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Evaluation of Self-Penetration Potential of a Bio-Inspired Site Characterization Probe by Cavity Expansion Analysis

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ABSTRACT: Site investigations at limited-access project sites often require mobilization of smaller rigs that may not have the reaction mass required to perform soundings to the desired depth. This study explores the feasibility of a new conceptual bio-inspired solution by adapting functional principals from organisms whose primary mode of locomotion is soil burrowing, including razor clams, caecilians, and earthworms. These organisms radially expand a segment of their body to increase the normal radial pressure acting on it. This study evaluates the dimensions required for self-penetration of an idealized bio-inspired probe consisting of a radially expanding shaft and a penetrating tip. Cavity expansion analyses, field test data and theoretical relationships
from the literature are used to evaluate the self-penetration potential in different soil types. The results indicate that the resistance to self-penetration is higher in dense sands than in silts and clays. In sands, the resistance to self-penetration is greater in sands that exhibit a more dilative behavior at a given overburden pressure. On the other hand, the resistance to self-penetration in clays slightly decreases as the overconsolidation ratio is increased. The relative dimensions required to initiate self-penetration predicted by cavity expansion analysis are compared with the dimensions of various burrowing organisms.

**Keywords:** Cavity expansion, site characterization, cone penetration test, bio-inspiration

**Introduction and Bio-Inspiration**

Site investigations at limited-access project sites, such as slopes, forested areas, or congested urban locations, often require mobilization of lighter, smaller rigs that may not provide the reaction force necessary to perform in-situ tests such as the cone penetration test (CPT), field vane test (FVT), and flat dilatometer test (DMT) to desired depths and/or into stiff or dense soils. While temporary anchors may be used to generate additional reaction force, these can perform unreliably, compromise the site investigation, and disturb the ground. Bio-inspiration may assist in development of a self-penetrating site characterization probe, thereby increasing the feasibility of investigating such sites.

A number of organisms have developed self-reaction propulsion mechanisms that allow them to burrow in a variety of soils. These include razor clams, which typically inhabit sandy beaches, have bodies with lengths between 5 and 20 cm, and can burrow to depths over 70 cm. They use a combination of methods for burrowing, including a two-anchor system with alternating penetrating and terminal anchors, and local soil fluidization caused by soil deformations and water injection.
into the soil (Trueman 1966; Winter et al. 2012). Other burrowing organisms are caecilians, a group of limbless amphibians with elongated and segmented bodies with lengths between 100 to 1500 mm that live in tropical climates (Summers and O’Reilly 1997). They primarily live underground and have been observed to burrow up to 70 cm depth (Kupfer et al. 2008). Soil penetration in caecilian species such as *Dermophis Mexicunus* and *Hypogeophis rostratus* is enabled using internal concertina locomotion, which consists of laterally extending a portion of their body by undulating their vertebral column. This increases the soil normal pressure acting against their body, which is used as a static anchor to produce reaction force to enable forward movement (Gaymer 1971; Summers and O’Reilly 1997). A third relevant organism is the earthworm, which has a tube-shaped body with a length varying from 1.2 cm to 320 cm depending on the species and can live in a variety of soils, from sands to clays. Earthworms primarily use peristalsis for propulsion, consisting of forward- or backward-traveling waves of expansion and compression of their hydrostatic skeleton that allows them to generate propulsive reaction forces at several locations along their body (Gans 1973; Dorgan et al. 2005; Dorgan 2018).

A generalized mechanism used by razor clams, caecilians, and earthworms consists of the following stages: (i) radial expansion of a segment of the body to increase the normal radial soil pressure acting on it, (ii) elongation of a segment of the body near the organism’s tip to advance and penetrate the soil, (iii) radial contraction to induce radial pressure relaxation, and (iv) retraction of the body towards the tip. This sequence of movements is then repeated throughout the soil penetration process.

