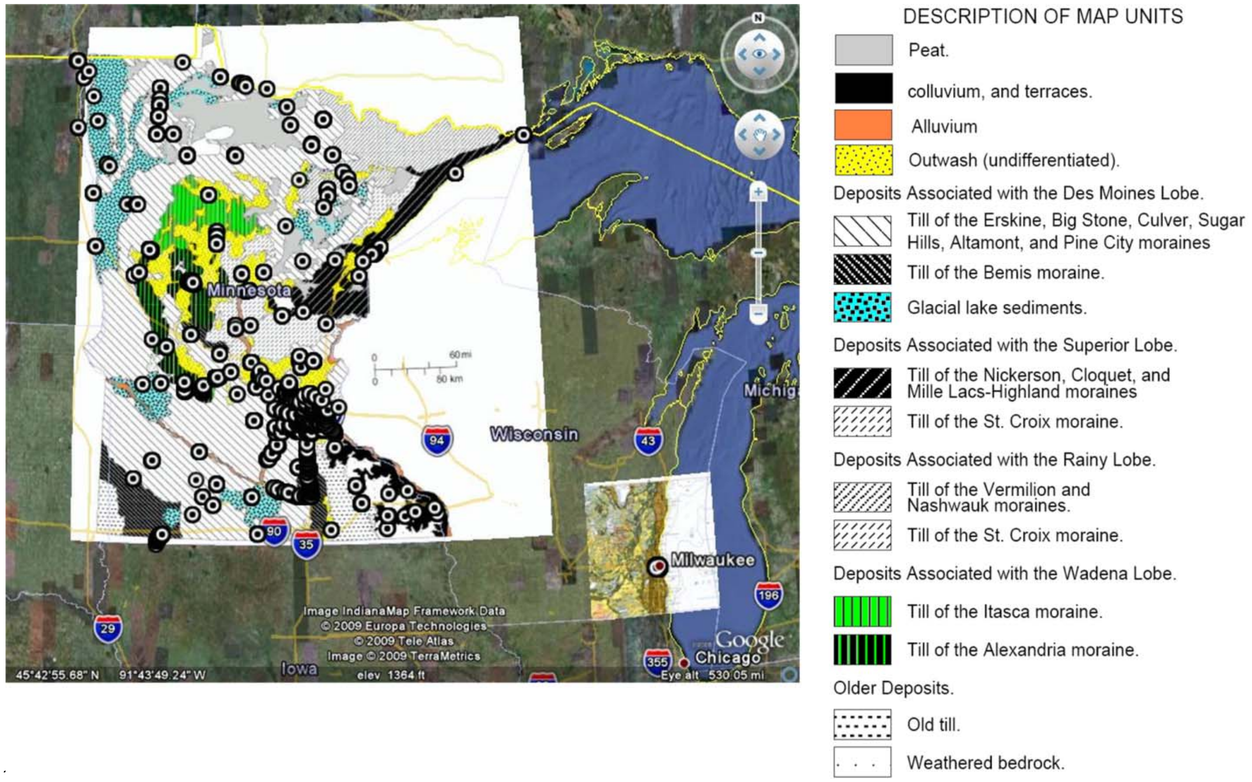


1.2.1. Work Plan / Experimental Design

The work plan and experimental design are developed around aiding engineers and geologists within the Wisconsin Department of Transportation to understand the mechanisms controlling cone penetration test results so that they can decide when the testing method is appropriate for use, know how to design an appropriate exploration program, and rapidly interpret the results of the tests for more efficient and reliable engineering. When initially gaining experience with the use and interpretation of the cone penetration test, one will notice sharp contrasts in measured parameters with depth. These sharp contrasts indicate changes in soil behavior due to insertion of a cone of a given diameter at a given rate. Figure 4 shows a vertical profile of measured CPT parameters at the Wakota Bridge site in Minneapolis, MN (data from Mn/DOT). The left most plot is the corrected cone tip resistance [$q_t=q_c+(1-a_n)u_2$, where a_n is the area ratio of the penetrometer], and the friction ratio, or ratio of sleeve friction to cone tip resistance ($F_r = f_s/q_t\cdot 100$), is plotted instead of f_s as F_r is more indicative of changes in soil type. Dashed horizontal lines are included in the profile to indicate major changes in CPT measurements, and thus materials that behave differently due to insertion of a penetrometer. The differences in each layer will be discussed primarily in relation to drainage conditions, with 'undrained' behavior associated with clayey soils, and 'drained' behavior associated with sandy soils.

