Evaluation of the efficiency of different ground improvement techniques

Évaluation de l'efficacité des différentes techniques d'amélioration des sols

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ABSTRACT: There are two primary reasons why developments continue in areas with poor subgrade soil conditions. The first is the lack of space and increased pressure to develop within a particular region. The second is for economic reasons such as road construction where it is not feasible, and may not be physically possible, to modify routes to avoid crossing areas of soft soils. This paper investigates the performance of various ground improvement methods used in construction of embankments on soft soils using three-dimensional numerical modeling.
Multiple forms of ground improvements were analyzed including deep soil mixing, light-weight fill, and stone columns. The efficiency of each type of ground improvement was evaluated based on the reduction of predicted settlement compared to a baseline model where improvements were not used. It is suggested that the economic feasibility of ground improvements be highly dependent on the geographic location of the site; however, the gain in performance may be worth the extra material costs in some cases.

RÉSUMÉ : Il y a deux raisons principales pour lesquelles on continue à développer dans les zones où les conditions du sol de fondation sont mauvaises. La première est le manque d'espace, ainsi qu'une pression accrue à se développer dans une région donnée. La seconde étant, pour des raisons économiques telles que la construction de routes où il n'est pas probable, et peut-être pas physiquement possible, de modifier les routes pour éviter de traverser les zones de sols mous. Cet article examine la performance des différentes méthodes d'amélioration des sols utilisées dans la construction de remblais sur sols mous en utilisant la modélisation tridimensionnelle numérique.
De multiples formes d'amélioration du sol ont été analysées, y compris un sol de mélange profond, légèrement rempli et en colonnes de pierre. L'efficacité de chaque type d'amélioration des sols a été évaluée en fonction de la réduction de tassement prédit par rapport à un modèle de référence où des améliorations n'ont pas été utilisées. Il est suggéré que la faisabilité économique des améliorations du sol est fortement tributaire à la situation géographique du site, cependant dans certains cas le gain en performance vaut la peine d'avoir des coûts supplémentaires de matériels.

KEYWORDS: Ground improvement, deep soil mixing, light-weight fill, stone columns, embankments, soft soils

1 INTRODUCTION

Lack of space, increased pressure to develop within a particular region or any other economic or political motivations are all valid reasons for developments to continue in areas with poor subgrade soil conditions. There are several methods of improving the properties of soft soils to reduce the post-construction settlement or to improve the stability and the overall performance of embankments and dams. Improvement techniques used in construction of embankments and dams on soft clay such as stone columns, deep soil mixing, vibrocompaction, etc., are becoming increasingly popular in North America. The San Pablo Dam, Sunset North Basin Dam, the Clemson Upper and Lower Dams, and the I-95/Route1 project are all examples of case studies in the United States where ground improvements have been implemented under foundations of dams and embankments.

Methods of construction of embankments on soft soils have been well documented; however, to the authors' knowledge, there is a lack of literature related to the comparison and process of selecting ground improvements. The main purpose of this study was to investigate the performance of various ground improvement methods used in construction of embankments on soft soils using three-dimensional numerical modeling to identify which method is most efficient at reducing settlements for the considered case.

2 NUMERICAL MODEL

The parametric analyses completed for this study were done using an explicit three dimensional finite difference numerical model. Materials modeled using the finite difference method are represented by polyhedral elements to which variables are assigned at discrete locations and the zones will behave independently. The explicit time marching scheme calculates the velocity and stresses for every element during each time step based on the initial values. The new stresses and velocities are then applied to the elements to be used in the following time step. The model uses the velocity and time step to determine the displacements for each element. The finite difference methods allow grid points within the model to move and deform as incremental displacements are applied during each time step which makes it better suited to be used for analysis of nonlinear large strain problems, such as the deformation of soft soil during embankment construction (Itasca 2009).

2.1 Model details

For the purpose of the parametric study a baseline model was developed using assumed stratigraphy, embankment dimensions, and material properties. The assumed stratigraphy was a 6 m thick layer of loose silt, overlying 2 m of normally consolidated, soft clay, over sandstone bedrock. The design embankment used in the model was 6 m high, with a crest width of 6 m and 3H:1V side slopes (see Figure 1). It was assumed that the ground improvements would extend as far as the toe of the embankment side slopes to the bottom of the soft clay.

Material properties were defined based on average values found in the literature review and are described in greater detail under the section titled Physical Properties. The groundwater table was assumed to be located at the surface of the loose silt deposit. The model was built to maintain a maximum aspect ratio of 3:1 between elements in the x, y, and z directions and used planes of symmetry to reduce the total number of elements in each model. The embankment was constructed in several phases to simulate more realistic loading conditions.

