LOW-TECHNOLOGY APPROACH TO EVALUATING SLOPE STABILITY IN FORESTED UPLANDS

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Abstract: Over the past four decades geotechnical specialists within the US Forest Service and geotechnical consultants to Federal and State resource agencies have developed field techniques that are relatively inexpensive, light weight and reasonably reliable in landslide investigations in rugged mountainous terrain. This study is part of an on going investigation of subsurface tools used as local standard exploration techniques. Part of this standard employs the "Field-Developed Cross Section" method initially developed by Williamson in the 1960's (Williamson, 1994). The goal with this method was to assemble a repeatable process in which data are gathered in the field, drafted in cross section view to depict the characteristics of soil and rock materials as well as the subsurface geometry of the site engineering conditions. The drive probe method that often accompanies this standard process is employed to provide some level of data for sites with difficult access.

There are many kinds of drive probes used in remote engineering projects, the method presented in this paper is typically referred to as the Williamson Drive Probe (WDP), (Williamson, 1994). The WDP apparatus employs driving a 0.5-inch (1.3-cm) OD, schedule 80 pipe that is threaded together in flights of 4 or 5 feet and fitted with a flat drive plug. The pipe is driven in 1.5-inch increments with a 12-pound slide hammer and an end plug used at the terminus. In many cases auger-holes are extended after the last (lowest) drive flight and perforated plastic pipe is installed to act as a "poor man's" piezometer/inclinometer for shallow ground water and subsurface movement monitoring in locations with difficult access. During the process of collecting data, the numbers of blows with the WDP are correlated with Standard Penetration Test (STP) results completed at the project location to assure quality assurance and control. The test is recommended for relatively shallow (less than 10 feet) depths in non-cohesive soil where squeezing and borehole wall friction issues can be kept to a minimum. Case studies completed on the Willamette National Forest (WNF), Pacific Lumber Company (PL) property and the El Dorado National Forest (ENF) indicate that the WDP is reasonably adequate for initial estimates of soil parameters as preliminary input to slope stability analyses. One main area of interest for the recent study on the El Dorado National Forest (ENF) in assessing variability is focused on differences imparted by equipment operators.

INTRODUCTION

The penetration resistance, measured in blow counts (N) of driven sampling devices such as the split spoon sampler (ASTM, 1972; and, Sowers, 1954) has been thoroughly investigated and presented in numerous publications 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 and currently used on a regular basis including those that employ flat-tipped or cone tipped rods (Sowers & 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 Standard Penetration Test (SPT) in detail. In our work we have applied the SPT with an Acker motorized cathead that is reasonably transportable in rugged forested terrain. With this apparatus the 140 pound (63.5 kilogram) hammer was slung from a tripod and the cathead pulley system provided a means for lifting and dropping the hammer the appropriate height as specified in the ASTM-D 1586 standard. This 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 (later 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 & Hedges, 1966).

Sowers (et al., 1966) also offers 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."

In our previous paper on this topic (Adams et al., 2003) we presented our conclusions about the application of the WDP (Williamson, 1994) in upland forest for on-going industrial timberland geotechnical studies. We report in this article an update of this on-going research and provide answers to some of the questions that we posed in our earlier document.

The WDP generally consists of a 12 pound (5.4 kilogram) hammer, raised by hand to the stop and then falling 3.5 feet (1.1 meter) on a 0.5 inch (1.3 centimeter) OD, schedule 80 standard pipe (threaded 4-foot long rods) fitted with a flat oversized 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 ground water 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 and the operator's experience.
- In addition to penetration tests the WDP can serve as a "poor man's" piezometer by extending the boreholes in the lowest flight for installation of perforated plastic pipe to assist with the measurement project site ground water levels.

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 useful in assisting with the estimates of relative soil density in "back analysis" of slope stability and shallow 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 reasonable estimates of the mechanisms for failure given the site slope geometry, and likely ground water conditions at the time of the slope movement (Koler, 1994, and 1998). The intent of this project was multi-faceted in that the results of these site-specific analyses could be extrapolated in a more regional slope stability investigation using a Level I Stability Analysis (Hammond et al., 1992). The regional and general approach proved an important consideration for land management planning over the approximately 220,000 acres of The Pacific Lumber Company property.