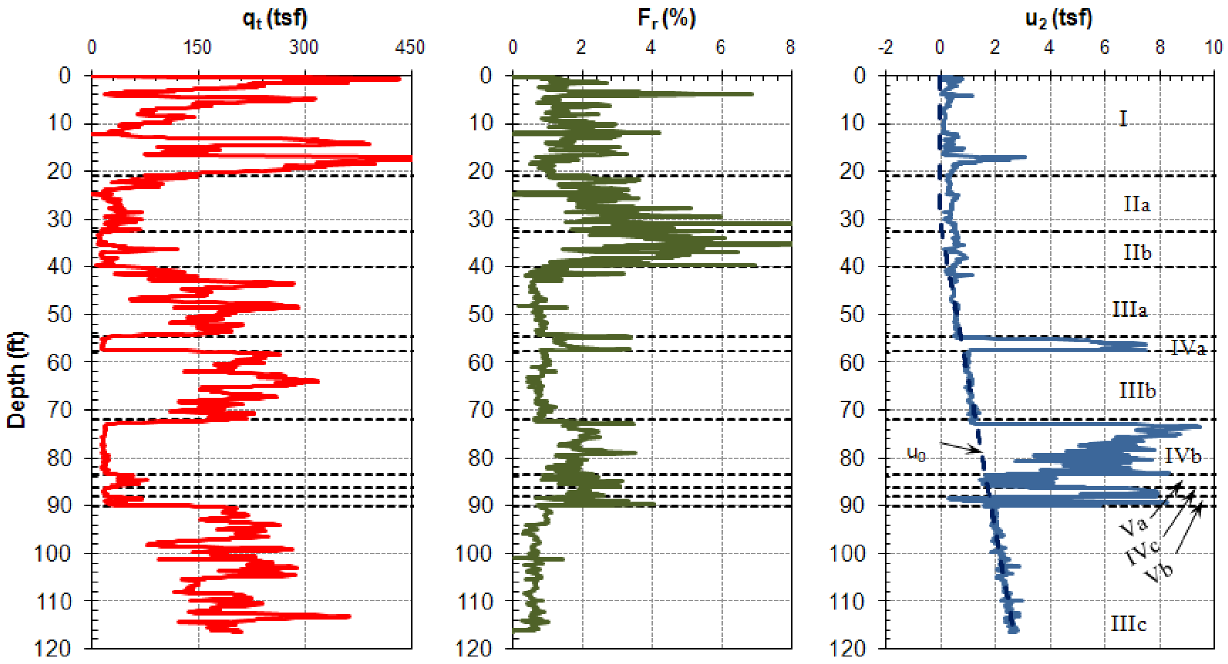
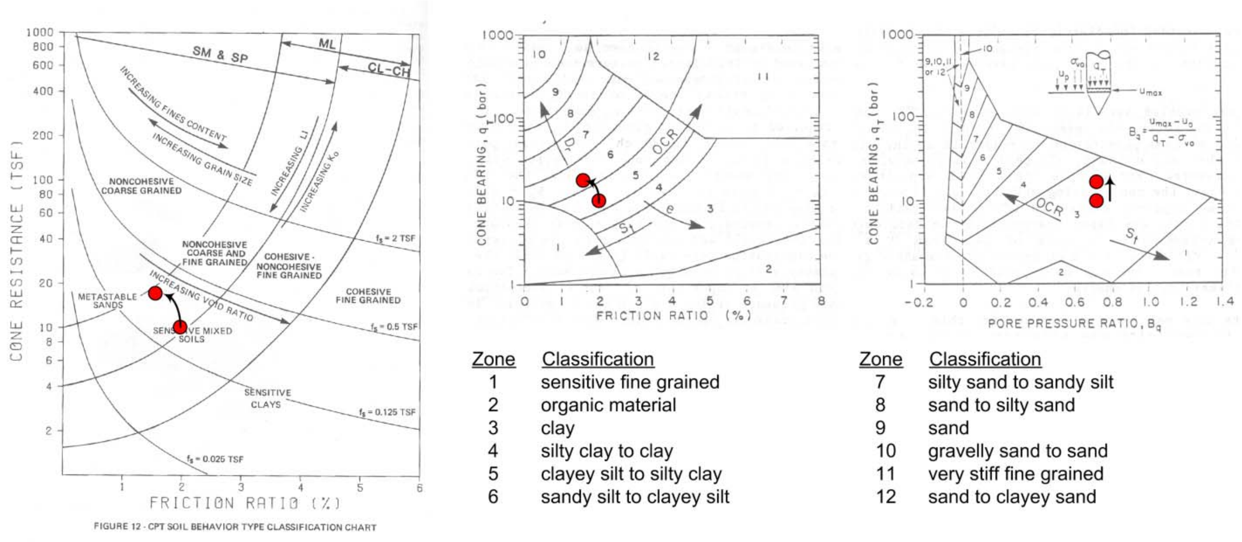


Figure 4. Vertical profile of CPT parameters at the sandy Wakota Bridge site, MN

Five major layers with up to three occurrences (at different vertical locations) are identified (on the u_2 plot) in Figure 4. It is evident that Layer I generally has a higher tip resistance and lower friction ratio than Layer II. From bearing capacity theory it is conceptually known that drained sandy soils have higher bearing capacity factors (N_q) than undrained clayey soils (N_c) [additionally noting that undrained strength (or c) is on the order of 0.25 to 1.0 times σ'_{v0}, after Ladd 1991] which is reflected in Figure 4 by higher q_t values for the Layer I 'drained' sands than the Layer II 'undrained' clayey soils. Layer II is split into two sub layers due to variation in friction ratio as well as tip resistance (which is difficult to see on this linear scale). Layer III is broadly similar to Layer I in that it has a high cone tip resistance. Additionally, for Layer III the measured penetration pore pressure (u_2) is increasing along the (dashed) hydrostatic (u_0) line. Hydrostatic penetration pore pressures below the water table are also indicative of drained penetration in sandy soils. Sharp drops in q_t are observed in Layer IV at about 55ft and 72ft, which are clear indications of changes in material behavior. The low tip resistance is coupled with high u_2 values, indicating undrained behavior in a clayey soil. Two thin silty layers are observed in Layer V between 80 and 90ft, which are characterized by tip resistance which is slightly higher than the undrained case and penetration pore pressures which are lower than the undrained case. As materials transition from clays to silts to sands, the cone penetration behavior shifts from undrained to partially drained to drained, and tip resistance increases while penetration pore pressures decrease. Corresponding friction ratios are generally low (< 1%) in drained sands, higher (> 2 to 4%) in undrained clays, and of intermediate value in partially drained silty soils (~ 2%).

