Manhattan College

Center for Geotechnology

Integrated Site Characterization and Foundation Analysis Research Project
-
A Technical Note re Effect of K_{onc} Assumption on Site-Characterization Algorithm for Coarse-Grain Soil

Report No. CGT-2004-2

by

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December 2004

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Preface

This report is another in a series of incremental contributions to the Integrated Site Characterization and Foundation Analysis Research Project. This project was one of three geotechnical projects conducted under the auspices of the Manhattan College School of Engineering Center for Geotechnology (CGT). The origins and overall goals of this particular project, which was originally called the Coupled Site Characterization and Foundation Analysis Project, have been discussed in detail in earlier reports (see, for example, Horvath (2002) which is listed in the References section of this report).

This particular report addresses issues concerning a comprehensive site-characterization algorithm for coarse-grain soils that is intended to produce rational, intelligent input parameters for a wide variety of geotechnical analysis and design methodologies used in routine practice. Because this report focuses on only one narrow aspect of this algorithm, it is necessary to have first read the original reports in this series (Horvath 2000a, 2000b, 2002, 2003) to become familiar with the background of this work.

As a final note, this report, although modest in size and content, is nevertheless a milestone as it is the last to be published under the auspices of the CGT. As a result of administrative and policy changes that have occurred within Manhattan College during the past two years and the recent withdrawal of support from an alumnus whose financial promises were a key reason the CGT was founded in the first place in 2001, it became apparent to me that a climate conducive to continuing the scholarly activities of the CGT in a manner that met my professional standards sadly no longer existed. Rather than have CGT activities continue in a substandard manner or wither away completely over time I felt it was better to terminate things on a positive note. Therefore the CGT ceased its activities on 31 December 2004 after four years of existence. Completing this report was my final act as the Founding Director of the CGT. I take pleasure in knowing that the CGT lived up to its self-imposed goals during its relatively brief tenure.

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Executive Summary

This report presents an incremental upgrade to a site-characterization algorithm for coarse-grain soils that was developed at Manhattan College during the 1990s and originally published in 2000. The specific change made at this time is the use of the constant-volume (critical state) value of the Mohr-Coulomb strength parameter, ϕ_{cv}, in lieu of a secant average of the peak value as obtained in a triaxial-compression test ($\phi_{peak(tc)}$).

Although the effect of this latest upgrade on calculated soil parameters was not studied in detail, a comparison for a site that is representative of conditions found at the John F. Kennedy International Airport in New York City suggests this change has relatively less effect compared to the previous update that was made in 2003. That earlier update changed some of the empirical relationships used to correlate the tip resistance, q_c, from a cone-penetrometer test (CPT) to various fundamental soil parameters. However, this conclusion must be considered tentative pending further, more-detailed study.

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INTRODUCTION

The origins and overall purpose and goals of the Manhattan College School of Engineering Center for Geotechnology (CGT) Integrated Site Characterization and Foundation Analysis Research Project have been discussed in detail previously (see, for example, Horvath (2002)). Consequently, they are not repeated here. To date, research efforts for this project have focused solely on coarse-grain soils. The primary reason for this is that historically, it has been impossible on routine projects to obtain relatively undisturbed samples of such soils and subject them to traditional laboratory tests as a way of producing accurate estimates of key soil properties for determining their stress history, strength, and compressibility. As a result, it has been difficult to implement modern geotechnical analysis and design concepts that require, for example, accurate estimates of soil parameters such as yield stress[a] and the stress-dependent Mohr-Coulomb strength parameter, ϕ.

Advancements in in-situ testing, and, more importantly, interpretation of in-situ test results, that have been made during the latter part of the 20th century have now made implementing modern geotechnical engineering concepts into routine analysis and design methodologies for coarse-grain soil relatively simple and straightforward. In fact, nothing more exotic than Standard Penetration Test (SPT) N-values and hand calculations are required to accomplish this although cone-penetrometer test (CPT) tip resistance, q_c, data and a digital computer for rapid data manipulation certainly enhance the process by removing several uncertainties surrounding SPT N-values as well as the tedious element of repetitive calculation. However, experience indicates that the many advances in site characterization for coarse-grain soils have, unfortunately, far outpaced the implementation of these advances into practice. Consequently, it was decided that research efforts for the Integrated Site Characterization and Foundation Analysis Research Project were best directed toward coarse-grain soils. This is in keeping with the practice-oriented nature of all CGT research projects.

BACKGROUND

The original algorithm developed at Manhattan College for comprehensive site characterization of coarse-grain soils based on CPT q_c data or, if necessary, SPT N-values had its origins in contributions by Professor John S. Horvath, Ph.D., P.E. of the Manhattan College Civil Engineering Department[b] to American Society of Civil Engineers (ASCE) specialty conference foundation-behavior prediction symposia in the late 1980s (for deep foundations) and early 1990s (for shallow foundations). These predictive efforts collectively indicated the need for a more thorough, methodical investigation of this subject. These investigative efforts were performed on an intermittent basis throughout the 1990s and culminated in 2000 with the formal publication of a site-characterization algorithm for coarse-grain soils and an illustration of its use as a practical tool in foundation analysis using the classical problem of shallow-foundation bearing capacity of a spread footing (Horvath 2000a, 2000b). A significant aspect of that initial application was that the calculated results were compared to measured results obtained on full-scale footings (from a research site located at Texas A&M University that had been used for an early 1990s ASCE prediction symposium and which is referred to in this report as the "Texas site"). Well-documented, instrumented load tests to ultimate geotechnical ('bearing-capacity') failure[c] on full-

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[a] Also referred to using a variety of alternative terms such as *maximum past effective stress*, *natural prestress*, *preconsolidation pressure*, and many others. There has also been a variety of notation used for this parameter as well, usually involving the letters σ or p and usually with a bar or prime to indicate an effective stress or pressure.

[b] Currently the Civil and Environmental Engineering Department.

[c] Sometimes referred to as the geotechnical *ultimate limit state* (ULS).

scale spread footings are extremely rare and thus the published data from the Texas site represented an unusual opportunity to compare calculated and measured results.