Researchers have applied the burrowing processes described here to perform mechanical analysis that is relevant to the design and development of self-burrowing probes. Winter et al. (2014) analyzed and developed a razor clam-inspired probe that uses local fluidization to decrease
the penetration and drag forces acting on the probe. Huang and Tao (2017; 2018) presented results of Discrete Element Modeling (DEM) simulations of razor clam-inspired probes. Their results indicate that the penetration force decreases as the rate and magnitude of body expansion is decreased. Other researchers have investigated a mechanism used by earthworms and tree roots to decrease the penetration resistance, consisting of radially expanding a zone close to the worm or root tip (Savioli et al. 2014; Cortes and John 2018). In cohesive soils, this radial motion generates tensile stresses within the soil ahead of the tip that can initiate and propagate a fracture (Dorgan et al. 2007). In non-cohesive soils, the radial expansion has been shown to cause a decrease in effective stress within the soil ahead of the tip (Cortes and John 2018; Khosravi et al. 2018). Ruiz et al. (2015) estimated the energy required by earthworms and growing plant roots to penetrate cohesive soil using cavity expansion theory. The authors concluded that the mechanical energy required per unit of displaced soil volume decreases with increasing organism radius and with increasing soil water content. Other authors have developed burrowing robots based on bio-inspiration from organisms such as mole crabs (Russel 2011), bivalves (Koller-Hodac et al. 2010), earthworms (Fukunaga et al. 1998), and inchworms (Gorevan et al. 2003).

The purpose of the investigation presented herein is to use cavity expansion analysis, along with a review of published experimental and analytical results, to estimate the relative dimensions required by an idealized bio-inspired probe to initiate self-penetration. In addition, the predicted relative dimensions are compared to those of various burrowing organisms, where data is available, to evaluate whether the results reasonably capture the mechanisms involved in soil burrowing.

**Framework for Evaluation of Self-Penetration Potential**
An in-situ testing probe capable of self-penetration would be required to generate enough reaction force within its drill string (body) to overcome the soil pressure resisting advancement of the tip and the friction along the shaft. A schematic of the idealized probe, along with soil resistance and reaction components mobilized during radial expansion and self-penetration, is presented in Figures 1a through 1c. During self-penetration, the upper and lower sections of the probe simultaneously separate at a joint. Only the friction along the expanded probe section is considered in this analysis, while possible additional friction along other sections is ignored. Additionally, the soil penetration resistance is considered as the only resistance component, and it is assumed to be equal in magnitude to the tip resistance measurement \( q_t \) during cone penetration testing. The reaction forces for self-penetration are assumed to be generated from shear stresses along the probe section that expands radially to mobilize the soil’s radial limit pressure \( P_L \), defined as the limiting pressure mobilized during expansion of a cavity. The \( P_L \) is also assumed to be equivalent to the radial soil pressure mobilized during pressuremeter testing (PMT).

Analysis of the balance of forces acting on the probe along the vertical direction (z-coordinate in Figure 1c) during self-penetration leads to a relationship for the ratio of length of the expanding shaft section (\( L \)) to tip diameter (\( D \)) as follows:

\[
\frac{L}{D} = \frac{q_t}{4(1 + \varepsilon) \tau}
\]  

where \( q_t \) is the tip resistance, \( \tau \) is the strength of the probe-soil interface in drained or undrained conditions, and \( \varepsilon \) is the expansion ratio = \( (D_e - D) / D \) where \( D_e \) is the diameter after expansion (where no data is available, \( \varepsilon \) is taken as 20% based on typical results from field tests, e.g. Withers et al. 1989; Schnaid 1990; Yu et al. 1996; Fawaz et al. 2002; Hoopes and Hughes 2014).

In an effective stress formulation, the shear strength of the expanded probe-soil interface is calculated as follows:
\[ \tau = P'_L \tan (\delta) \]  

(2)

where \( P'_L \) is the effective limit pressure and \( \delta \) is the probe-soil interface friction angle taken as \( \frac{2}{3} \) of the soil internal friction angle for sands and as equal to the soil friction angle for silts and clays, following experimental trends provided in the literature (e.g. Uesugi and Kishida 1986; Ho et al. 2011). The analysis presented herein considers the critical state friction angle for calculation of the soil-probe interface shear strength.