The groundwater table was modeled using a normal groundwater force rather than using a groundwater flow model. This was done to simplify the analyses as the behavior of the groundwater within the soil was not the focus of the study. As a result the simplified groundwater conditions the Mohr Coulomb constitutive model was used to simulate soil response.

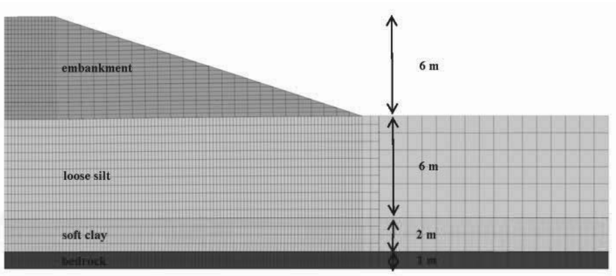

Figure 1. Model Stratigraphy

3 METHODS OF GROUND IMPROVEMENTS

3.1 Stone columns

Stone columns, like sand drains, enhance the drainage properties of soft soils, however, the interlocking granular nature provides additional shear strength to the surrounding soils compared to sand drains. Stone columns can be installed as either independent columns or as continuous walls or panels of columns. Stone columns reduce settlements by promoting soil arching which transfers the embankment loading to the stiffer columns once the soft surrounding soils begin to yield (Terzaghi 1943). Typically stone column wall thicknesses and area replacement ratio (ARR) range between 0.4 and 1.2 m and 10% to 30%, respectively (Abusharar and Han 2011). Analyses were completed for stone columns panels with thicknesses of 0.4 m, 0.8 m, and 1.2 m with spacings corresponding to an ARR of 30%.

3.2 Deep mixed columns

Deep mixed columns (DMC) are very similar to stone columns in terms of typical dimensions, and promoting soil arching to transfer loading to panels rather than insitu soil. Deep mixed columns are constructed by mixing lime or cement and insitu soil to create a column, or panel of columns, of stronger soil which carries embankment loads and reduces expected settlements. The primary difference between stone columns and deep mixed columns is that strength of stone columns is dependent on the friction angle of the aggregate and confinement from surrounding soils (Abusharar and Han 2011); while deep mixed columns have internal strength from cohesion. It is noted that the deep mixed columns are constructed such that they are continuous panels and the flow of groundwater will be inhibited or significantly reduced. For comparison purposes, panel thicknesses of 0.4 m, 0.8 m, and 1.2 m with spacings corresponding to an ARR of 30% were used to analyze the efficiency of the deep mixed columns.

3.3 Light weight fill

An alternative to improving the in situ soil in order to increase the bearing capacity is to reduce the total loading. Light weight fills such as sawdust, tire derived aggregate, and geofoam are frequently used during construction of embankments on soft soils to minimize consolidation, differential settlements, and/or construction schedules. Analyses were completed using both sawdust and geofoam as embankment fills, ranging between 2 and 4 m in thickness, to compare against the results of the ground improvement methods listed above.

3.4 Comparison of methods

Several factors may impact the suitability of each method for a particular site and may govern which method is selected over another as follows:

- Stone and deep mixed columns cause densification of the surrounding soil as a result of displacements during installation. Larger columns and smaller spacing will increase densification.
- Stone columns are highly permeable and therefore will reduce the liquefaction potential of a material by allowing excess pore pressures to dissipate.
- Specialized equipment is required for construction of stone/deep mixed columns.
- Light weight aggregates may be placed with typical construction equipment.
- Strength characteristics of deep mixed soils may be influenced by geochemical properties of the surrounding soil (Jacobson et al., 2003) and thus rigorous mix designs are recommended for all sites.
- Sawdust may degrade over time due to its organic nature; however, rates of degradation may be minimized by limiting exposure to free oxygen and moisture.
- Geofoam is susceptible to rapid degradation when exposed to hydrocarbons; therefore geosynthetic liners are often installed.

Cost-benefit comparisons for the different methods are highly dependent on the location of particular sites and the availability of materials and therefore have not been included as part of this study.

4 PHYSICAL PROPERTIES

For the purpose of the parametric study typical values described in literature or published case studies were used as input soil parameters for the numerical models. In FLAC3D, the Mohr Coulomb constitutive model requires wet density, internal angle of friction, cohesion, tensile strength, and bulk and shear modulii. The bulk and shear modulii are both functions of the Young's modulus and Poisson's ratio of a material that are calculated using the following equations:

Bulk Modulus,

$$K = E(1-\nu)/(((1+\nu)(1-2\nu)) \quad (1)$$

Shear Modulus,

$$G = \frac{E}{(2(1+\nu))} \quad (2)$$

A summary of the physical and elastic material properties are provided in Table 1. The material properties were assumed values unless noted otherwise.