One question that has sprung from previous work concerns the potential variability in the application of the WDP. Simply stated: "Can the variability in test results (correlations between SPT and WDP) be explained by the differences between individual equipment operators when they apply the WDP?" Providing an answer to this question is the purpose of this paper.

PREVIOUS WORK AND CORRELATIONS

Data correlations for this method are presented (Adams, et. al., 2003) that include correlation coefficient (R^2) values ranging from 0.30 to 0.58. Although these R^2 values are low we are able to show during stability analyses that the range of the selected corresponding strength parameters is relatively narrow.

Table 1. Sample Data used in the unpublished studies for The Pacific Lumber Company

WDP	**SPT**	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, "WDP" = WDP measured blow count; "SPT" = 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 material with thin lenses of low plasticity clay that may influence results. However the plotted SPT – WDP points were 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 (i.e., CL or CH Unified Soil Classification System (USCS)). Therefore it may be informative to include soil with a low plasticity index in future work.
- 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 SPT and the WDP ranged from an R^2 equal to about 0.68 for our work in the ENF to about 0.30 in the Elk River watershed on PL property.
- Different equipment operators can adversely influence (increase) the variability of the correlations. The raising and dropping of the hammer should be completed carefully in both the SPT and the WDP.
- The greater number of samples the better the correlation.
- The best fit for correlations between the SPT and WDP are made using the power function.

- Once a correlation is determined between WDP and SPT data, it is practical and cost-effective to rely on the WDP to investigate subsurface conditions in difficult remote terrane to determine such things 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 in turn can be useful in back analyses for soil friction in 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 in our studies were not corrected for overburden pressures. The SPTs and WDPs were observed at the same depths in the same materials at relatively shallow (less than about 10 feet) 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. Since there are potentially several influencing physical site factors, such as parent materials, moisture content, amount of fine material (i.e., percent passing the #200 US sieve) it is best to complete correlations at the basin or sub-basin scale with in the watershed.
- The schedule 80 drive rods with the oversized end plug and couplings provide a potential for added skin friction that may contribute to the data variation. However, for our most recent study we have observed little contact with surrounding soil and expect that the WDP rods developed little side friction when fitted with the slightly oversized end plug.
- Differences in moisture and minor seepage may have a minor affect the SPT and the WDP differently based on the size and shape of the surface areas in contact with the soil.

EL DORADO NATIONAL FOREST STUDY

The recent study focused on the most common soil units within the El Dorado National Forest (ENF) boundaries as delineated in the Forest's soil resource inventory (Mitchell et al., 1994) and the GIS data library. In order to maximize the field time, and include SPT sampling, we made our site selection along existing forest roads where the apparatus could be transported by vehicle with relative ease. A total of 38 sites were sampled in 18 field days (averaging about 2 completed sites per day) to soil depths averaging about 4 feet. In terms of area, as measured by the ENF GIS, a majority of the common soil units are located within the Georgetown Ranger District located in the northwest portion of the ENF. The most common soil by this selection process are identified by the soil scientists as the "Mariposa" and "Jocal" soil units according to the soil resource inventory and these soil units are generally described as comprised of non-cohesive silts and sands (i.e., ML and SM) and slightly plastic silts with a high liquid limit (i.e., MH) or slightly plastic soils with a low plastic index (i.e., SC). We completed a field classification of the soil collected at each site using the visual method of the USCS (Howard, 1986). We classified the majority of these samples as silty-clayey sand, SC. The distinction between silt and clay by the USCS method is based on two "wet tests" made in the field and termed "plasticity" and "dilatancy"; and on one dry test termed "dry strength". Most of these soil units displayed both of these characteristics but were classified as SC rather than SM primarily due to their moderate plasticity and high dry strength. However, due to the amount of sand and its fine texture in the samples we determined that the differences between the SM and SC soils were small. Table 2 provides a summary of the number of soil types identified at the 38 sites.

Table 2. Project soil summary sheet.

