressures with depth and is presented in the following equation (Fredlund and Rahardjo 1993):

$$\Delta h_{unt} = \sum_{i=1}^{n} \frac{C_{s,i} h_i}{1+e_{o,i}} log \frac{p'_{f,i}}{p'_{s,i}} \qquad (1)$$

Where $C_{s,i}$, $e_{o,i}$, $p'_{f,i}$, $p'_{s,i}$ and h_i are the Swell Index, Initial Void Ratio, final stress (overburden ± any changes in total stress), initial stress (Swell Pressure), and thickness of each layer 'i', respectively (Fig. 1).

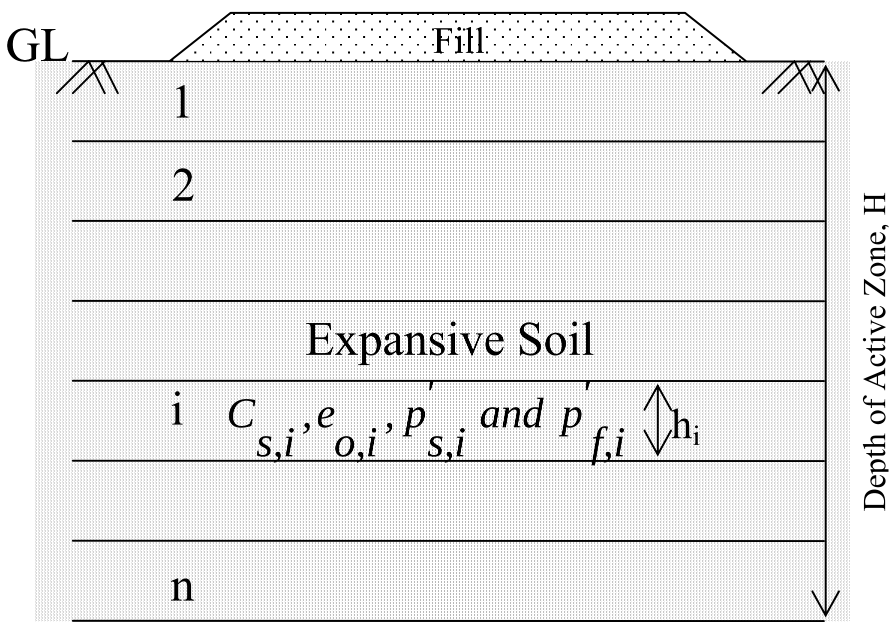


Figure 1: Schematic of Untreated Ground Depicting Layers for Heave Prediction

According to Rao et al. (1988), in an unsaturated expansive soil, the initial stress state is measured as the corrected Swell Pressure, $p'_{s,i}$, from the 'constant volume' type oedometer test. The final stress state, $p'_{f,i}$, accounts for the overburden stress as well as any net changes in total stresses from either excavation or surcharge type loading. It is assumed that the final water content profile of the subgrade strata is near saturation at the time of full heaving.

Equation 1 is extended to predict the heave of the DSM-treated composite test sections, in the following equation.

$$\Delta h = \sum_{i=1}^{n} \frac{C_{comp,i} h_i}{1 + e_{o,i}^{comp}} log \frac{p'_{f,comp}}{p'_{s,comp}} \tag{2}$$

Where the parameters $C_{comp,i}$, $e_{o,i}^{comp}$, $p'_{f,comp}$ and $p'_{s,comp}$ are the composite properties of layer 'i' in the treated ground (Fig. 2). These parameters are estimated as shown below, based on the treated and untreated soil properties determined from laboratory studies.

$$C_{s,comp} = C_{s,col} \times a_r + C_{s,soil} \times (1 - a_r) \tag{3}$$

$$p'_{s,comp} = p'_{s,col} \times a_r + p'_{s,soil} \times (1 - a_r) \tag{4}$$

The symbols with 'soil' in the subscript indicate untreated soil properties and those with 'col' represent lime-cement column properties. The effect of DSM treatment is incorporated into the model by estimating the weighted average of the treated and untreated soil properties. Parameter α_r (area ratio), which is defined as the ratio of the area of treated columns to the total area, is the weighting factor.

