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An Economical Approach to Supplement Investigations of Soil Relative Density in Forest Engineering Geology

Una Metodología Económica para Suplir las Investigaciones de Densidad Relativa del Suelo en la Ingeniería Geológica Forestal

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Abstract

Investigating cohesionless soil relative density and strength parameters using field data from driven (dynamic) cone penetration test (CPT) technology is a well-documented method in the standard practice for geotechnical projects. In general, CPT work is often relatively expensive, requires a wire-line system and large reaction mass. In remote forest work; access limitations, mobilizing costs and wire-line drill rig operation may be beyond the budget for many projects. We present data correlations (R^2 from 0.30 to 0.58) between the Standard Penetration Test SPT and adjacent Williamson Drive Probe WDP for recent projects in Northern California. Costs average about 3 to 6 percent of the costs to mobilize a drill for the SPT. The data should be used only with a) direct observation of subsurface conditions by the responsible professional, and b) some SPT site data for correlation. Selection of design strength parameters requires the active participation of a registered professional engineer.

Investigar y determinar la densidad relativa y los parámetros de resistencia del suelo, tales como fricción, usando datos obtenidos en campo con el ensayo de cono de penetración (CPT), es un método bien documentado en la práctica de la ingeniería geotécnica. En general, realizar un ensayo CPT requiere de un equipo costoso y en muchos casos de un sistema de perforación "wire-line" y una masa de reacción grande. En ingeniería forestal, las limitaciones de acceso y el costo de movilizar y operar la máquina de perforación "wire-line" pueden ser superiores al presupuesto de muchos proyectos. En los últimos años, se han usado equipos dinámicos de CPT más portátiles, y por tanto menos costosos, para recoger datos suplementarios para evaluaciones preliminares de la densidad relativa del suelo aplicada a estabilidad de subrasante de carreteras y de taludes en bosques administrados por agencias federales y por dueños industriales de bosques madereros. Una metodología, la Sonda de Impulsión de Williamson (WDP por sus siglas en inglés), ha producido resultados prometedores. Datos recogidos en el pacífico noroeste y sudoeste proporcionan correlaciones entre los datos de impulsión de la WDP y del Ensayo de Penetración Estándar (SPT). En este artículo presentamos las correlaciones (R^2 varia entre 0.30 y 0.58) de los resultados de ensayos adyacentes de SPT y SIW en proyectos recientes en la parte norte de California. El costo de la sonda de impulsión varía entre el 3 y el 6 por ciento de los costos de movilización de una máquina de perforación para SPT. Por lo tanto, muchos especialistas en ingeniería geológica y geotécnica que trabajan en los bosques de los altiplanos occidentales en EE.UU. están usando ahora el SIW para tratar de recoger datos preliminares y hacer una correlación empírica con los parámetros de resistencia del suelo a un bajo costo. Recomendamos que los datos de CPT sean utilizados solamente en conjunto con a) observación directa de condiciones del terreno por el profesional responsable y b) algunos datos de ensayos SPT en el sitio para su correlación. La selección de los parámetros de resistencia del diseño requiere la participación activa de un ingeniero profesional registrado.

1 INTRODUCTION

1.1 Study Area and Local Geology

The study area discussed below is owned by The Pacific Lumber Company and is located in Humboldt County, near Scotia, California, see Figure 1.