The next foundation application considered using the 2000 version of the site-characterization algorithm was that of driven piles. A comprehensive report detailing the results of that work was published in 2002 (Horvath 2002). Several extensions and summaries of this work were researched and published subsequently (Horvath 2003a, 2003b, 2003c; Horvath and Trochalides 2004; Horvath et al 2004a, 2004b). All research and associated publications related to driven piles used actual field and instrumented-test-pile data from the John F. Kennedy International Airport (JFKIA) in New York City (referred to in this report as the "New York site").

One of the concluding comments contained in Horvath (2002) was the following statement:

> *"Site characterization is clearly the key component of the proposed analytical methodology. Therefore the various correlations and algorithms used and presented herein should be updated on an ongoing basis to take advantage of the latest developments in this regard. The emerging picture of the key, underappreciated role played by site characterization in foundation design also indicates that future research and development as well as technology transfer funding should be devoted to this topic which is clearly the crucial, fundamental heart of deep foundation capacity calculation."*

While this statement was specific to driven piles, it is equally applicable to all analysis and design applications in geotechnical engineering.

In keeping with the spirit of this recommendation, the first major update to the Manhattan College site-characterization algorithm for coarse-grain soils was made in 2003 (Horvath 2003a). This update was based on further research and reinterpretation of CPT data during the 1990s by Prof. Paul W. Mayne, Ph.D., P.E. of the Georgia Institute of Technology. His work had resulted in updated empirical correlations between CPT q_c data and fundamental soil stress-state parameters (P. W. Mayne, personal communication, 2003). As discussed in Horvath (2003a), some of the calculated parameters, particularly those related to stress history (yield stress, $\overline{\sigma}_{v_m}$; overconsolidation ratio, *OCR*; coefficient of lateral earth pressure at rest, K_o), were significantly affected by the changes made in the algorithm, at least for the limited investigation that was performed at the time using data from the New York site.

PURPOSE AND SCOPE OF PRESENT STUDY

The study documented in this report is another contribution to updating the Manhattan College site-characterization algorithm for coarse-grain soils. The present study was motivated by newly published work by others. It is centered around the fact that one of the choices that had to be made when developing the algorithm initially was how to evaluate K_{onc}, the coefficient of lateral earth pressure at rest under normally consolidated conditions (Horvath 2000a, 2002).

As background information, it is widely accepted that

$$K_{onc} = 1 - \sin\phi \qquad \textbf{(1)}$$

where ϕ is the stress-dependent Mohr-Coulomb strength parameter that is often referred to colloquially as the *friction angle* of the soil. When the original (2000) version of the algorithm was under development in the mid- to late 1990s, there was disagreement in the published literature as to whether the operative value of ϕ to be used in Equation 1 should be the constant-volume (critical-state) value, ϕ_{cv}, or peak value (typically taken to be an average or secant value obtained using triaxial-compression-test data), $\phi_{peak(tc)}$. Arguments for each case can be found in Mesri and Hayat (1993) for the former and Mayne and Kulhawy (1994) for the latter. The decision was made to use $\phi_{peak(tc)}$ in the Manhattan College algorithm as that algorithm drew heavily on work developed and published by the latter authors (Kulhawy and Mayne 1990). For simplicity, this combination of the original (2000) algorithm using $\phi = \phi_{peak(tc)}$ is referred to in this report as Version 1.0. It is important to note that the use of $\phi = \phi_{peak(tc)}$ was retained in the development of the updated (2003) version of the algorithm. For simplicity, this combination of the revised (2003) algorithm using $\phi = \phi_{peak(tc)}$ is referred to in this report as Version 2.0.

The choice of the operative value of ϕ used in Equation 1 has more implications than may be obvious. First of all, it is not a matter of simply using one constant value versus a slightly different one as input to the algorithm. In reality, for a given soil one value of ϕ can reasonably be assumed to be a constant whereas the other never can be. Specifically, ϕ_{cv} can, with acceptable accuracy, be assumed to be a material constant for a given soil. On the other hand, due to the well-known curvature of the peak-strength Mohr-Coulomb failure envelope, ϕ_{peak} in general and $\phi_{peak(tc)}$ in particular is never a constant. Furthermore, the magnitude of potential variation in ϕ_{peak} for a given soil is such that it should never be taken to be a constant, even approximately. The reason is that the magnitude of ϕ_{peak} varies with stress level. In addition, even for a given stress level it is not uncommon to define two distinct values of ϕ_{peak} depending on how they will be used in some subsequent analysis or design procedure. One value is defined using the instantaneous slope of the curved failure envelope at a given stress level and is referred to as the *tangent* value of ϕ_{peak} ($\phi_{peak(tangent)}$). Tangent values are commonly used in advanced computer software such as numerical solutions (e.g. finite-element) of a continuum where construction and load application are simulated in multiple steps that easily allows the magnitude of ϕ_{peak} to be changed with each step. The other way to define ϕ_{peak} is using an average value between two points (stress levels). The choice of points is, theoretically, arbitrary but they are generally taken to be zero stress (i.e. the origin of the Mohr's circle-of-stress plot) and some stress level of interest in a specific application. In any event, the value of ϕ_{peak} that corresponds to the slope of this line is called the secant value of ϕ_{peak} ($\phi_{peak(secant)}$). Although $\phi_{peak(secant)}$ is, in reality, a fictitious value as it only represents an average over some stress range it is nonetheless very attractive in practice when using some type of traditional analysis or design procedure that requires a single value of ϕ to be input. Relevant to the present discussion is that Kulhawy and Mayne (1990) defined $\phi_{peak(tc)}$ as being the secant value based on a line drawn between the zero-stress point (plot origin) and some stress level of interest in a triaxial-compression test. The latter stress level could be taken to be overburden stresses in a free-field condition or an average stress level at failure under some type of loading. In either case, the stress dependency of $\phi_{peak(tc)}$ resulted in its having to be incorporated into both Version 1.0 and Version 2.0 of the site-characterization algorithm as an application-specific variable that was determined as part of the solution process.