Rock Type:	Granodiorite	Medium-Grade Metamorphic Rock			Volcaniclastics		
USCS	SM	SC	SM	GM	SC	SM	GM
Number of Sample Sites	1	9	3	2	18	3	2

Most of the sample sites contained shallow soil depths, less than 5 feet, and were classified as being composed of residual soil derived from the underlying rock. The medium-grade metamorphic rock we encountered belonged to the Devonian-Silurian Shoo Fly Complex that lies to the west of the Jurassic-Cretaceous plutons. These rock units are mostly composed of granodiorite and to a lesser extent diorite and gabbro. The rocks formed an ancestral topography upon which Pliocene volcaniclastics of the Merhten Formation were deposited as intracanyon flows. These volcanic flows are exposed on the area ridge tops. The majority of a typical field day was spent in travelling and selecting appropriate sample locations. Once a site was selected, several SPT and WDP drive holes were sampled with relatively little lost field time between holes. We completed two SPT holes about 10 feet apart at each site. In between the two SPT holes, we drove three WDP holes at the quarter points (spaced mid-point and half the distance from the midpoint to the respective SPT hole). This provided sufficient penetration testing on which to base a regression analysis for the WDP and SPT data.

WDP/SPT Data Correlation

The two SPT holes were averaged together for each exploration site, as were the data for the three WDP holes. We completed a regression analysis using the averaged SPT and WDP results from each site using a power function. A power function has been found to be the "best fit" to the data from previous work in the Willamette National Forest (WNF) and The Pacific Lumber Company (PL) property. We collected a total of 103 WDP/SPT data sets from the 38 sites on the ENF. The resulting power-function regression best fit was:

$$y = 0.648 * x^{0.846}$$

Where "y" in the equation is the estimated corresponding value for the SPT blows per foot (bpf) and "x" represents the input variable for the corresponding WDP bpf value. The resulting correlation coefficient R^2 for our ENF study was equal to 0.68.

Combining all data collected from the ENF and PL we have a total of 235 data sets. The power-function regression best fit for these data with a correlation coefficient R^2 equal to 0.52 is:

$$y = 1.445 * x^{0.593}$$

We selected this last equation for use in data reduction in our stability analyses because it combined the two most recent studies that also used the same equipment. The data collected in the WNF study used truck-mounted SPT equipment on a variety of projects across the forest. These were completed over time with no prior planning for sample locations and thus did not offer a meaningful regression analysis. The truck-mounted drill-rig SPT hammer used in this correlation on the WNF was likely more efficient in comparison to the portable Acker motorized cathead equipment used on the other projects.

The four regression plots for the ENF data combined with PL data are displayed in Figure 1. Note that the best-fit plots for the ENF and the Lower Eel watershed have similar plots for WDP for blow counts less than about 30 bpf. This is likely a reflection of generally using the same operators on the equipment for those two sites. There is also improved data coverage for the WDP in this blow count range compared to the other projects that have a much wider range of WDP bpf.

