Discussion of "Biological Considerations in Geotechnical Engineering" by James K. Mitchell and J. Carlos Santamarina

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The authors have presented an interesting and useful paper on the applicability of biological approaches to geotechnical engineering and are to be congratulated on having produced a pioneering study of considerable value. The authors have pointed out the significance of a strong multidisciplinary study covering geotechnical engineering and biology research in an era of expanding knowledge and, also faced with challenges that need the application of new developments to eliminate difficulties in geotechnical engineering. As the authors have said, their review of biochemical processes and microbiology-related studies in geotechnical engineering is based on the readily available references; this limitation has no doubt forced them to leave out some other studies that could have made the biological considerations in geotechnical engineering wider to the reader. A critical review of the literature enables one to identify some important characteristics of the behavior of microorganism-induced geotechnical materials. The discusser therefore considers it is to be further noted that the studies from other disciplines such as, Jansson (1975); Lappin-Scott et al. (1988); MacLeod et al. (1988), Hassler and Doherty (1990), Yang et al. (1994), Ohashi and Harada (1996), Stocks-Fischer et al. (1999), Perkins et al. (2000), Ramachandran et al. (2001), Hillgärtner et al. (2001), and Kim et al. (2004), etc., which are not referred by the authors, have always shown large divergence from the geotechnical studies. Based on the overview of the previous works dealing with biotechnological applications in various engineering disciplines, Çanakci and Çabalar (2002) proposed the possibility of a ground improvement technique using bacteria, and then highlighted the names of some bacteria, including *Alcaligenes eutrophus, Alcaligenes feacalis, Alcaligenes viscolactics, Pseudomonas olevorans, Pseudomonas aeruginosa, Xanthomonas compestris, Bacillus pasteruii*, and *Zoogloe ramigera*.

The authors' study further points out that the microbial processes influence rock weathering, mineralization, soil formation and fabric, and soil grain surface properties. As previously pointed out by Perkins et al. (2000), the authors have similarly stated that the microorganisms can produce gel, slime, polymer, and biomass; they can cause pore and filter clogging, and they can change deformation and strength properties. However, it seems that the authors may have missed other points concerning the role of these products on lubrication through the soil particles, its tensile force, and shear force, which seem to have influence on the microstructural behaviors of the soils in particular at very small strain levels. It is also interesting to note that the development of a microbiology-related approach requires input from bacteria having the capability of solid precipitation ($CaCO_3$) and crystal growth among the soil particles, as well as slime-forming bacteria. The discusser suggests that it seems worthy to bear in mind the influence of crystal growth over geological times, which could deform a soil matrix slowly.

Another aspect of the evaluation of the study is the issue of a terminology used in the text and one of the common characteristics in a cell shown in Fig. 1 of the original paper, which made the discusser puzzled. The authors referred to three different types of biopolymers, under the title of strength and stiffness, by giving the names of (1) Xanthan gum; (2) sodium alginate; and (3) slime-forming bacteria. However, it looks that the third one is a type of bacteria rather than a specific type of biopolymer. In addition, a chemical composition in bacteria and archea, that is shown by number 3 (cytoplasm), is not apparent in the Fig. 1. The discusser, as a geotechnical engineer, would be interested in the authors' opinions concerning whether it is simply a typing mistake or if the cytoplasm is evenly distributed in a cell.

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The writers are grateful to the discusser for the information provided. The study with biopolymers (xanthan gum, sodium alginate, and slime) reported by the writers provides only partial insight into the potential stabilization effects associated to biomineralization. In fact, microorganisms are at the center of a wide range of mineralization processes due to their participation in various biochemical pathways and the consequent release of a series of metabolic by-products. More than 60 types of minerals of biological origin have been identified (Lowenstam and Weiner 1983); most of them have Ca as the major cation and Fe as the next most common metal (Simkiss and Wilbur 1989). The wide variety of minerals includes carbonates, oxides, phosphates, sulfides, and silicates (Erhlich 2002).

Exciting discoveries have been reported since our paper was first submitted for publication, ranging from potential in situ bioremediation of uranium-contaminated subsurface (Anderson et al. 2003) to the role of pili as microbial nanowires that allow electron transfer from cell surfaces to oxide surfaces (Reguera et al. 2005). These developments further support our contention that geo-engineering could benefit from further study of bio-influences on soil behavior.