Equation 2 is further simplified assuming that: (1) the Initial Void Ratio ($\boldsymbol{e_{o,i}}$) and Bulk Unit Weight for both untreated and treated sections are the same and constant with the depth and (2) the composite properties $C_{comp,i}$, $p'_{s,comp}$ are constant with depth. The simplified equation is in the form of

$$\Delta h = \frac{C_{s,comp} h}{1 + e_o} \sum_{i=1}^{n} log \frac{p'_f}{p'_{s,comp}} \tag{5}$$

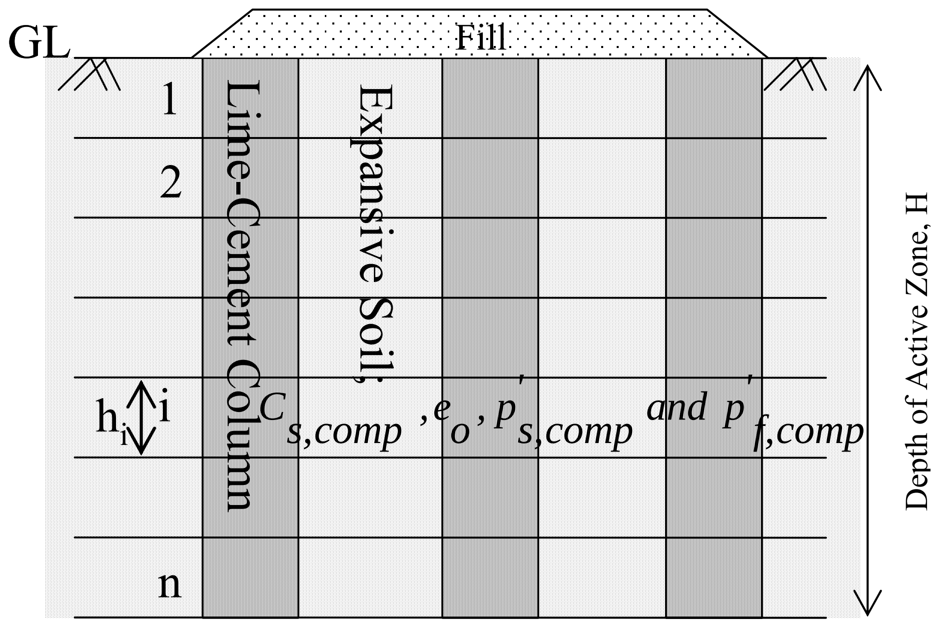


Figure 2: Schematic of Composite Ground Depicting Layers for Heave Prediction

Design Steps:

Based on the heave prediction models in Equations 1 through 5, the design steps shown in the flow chart (Fig. 3) are used for determining the diameter, length and spacing of the DSM columns for mitigating the heave distress emanating from deep expansive subgrades:

1. Determine the representative Swell Index, Swell Pressure, Initial Void Ratio and Total Unit Weight of untreated soil retrieved from the site per the following tests:

   - Swell Index and Initial Void Ratio – consolidation test per ASTM D2435-04
   - Swell Pressure – oedometer test per ASTM D4546-03
   - Specific gravity test per Tex-108-E
   - Total Unit Weight – nuclear density test per Tex-115-E

If the in-situ soil contains several different strata layers, tests should be carried out on each individual layer. The representative Swell Index, Swell Pressure, Initial Void Ratio and Bulk Unit

Weight are determined as the weighted average of the individual properties of the soil layers from the surface to the maximum active depth.