Another implication regarding the value of ϕ used in Equation 1 is that it impacts another aspect of the algorithm. It is widely accepted that *OCR* is related to K_o by the following empirical relationship:

$$OCR = \left(\frac{K_o}{K_{onc}}\right)^{\left(\frac{1}{\sin\phi}\right)} . \qquad \mathbf{(2)}$$

Note that the assumption as to the operative value of ϕ (i.e. ϕ_{cv} or $\phi_{peak(tc)}$) used in Equation 2 affects the calculated result for *OCR* both directly and indirectly, the latter by virtue of how K_{onc} was calculated per Equation 1 and as discussed above. Again, at the time Version 1.0 of the site-characterization algorithm was under development during the 1990s there were opposing views as to the appropriate value of ϕ to be used in Equation 2 given by Mesri and Hayat (1993) and Mayne and Kulhawy (1994). Once again, the decision was made to use $\phi_{peak(tc)}$ in the original

(Version 1.0) algorithm and this assumption was retained in the updated Version 2.0 of the algorithm that was developed in 2003.

This detailed discussion of the time line is relevant as a relatively recent (presented at a conference in 2001 but not published until 2003 and not read by the author until 2004) state-of-art assessment of the site characterization of coarse-grain soils by researchers who have been actively involved in the subject for many years indicated unequivocally that ϕ_{cv} should be used in Equation 1 (Jamiolkowski et al. 2003). A reasonable extrapolation is that ϕ_{cv} should be used in Equation 2 as well. Consequently, it was judged to be worthwhile to modify the Manhattan College site-characterization algorithm for coarse-grain soil to investigate the effect of using $\phi = \phi_{cv}$ in both Equation 1 and Equation 2. The overall goal of this exercise was to evaluate, at least on a limited and preliminary basis, the relative effect that the assumption regarding the value of ϕ used in equations 1 and 2 has on key calculated results from the Manhattan College site-characterization algorithm for coarse-grain soils.

It is important to note that this report has been prepared based on the assumption that key earlier reports that explain in detail the fundamental rationale and details of both the original (2000) as well as updated (2003) versions of the algorithm have been reviewed by the reader. For simplicity, this report just focuses on new information. As a minimum, the reports that provide the necessary background for this report are either Horvath (2000a) or Horvath (2002) plus Horvath (2003a).

RESULTS OF PRESENT STUDY

Analyses Performed

For the purposes of the study reported herein there were only two variables to be considered:

- overall site-characterization algorithm used (2000 versus 2003 version), and
- assumed value of ϕ in equations 1 and 2 ($\phi_{peak(tc)}$ versus ϕ_{cv}).

As shown in Table 1a, two of the possible four combinations of these variables have been considered in previous studies and incorporated into the two versions of the site-characterization algorithm used to date.

Table 1a. Combinations of Variables Considered in Previous Studies

assumption regarding value of ϕ used in equations 1 and 2	development date of overall algorithm	
	2000	2003
$\phi_{peak(tc)}$	Version 1.0	Version 2.0
ϕ_{cv}	-	-

Theoretically at least, it is only necessary to consider one of the two remaining possible combinations of variables: the current (2003) algorithm but using ϕ_{cv} as opposed to $\phi_{peak(tc)}$ as was done previously in Version 2.0. This new combination of variables will be referred to in this report as Version 2.1. However, the remaining fourth combination of variables will also be considered: the original (2000) algorithm but using ϕ_{cv} as opposed to $\phi_{peak(tc)}$ as was done previously in Version 1.0. Given the fact that the use of ϕ_{cv} as opposed to $\phi_{peak(tc)}$ was a viable option during the 1990s time frame when the original algorithm was being developed, there is a legitimate historical interest to investigate this combination of variables retroactively to see if they differ significantly from the Version 1.0 results. If there is a substantive difference, some of the analytical results and conclusions drawn previously for both shallow and deep foundations could be affected. In any event, this retrospective combination of variables is referred to as Version 1.1 in this report. Table 1b summarizes the version designations used for the combination of variables considered in this report. Although the Version 1.0 and 2.0 results were available from previous studies (theoretically only the Version 2.1 and 1.1 analyses needed to be run from scratch), these two earlier cases were reanalyzed for the present study for the sake of completeness from a research perspective.

Table 1b. Combinations of Variables Considered in Present Study

assumption regarding value of ϕ used in equations 1 and 2	development date of overall algorithm	
	2000	2003
$\phi_{peak(tc)}$	Version 1.0	Version 2.0
ϕ_{cv}	Version 1.1	Version 2.1

Subsurface Conditions for Site Studied

To provide a link with past work, the present study utilized data from the New York site which was used for previous research involving driven piles. The single most important aspect of this site from a site-characterization perspective is that, with the exception of a relatively thin near-surface stratum of Holocene organic soils (clay and peat), the coarse-grain strata extend from the ground surface to a depth in excess of 100 feet (30 metres). This allows results calculated using the four versions of the site-characterization algorithm to be compared over a range in vertical overburden stresses that encompass most of what is encountered in routine foundation-engineering practice, at least for sites located either on land or relatively shallow-water environments.

Figure 1 shows typical subsurface conditions encountered within the Central Terminal Area (CTA) of JFKIA for both a traditional soil boring with SPT sampling and a CPT sounding that were performed in relatively close proximity. The SPT driving energy for this particular boring was not measured directly but was estimated at 45% average efficiency based on the type of hammer and drive system used. Consequently the field N-values (N_{field}) from this boring are assumed to be N_{45}. These were adjusted empirically to N_{60} values, i.e. values at 60% average drive-system efficiency. The CPT q_c data, both measured directly in the CPT sounding as well as inferred from the SPT N_{60} values using empirical correlations (Horvath 2000a, 2002) were normalized to atmospheric pressure, p_{atm}, solely to non-dimensionalize the plotted data.