Observations, such as those described in relation to Figure 4, have lead to the development of CPT soil classification (or soil behavior type, SBT) charts (e.g., Douglas & Olsen 1981, Robertson et al. 1986). Soil behavior type charts compare multiple measurements from the CPT at a given depth to infer soil type and are the cornerstone of many engineering analyses using the cone penetration test. Common non normalized charts are illustrated in Figure 5. To understand whether correlations developed for 'drained' sands or 'undrained' clays are appropriate for use in analysis (there is still limited understanding of partially drained materials), one must first establish a vertical profile of soil type. Existing classification charts are often broadly similar, but may have significant differences when applied to practice. These differences likely arose from the size and characteristics of the databases used to develop the charts, which also likely differ from soil conditions typical of Wisconsin. In a survey of state DOTs, Mayne (2007) reported that over 50% of DOTs surveyed are using a Robertson based soil classification chart, while only 4% are using the Douglas & Olson (1981) chart. This likely comes from the fact that most software available for automatic interpretation of CPT data includes the Robertson charts.



Zone	Classification	Zone	Classification
1	sensitive fine grained	7	silty sand to sandy silt
2	organic material	8	sand to silty sand
3	clay	9	sand
4	silty clay to clay	10	gravelly sand to sand
5	clayey silt to silty clay	11	very stiff fine grained
6	sandy silt to clayey silt	12	sand to clayey sand

(a) Douglas & Olsen 1981 (b) Robertson et al. 1986

Figure 5. Comparison of non-normalized soil behavior type (SPT) classification charts (red dots indicate St. Vincent's CPT data in soft clay at 70ft and 125ft, see also Figure 6)

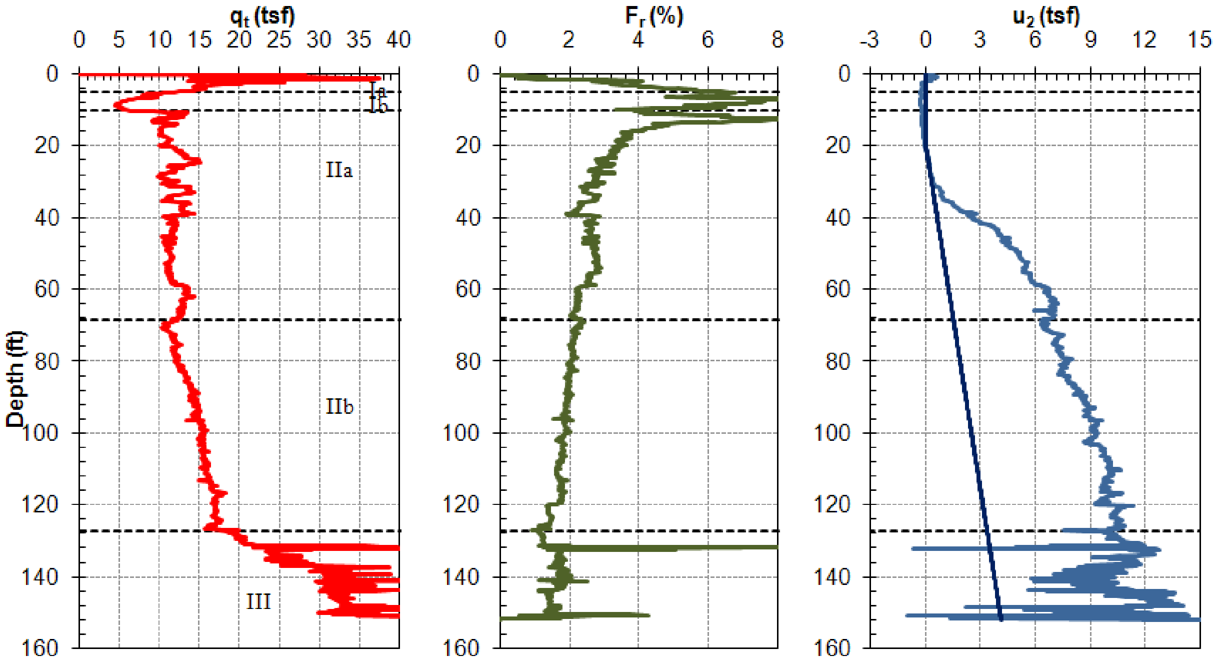


Figure 6. Influence of depth on changes in CPT parameters at the clayey St. Vincent site, MN

One of the major limitations of many soil classification charts used in practice is the neglect of the influence of the increase in initial effective stress on measured CPT parameters. Figure 6 illustrates a profile of CPT parameters at the St. Vincent site in Minnesota (data from Mn/DOT), and characterization of Layer IIb is included in Figure 5. Taking that the friction ratio (F_r) is approximately 2, the linear increase in tip resistance with depth below about 70ft (Layer IIb) will lead to errors in soil classification based on non normalized charts. For soils with a F_r of 2 and tip resistance increasing from 10 to 20 tsf in Figure 6, non normalized friction ratio based charts in Figure 5 will indicate that the grain size of the soil is changing from a clayey material to a 'non cohesive' coarse grained material. This is not the case, the material type is staying the same but the soil strength and stiffness are increasing and the soil compressibility is decreasing due to increases in initial effective stress, thus, the tip resistance is increasing. The pore pressure based chart (far right) appears to have acceptable performance, but indicates strongly different behavior than the tip resistance and friction ratio based charts. There are other limitations of pore pressure based charts, particularly in overconsolidated clays (Schneider et al. 2008a).