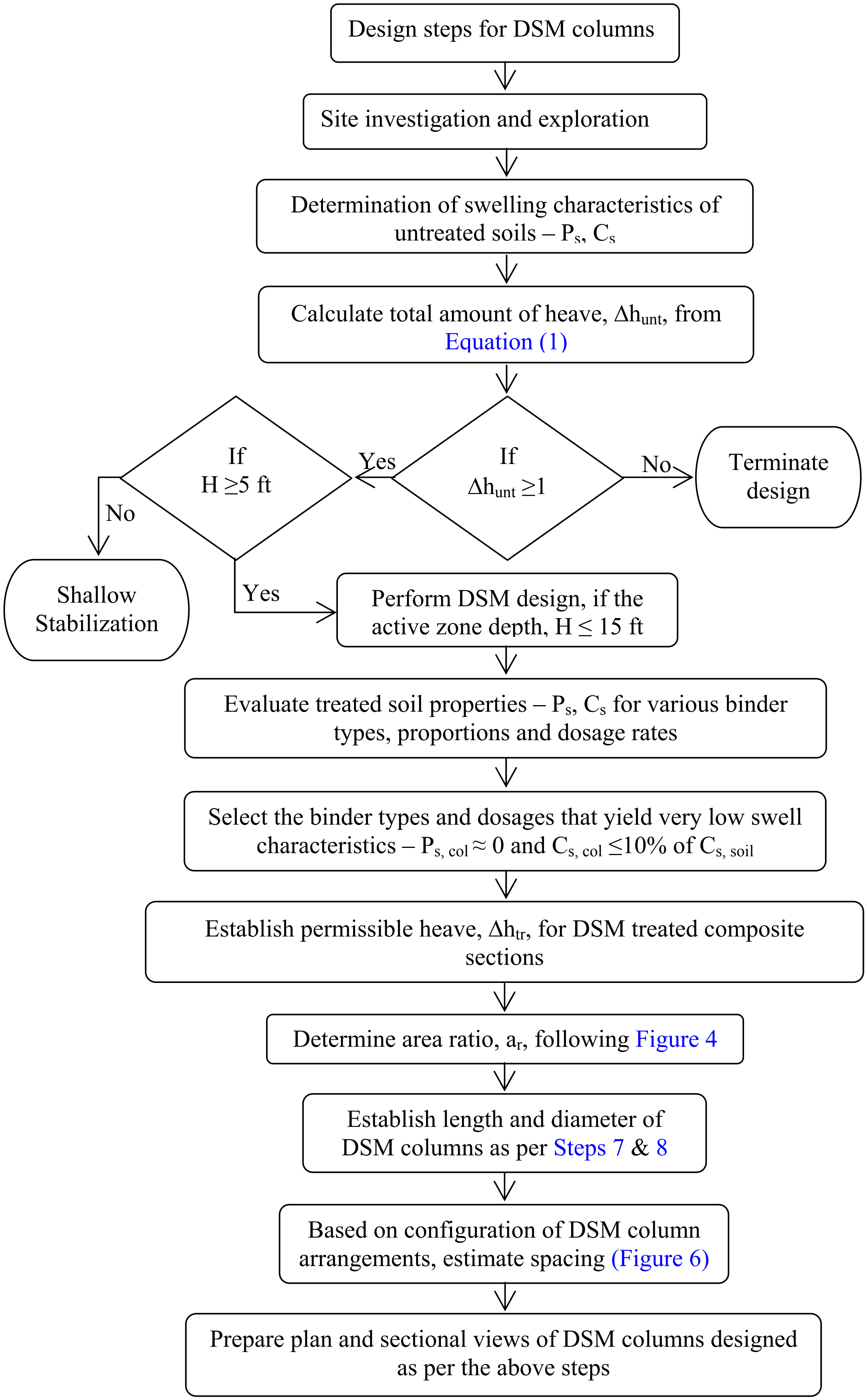


Figure 3: Design Flow Chart for DSM Treatment

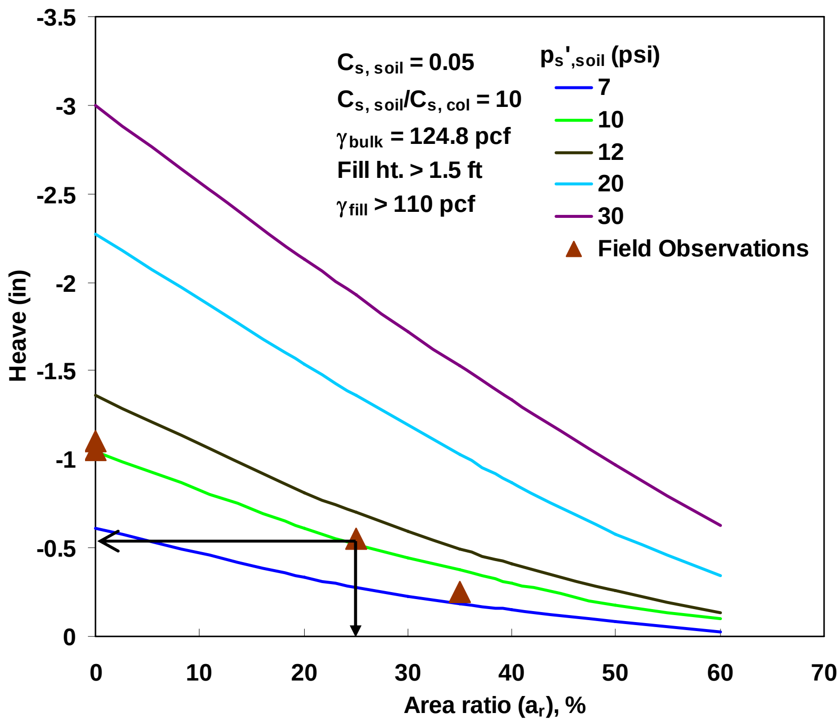
2. Estimate the amount of heave, Δh_{unt}, of the untreated soil using Equation 1. In addition, use Tex-124-E, PVR (Potential Vertical Rise) for each borehole to estimate and compare the amount of heave to Equation 1 above. The two methods may not yield the same results, as they are developed from different theoretical and empirical formulations. Compare the results from both methods in Figure 3 for best or most practical design.
3. Establish the permissible heave, Δh_{tr}, for a given project. For flexible and rigid pavement structures, permissible heaves of 0.5 in. and 0.7 in., respectively, are recommended. These values are arbitrarily established, as heaves around 1 in. are known to induce excessive pavement roughness (International Roughness Index, IRI $\geq$ 170). If the estimated heave for the soil before treatment (estimated in Step 2) is less than the permissible level, soil treatment will not be necessary. If the estimated heave is greater than the permissible heave, follow the next steps to design and establish the DSM treatments for the project site. The costs involved with the field treatments are inversely proportional to the magnitudes of the established permissible heave used in this step. The lower the permissible heaving, the higher the costs involved with the ground treatment, as more DSM columns will be needed. Δh_{tr} of less than 1 in. is needed in order to mitigate the pavement roughness.