Presentation of Results

The results of these assessments are summarized and presented in the following figures. Note that each of the parameters shown in these figures is produced as part of the primary output from the site-characterization algorithm. These calculated parameters can then be manipulated further to obtain other parameters of interest such as various moduli (e.g. Young's, constrained, etc.):

- Figure 2 shows the calculated dry unit weight of the soil, γ_d (non-dimensionalized to the unit weight of water, γ_w, solely for generalization) plotted as a function of depth. Although in most practical applications soil unit weights can be estimated with sufficient accuracy for most any analysis or design problem, as noted in previous reports this parameter was intentionally made a solution variable in this site-characterization algorithm to demonstrate the most-general capabilities of the algorithm.

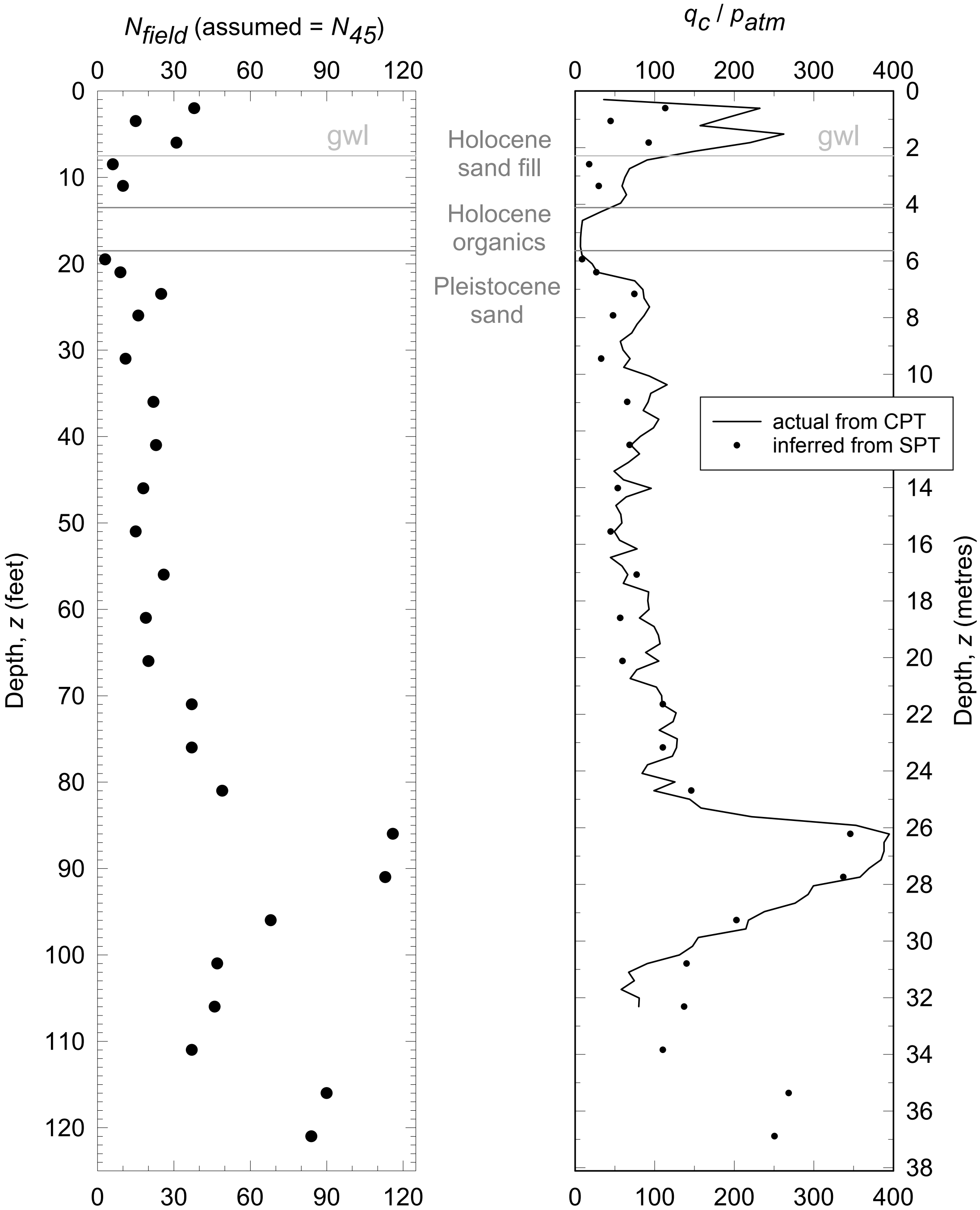

Figure 1. New York Site - Overall Stratigraphy and In-Situ Test Data

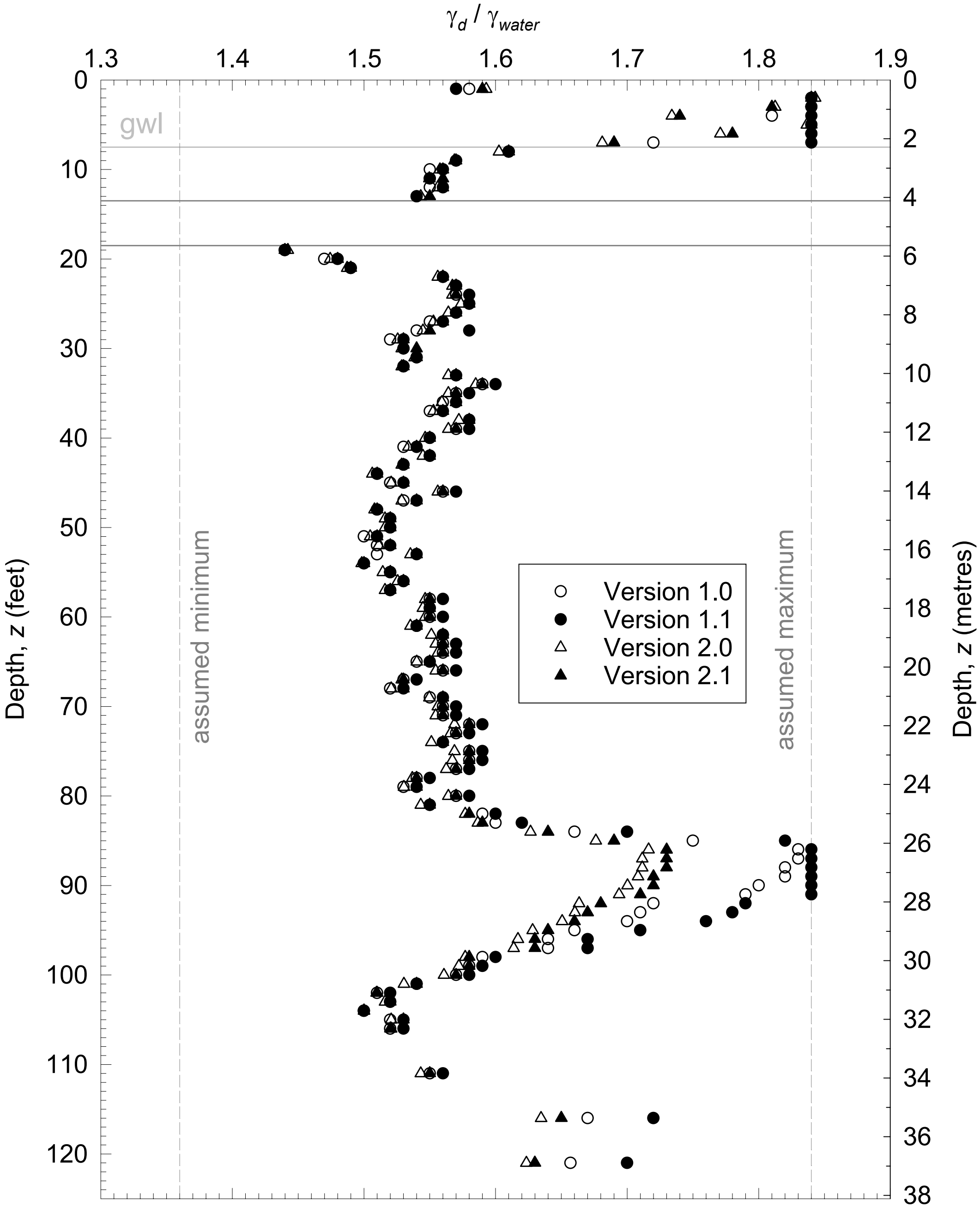

Figure 2. Dry Unit Weight, γ_d, versus Depth

- Figure 3 shows vertical effective stresses as a function of depth. Both the calculated (based on the unit weights shown in Figure 2) overburden stress, $\overline{\sigma}_{v_o}$, and calculated (from the site-characterization algorithm) yield stress, $\overline{\sigma}_{v_m}$, are shown. Each is non-dimensionalized to atmospheric pressure, p_{atm}, solely for the purpose of generalization.

- Figure 4 shows the calculated overconsolidation ratio, *OCR*, as a function of depth.

- Figure 5 shows the calculated coefficient of lateral earth pressure at rest, K_o, as a function of depth.

- Figure 6 shows the calculated relative density, D_r, as a function of depth.