Normalized soil classification charts exist (e.g., Robertson 1990, Stratigraphics 2003a,b), although due to the lack of understanding in normalization schemes practitioners commonly compare the results of normalized and non- normalized charts. Schneider et al. (2008a) reviewed and updated normalized pore pressure based soil classification charts based on theoretical considerations, variable rate penetration testing, and expanded databases of tests sites in sands, silts, clays, and mixed soil types. That study agreed with previous studies by Wroth (1984, 1988) and Robertson (1990) that normalization of cone tip resistance to initial vertical effective stress ($Q=q_{cnet}/\sigma'_{v0}$) is the most practical option, and that trends can be analyzed analytically in development of design charts. Work is still continuing on updating friction ratio based soil classification charts (e.g., Schneider 2008).

The previous discussion has outlined factors which control CPT measurements in relation to commonly understood soil parameters, such as strength, stiffness, and compressibility. A more thorough discussion is presented by Schneider et al. (2008a). Soil behavior is controlled by soil state (overconsolidation ratio in undrained 'clays'; stress level and relative density in drained 'sands'), degree of drainage during loading, initial effective stress, and soil compressibility. Since these parameters also control cone penetration testing measurements, an integrated discussion of soil and cone behavior will lead to understand of CPT data and ease of application within transportation projects in Wisconsin. It is the intent of this project to discuss cone penetration test data in relation to controlling soil parameters to eliminate the reliance on 'black box' software for interpretation of results.

The work undertaken for this project will include four phases; (i) Comprehensive Literature Search; (ii) Obtain and Analyze existing WisDOT CPT data; (iii) CPT investigations adjacent to past and current WisDOT borings; and (iv) analysis of data and summarization in a final report. The work plan is devised to test in soil conditions typical of Wisconsin and generate a fundamental understanding of factors controlling CPT parameters, namely, cone tip resistance (q_c), penetration pore pressures (u_2), and sleeve friction (f_s) or friction ratio ($F_r=f_s/q_c\cdot100$). Additionally, once these parameters are understood, application of the data to evaluation of stratigraphy and soil parameters for use in engineering design are straight forward, eliminating the need for reliance of 'black box' software packages and statistically based empirical correlations that are likely not valid for the wide range of geologic conditions present in Wisconsin.

1.2.1.1 Phase 1: Comprehensive Literature Search

The literature review in this study will extend the database of cone penetration test results previously compiled by the principal investigator and collaborators. This database currently contains over 300 different sites with geological conditions ranging from marine, to glacial, alluvial, and residuum. Soil types within the database include (i) stiff clays and silty clays; (ii) granular and clayey silts; (iii) soft clays; and (iv) sands of different mineralogy (e.g., Schneider et al. 2001a, Schneider et al 2001b, Schneider et al. 2007, Schneider et al. 2008a, Schneider et al. 2008b). Many CPT analysis methods currently used in practice do not work well in stiff clays since normalized tip resistance ($Q=q_{cnet}/\sigma'_{v0}$) tends to increase with overconsolidation ratio (OCR) as well as drainage during penetration (i.e., as a soil transitions from a clay to a silt to a sand, Schneider et al 2008a, Schneider et al. 2008c). These limitations must be understood for effective use of CPT technology in glacial geologies of Wisconsin.

States with similar (glacial) geological conditions include (i) Minnesota (as previously discussed); and (ii) Michigan; as well as potions of (iii) Iowa; (iv) Illinois; (v) Indiana; and (vi) Ohio. Illinois and Michigan DOTs perform little to no CPT work (Mayne 2007), Indiana has a CPT rig but is still getting operations underway (personal communication, Rodrigo Salgado, Purdue University), and Ohio will be acquiring a track CPT rig within the next month (personal communication Pat Fox, OSU). Ohio State University (OSU) has a similar project to that discussed in this RFP where they will be visiting approximately 30 different sites. Professor Fox has indicated willingness to share their data such that the impact of both research projects can be enhanced. The preliminary discussions with the previously mentioned six states will be continued during the research project, and additional discussion with Professor Roman Hryciw, who runs CPT operations for the University of Michigan, will be pursued.

To date, most discussions of CPT operations in Midwestern glacial geologies undertaken by the PI has been with Mn/DOT. Locations from Figure 2 have been culled to 20 different sites representing at least two sites in seven major geological conditions. A number of CPTs have been performed by Mn/DOT at each site, resulting in a total of 426 CPT profiles that will be analyzed in this section of the work plan. Soil classification, spatial variability , the ratio of CPT tip resistance to SPT-N value (q_c/N) correlations, and engineering properties (when data are available) will be discussed.