In fact, there have been significant steps in this direction within the geo-engineering community in the last two years. K. Rowe (2005) addressed the issue of bio-mediated clogging in relation to liners and drains in landfills during his 2005 Rankine Lecture. And, just in the United States:

- The GeoMechanics and GeoTechnical Systems Division at the National Science Foundation has received several unsolicited proposals related to bio-geo processes in the last year alone (R. Fragaszy);
- The recent NRC report "Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation" identified the bio-dimension in geo-engineering as one of the most fruitful areas for future research in the short term (Long et al. 2005);
- M. Roth and co-workers at Lafayette College have confirmed the increase in strength of sands due to bio-film forming bacteria;
- J. deJong at UC-Davis and colleagues at Idaho National Laboratory have achieved controlled ureolysis by aerobic microbes to raise the pH in a supersaturated solution, forcing precipitation of calcite within granular porous media. They have corroborated the process through microscopy and chemical analysis. Furthermore, they have measured both increased stiffness, using S-wave velocity measurements, and increased undrained strength;
- E. Kavazanjian, B. Rittman, and M. Abbaszadegan at Arizona State University are studying various microbiological processes (precipitation, mineral transformation, and biofilm and biopolymer growth) to attain beneficial changes in engineering properties of soils in short time frames (carbonate precipitation, microbial transformation of smectite to illite, and biopolymer plugging); and
- Rebata-Landa and Santamarina at Georgia Tech are conducting research on survivability (an extension of Fig. 2 in our original paper) to accommodate grain size and depth of burial, clogging for the controlled modification of hydraulic conductivity, and gas generation for bulk stiffness control.

As we move forward in exploring the biological dimension in soil behavior and the potential augmentation/stimulation of bioprocesses in the subsurface, we must keep in mind the governing limiting factors, the inherent size limitations in clayey soils, the complexity of biogeochemical interactions, and the innate tendency to long-term in-situ equilibrium (which may cause the dissolution of formed gases, the erosion of new precipitates, and the vanishing of biofilms and clogs).

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Discussion of "Energy Efficiency for Standard Penetration Tests" by Edgar Odebrecht, Fernando Schnaid, Marcelo Maia Rocha, and George de Paula Bernardes

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We found the authors' paper interesting and look forward to publication of their companion paper. The purpose of our discussion is to provide previously unpublished SPT energy transmission data that we obtained on six projects between 1999 and 2006 where we took simultaneous measurements at both the top and bottom of the drill string.

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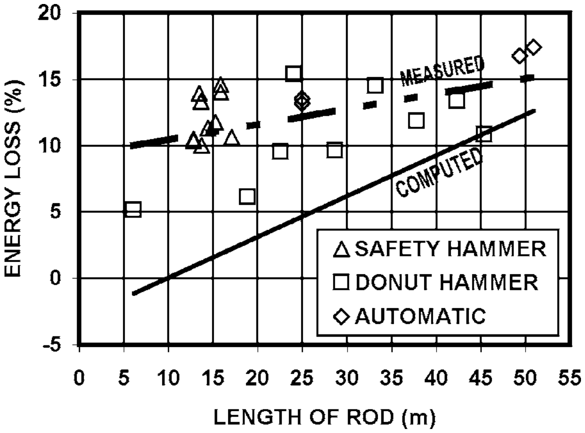

Fig. 1. Energy loss versus rod length

Our testing equipment consists of a pile driving analyzer (PDA), PAK Model manufactured by Pile Dynamics, Inc., and two instrumented 0.61 m (2 ft) long drill rods. The eight-channel capacity of the PDA allows us to take simultaneous top and bottom readings. Typically, the top instrumented rod is attached immediately below the anvil, and the bottom instrumented rod is placed approximately 3.05 m (10 ft) above the SPT sampler.

The six projects are located in the northeastern United States. Soils typically included medium dense to very dense silty sand and sand. The SPT hammers included Diedrich and Aker automatic hammers, 140-lb rope and cathead donut hammers, and 140-lb rope and cathead safety hammers. The drilling rods used on the six projects consisted of type NWJ with joints at 10 ft o.c.

Fig. 1 plots the measured and computed energy loss between the top and bottom energy testing points versus the length of the drill string between those measurement points. It is apparent from the plot that our measured energy losses are significantly greater than the energy losses computed using the authors' method, particularly at shorter rod lengths.