In a total stress formulation, the probe-soil interface strength is calculated assuming that it is equal to the soil’s undrained shear strength, \( S_u \), estimated using the modified cam-clay framework (e.g. Wood 1984) as follows:

\[ \tau = S_u = P'_c S OCR^m \]  

(3)

where \( P'_c \) is the mean effective consolidation pressure, OCR is the overconsolidation ratio, and \( S \) and \( m \) are material properties taken as 0.23 and 0.8, respectively, based on typical values (Ladd and Foott 1974).

The L/D ratio provides an estimate of the probe dimensions required for self-penetration initiation, and it is used throughout this study as a metric of self-penetration potential. Soils offering more challenging self-penetration conditions are characterized by larger \( q_t/P_L \) and associated L/D ratios, meaning that a longer expanding section is required to overcome the mobilized soil tip penetration resistance. The \( q_t/P_L \) ratio, rather than \( q_t/\tau \), is used to evaluate self-penetration potential because \( P_L \) depends only on soil properties while \( \tau \) also depends on the strength of the soil-probe interface. In addition, use of \( q_t/P_L \) allows for comparison of the results from this investigation with published analytical solutions and field data.

Evaluation of the self-penetration ability of a probe utilizing the balance of forces described above, along with Equations (2) and (3), requires the following simplifying assumptions: (i) the \( q_t \)
and $P_L$ components do not interact due to the assumed large spacing between the two, (ii) the $q_t$ and $P_L$ components are measured under the same overburden stress, (iii) the magnitude of $q_t$ and $P_L$ can be estimated using cylindrical cavity expansion analysis (e.g. Yu and Mitchell 1998; Yu 2000), and (iv) there is no additional reaction force contribution that may be generated from the top boundary of the cylindrical expanded section (shown in Figure 1b), although this contribution has been explicitly considered in other numerical analysis studies (e.g. Khosravi et al. 2018).

Note that although assumption (i) is in contrast with prior studies that have shown interaction effects when the tip and anchor are in close proximity (Dorgan et al. 2007; Savioli et al. 2014; Ruiz et al. 2015; Huang and Tao 2018; Cortes and John 2018; Khosravi et al. 2018), it is likely valid where the probe’s expanded section and tip are sufficiently spaced from each other such that their influence zones do not interact. While the authors of this manuscript have not yet completed an investigation to determine what distance is required between the tip and anchor to avoid these interactions, results by Houlsy and Carter (1993) indicate that the zone of significant influence around an expanding cylinder in clay reaches a distance of about 5 diameters ahead of the cylinder. In addition, preliminary results obtained by the authors of this manuscript using DEM modeling indicate a zone of influence that reaches a distance of about 8 diameters ahead of the expanded anchor. Assumption (i) may successfully approximate the boundary condition imposed at the probe-soil interface in the field if a pressure-controlled system (e.g. hydraulic) was used to expand the anchor and to maintain the lateral pressure acting against it while the diameter is allowed to change.