The literature search in this section will not be limited to collection and interpretation of CPT data. A section will be prepared on costs associated with commercial testing services as compared to purchase and operation of in house CPT equipment. Equipment purchasing and operation costs of Mn/DOT, Ohio DOT, and other regional Departments of Transportation will be compared to commercial testing rates of local contractors in relation to the number of investigations performed each year by WisDOT.

1.2.1.2 Phase 2: Obtain and Analyze existing WisDOT CPT data

The PI has obtained hard copy reports and electronic CPT data for 27 piezocone profiles (at 24 different locations) from the Marquette Interchange project. Additionally, results from 38 pressuremeter tests at 9 locations have been obtained. The location of CPTs and PMTs are shown in Figure 7, with a demarcation of clayey till and lake clay geologies based on sounding data and geological maps of the area (Lineback et al. 1983). The Marquette interchange project provides some interesting data in that the geology transitions from clayey glacial till (ground moraine) to marine clays and silts. Both soft and stiff clay deposits are therefore present in the profiles. On the western side of the alignment and at depth, significant thicknesses of sandy soils are present. Figure 8 illustrates a West-East cross section including selected CPTs overlying boring logs.

Cross section such as that in Figure 8 can rapidly be produced in CADD software as well as using other computer programs. Tip resistance and pore pressure data are included in the cross section since the relative constant friction ratio value of 2 for the Marquette profiles does not aid in interpretation of soil layers. Pore pressures are plotted with the positive x-axis to the left, and tip resistance is plotted with the positive x-axis to the right, such that the two different types of data can be included at the same horizontal location and distinguished from one another. The CPT ID’s from left to right are (i) TWW5-09; (ii) PB-41; and (iii) TWE-101. There is a 45:1 vertical exaggeration to the cross section. As previously discussed, differences in sand and clay layers can be easily observed as sands typically have (i) relatively high tip resistance and (ii) relatively low (hydrostatic) penetration pore pressures. Conversely , the clays have (i) relatively low tip resistance; and (ii) relatively high pore pressures. Each CPT has a relatively thin layer of fill near the surface, with TWW5-09 having stiff clay over sand; PB-41 having silty clay over a thin layer of soft clay , underline by stiff clay; and TWE-101 having soft clay before encountering a sand layer at depth. The high tip resistance in the sands is evident, but the distinction between the soft clays and stiff clays is less clear. The upper layer stiff clay at TWW5-09 is likely similar to the stiff clay at depth in PB-41. That clay layer is vastly different than the soft clay in TWE-101 which shows much lower pore pressures (and tip resistance). Measured penetration pore pressures in intact clay materials typically increase with strength. A more detailed analysis of these clay layers shows essentially a normally consolidated deposit in TWE-101, and heavily overconsolidated deposits in TWW5-09 and PB-41, in agreement with the change in geological conditions in Figure 7.

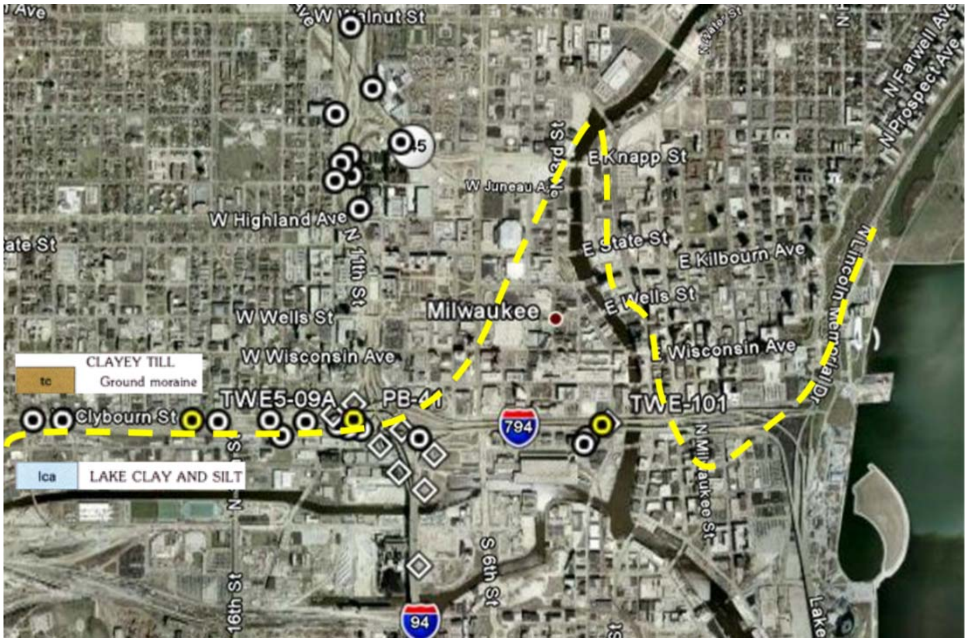


Figure 7. Location of collected CPT (circle) and PMT (diamond) data from the Marquette Interchange Project, Yellow dashed line approximate separation of Clayey Till and Lake Clay, Yellow labeled points used in cross section