4. Estimate the appropriate amount of additives for soil elements by repeating the tests included in Step 1 on soil specimens stabilized with different concentrations of additives. The main goal is to minimize the representative Swell Index value of the soil-additive mixtures. It is desirable to add an adequate amount of additives to reduce the Swell Index value of the treated soil close to 10% of the untreated soil without using more than 8% of the additives in the soil.

5. Estimate the treated area ratio required for the project for reducing the overall heaving of the treated ground to a permissible heave value prescribed in Step 3. Based on the Swell Index of the untreated soil measured in Step 1 and the permissible heave in Step 3, the following appropriate Figure 4a, or 4b or 4c is used to estimate the area treatment ratio. This area treatment ratio is used in Figure 6 to estimate the column spacing.

   Each figure presents various predicted heave (which is equivalent to permissible heave for design) versus area ratio plots for different untreated Swell Pressures and for a given Swell Index value. Equation 5 is used in the preparation of these figures. Please note that this equation for area ratio already accounts for composite swell properties of the treated and untreated ground. Binders and dosage rates that yield very low swell characteristics (Step 3) are only recommended for field implementation.

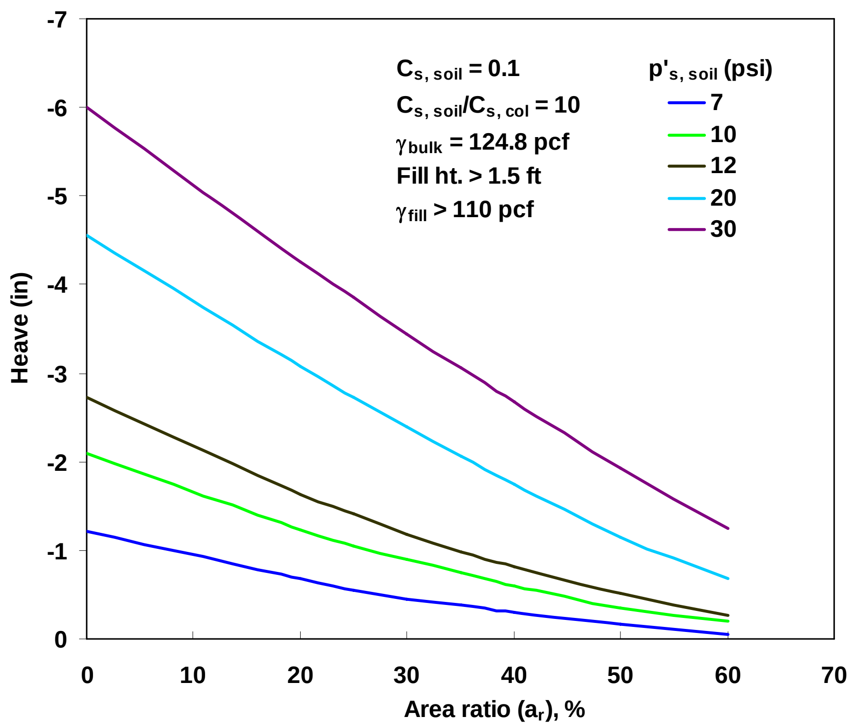
6. If the Swell Index of the untreated soil lies in between those that were used in the development of the design charts, then the linear interpolation method should be followed by using two charts, one lower than the Swell Index value under consideration and the other above the Swell Index value.