Table 1. Physical Properties

Parameter	ρ (kg/m^3)	*E* (Pa)	Φ (°)	ν	c' (Pa)
Bedrock	2200[5]	1.93e10[5]	30[5]	0.38[5]	3.0e5[5]
Clay	1631	2.00e6	0	0.4[6]	1.5e4
Loose Silt	1835	1.24e7	27	0.3	0
Embankment Fill	2039	3.03e7[6]	34	0.4[6]	0
Stone	1983[2]	3.03e7[6]	36[2]	0.4[6]	0
Deep Mixed Soil	1631[1]	1.25e9	32	0.2[6]	3.4e5
Sawdust	1040[3]	8.50e5	32[3]	0.05[3]	0
Geofoam	15[4]	3.76e6	32	0.09[7]	1.1e5[4]

[1]Oliveira et al, 2011, [2]Abusharar and Han, 2011, [3]Rowe and Soderman, 1984, [4]Geotech Systems Corporation, 1993, [5]Itasca, 2009, [6]Kulhawy and Mayne, 1990, [7]Hazarika, 2006

5 NUMERICAL MODELING RESULTS

To evaluate the efficiency of each method of ground improvement a baseline model was run which simulated the construction of a 6 m embankment without neither ground improvements nor light weight fill. All results have been normalized against the vertical displacements and vertical stresses calculated using the baseline model.

5.1 Settlement

Settlements calculated at the top of the silt layer at the centerline of the embankment were used for comparisons. Figure 2 illustrates magnitudes of settlement calculated for each method. The baseline model predicted a total settlement of 0.170 m. The model with 2 m of sawdust showed negligible improvement while the models with 4 m of geofoam, and 400 mm deep mixed columns, were the most effective with predicted settlements of 0.040 m, or a 76% reduction. It can be seen from Figure 2 that in general the geofoam and the deep mixed coulmns performed better than the sawdust and the stone columns with respect to the reduction of settlement.

5.2 Vertical stress

Figure 3 shows the maximum vertical stresses calculated near the surface of bedrock for the different considered ground improvement methods in comparison to the baseline model. For illustration purposes only one example for each method is provided. The following paragraphs include results for all of the analyses carried out.

The baseline model predicted a vertical stress of 217 kPa near the surface of bedrock. The model with 4 m of geofoam, as expected, experienced the greatest reduction in predicted vertical stresses at 32% of the baseline value, or 68 kPa. The difference in vertical stress was based on comparison of the vertical stresses between the respective models and the baseline calculated at the same point. The stone and deep mixed columns, as result of the stiffness contrast between the column material and surrounding soils, are attracting additional loads due to soil arching. The ability of the stone columns to accumulate stress from soil arching is limited because the columns are yielding themselves; however, the trend is still visible as shown in Figure 4. Figure 5 illustrates how soil arching reduces the vertical stresses as the column's diameter increases to a point at which is becomes less effective. The percentage difference in vertical stress is based on a comparison of the vertical stresses calculated at the centerline of the column and the midspan between columns for each model near the ground surface. It is noted that the behavior for both types of columns is very similar and that the overall strength characteristics will determine the magnitude of the percentage reduction in stresses. The decrease in soil arching effectiveness is attributed to the increased spacing between columns. In this analysis a constant replacement ratio was maintained, therefore, as the column diameter increased the spacing was increased as well.

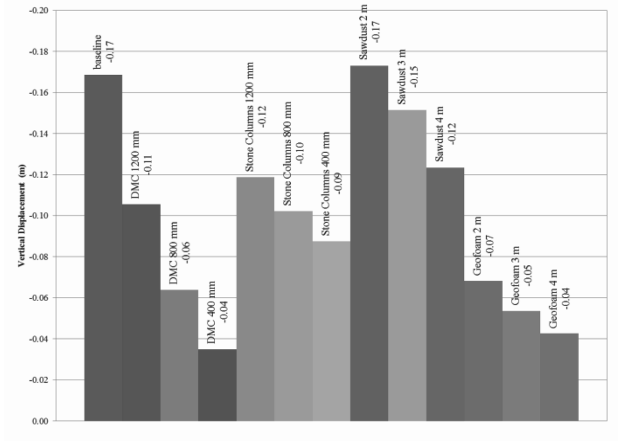

Figure 2. Comparison of predicted settlements at the interface between the embankment and the ground surface based on different methods of ground improvements