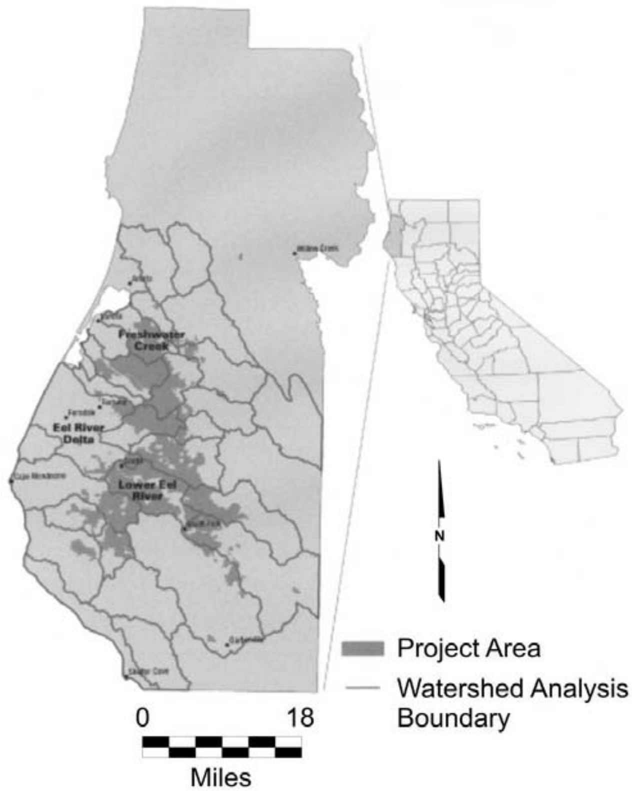


Figure 1 Site Location in Northern California

Here we were able to find sample locations for our comparison testing of the Standard Penetration Test (SPT) and the Williamson Drive Probe (WDP) in various soil conditions. We completed most of our sampling in the Freshwater Creek, Elk River, and the Lower Eel River watersheds. The local geologic conditions are most recently mapped and described by McLaughlin et al. *(2000)*. The regional geology of the coastal area in Northern California is influenced by an active tectonic regime. The physical nature of movement along the continental plate boundaries occurs in the form of subduction, transverse, thrust, and other more complicated mechanisms.

Geologic mapping *(McLaughlin et al., 2000)* indicates the majority of the study area is underlain by formations of the Wildcat Group and the Central and Coastal Belts (Yager and Coastal Terranes) of the Franciscan Complex. The Franciscan deposits are generally late Cretaceous to Tertiary in age.

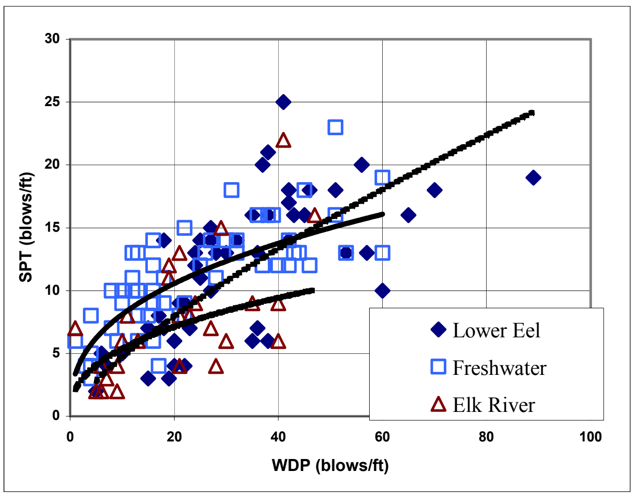
1.1.1 Colluvial and Residual Soil

Colluvial and residual soil covers much of the landscape in the watersheds, except where bedrock is exposed. These deposits are generally relatively thin (on the order of a few feet thick) on ridge tops and steep upper slopes and increase in thickness down hillsides toward the bottom of slopes where they can form thick accumulations (in excess of 20 feet thick, or 6.2 meters [m]). Residual soil forms from the mechanical breakdown and chemical weathering of the underlying rock units or unconsolidated geologic materials. Colluvium is defined as weathered material that has moved down-slope by gravity-induced movement and accumulated on the hillside. We have observed the colluvial deposits are generally about 8 to 10 feet (2.4 to 3.1 meters [m]) in depth and residual soil to depths of at least 3 to 4 feet (about 1 to 1.2 meters [m]).