7. The diameter of the DSM column is pre-established based on the DSM rigs used by the hired contractor in the field. Typical sizes of the DSM columns range between 12 in. to 24 in.



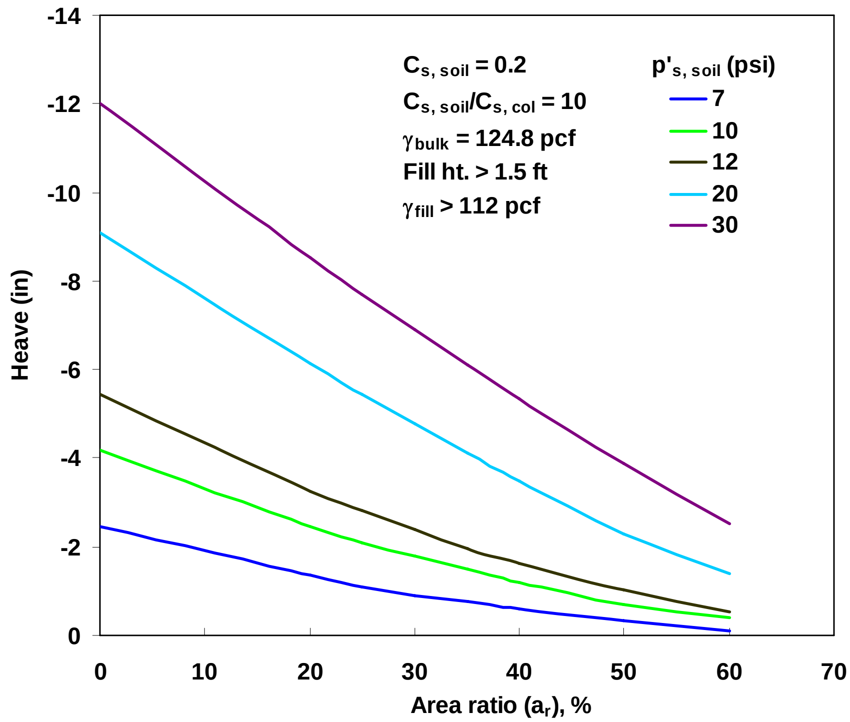
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
Heave (in)
0
10
20
30
40
50
60
70
Area ratio (a_r), %
C_s, soil = 0.05
C_s, soil/C_s, col = 10
γ_bulk = 124.8 pcf
Fill ht. > 1.5 ft
γ_fill > 110 pcf
p_s',soil (psi)
7
10
12
20
30
Field Observations

(a)



-7
-6
-5
-4
-3
-2
-1
0
Heave (in)
0
10
20
30
40
50
60
70
Area ratio (a_r), %
C_s, soil = 0.1
C_s, soil/C_s, col = 10
γ_bulk = 124.8 pcf
Fill ht. > 1.5 ft
γ_fill > 110 pcf
p'_s, soil (psi)
7
10
12
20
30

(b)



(c)

Figure 4: Design Charts for Estimating DSM Area Ratios for Swell Index, C_s

Values of (a) 0.05 (b) 0.1 and (c) 0.2

8. The length of the DSM column is generally established by considering the depth of the column beyond the active zone of the subsoil. It is recommended that the length of DSM columns be close to or below an active depth until a hard stratum or a non-expansive soil is encountered. The active depths at a site can be determined by studying moisture fluctuations in the subsoils or based on PVR calculations of layers that contribute to overall heaving or from construction records of other projects near the project site under consideration. Typically, the active depths can vary between 5 ft and 30 ft for different regions of Texas (Table 1). In the present research, the DSM columns of diameter 2 ft and length of 10 ft were installed in both test sites 1 and 2.