**Data from Literature, Calibration Chamber, and Field Studies**
The envisioned bio-inspired probe has conceptual similarities in configuration to the Cone Pressuremeter (CPMT) probe described by Withers et al. (1986), Hers (1986), and Withers et al. (1989). Consequently, the theoretical advances and experimental data obtained as part of the CPMT development can be used to perform an initial evaluation of the self-penetration potential in different soil types for the probe described herein. Yu et al. (1996) provided a theoretical correlation for CPMT tests in sands relating the ratio of the effective tip resistance (\(q'_c\)) to the effective limit pressure (\(P'_L\)) with the soil state parameter (\(\xi\), equal to the difference in void ratio between the current state and the critical state as defined by Been and Jefferies 1985, where larger values characterize soils with more contractive behavior). This relationship indicates that the \(q'_c/P'_L\) ratio (here \(q'_c/P'_L\) is taken equal to \(q_t/P_L\) due to assumed drained conditions by Yu et al. 1996) decreases as \(\xi\) increases, as shown in Figure 2a; Figure 2b also shows an inverse relationship with \(\xi\) for the corresponding L/D ratio values calculated using Equations (1) and (2). The relationship provided by Yu et al. (1996) is dependent on the mean initial effective stress, with the slope in semi-log \(q_t/P_L\) vs. \(\xi\) space decreasing as the mean initial effective stress is increased. The trends indicate that sands with smaller \(\xi\) (i.e. with more dilative behavior) require larger L/D ratios for self-penetration, with values as large as 6.2. In contrast, sands with larger \(\xi\) (i.e. with more contractive behavior) require smaller L/D ratios, as small as 1.6.

The CPMT tests performed in a calibration chamber by Schnaid (1990) on dry sands of varying density can be used to further assess self-penetration potential. The measured \(q_t/P_L\) values, equivalent to \(q_t/P_L\) ratios due to the dry conditions in the tests, and the calculated L/D ratios using Equations (1) and (2) are presented in Figures 3a and Figure 3b, both as functions of initial horizontal stress. The results from the calibration chamber tests indicate \(q_t/P_L\) ratios close to 12 for dense sands, 10 for medium dense sands, and 5 for loose sands. The corresponding L/D values are
about 6.25, 5.25, and 2.75 for the dense, medium, and loose sands, respectively. The corresponding
$q_t/P_L$ and $L/D$ values at a mean effective stress of 100 kPa, as well as their decrease with increasing
horizontal stress, are in agreement with the predictions from the Yu et al. (1996) relationships.

Data from field CPMT soundings and from separate CPT and PMT soundings performed
adjacently can be used to assess self-penetration potential using the effective stress formulation
(Equation 2) in sands and the total stress formulation (Equation 3) in silts and clays (with $S_u$
estimated from $q_t$ profiles). Figure 4a presents $q_t/P_L$ and $L/D$ ratios as a function of depth for
soundings performed on sites with sandy soils (note that a soil friction angle of 30° was assumed
for all sands; data from Withers et al. 1986; Withers et al. 1989; Briaud 2000). As shown, the $q_t/P_L$
ratios are between 4.2 and 11.2, resulting in $L/D$ ratios roughly between 2.7 and 6.5. These values
are in agreement with those obtained from the Yu et al. (1996) relationships and the Schnaid (1990)
calibration chamber test data. A similar analysis on data from soundings on sites with fine-grained
soils yielded $q_t/P_L$ values between 1.2 and 6.0, with most of the data having $q_t/P_L$ ratios from about
1.2 to 2.0 (Figure 4b; data from soft clays, organic clayey silt, silty clay, silty mixtures, and
overconsolidated clays from Hers 1986; Briaud 2000; and Mayne et al. 2000). The $L/D$ values for
the silty and clayey soils are between 3.0 and 4.0. The values estimated for the soft clays are in
good agreement with the $q_t/P_L$ and $L/D$ ratios of 1.4 to 1.5 and 2.5 to 3.5, respectively, predicted
using the Gibson and Anderson (1961) cavity expansion limit pressures combined with the

Comparison of $q_t/P_L$ and $L/D$ values obtained from the analytical relationship, calibration
chamber tests, and field tests provide qualitative evidence that self-penetration in sandy soils
requires larger reaction forces, which can be provided by larger $L/D$ ratios (i.e. longer expanding
sections). In addition, the $L/D$ ratios required for self-penetration increase as the soil becomes
more dilative (i.e. $\zeta$ is decreased), likely due to the increase in strength and stiffness as the dilative tendencies become more pronounced.