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The authors have summarized previous work and added their own contributions aimed at a better measurement of total ENTHRU. They made frequent references to the "pioneering" work of Schmertmann and Palacios (1979) and their present work perhaps represents an attempt to update and extend that paper. The discusser has a few comments for the authors to consider about the following aspects of their paper:

1. The F^2 and F-V methods;
2. First-time claim;
3. Refining ENTHRU; and
4. Rod and hammer potential energy.

F^2 versus F-V

The readers might find some comments about the F^2 and F-V methods of interest. Palacios (1977) recognized the theoretical superiority of the F-V versus the F^2 method. F^2 involves an additional assumption. However, he also discovered that the accelerometers available at the time did not have sufficient high-frequency resolution to permit accurate integrations for velocity following the steel/steel, hammer/rod impact of the SPT. (From the authors' discussion and references others also reported accelerometer problems in 1993, 1998, and 2000.) That resulted in our using the F^2 method because force load cells did have sufficient sensitivity. We thought that the major errors using F^2 resulted from the local reflections of waves at large changes in rod and rod/cell cross sections. For the cells used we got our best results using AW rods—hence their extensive use in the 1979 paper. Later, when we found more serious problems with the F^2 method with other, particularly heavier rods, and large anvils, we also found that controlled-height, cut-string hammer drops allowed us to calibrate the method approximately.

First-Time Claim

The authors state, "The present paper introduces for the first time measurements at two different positions—immediately below the anvil and immediately above the sampler. . . ." However, Schmertmann and Palacios (1979) over 25 years ago made extensive use of data from load cells both below the hammer and above the sampler as noted in their Introduction and repeatedly in the text and figures. In 1979 we avoided writing that we had used both below-anvil and above-sampler cells for the first time, although to our knowledge we did.

Refining ENTHRU

Although using the F-V method over more than one hammer impact cycle does measure more of the total energy transferred from the hammer to the rods, it does not automatically follow that using this greater energy will produce a better practical understanding of the SPT. To achieve that may also require considering static and dynamic forces and momentum.

Much of the hammer energy dissipates in sampler quake and rod loses after the net penetration force, and the time it acts reduces to values that no longer cause significant additional sampler penetration. A paper by Crapps (2004) and a discussion (Crapps 2005) indicate that momentum transfer and force considerations have significant importance versus only energy considerations when analyzing the similar pile-driving problem. Significant additional improvement in our understanding of the SPT process may, in the discusser's opinion, involve better understanding of these factors rather than more refinement in energy determinations. However, perhaps the authors' expected future companion paper will demonstrate otherwise.

ASTM D 4633-86 ended with: "7.1.6 Overall precision—the estimated standard deviation between ER_i determinations by two knowledgeable operators using apparatus in ordinary working condition is 5 percentage points of ER_i. Thus, making changes or adjustments when used for purposes such as noted in 3.5 has questionable validity when differences in ER_i are less than 5%."

Note that $5\% = 28$ J. Judging by the scatter of the research SPT data in the authors' Figs. 7 and 12–15, and applying 7.1.6 to the SPT, this situation has not improved much even with the total energy measurement refinements presented in the paper. This may relate to the discusser's opinion, stated often in his aforementioned papers, that an energy-based adjustment of N-values gives only an approximate result. Schmertmann and Palacios (1979) also limited the suggested approximate validity of the inverse *N*-ENTHRU relationship to $N \leqslant 50$. In practice the writer also uses $N \geqslant 5$. Perhaps the authors' ENTHRU measurement refinements will allow them to determine a lower limit and an extended upper limit for N while retaining the simplicity of *N* inversely proportional to a refined ENTHRU.

Rod and Hammer PE

Rod PE

The authors, at the end of their Experimental Results section, say the following: "In conclusion, of the experimental results the energy transferred to the soil is a function of the nominal potential energy E^*, the permanent penetration of the sampler, the rod length, and rod weight. A rational method of interpretation of SPT test results should take into account the combined effect of these four variables which has not been considered by the theoretical framework proposed by Schmertmann and Palacios (1979) and later incorporated to national standards."

The Schmertmann and Palacios (1979) paper begins with, "The research that provides the basis for this paper began with a study of the quasi statics of the SPT (12, 14)." Reference 14 therein denotes a paper titled "Statics of SPT" (1979) by the discusser, published in the same ASCE *Journal* three months before "Energy Dynamics of the SPT." The authors do not mention this related reference, but it includes the term $\mathbf{W}'$ to denote the weight of rods and sampler and makes numerous uses of $\mathbf{W}'$ for additional force and energy calculations. We definitely included $\mathbf{W}'$ in the total static+dynamic theoretical framework.