Table 1 Typical Active Depths in Texas (O'Neill and Poormoayed 1980)

City	Active Depth (ft)
Dallas/Fort Worth	7 to 15
Houston	5 to 10
San Antonio	10 to 30

9. In this step, the configuration of DSM columns in the field needs to be established. Two configuration types are generally used in practice, 'square' and 'triangular' type. Figure 5 provides schematics of these configurations. Based on the area ratio a_r derived in Step 5, and the diameter as well as the length of the DSM columns, the optimum spacing of DSM columns is determined by using Figure 6.

10. In the case of multi-axial rigs, treated area under multiple shafts can be idealized as an equivalent circle and then the same spacing calculation can be followed as per the above step.

11. Since the aim of the construction project is to control the heaving of expansive subsoils, two other elements are needed. These are the use of geogrid to be placed over the columns and a placement of anchor rods that connect the geogrid to each DSM column. Details of both geogrid and anchor rod specifications are provided in Table 2.

12. The final plans and section details shall be prepared using the above designed DSM column diameter, length and spacing information. In case the estimated spacing has a decimal, it is recommended to round the value to lower bound. For example, if the design spacing is 3.2 ft, then design spacing should be taken as 3 ft. This ensures that the final area treatment ratio is higher than the value determined from the design chart.

Table 2: Details of Anchor Rod and Geogrid

Anchor Rods:
Anchor rod length: 3 ft.
Anchor rod diameter: ¾ in.
Material: Galvanized Iron
ANCHOR PLATE:
Size: 8 x 8 in.
Thickness: ½ in.
Material: Polypropylene
GEOGRID:
Type: Biaxial geogrid
Tensile Strength: 20 kN/m (both in machine and cross-machine directions)
Material: Polypropylene

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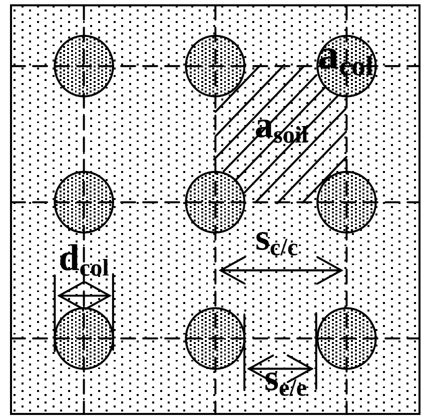
SQUARE ARRANGEMENT:

$$a_r = \frac{a_{col}}{a_{soil} + a_{col}}$$

$$= \frac{\text{area of column}}{\text{area of square}} = \frac{\left(\pi d_{col}^2 / 4\right)}{s \times s}$$

$$\boldsymbol{s = \sqrt{\frac{\pi}{4a_r}} d_{col}}$$



TRIANGULAR ARRANGEMENT:

$$a_r = \frac{\frac{1}{2} a_{col}}{a_{soil} + \frac{1}{2} a_{col}}$$

$$= \frac{\frac{1}{2}\text{area of column}}{\text{area of equilateral } \Delta\text{le}} = \frac{\frac{1}{2}\left(\frac{\pi d_{col}^2}{4}\right)}{\frac{1}{2} \times s \times \frac{\sqrt{3}}{2} \times s}$$