1.1.2 Investigation of Subsurface Conditions

We generated soil descriptions from extensive field investigations and soil laboratory testing. This field and laboratory work was preformed on soil retrieved from shallow subsurface soil sampling described later in this manuscript. The authors defined sample sites using a grid system of 1,500 by 1,500 feet (457.2 by 457.2 m) between nodes for a stratified random number sampling. We completed stratification by defining; a) topographic polygons of concave, convex, planar, complex, and incised hill-slope geomorphic shapes, and b) the underlying geologic units. We selected the number of samples for each geologic stratum to ensure a representative sample size distribution and each sample site was selected by a random number process. We collected and field classified the soil samples during our investigation of in-place soil relative density. We estimated in-place relative densities using common correlations with SPT and the WDP described below in Section 3. Our subsurface measurements of the blow counts for relative soil density continued until the drive probe reached refusal (average depth of about 5 feet (1.52 m). Refusal typically occurred when relatively unweathered rock was encountered at depth. We colleted representative grab samples in the field, sealed in moisture-proof sample bags, and returned to our soil laboratory for confirmation of field classification. We completed grain size analysis for index testing and Unified Soil Classification (USC) (ASTM D 422 and D 1140) and Atterberg limits (ASTM D 4318) for representative samples taken from the SPT split-spoon and grab samples from hand advanced auger boreholes.

It is important to note from our subsurface investigations that the Franciscan Mélange (mapping unit "co1") rock units are associated with soil that produces nearly as many fines as those associated with the Wildcat rock units. Our analyses indicate that soils throughout the watersheds are largely non-plastic silts, sands, and gravels. We observed and sampled isolated areas of low plasticity silty clay soil. However, we excluded WDP data that was collected in clayey soil. In preparing the correlations shown on Figure 2, we selected data from 16 representative sites. The depth of the SPT boreholes and WDP boreholes typically ranged from about 5 to 20 feet.



Lower Eel	Freshwater	Elk River
$y=0.845x^{0.7474}$	$y=3.364x^{0.382}$	$y=2.108x^{0.4059}$
$R^2=0.5761$	$R^2=0.5824$	$R^2=0.3027$
n = 50	n = 56	n = 26

Figure 2 Comparison of SPT and WDP in the three watershed basins.

1.2 Brief Background of Penetration Testing

The penetration resistance, measured in blow counts (N) of driven sampling devices such as the split spoon sampler *(ASTM, 1972 and Sowers, 1954)* and dynamic cone *(Sowers, 1954)* has been investigated and presented in many ways over the years. The main focus of these techniques is to provide information on thickness of soil materials, and relative density of various strata using empirical relations to penetration resistance *(Meyerhof, 1956)*. These methods have proven particularly valuable for preliminary estimates of cohesionless soil strength parameters. Several types and shapes of penetrometers are described in the literature including flat-tipped or cone tipped rods *(Sowers and Hedges, 1966)*. Sowers and Hedges *(1966)* and Sowers *(1963)* assert that the "…experiences of those who make and interpret the test results rather than any well-defined merits of any one method or device appear to be the factor determining selection and use of the various devices."

The American Society for Testing and Materials (ASTM-D 1586) describes the SPT in detail. In this project the 140 pound (lb) (63.5-kilogram [kg]) hammer was slung from a tripod and pulley system that was reasonably easy to set up in remote forested locations. The test is described by Fletcher *(1965)* as a practice first introduced by Col. Charles R. Gow in 1902. The test was further developed by The Gow Company (merged with the Raymond Concrete Pile Company) and used a 2-inch (5.1-cm)-diameter sampler applying the now standard hammer weight and drop *(Sowers and Hedges, 1966)*.

Sowers *(1966)* also provides a cautionary note as prescribed by Terzaghi *(1943)* that, "…the results of dynamic penetration testing must be utilized judiciously with proper engineering interpretation of the results. The indiscriminate use of any test result is fraught with danger, and this test is no exception."

1.2.1. WDP Method in Forested Terrain

The results we obtained from the Williamson Drive Probe (WDP) method *(Williamson, 1994)* are presented in the following sections as they relate to the SPT data. We found this method is particularly useful in areas of difficult access in steep forested terrain where relative density is an important soil parameter for input to construction of short-term, relatively low budget projects, such as completion of timber harvesting and low-volume roadways.