**Cavity Expansion Analyses**

Cylindrical cavity expansion simulations were performed with the cavity expansion analysis code ASCEND (Applications for Spherical and Cylindrical Cavity Expansion in Nonlinearly Deforming geomaterials), developed by Jaeger (personal communication 2018). The ASCEND program was developed based on the exact semi-analytical analysis procedures presented by Chen and Abousleiman (2012) and Chen and Abousleiman (2013) for undrained and drained cylindrical cavity expansion. ASCEND incorporates the advanced constitutive model MIT-S1 (Pestana and Whittle 1999), which is capable of simulating the behaviors of soils ranging from sands to clays (e.g., Pestana et al. 2002a; Pestana et al. 2002b; Jaeger 2012; Price 2018). The ASCEND program allows for simulation of cavity expansion considering isotropic and anisotropic stress states, while use of the MIT-S1 constitutive model allows for incorporation of shear strength anisotropy. The program also allows for use of the Mohr-Coulomb model, which was compared against known closed-form solutions for drained and undrained cavity expansion (Gibson and Anderson 1961; Yu and Houlsby 1991) to verify the implementation and solution of the governing equations. ASCEND simulations with the MIT-S1 model were also verified by comparison to cavity expansion simulations in FLAC from Jaeger (2012).

A parametric study was performed to evaluate the influence of soil type, state parameter, and stress history on the self-penetration potential. All simulations were performed using cylindrical cavity expansion, where sands were analyzed in drained conditions, silts in drained and undrained conditions, and the clay was considered undrained, according to expected drainage conditions
during in-situ tests. The state parameter was varied for sands and silts, whereas the overconsolidation ratio (OCR) was varied for the clay. Simulations were performed with the MIT-S1 constitutive model calibrated to four soils: Toyoura sand representing a clean sand, FC35 sand (mixture of 65% Nevada sand and 35% Yolo loam) representing a silty sand, silica flour representing a silt, and Boston blue clay representing a plastic clay. The calibration parameters for these soils, originally presented in Jaeger (2012) and Price (2018), are shown in Table 1. Pestana and Whittle (1999), Jaeger (2014), and Price (2018) provide detailed descriptions of the parameter definitions.

Typical results

The results produced by the ASCEND code consist of the total and effective radial stresses ($\sigma_r$ and $\sigma'_r$), vertical stresses ($\sigma_v$ and $\sigma'_v$), and hoop stresses ($\sigma_\theta$ and $\sigma'_\theta$), along with the mean effective stress ($p'$), deviatoric stress ($q$), excess pore pressure ($\Delta u$), and void ratio ($e$), all as a function of expansion ratio ($De/D$). All simulations were initiated with 1-D consolidation. The normally consolidated lateral earth pressure coefficient at rest ($K_{0NC}$) was defined to be 0.49 for all soils, while the equivalent coefficient for the overconsolidated cases ($K_{0OC}$) was computed by simulating 1D unloading with the MIT-S1 model from a normally-consolidated state.

The results obtained from ASCEND allow for analysis of the different stress components as the cavity is expanded, as shown in Figure 5. The stress components from drained simulations on Toyoura sand with state parameters ($\xi$) of 0.1 and -0.1, shown in Figures 5a and 5b respectively, indicate that in both cases the effective radial stress becomes the largest magnitude component as the cavity expands. The stresses mobilized by Toyoura sand with $\xi = -0.1$ are larger in magnitude than those mobilized by the $\xi = 0.1$ sand due to the former’s more pronounced dilative behavior.
that results in greater sand stiffness and strength. Figures 5c and 5d present stress components during undrained simulations on Boston blue clay with OCR of 1.0 and 8.0, respectively. As shown, excess pore pressures are generated and the magnitude of all stress components is larger for the simulation on the heavily overconsolidated clay.