- Figure 7 shows the calculated constant-volume friction angle, ϕ_{cv}, as a function of depth.

Discussion of Results

The broad conclusion drawn from figures 2 through 7 is that the calculated results using the Manhattan College site-characterization algorithm for coarse-grain soils is more sensitive to the specific version of the algorithm used (i.e. the original (2000) versus update No. 1 (2003)) compared to the whether $\phi_{peak(tc)}$ versus ϕ_{cv} is used in equations 1 and 2. This is apparent visually by noting the greater difference between the Version 1.x and 2.x results compared to the Version x.0 and x.1 results.

CLOSING COMMENTS

Based on the limited investigation described in this report, it appears the empirical relationships used to relate CPT q_c values to various soil parameters have far more effect on calculated site-characterization results than whether the peak or constant-volume friction angle is used. Therefore it would seem that future research efforts are best concentrated on improving these empirical relationships on a continual, ongoing basis. Furthermore, it seems appropriate to settle on using the constant-volume friction angle for use in site-characterization algorithms. It is certainly easier to use as it can reasonably be assumed to be a stress-independent constant for a given soil whereas the peak friction angle never can be constant. In addition, it is clear that most researchers involved in site characterization have already settled on using ϕ_{cv}. Therefore, what has been defined in this report as Version 2.1 of the Manhattan College site-characterization for coarse-grain soils can be considered to be the current algorithm of choice.

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(reference section continued on page 14)

