The Ohio Department of Transportation
Office of Research & Development
Executive Summary Report

Shear Strength of Clay and Silt Embankments

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Problem

Highway embankments constitute some of the most common geotechnical facilities being constructed by highway and transportation agencies. The design, construction, and field performance of these embankments are great importance to federal and state transportation costs and public safety. When the embankments are not properly designed and/or constructed, serious problems such as slope instability and excessive settlement can arise. Very conservatively designed embankments can lead to significant budgetary waste for the highway agencies.

In Ohio, highway embankments are typically built using silty and clayey soils found at or near the construction sites. In some areas of Ohio, weathered shale is also used to construct highway embankments. It has been known that some cohesive soils in Ohio have low to medium shear strengths and weathered shale can undergo further weathering over time. From these considerations, it is important that civil engineers know engineering properties of soils available for their projects. This typically requires extensive subsurface exploration and laboratory testing of soil samples. In reality, detailed examinations of the on-site fill materials are rarely conducted due to cost and time constraints. Instead, highway engineers consult empirical correlations established by the Department of Navy or others to estimate shear strength properties of embankment fill materials. This short-cutting practice can potentially result in improper designing of highway embankments, since the empirical correlations published in the past are based on studies of soils found in different regions of the world and they have not been verified for the embankment fill soils used in Ohio.

Objectives

- Conduct a literature review to document information relevant to the design and construction of highway embankments and geological features/soils found in Ohio;
- Identify a total of nine highway embankment sites in Ohio, which represent a wide range of geographical regions, geological settings, and soil types;
- Perform in-situ soil testing and sampling work at each highway embankment site;
- Obtain engineering properties of the soil samples recovered from the highway embankment sites by conducting index property and shear strength tests in the laboratory;
- Perform a variety of statistical analysis on the geotechnical data compiled for the highway embankment fill soils in Ohio to develop reliable correlations for predicting shear strength properties of these fill materials; and
- Based on the outcomes of all the tests and analyses conducted, propose geotechnical guidelines concerning shear strength properties of cohesive soils commonly used for highway embankment construction in Ohio.

Project Tasks

In order to meet the above objectives, the following four tasks were created and carried out:

Task 1 – Conduct a review of literature related to soil shear strength, embankment stability, standard penetration test (SPT), and geological features of Ohio. Document empirical correlations that appear to be useful for the design of highway embankments;

Task 2 – Select nine highway embankment sites across Ohio that cover various geographical regions, geological settings, and soil types. At each site, place a continuous SPT to a depth of 25 ft. Obtain twelve Shelby tube soil samples at three depths, next to the SPT hole;

Task 3 – Test the soil samples recovered from the sites in the laboratory to determine their index properties and shear strength parameter values; and

Task 4 – Evaluate general reliability of the empirical correlations that were identified in Task 1. Analyze the field and laboratory test data gathered in Tasks 2 and 3 by employing single-variable and multi-variable regression techniques. Based on the results of all the analyses performed, formulate a set of guidelines which highway embankment design engineers can use to estimate shear strength properties of Ohio soils more confidently.

Conclusions

Task 1: Literature Review

- Factors that dictate stability of highway embankments are – 1) shear strength of the embankment fill soil; 2) unit weight of the fill soil; 3) embankment height; 4) steepness of embankment slopes; and 5) pore pressures in the fill soil.

- The soils in Ohio formed over thousands of years ago, derived from bedrock, glaciers, streams, climate, and biota. Lake deposits persist along the lake shores in the northern Ohio. Glacial till soils are abundant throughout the central and southwestern parts. Unglaciated (residual) soils are common in the eastern and southeastern regions.

- Shear strength of soil is influenced by the normal stress level, the soil type, and physical state of the soil. The basic theory for soil shear strength is the Mohr-Coulomb theory, which involves two key parameters – angle of internal friction (ϕ) and cohesion (c).

- Undrained cohesion (c_u) is critical for the short-term (or end-of-construction) embankment slope stability. In contrast, drained friction angle and cohesion (ϕ', c') are both key factors for the long-term embankment slope stability.

- Currently a few standard test methods are available for measuring soil shear strength. Among them, triaxial compression test method appears to be one of the most advanced and realistic test methods.

- Embankment soils in Ohio are usually unsaturated. Experimental evidences show that most soils possess higher shear strength when unsaturated. However, the unsaturated state may not exist constantly. At many embankment sites, soils do become saturated periodically due to precipitation and subsurface drainage events.