As for inclusion in(to) national standards, presumably the authors here refer to their referenced ASTM-D 4633-86. My 1992 copy titles this standard as "Stress Wave Energy Measurement for Dynamic Penetrometer Systems." One should not expect a thorough study of the energy-SPT interaction in a standard with this limited scope. In fact, after much discussion and argument at the time, the ASTM subcommittee 18.02 developing this standard, with the discusser participating, voted to exclude any mention of the SPT in its title or text.

Hammer PE

The aforementioned $\mathbf{W}'$ does not include the weight of the hammer or its possible potential energy (PE) contribution to ENTHRU. The writer considered this negligible for two reasons. First, consider a "typical" SPT with $N=9$, and a convenient example blow for $N=9$ presented in static and dynamic detail by Schmertmann and Palacios (1979) in their Table 1 and Fig. 9 (blow No. 28). With $N=9$ the hammer loses PE at an average of 21 J/blow, or 4.4% of the authors' E^*. Note that this by itself does not meet the ASTM 7.1.6 aforementioned 5% significance criteria.

Second, Fig. 9 in Schmertmann and Palacios (1979) shows that the hammer remains in contact with the rods for only about 0.33 in(0.008 m) of the total 1.3 in(0.032 m) penetration for blow no. 28, or for 25% of the penetration. Even assuming complete hammer PE transfer to ENTHRU during this 25%, it now only amounts to a negligible $0.25 \times 4.4 = 1.1\%$ of E^*. The remaining 3.3% does not arrive at the sampler in time to contribute significantly to the penetration and therefore to the *N*-value.

To summarize the points made in this discussion:

1. In Schmertmann and Palacios (1979), the F^2 method for ENTHRU provided the only practical method available at the time and using it gave informative and useful results;
2. The authors incorrectly claim they used an above-sampler second load cell for the first time;
3. The authors' various methods for refining ENTHRU do not necessarily lead to a significantly improved understanding of the SPT; their future paper may provide additional insight; and
4. The work by Schmertmann and Palacios (1979) included consideration of the weight and PE contribution of the rods and hammer.

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The writers would like to express their appreciation to Professor Schmertmann and Drs. Johnsen and Jagello for their interest in our publication and for their work in preparing their discussions. Our paper can be viewed as a follow-up of research efforts carried out in the past 30 years from which the concepts of wave propagation on dynamic tests have been acknowledged. Our contribution was twofold: to produce systematic measurements of load and acceleration at different depths along the rods to determine

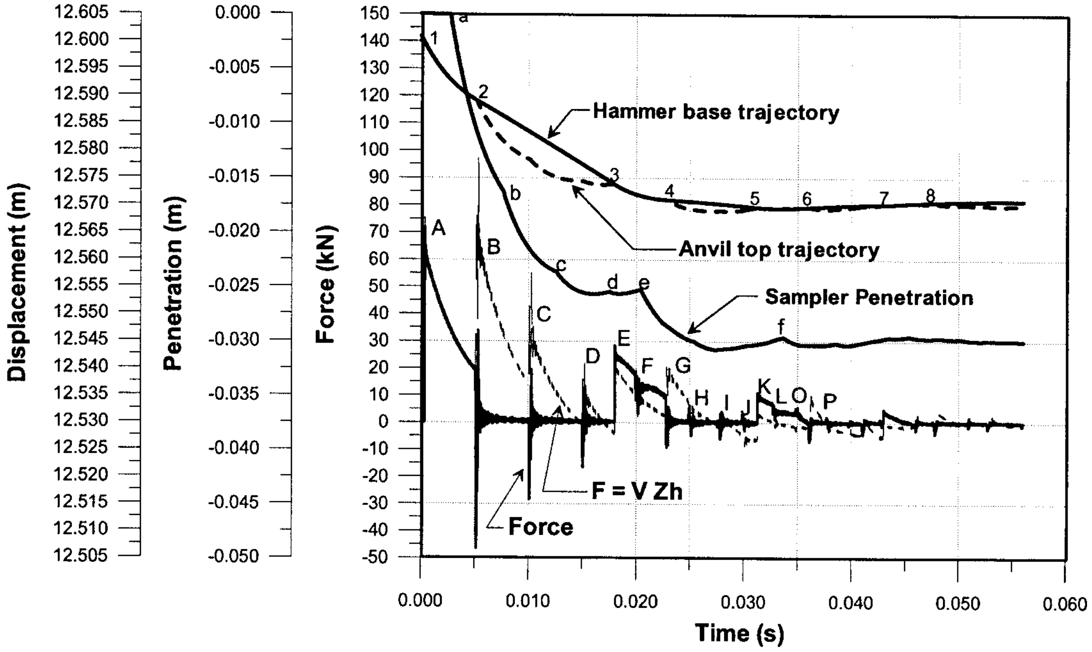

Fig. 1. Numerical simulation of the penetration mechanism of a 12.6-m rod stem

the actual loss in energy in dynamic events and to introduce an analytical solution to calculate the maximum potential energy delivered to the soil during the energy transference process.