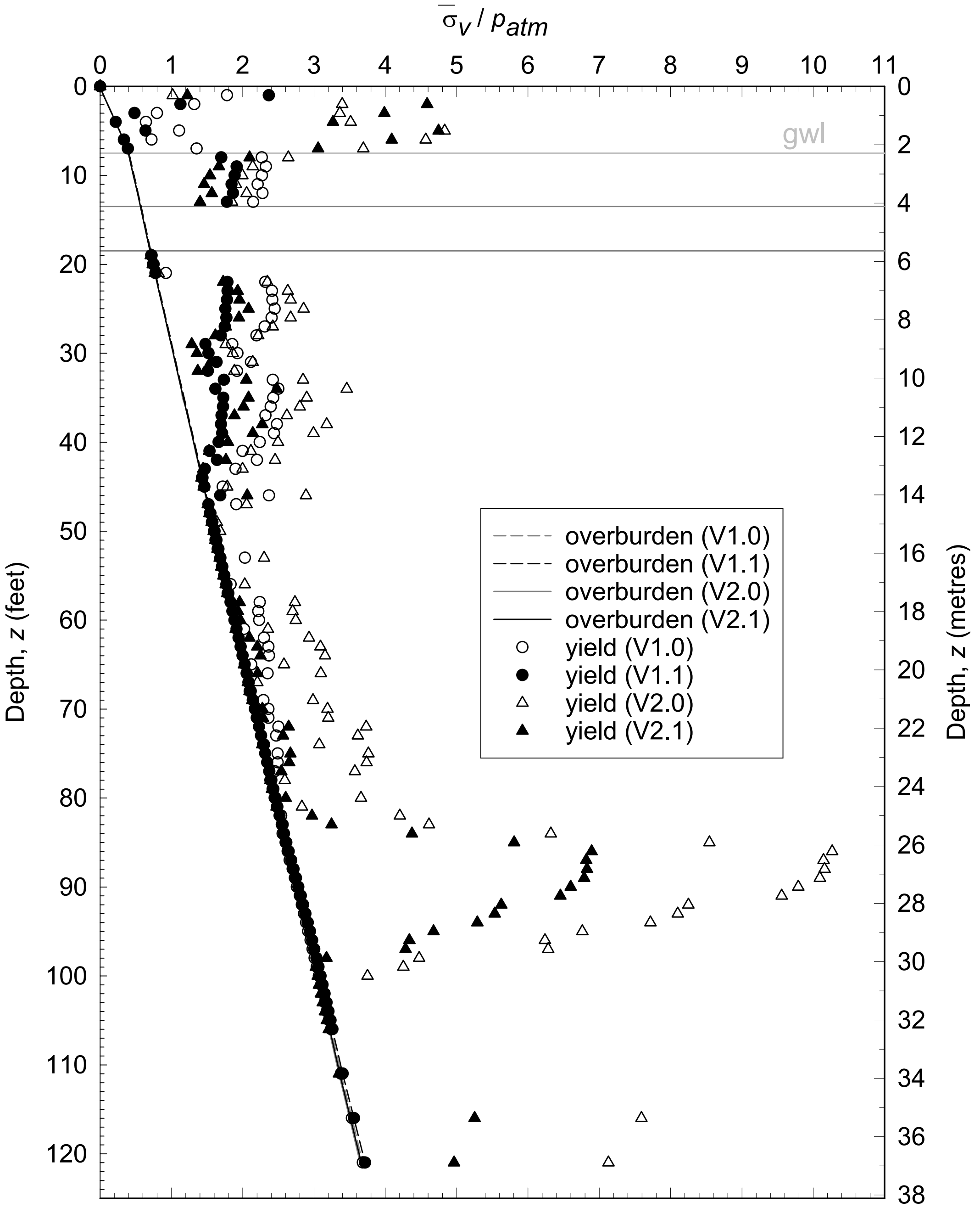

Figure 3. Vertical Effective Stresses versus Depth

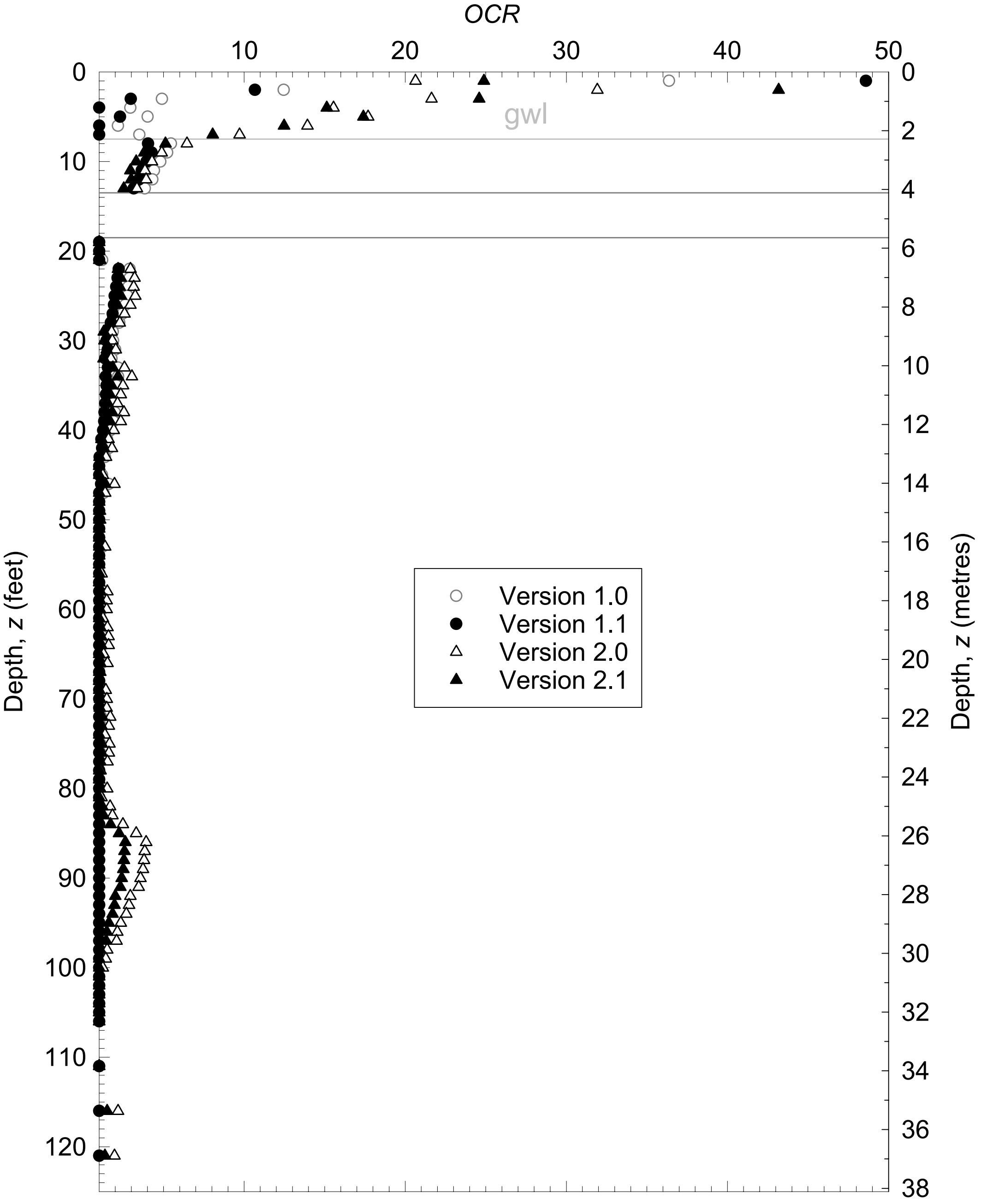

Figure 4. Overconsolidation Ratio, *OCR*, versus Depth