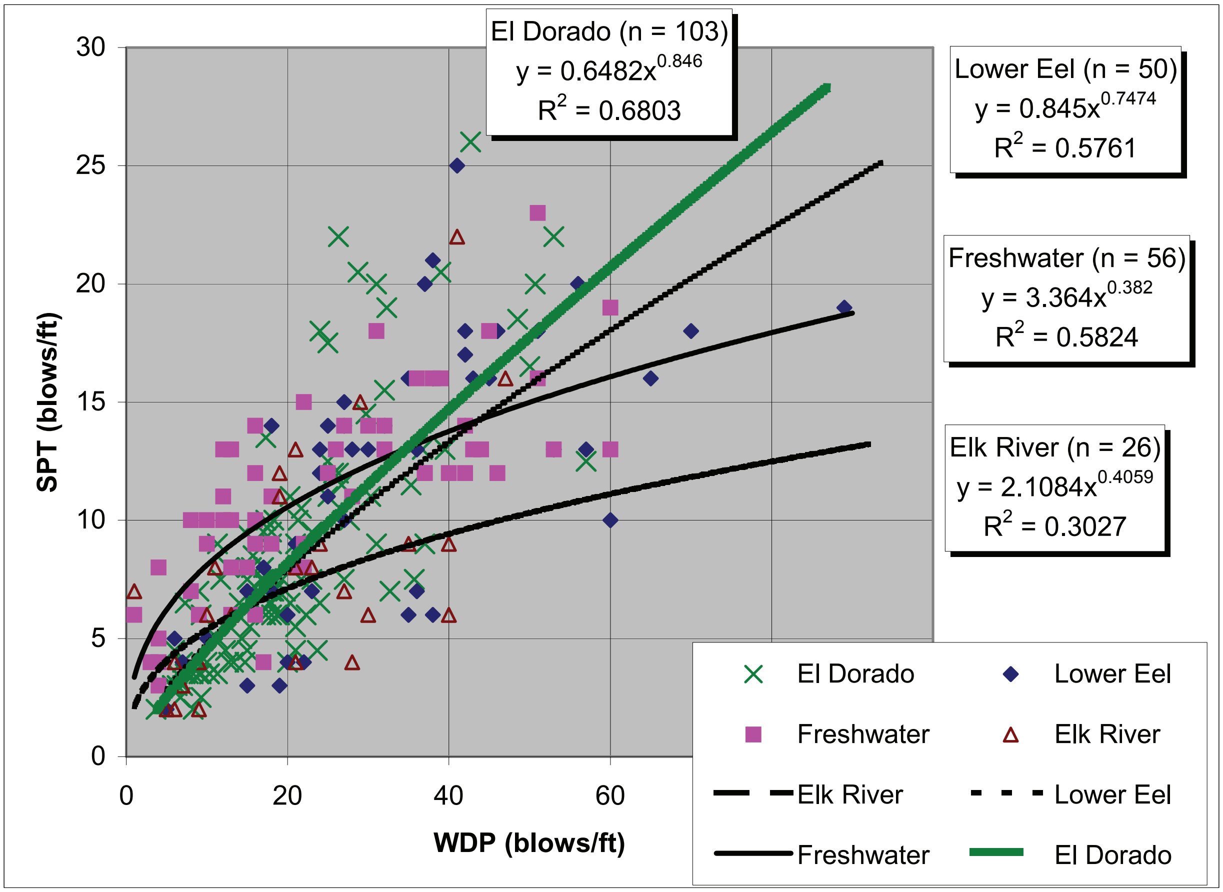

Figure 1. Regression curves from the ENF and PL studies.

Variation in Data Correlation

Previous reviewers of our work have noted the scatter in the data with the relatively low R^2 coefficients ranging from 0.30 to 0.68. We have also noted this and a primary apprehension in developing the equations for comparing data for the two methods includes a consideration for variation in drive results caused by the individual test methods or resulting from varying subsurface conditions at the site (i.e., non-homogeneous and anisotropic subsurface conditions). One method for evaluating the degree of the non-homogeneous and anisotropic conditions effects on penetration rate is to compare the results of the same test performed in the same manner by the same operator at any given site. This was possible to accomplish for the ENF project since multiple SPT and WDP tests were made at each site with the same equipment and operators with a limited amount of variability resulting from the test procedure. The result from this work is our interpretation that the varying subsurface conditions is shown to affect the penetration resistance of the same test in adjacent holes at a given site is likely the same factor which has the most influence of the correlation.

In an even more practical sense, the real concern in our opinion is not the low R^2 but what affects the errors in the correlation might have on the results of the φ and γ parameters selected for stability analyses. To test the applicability of the correlation equations and the sensitivity of the analysis, the average SPT and WDP data for each site were used in separate independent analyses to estimate the angle of φ and γ. A comparison of the minimum, maximum, and average values as determined by the two independent analyses provides some measure of the sensitivity to variations in the data either caused by the non-homogeneous and anisotropic soil conditions or by the WDP/SPT correlation equation used in the WDP analysis. In order to put these variations into a practical perspective, in slope stability analyses unit weight is often rounded to the nearest 5 pounds per square feet (pcf) and friction angle to the nearest degree.

Standard deviation provides another perspective of these data. Considering a normal distribution of results, 67 percent of the test data should be between ± 1 standard deviation of the average. Comparing the standard deviations indicates negligible difference in the results of the two independent analyses. These standard deviations are also well within the range to be expected from laboratory shear strength testing to estimate φ using the same direct shear or triaxial tests performed by different soils laboratories (Singh & Lee, 1970).

CONCLUSIONS

Based on our current study and the addition of the ENF data set, the most intuitive and meaningful source for the data spread from all sites is the variation in the equipment operating procedures between individuals using the WDP. It is possible that this kind of variation could be managed through a type of calibration of hammer energy. It may also prove important to have the same operator using the same equipment throughout an investigation that requires the same regression equation. Another source of potential variation, skin friction can also become an issue and appears to require careful use of the rod and hammer apparatus during driving in soil materials that exhibit minimal potential for sidewall "squeezing" during advance of the borehole. Different diameters of drive tip help enlarge the drive hole annulus, thus reducing the influence of drag along the sidewall.

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