In the 1970s, Schmertmann's pioneering work was used to clarify aspects of the mechanism of wave propagation along the rods and to quantify the so-called "rod energy ratio." In light of the new evidences introduced in our paper, Schmertmann has raised a number of questions that the writers tried to answer in the four comments addressed below

1. *F^2 and F-V methods.* Experimental measurements of energy can be calculated by the so-called F^2 and F-V methods. The writers believe that nowadays there is no justification not to use the F-V method since accelerometers have become cheap, easy-to-use instruments, and that velocity determination from acceleration measurements has became more accurate due to improved frequency response. The use of both accelerometers and load cell give redundancy to measurements and lead to more reliable interpretation of dynamic events.
2. *First-time claim.* There has been no intention on our side not to acknowledge previous work on this area. In fact we have frequently made reference to the pioneering research work published by Schmertmann and Palacios in 1979, in which reported data are plotted as energy ratio against blow count number. However, the discusser yields a conclusion that differs from our own findings in respect to the influence of the rod energy when calculating sampler energy and sampler penetration. The discusser shows that the energy reaching the sampler increases with decreasing penetration. As extensively demonstrated in our paper both experimentally and numerically, for low resistance soils (low N-values) the gain in energy from weight of the rods can be sometimes greater than the energy losses resulting from wave propagation and the combination of a very long rod and a significant sampler penetration can result in an energy ratio (PE_{h+r}/E^*) greater than unit.
3. *Refining ENTHRU.* The discusser argues that although the several impacts of a hammer produce an increase in the total

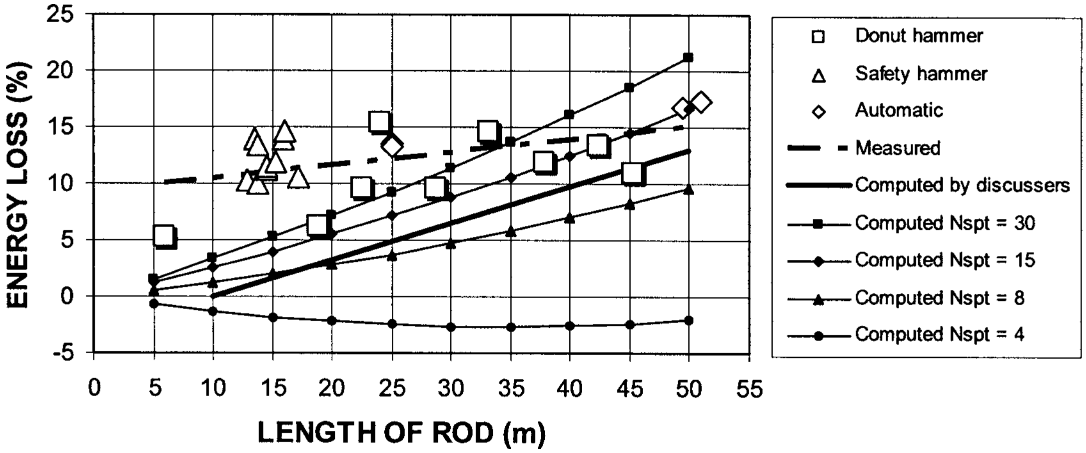

Fig. 2. Energy losses versus length of rod

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transmitted energy, it does not automatically follow that using this greater energy produces a better understanding of the SPT. This point deserves a constructive discussion. The importance of considering the influence of the several impacts produced by an SPT blow is not only a refinement to the actual measurements of the rod energy ratio but a method of building a proper understanding of the energy transfer process. From fairly accurate measurements we have concluded that the maximum potential energy can be conveniently expressed as a function of nominal potential energy E^{*}, sampler permanent penetration, and weight of both hammer and rods. Once this is acknoweledged we managed to infer that the greater the length of the rods the greater the energy available to be transmitted to the sampler-soil system.