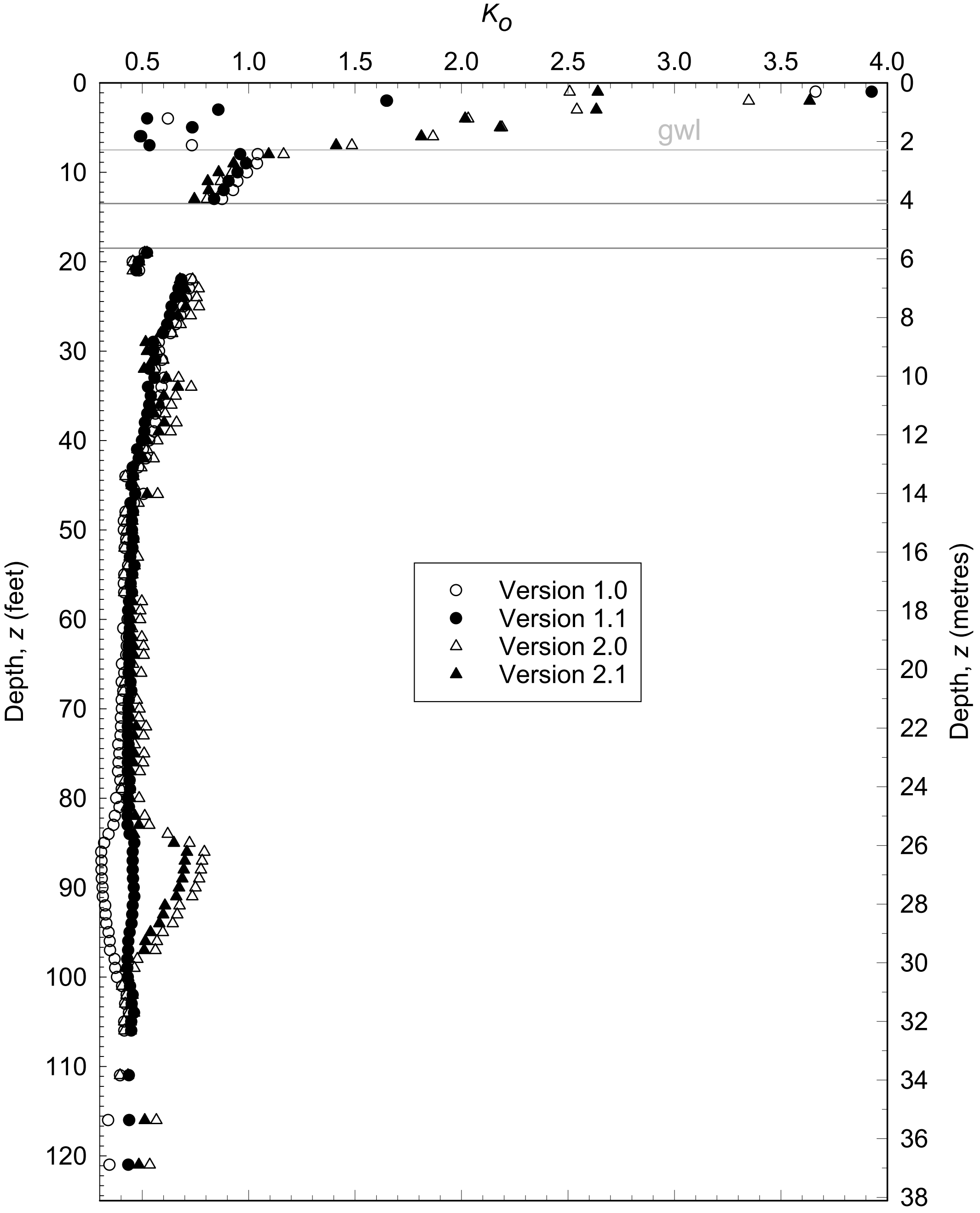

Figure 5. Coefficient of Lateral Earth Pressure at Rest, K_o, versus Depth

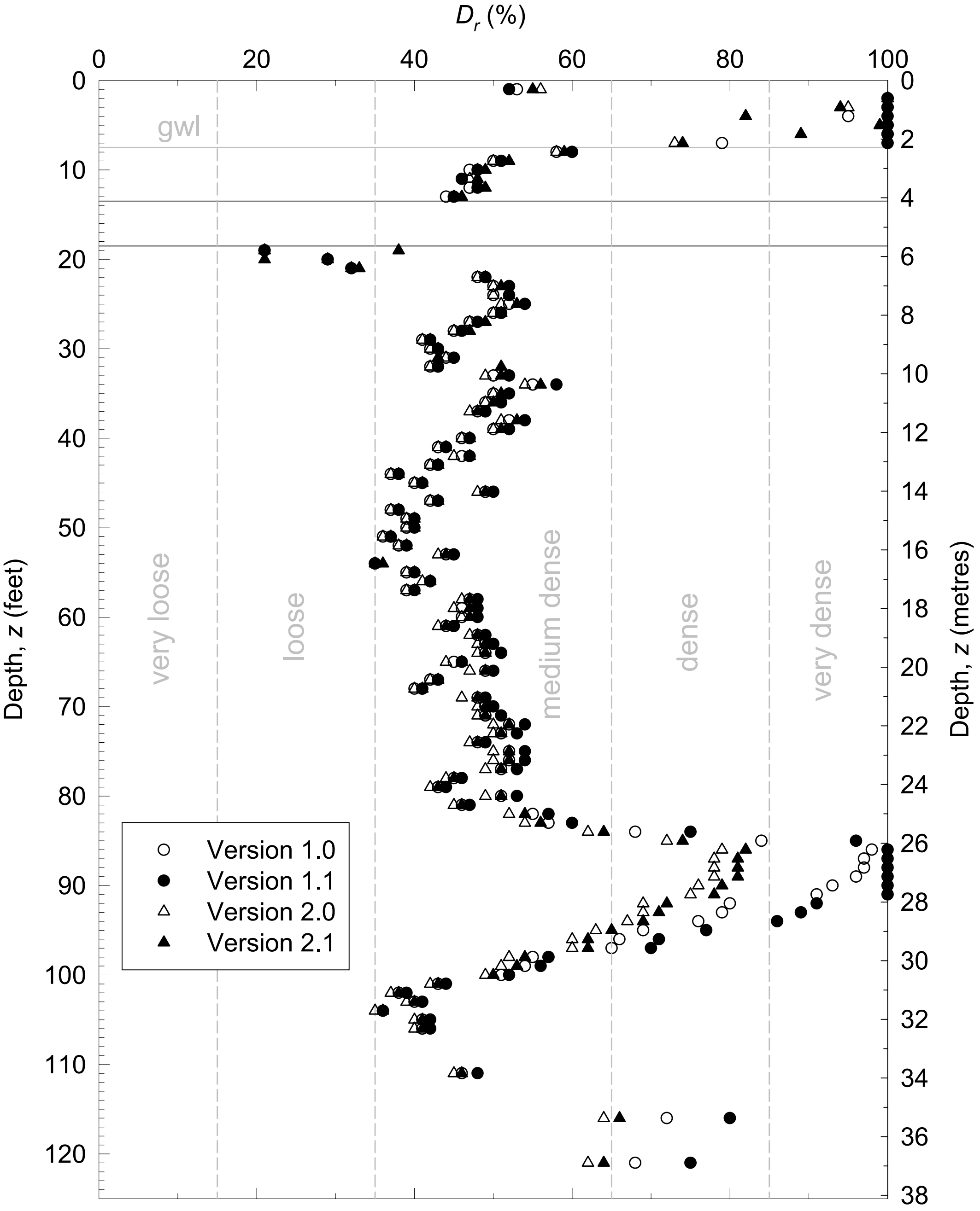