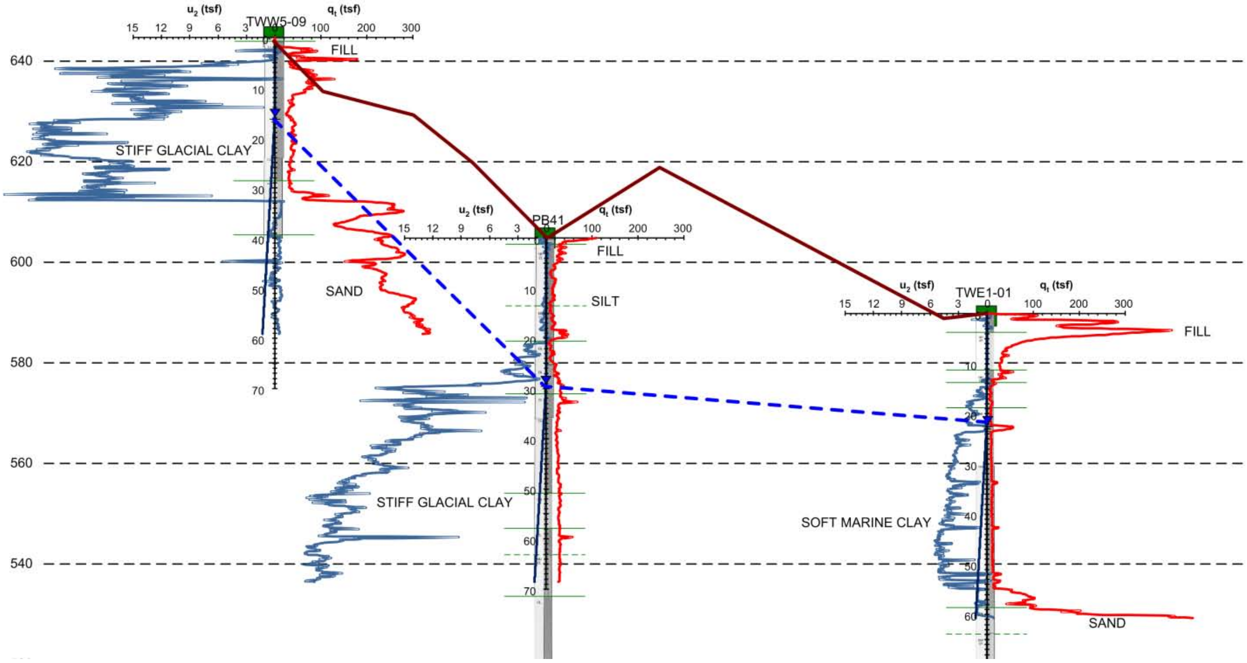


Figure 8. West-East cross section of CPT profiles and boring logs at the Marquette Interchange [blue dashed line = inferred water table, tip resistance in red (right positive), pore pressure blue (left positive)]

Analyses of the Marquette Interchange CPT data will include: (i) performance of soils classification charts of Robertson et al. (1986), Robertson (1990), Stratigraphics (2003a,b), and Schneider et al. (2008a) / Schneider (2008); (ii) correlations between SPT blow count and CPT q_c value; (iii) evaluation of axial and lateral pile capacity (for drivability data and available static and dynamic load tests); (iv) correlation between CPT parameters and pressuremeter measurements, and (v) evaluation of soil parameters (ϕ', D_r, s_u, OCR, c_v, k, stiffness, compressibility) when corresponding laboratory data are available.

As environmental and engineering analysis of the Zoo Interchange in western Milwaukee (Wisconsin's busiest interchange) are underway, boring logs for this project will be reviewed and a discussion of the possibility of increasing the efficiency of the project by use of CPT will be presented. The geological conditions at the Zoo Interchange are similar to those of the western and northern portions of Marquette, which will aid in determining the feasibility of CPT for this upcoming project. Preliminary discussion of the use of CPT on the Zoo interchange project has already been undertaken with Gary Whited (Wisconsin Department of Transportation / UW-Madison).

1.2.1.3 Phase 3: CPT investigations adjacent to past and current WisDOT borings

Based on the variety of geological conditions in the state of Wisconsin, the PI considers that performing only 10 full depth CPT probes will not provide adequate information on cone penetration testing in Wisconsin soils such that rapid integration of this technology into state DOT projects can be achieved. As the University of Wisconsin – Madison operates their own 20 tonne CPT rig, the following proposed expanded scope can be performed within the allotted budget:

- Testing will be performed at at least **15 sites**
- At least **4 full depth** CPT soundings will be performed at each site, for a total of at least **60 full depth soundings**
- At least one **seismic cone penetration test** measuring shear wave velocity will be performed at each site
- **Extended dissipation tests** in excess of the time for 50% dissipation (t_{50}) will be performed at each site

Depending upon site location within the state, penetration depths are planned to vary between 50 and 100ft. Soil thickness map for Wisconsin (Mudrey et al. 1982) indicate many areas of the state with less than 100 feet of soil thickness. It is noted that the Marquette Interchange project was located in an area mapped to have greater than 100 feet of soil, but the average CPT sounding depth was 50 feet and the maximum CPT sounding depth was 93feet (Stratigraphics 2003a,b).