- An empirical correlation between fully corrected SPT-N value $(N_{60})_1$ and unconfined compression strength has been published for cohesive soils by Terzaghi and by the Dept. of Navy. Terzaghi also came up with a chart that relates plasticity index (PI) to the drained friction angle (ϕ'). The Dept. of Navy presented typical shear strength parameter values for each cohesive soil type (A-4, A-6, A-7-6).

Task 2: Site Selection & Field Testing

- A set of criteria was established to screen candidate embankment sites. In the end, the following nine highway embankment sites were selected for the current study – I 275 site in Hamilton County (Site 1: HAM-275), USR 35 site in Fayette County (Site 2: FAY-35), SR 2 site in Lake County (Site 3: LAK-2), USR 33 site in Athens County (Site 4: ATH-33), I 71 site in Morrow County (Site 5: MRW-71), SR 2 site in Erie County (Site 6: ERI-2), I 75 site in Hancock County (Site 7: HAN-75), I 70 site in Muskingum County (Site 8:

MUS-70), and I 77 site in Noble County (Site 9: NOB-77). Figure 1 shows general locations of these sites.

- Prior to the field phase, a BBC & M's mobile, rig equipped with an automatic SPT hammer, was calibrated by GRL Engineers, Inc. (Cleveland, Ohio). According to the results, the hammer delivers 81.7% of the free-fall energy.

- For normalizing the SPT-N values, the correction method proposed by Seed et al. appears to be most reasonable.

- During the subsurface exploration, A-4a soils were encountered at three sites (FAY-35, LAK-2, MRW-71), A-4b soils at only one site (MUS-70), A-6a soils at six sites (ATH-33, FAY-35, LAK-2, MRW-71, MUS-70, NOB-77), A-6b soils at two sites (HAN-75, NOB-77), and A-7-6 soils at four sites (ATH-33, ERI-2, HAM-275, HAN-75). This indicates that A-6a soils are widespread and A-4b soils are rare in Ohio.

Task 3: Laboratory Tests

- The subcontractor BBC & M Engineering (Dublin, Ohio) performed all of the index property and unconfined compression (UC) strength tests. The index properties included moisture content, specific gravity, grain size distribution, Atterberg limits, and AASHTO/ODOT soil classification. The ORITE team conducted consolidated-undrained (C-U) triaxial compression tests.

Task 4: Data Analysis and Guidelines

- The empirical correlation between fully corrected SPT-N value $(N_{60})_1$ and unconfined compression strength, published by Terzaghi, is not reliable for cohesive soils in Ohio. The similar empirical correlation published by the Dept. of Navy also is unreliable for cohesive soils found in Ohio.

- The chart by Terzaghi, which relates plasticity index (PI) to the drained friction angle (ϕ'), is applicable to cohesive soils in Ohio. This is particularly true for A-4 and A-6 soils. For A-7-6 soils in Ohio, the average ϕ' angle resulting from the chart should be lowered by 3°. See Figure 4.

- The default ϕ' angle value recommended by the Dept. of Navy is reasonable for A-4 soils found in Ohio. However, for A-6 and A-7-6 soils in Ohio, the ϕ' values listed by the Dept. of Navy are lower than the average (ϕ') values measured for these soil types.

- Single-variable linear regression analysis was successful in locating statistically strong correlations for shear strength properties of A-6b soils. This analysis did not deliver good results for the remaining soil types (A-4, A-6a, A-7-6).
- Single-variable nonlinear regression analysis produced many statistically strong correlations for the shear strength properties of each soil type.

Among the nonlinear models tried, hyperbolic function proved to be most successful in expressing various correlations (see Figure 5). Among the independent variables (with many of them being either an index property or a physical state indicator), % silt, % clay, time for 50% consolidation, and dry unit weight surfaced as important indicators of soil shear strength.

- Multi-variable linear regression analysis performed with SPSS was successful for the A-4a soil data. For other soil types, the analysis was only partially satisfactory. Among the independent variables, % compaction, % sand, specific gravity, and fully corrected SPT-N value $(N_{60})_1$ appeared frequently in the reliable models.

- Multi-variable nonlinear regression analysis did not yield as many good results.