Figure 6. Relative Density, D_r, versus Depth

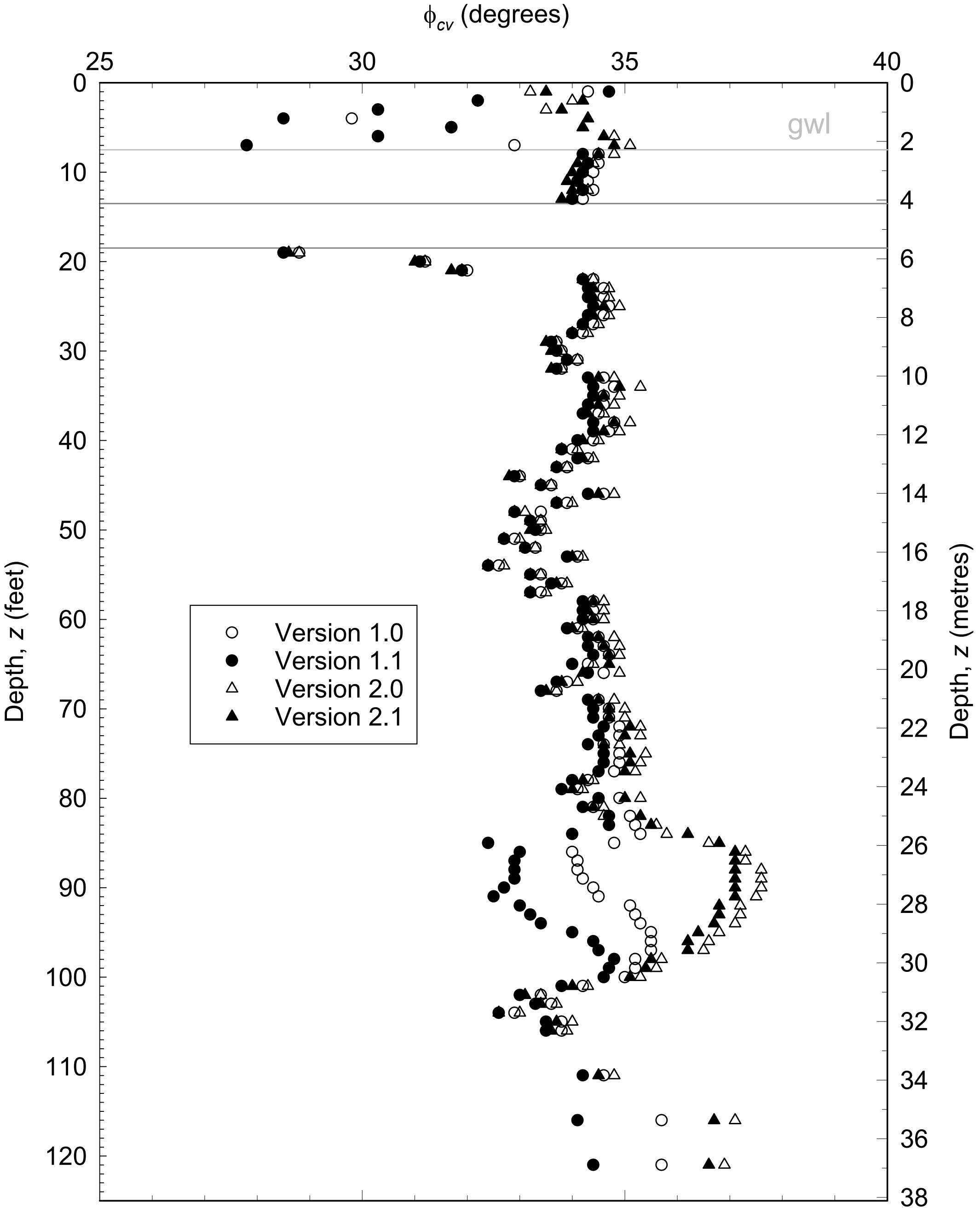

Figure 7. Constant-Volume Friction Angle, ϕ_{cv}, versus Depth

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