All tests performed will be piezocone penetration tests, with at least one test at each site including measurements of small strain shear modulus (seismic cone tests). Dissipation tests will be performed in clayey soils, and dissipation durations of up to 12 hours are planned. While in practice it is adequate to only perform a dissipation test to 50% reduction in excess pore pressure, during research it is necessary to carry the tests out for longer durations so that the true behavior is measured and any regional variation to analysis techniques can be recommended (e.g., variations in interpretation due to initial increase in pore pressure at start of dissipation in stiff clays). Cone holes will be sealed with bentonite pellets upon extraction of the penetrometer.

1.2.1.4 Analysis of Data and Summarization in Final Report

Many studies which analyze CPT data focus on statistical performance of the 'predictions' as compared to databases of measured results. These studies often neglect the physical reality of what is occurring when a cone of a certain diameter is penetrated into the ground at a certain rate. A correlation might have good performance towards a given database, but have very poor performance when extrapolated to differing conditions, such as those of Wisconsin. The characteristics of databases are typically not provided, and therefore it is difficult to verify whether a given site is similar to those which were used to develop the correlations. The analysis of data collected in this report will utilize theoretically based correlations. Whether specific data from Wisconsin agree or disagree with these correlations will be evaluated, and the reason for this agreement of disagreement will be discussed in light of differences in soil properties [strength (ϕ, s_u or c), stiffness, compressibility, sensitivity/structure/cementation/bonding]. A proposed table of contents for the Final Report is presented in Section 1.3.

1.2.2. Expected Contribution from WisDOT staff

The location of potential testing sites will be discussed with WisDOT staff. When the sites are decided upon, previous borehole data will need to be provided by WisDOT and contacts for arranging site access will need to be provided. The PI will arrange site access with those contacts as well as utility clearance. If WisDOT CPT data in addition to those outlined for the Marquette Interchange project (Phase 2) exist, the PI would need contact information and a release letter so that electronic versions of the data can be obtained. Pressuremeter data has been obtained for a number of locations for the Marquette Interchange project (1XXX series and PBXX series), although it appears that additional data may be available for TWXXX-XX boreholes. It would be useful for WisDOT to arrange access to the additional pressuremeter data from the Marquette Interchange project, if available.

1.3. Anticipated Research Results and Implementation Plan

The anticipated research results will be a manual that can be used primarily by WisDOT geoengineering staff. The proposed chapter outline will be:

1. Introduction
2. Equipment
3. Testing procedures
4. Data presentation, stratigraphy, and cross sections
5. Evaluation of soil parameters (ϕ', D_r, s_u, OCR, c_v, k, stiffness, compressibility)
6. Applications (shallow foundations, deep foundations, embankments, etc.)
7. Specialized equipment and non-standard procedures (including hard ground conditions)
8. Conclusions and Recommendations

Appendix A1 – Case histories in Minnesota Glacial deposits
Appendix A2 – Case histories in Ohio Glacial deposits
Appendix A3 – Case histories in Wisconsin deposits

The PI will develop and maintain a web site for at least the duration of the project with a Google Earth interface such that CPT data and reports can be easily accessed and understood in the context of the geographic and geologic conditions of Wisconsin. Additionally, three 4 to 8 hour seminars at WisDOT regional offices can be provided. These seminars would cover the main emphasis of the technical manual so that cone penetration testing can be rapidly and effective implemented into WisDOT projects. Costs for the seminars included in this proposal are the time and transportation for the speaker.

There are minimal potential impediments to implementation. Mn/DOT has agreed to provide electronic CPT data and boring logs for the 20 selected sites (426 CPT soundings) outlined by the PI, which will complement the existing database for Phase I activities. Data has already been collected in paper and electronic formats for Phase II. The UW-Madison CPT rig for use in Phase III is operating well and in storage at the WGNHS in Mt. Horeb until the spring. The project team has sufficient time and resources to prepare the report documents for Phase IV. The activities necessary for successful implementation have been outlined in the preceding pages, and involve (i) collection and interpretation of data for the literature review; (ii) collection of CPT data at sites in Wisconsin; (iii) analysis, and (iv) report preparation.

2. Time Requirements

Time requirements for this project are summarized in Figure 3, ‘ Summary of hours worksheet’. Tasks will primarily be performed by a masters or PhD student under the supervision of the PI, with additional support from hourly students. A detailed time schedule for the project is included on the next page.