The WDP is more completely described by Williamson *(1994)* and for the project described here the system generally consisted of a 12-lb (5.4-kg) hammer, raised by hand to the stop and then falling 3.5 feet (1.1 m) on a 1/2-inch (1.3-cm) OD, schedule 80 standard pipe (threaded 4-foot long rods) fitted with a flat drive plug on the end of the pipe. Our observations during driving and data reduction indicated that:

- The WDP rods developed little side friction when fitted with the slightly oversized end plug. This is evident from the visible annular space between the rods and the hole;
- WDP blow counts recorded in soil determined to be below the plastic limit in our soil

laboratory tests (ASTM D 4318) had a much wider variance in comparison to the STP blow counts;
- High moisture content and groundwater in the boreholes likely influence readings (lower blow counts) in the granular materials of this study; and
- We have found a reasonable correlation in some areas between the N from the SPT and the WDP, and these correlations appear dependent on the number of samples.

Specifically, the drive probe work *(Prellwitz, et al., unpublished, Pacific Lumber Company, unpublished and Hart Crowser, unpublished)* performed for The Pacific Lumber Company between 1999 and 2001 was extremely useful in assisting with the estimates of relative soil density for "back analysis" of debris slide features where very little engineering information was available and site access did not warrant or accommodate the SPT apparatus. Using empirical relations to estimate the soil strength parameters, the back analyses provided a basis for determining the mechanisms for failure given the site slope geometry, and likely groundwater conditions at the time of the slope movement *(Koler, 1994 and Koler, 1998)*. The intent of the project was multi-faceted in that the results of these site-specific analyses could be extrapolated to a more regional slope stability investigation using a Level I Stability Analysis *(Hammond et al., 1992)*. The regional and general picture proved an important consideration for land management over the approximately 220,000 acres of The Pacific Lumber Company property.

2. FIELD METHODS DESCRIPTION

2.1. Field Investigation Sites

We completed a comparison of the data from the SPT and the WDP on 14 modified random grid sites. We set up our borehole locations to ensure that five SPTs were completed to refusal at each of five WDP test locations at each site. The test locations were completed in a plan shape approximating a "+" pattern. One WDP test location being adjacent to the SPT borehole at the center of the "+" and four other similar pairs of tests located at what would be the ends of the "+" where each end was approximately 100 feet (30.5 m) from the center of the sample area *(Hart Crowser, unpublished)*. Field developed geologic cross sections *(Williamson et al., 1994)* were drawn along each "line" of the "+" subsurface investigation pattern to portray the subsurface geometry of the soil units, geologic strata and zones of existing seepage. Comparing the SPT soil logs with the hand advanced auger samples provided a confirmation of the cross section geometry and adjustments were made when necessary to rectify spatial changes in stratification.

3. SPT AND WDP DATA CORRELATION

Once a satisfactory correlation is established to estimate equivalent STP blow counts from the WDP blow counts the investigator can review several sources for selecting potential ranges of soil strength parameters. The two most commonly used sources for this project were a) "Correlation of Strength Characteristics for Granular Soils" (Figure 7, US Department of Navy, 1982) and b) Correlation plots for estimating saturated density, effective friction, and relative density for cohesionless (non-plastic) soil by Rose (USFS, 1994). One can use the STP to relate to relative density (D_r) then consult several sources to cross-check soil strength parameters using the soil classification (USC), laboratory moisture content and the range of typical values from the above mentioned sources. Hammond (et al., 1992) presents a useful compilation in Figure 5.5 of that document.

Table 1 presents an example of the estimated range of soil parameters in the Freshwater Creek watershed using the WDP correlated to SPT blow counts and the empirical relations previously described:

Table 1: Sample Data used in the Freshwater.