4. *Rod and hammer PE*. The discusser considers the contribution of the weight of the hammer or its potential energy PE to be negligible. We have both experimental and numerical evidences showing that the weight of hammer and rods might have an important effect on the actual energy delivered to the sampler-soil system. Fig. 1 gives an example of a numerical analysis designed to illustrate the penetration mechanism of a 12.6 m rod. The hammer base and anvil trajectories are shown and are used to visualize the actual penetration of the sampler. A late impact at (3 to 4) and (E to G) cannot be disregarded when calculating the energy transmitted to the hammer blow.

Johnsen and Jagello presented unpublished data from simultaneous measurements at both top and bottom of the drill rod from which it became apparent that measured energy losses are significantly greater than the energy losses obtained in our paper. More than identifying any inconsistency in our approach, this set of data reinforces the need to account for the lack of standardization in equipment and test procedures and to correct the measured penetration resistance to a reference value of the potential energy. Here it is important to recall that Brazilian standards recommend Schedule 80 (3.23 kg/m) rods to be used, whereas ASTM standards require that the drill rod must have a stiffness greater than A rod (>4.57 kg/m).

The discussers presented a figure that correlates energy loss with length of rod for safety, donut, and automatic hammers. These data are replotted in Fig. 2 to compare the experimental measurements with calculated energy losses using the writers' method, expressed as a family of curves for different values of the permanent penetration of the sampler. Some assumptions are adopted in this calculation. The coefficients η_1, η_2 e η_3 proposed in our paper follow Brazilian standards: $\eta_1=0,76$; $\eta_2=1$ e $\eta_3=(1-0,0042l)$, where l=total rod length. The computed energy of an element of the rod is calculated by Eq. (1)

$$E=\int_{t=0}^{t=\infty} F(t)V(t)dt \tag{1}$$

The $F(t)$ term is

$$F(t)=f(t)+F_H \tag{2}$$

where $f(t)$=force measured on the load cell that is set to zero under the rod self-weight, and hence corresponds only to the dynamic force resulting from wave propagation; F_H=force produced by the rod self-weight, and hence corresponds to a constant static force; and the $V(t)$ term=integration of the acceleration signal that includes both the relative particle velocity and the rigid body velocity of the complete rod system. Hence

$$\int F(t)\cdot V(t)\cdot dt=\int [f(t)+F_H]\cdot V(t)\cdot dt$$

$$=\int f(t)\cdot V(t)dt+F_H\int V(t)dt \tag{4}$$

Where $\int f(t)\cdot V(t)\cdot dt$=integral calculated with the recorded signal of the load cell; and $F_H\int V(t)dt=F_H\bar{V}\cdot t_{total}$=actual work produced by the rod weight, with $\bar{V}$ denoting an average rigid body velocity of the rod.

But $\bar{V}=\Delta\rho/t_{total}$, and consequently the term $F_H\cdot\bar{V}\cdot t_{total}$ results equal to $F_H\cdot\Delta\rho$. From this set of equations it should become clear that when computing the energy from Eq. (4) to match experimental data, it is necessary to set the load cell as zero under the rod self weight, immediately before a hammer blow, and later add the energy produced by the rod weight above the element where measurements are being recorded (which is a function of the rod mass and length, as well as the permanent penetration of the sampler). Alternatively, $F(t)=f(t)+F_H$ can be calculated together as a single term by setting the load cell as zero before assembly the composition of rods.

With these assumptions it is possible to calculate typical energy losses and compare these theoretical results to the measurements shown in Fig. 2. Our predictions underestimate measured energy losses at shorter rod lengths, as already identified by the discussers. It is therefore recommended to adopt this database to recalibrate η_1, η_2 e η_3 in order to obtain values representative of the American practice.

It is worth reemphasizing that simultaneous measurements recorded at both the top and bottom of the rod stem are essential to the understanding of the mechanism of energy transfer to the sampler-soil system. From this mechanism it is possible to calculate the dynamic force produced by a hammer blow that can lead to a variety of interesting applications, as for example a direct comparison between different dynamic tests (SPT and LPT) without the need to rely on empirical correlations. From recent research efforts it was possible to develop new methods for the interpretation of SPT results by correlating the dynamic force to soil parameters both in sand and clay, as well as predicting pile bearing capacity (Schnaid 2005). This brief discussion does not fully elucidate the complexity of the mechanics of dynamic penetration tests, but demonstrates that our work updates previous concepts established in the 1970s.

References

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