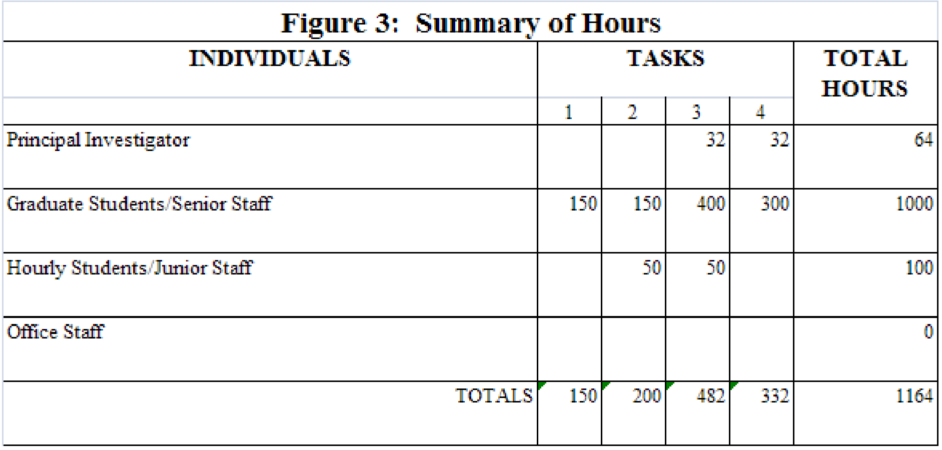
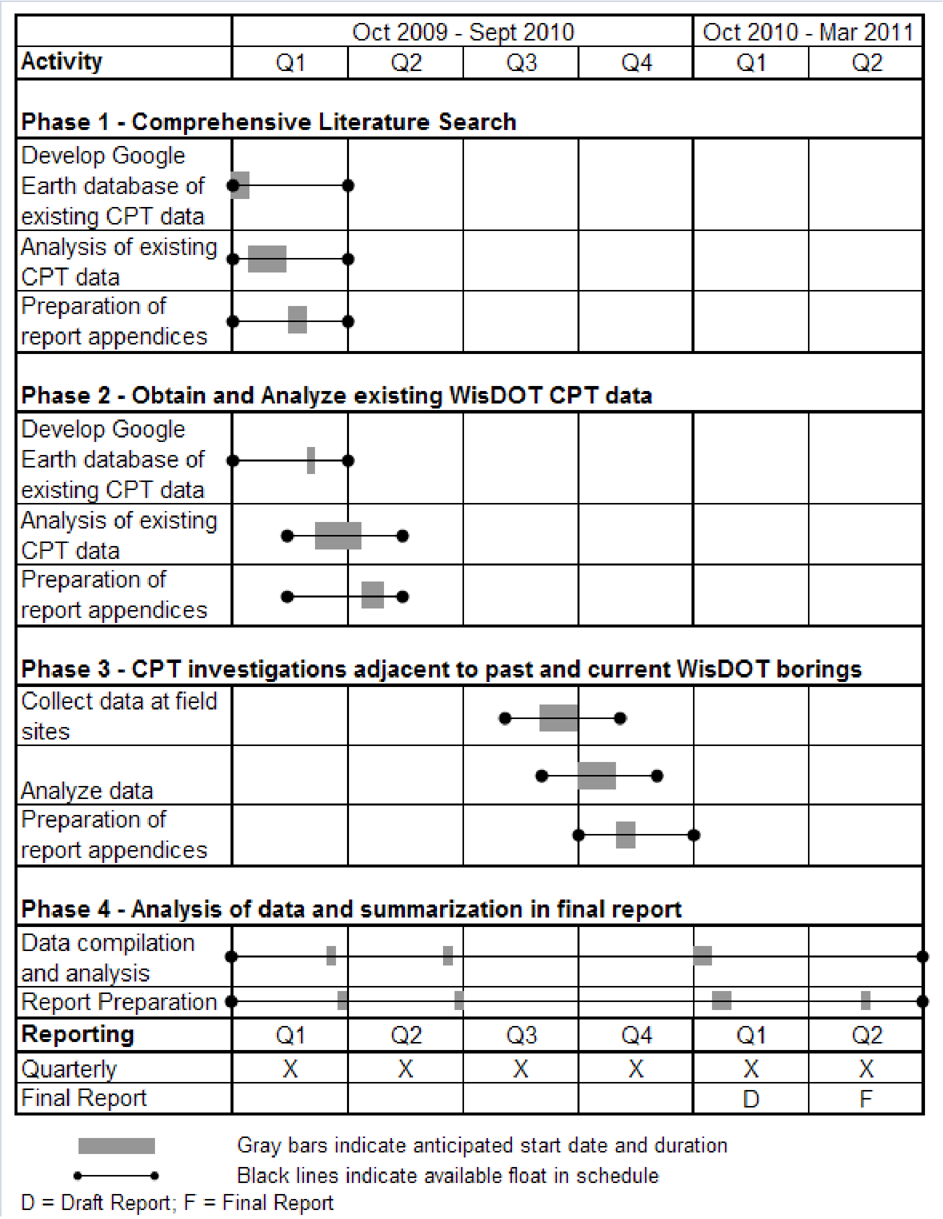


Figure 3: Summary of Hours

INDIVIDUALS	TASKS				TOTAL HOURS
	1	2	3	4	
Principal Investigator			32	32	64
Graduate Students/Senior Staff	150	150	400	300	1000
Hourly Students/Junior Staff		50	50		100
Office Staff					0
TOTALS	150	200	482	332	1164

Project Schedule



	Oct 2009 - Sept 2010				Oct 2010 - Mar 2011	
Activity	Q1	Q2	Q3	Q4	Q1	Q2
Phase 1 - Comprehensive Literature Search						
Develop Google Earth database of existing CPT data						
Analysis of existing CPT data						
Preparation of report appendices						
Phase 2 - Obtain and Analyze existing WisDOT CPT data						
Develop Google Earth database of existing CPT data						
Analysis of existing CPT data						
Preparation of report appendices						
Phase 3 - CPT investigations adjacent to past and current WisDOT borings						
Collect data at field sites						
Analyze data						
Preparation of report appendices						
Phase 4 - Analysis of data and summarization in final report						
Data compilation and analysis						
Report Preparation						
Reporting	Q1	Q2	Q3	Q4	Q1	Q2
Quarterly	X	X	X	X	X	X
Final Report					D	F

Gray bars indicate anticipated start date and duration

Black lines indicate available float in schedule

D = Draft Report; F = Final Report