- Multi-variable linear regression analysis was performed again with SPSS, since the initial analysis used variables (ex. SPT-N, unconfined compression strength, time for 50% consolidation, …) that cannot be obtained easily for any new highway embankment construction projects. Revised analysis yielded some good results. Here, % compaction, % sand, % gravel, and specific gravity emerged as important indicators of Ohio cohesive soil shear strength properties.

- A series of t-test were made to compare the average properties possessed by similar soil type subsets found in Ohio. It was noted that A-4a and A-4b soils share nearly identical properties. Shear strength properties are slightly different between A-6a and A-6b soils. A-7-6 soils found in the northern and southern Ohio share many basic properties that are different but their shear strength properties are very close.

- The geotechnical guidelines address both short-term and long-term soil shear strength properties and are multi-leveled to permit different levels of sophistication. At level 1, default shear strength values are listed for each cohesive soil type. Level 2 takes advantage of the statistically strong single-variable regression models. Level 3 utilizes the reliable multi-variable linear regression models.

Implementation

The following plans are recommended to be implemented by ODOT:

- A mobile rig equipped with an automatic SPT hammer should be always employed for major highway projects in Ohio.

- For normalizing original SPT-N values to the depth effect, the correction method by Seed et al. (1975) should be applied.

- Consider the Level 1 guidelines as basic tools for estimating shear strength properties of Ohio cohesive soils.

- Follow Level 2 or Level 3 guidelines for determining soil shear strength properties for any highway projects, for which fundamental engineering characteristics of the fill soil are known.

- Apply Level 3 guidelines for investigations of existing highway embankment structures in Ohio.

Figure 1: General Locations of Nine Highway Embankment Sites

Figure 2: Subsurface Exploration Work at Site No. 9 (NOB-77)

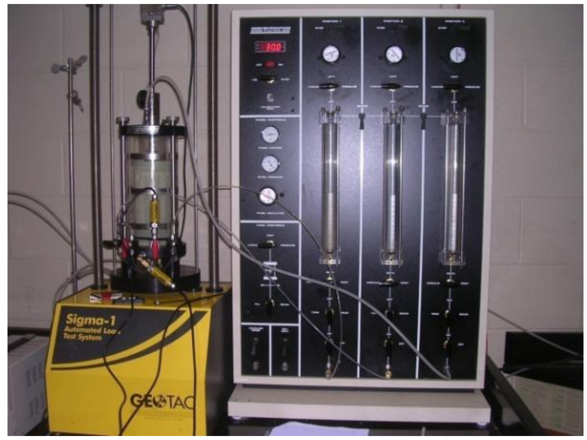

Figure 3: C-U Triaxial Compression Test Running at ORITE Laboratory

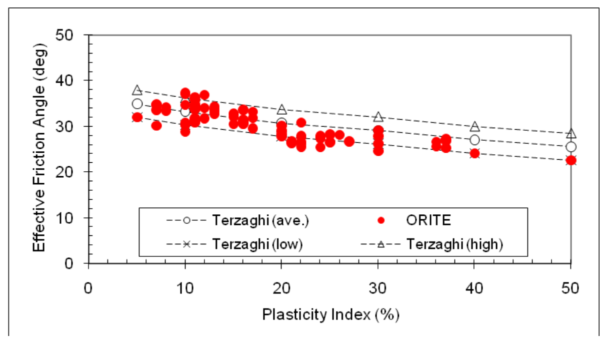

Figure 4: Evaluation of Drained Friction Angle (ϕ') vs. Plasticity Index (PI) Correlation Chart by Terzaghi et al. (1995)

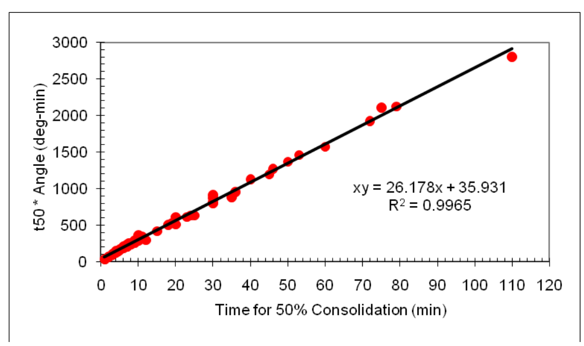

Figure 5: Relationship Between Drained Friction Angle (ϕ') and Time for 50% Consolidation (t_{50}) Described by Hyperbolic Function