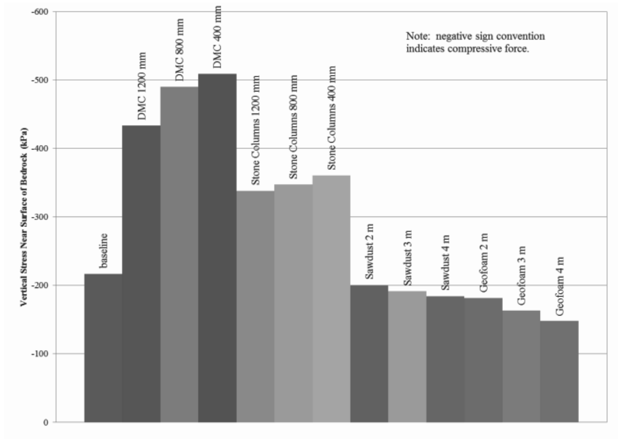

Figure 3. Comparison of predicted vertical stresses near the surface of bedrock based on different methods of ground improvements

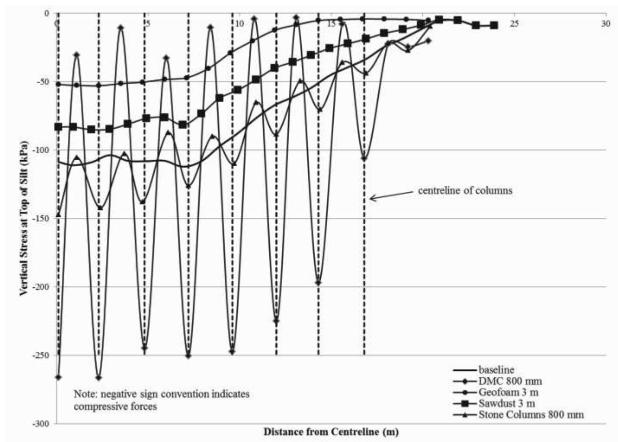

Figure 4. Comparison of predicted vertical stresses calculated at the top of the silt layer based on variable methods of ground improvements

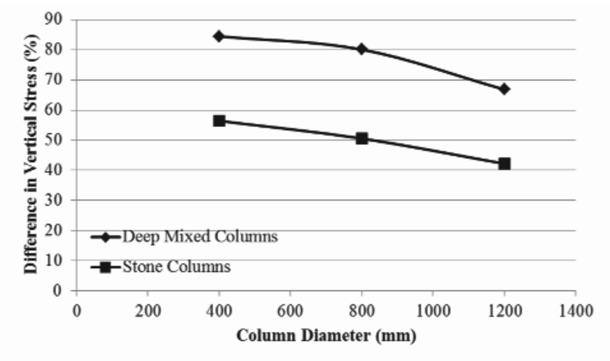

Figure 5. Reduction in effectiveness of soil arching effects as column diameter increases while maintaining a constant area replacement ratio based on vertical stresses calculated near the top of the loose silt.

6 DISCUSSION

The results presented in this study revealed that sawdust is not very beneficial as a standalone method as it is still reasonably dense and highly compressible. As the strength of stone columns is a result of both the friction characteristics of the aggregate and the confinement from surrounding soils, in cases where there is minimal confining pressure the columns will deform (bulge) under the embankment loading. The anticipated lateral loads in the stone columns should be considered to confirm that there is adequate confinement within loose cohesionless soils to prevent excessive internal deformation of the column.

Deep mixed columns are very effective at reducing the settlements due to the development of soil arching which is clearly illustrated in the vertical stress plots where the stress concentrations correspond with the midpoint of the columns within the model. As shown in Figure 5 the soil arching is increasingly effective as the diameter (and spacing) decrease. It is anticipated that a limiting diameter exists where the diameter will be controlled by the size of the mixing equipment that is commercially available. Based on the analysis completed, for a consistent area replacement ratio, the deep mixed columns attract 35% more load due to soil arching than the corresponding stone column.

Geofoam minimized settlements because it is so light in comparison to other materials. With a density of 15 to 30 kg/m^3 it is substantially less dense than other light weight aggregates such as sawdust which has a density of approximately 1040 kg/m^3.

7 CONCLUSIONS

This study focused on just four types of methods used to minimize overall settlements of embankments constructed on loose silt but in future studies it would be interesting to compare performances of columns (deep mixed or stone) vs panels of columns at constant replacement ratios, and then to compare the benefits of various replacement ratios. Increased lateral confinement as a result of berms or sheet piles may also reduce deformations, in addition to the use of geosynthetics for internal structural support within the embankment, or a combination of methods.

Based on the parametric analyses completed the following guidelines are proposed which may be used to assist in the selection of a method to reduce settlements.

1. The loose soil unit must be thick enough that there is adequate confinement for stone columns to be effective.
2. Deep mixed columns and geofoam may provide similar final results if utilized in the correct quantities.
3. Under constant area replacement ratios, settlements increase as column diameters increase.
4. Under constant area replacement ratios, soil arching becomes more effective as column diameters decrease.

8 ACKNOWLEDGEMENTS

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