$$s = \sqrt{\frac{\pi}{3.464 a_r}} d_{col}$$

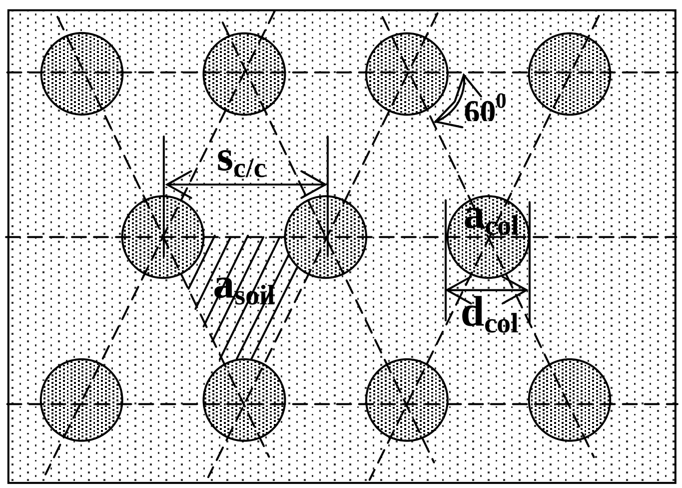
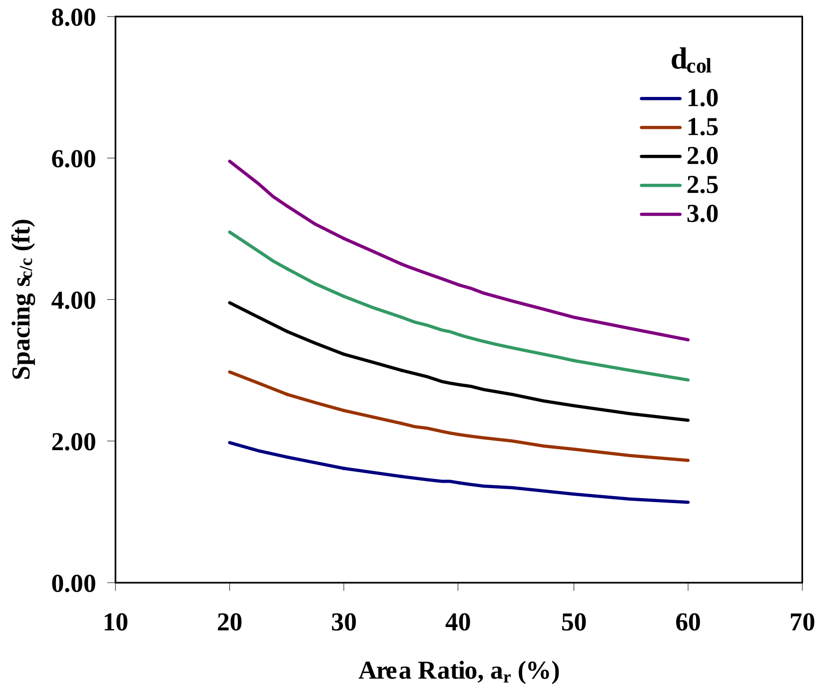
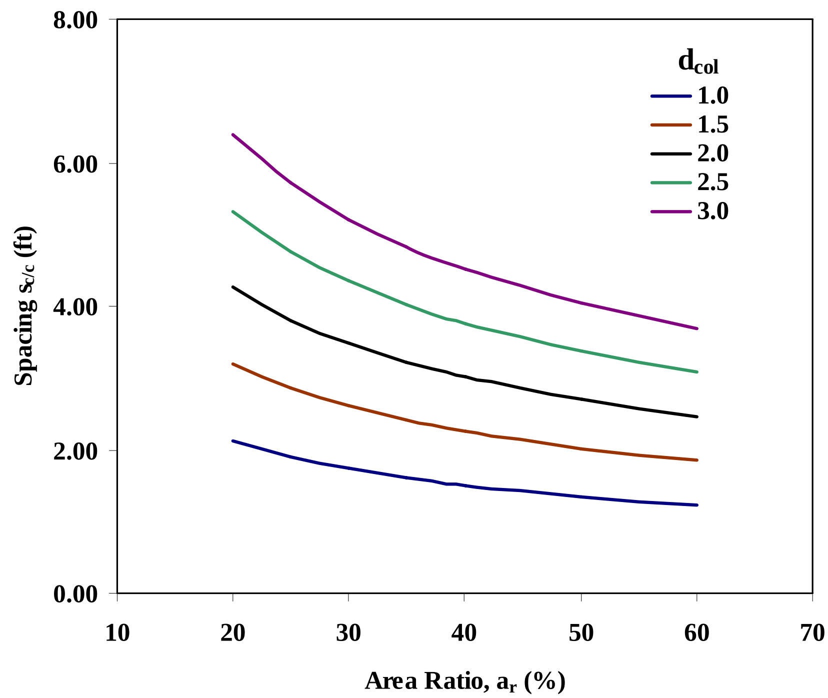


Figure 5 Configurations of DSM Columns and Equations for Spacing of DSM Columns



(a) Square Pattern



(b) Triangular Pattern

Figure 6 DSM Column Spacing Details (a) Square Pattern (b) Triangular Pattern