DP	SP	D_r	w	γ	ϕ
9	4	15-20	10-12	91-93	28-30
15	9	32-35	12-18	104-108	30-32
28	12	60-64	8-12	100-106	32-35

Where; "DP" = WDP measured blow count, "SP" = SPT correlated blow count, D_r = estimated relative density, w = laboratory moisture contents in percent, γ =estimated dry unit weight in pounds per cubic feet, and ϕ = estimated soil friction in degrees.

Considering the study parameters, methods, and results, we have made the following conclusions about the correlations between the SPT and the WDP:

- A few of our reported blow counts (SPT) were measured in thin lenses of low plasticity clay that may influence results. However the plotted SPT – WDP point was generally very close to the correlation curve. It is generally accepted that the SPT N values reflect the density of "non-cohesive soil" and are only a crude approximation for clays *(Tschebotarioff, 1973 and Peck et al., 1973)*. We did not include WDP data for any clayey soil (USCS: CL or CH).
- The local soil conditions are related to weathering and degradation of the area geology *(Hart Crowser, unpublished)* and the differences in correlations between each watershed are likely related to those differences.
- The correlation coefficients between the SPT and the WDP ranged from an R^2 equal to about 0.58 in the Freshwater Creek Watershed to about 0.30 in the Elk River watershed, see Figure 2.
- Different equipment operators can adversely influence (increase) the variability of the correlations. The raising and drop of the hammer should be completed carefully in both the SPT and the WDP.
- The greater the number of samples (n) the better the correlation.
- The best fit for correlations between SPT and WDP are made using a power function.
- Once a correlation is determined, it is practical and cost-effective to rely on the WDP to access difficult sites to investigate subsurface conditions such as the depth to dense conditions, changes in relative density along an alignment, and changes in moisture with depth.
- The WDP data are very useful in estimating the range of relative soil density of non-cohesive material, which is in turn useful for associating with soil friction and slope stability analyses. This is particularly true where the geometry of existing landslides can help the investigator "reconstruct" the potential mechanisms for failure in an area.
- The SPT and WDP data shown in the correlation chart of Figure 2 were not corrected for overburden pressures. The SPTs and the WDPs were observed at the same depths in the same materials at relatively shallow depths but such a correction may improve the results of the correlation in some cases *(Gibbs and Holtz, 1957)*.
- The variance in any given watershed can be wide (Figure 2). Since there are potentially several influencing physical site factors, such as parent materials, moisture content, amount of fine material (percent passing the #200 US sieve) it is best to complete correlations at the basin or sub-basin scale within the watershed.

4. ECONOMICS

A frequent concern in the forest engineering of low volume roads is the cost required to complete reliable and inexpensive subsurface investigations. In the western United States the range of daily shift costs for mobilizing and minimal sampling with a wire-line drill rig typically ranges from approximately $1800 to $3500. In most cases the drill rigs can be driven to the investigation sites with minimum effort but in some situations the access must be prepared with earth moving equipment. If site preparation for drill access is required the investigation costs will increase accordingly at rates in the range of $75 to $150 per hour for a single piece of equipment. Overall costs can amount to several thousand dollars (commonly ranging from $5,000 to $20,000) for a common low volume road project in the western United States.

The application of the WDP for subsurface investigations can significantly lower the costs for low volume road projects. Set-up and layout of the WDP sampling ranges typically between one-quarter and one-third of the time required for the tri-pod mounted SPT sampling. Generally a crew of two is best for the WDP method although data can be collected using a one-person field crew. The SPT apparatus generally requires no less than three field workers. We found that the average equipment cost per site was approximately $100 to $150. This is particularly significant when low volume road location and construction planning are in the early stages of design. In these situations the project engineer or assigned representative has located a road corridor, approximately 200 feet (61.0 m) wide. The field technician or professional can then complete the necessary field assessment for data input to the road design. Subsurface information within this corridor is critical for the successful design. Pioneering a track access for a wire-line drill rig within a proposed road corridor can be very expensive, in most cases can create budget difficulties and often defeats the purpose of the investigation to assess the viability of constructing temporary roadways. Therefore, applying the WDP method provides a very inexpensive, less intrusive approach to gathering the critical preliminary subsurface information.

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