The stress paths in q-p’ and e-p’ space for simulations on Toyoura sand (drained) and Boston blue clay (undrained) indicate that at large cavity strains, all simulations converge towards the respective critical state lines (Figures 6a and 6b). All simulations were performed on 1D consolidated soils, with normally consolidated conditions for all simulations on Toyoura sand, and on normally consolidated (OCR = 1), slightly overconsolidated (OCR = 4), and heavily overconsolidated (OCR = 8) conditions for simulations on Boston blue clay. As expected, the dilation exhibited by the sand increased as the state parameter was decreased. For the clay, dilative tendencies also increased as the OCR was increased. Similar results were obtained for simulations on FC35 sand and silica flour; they are not included here for brevity.

**Assessment of Self-Penetration Potential**

Assessment of self-penetration potential using cylindrical cavity expansion simulations requires determination of the tip resistance and limit pressures. The total (P_L) and effective (P'_L) radial stresses acting on the cavity wall are obtained directly from the simulations as the limiting values. The tip resistance (q_t) is estimated in drained conditions using a relationship provided by Jaeger (2012) that was modified after Yu et al. (1996):

\[
q_t = P'_L \exp \left[A_1(p'_0) - A_2(p'_0)\xi\right]
\]

where P'_L is the effective cylindrical cavity limit pressure, A_1 and A_2 are material constants that depend on the initial mean effective stress (p'_0), and \(\xi\) is the state parameter.
The tip resistance in undrained conditions is estimated using a relationship provided by LeBlanc and Randolph (2008) and modified by Jaeger (2012):

\[ q_t = \sigma' \gamma + u = P'_L \left[ \frac{1 + \tan(\delta)}{\tan(\alpha/2)} \right] + u \] (5)

where \( u \) is the pore water pressure at the limit condition, \( \delta \) is the cone-soil friction angle (assumed to be equal to 2/3 of the internal soil friction angle for sands and equal to the internal soil friction angle for silts and clays based on experimental data, e.g. Uesugi and Kishida 1986; Ho et al. 2011), and \( \alpha \) is the cone apex angle (equal to 60°).

Table 2 presents a summary of the limit pressures, tip resistance, and \( q_t/P_L \) and L/D ratios obtained during all the drained simulations on Toyoura sand, FC35 sand, and silica flour. In general, the limit pressures are in agreement with field and calibration chamber data from Withers et al. (1989), Schnaid (1990), and Yu et al. (1996), with \( P_L \) values ranging from 230 to 2500 kPa in the clean sand (Toyoura), 170 to 1700 kPa in the silty sand (FC35), and 100 to 1900 kPa in the silt (silica flour). Smaller \( P_L \) values were obtained from simulations with smaller initial vertical effective stresses and/or soils with larger state parameters. The calculated \( q_t \) values are also in general agreement with trends typically observed in field tests, with values as large as 16 MPa in dense clean sands. These values decrease with decreasing overburden, increasing soil state, and increasing fines content.

Table 3 presents the values obtained from undrained simulations on silica flour and Boston blue clay. The \( P_L \), \( P'_L \), and \( q_t \) values all increase as the overburden is increased. These values increase for silica flour as the soil state is decreased, and for Boston blue clay the values increase as the OCR is increased. The calculated tip resistance values are in general agreement with field experience, where \( q_t \) magnitudes in fine-grained soils rarely exceed 5 MPa.
The simulations yielded normalized cone resistances \((Q = q_t - \sigma_{vo}/\sigma'_{vo})\) that are within the range of those considered in the soil classification charts by Robertson (1990) and Robertson (2009). The \(Q\) values are 10 to 70 for Toyoura sand (Robertson range for clean sand is 28 to 200), 7 to 30 for FC35 (Robertson range for sand mixtures is 8 to 80), 13 to 38 and 3 to 14 for silica flour in drained and undrained conditions, respectively (Robertson range for silt mixtures is 4 to 60), and 2 to 15 for Boston blue clay (Robertson range for clays is 1 to 40).

The drained simulations on Toyoura sand, FC35 sand, and silica flour indicate similar changes in \(q_t/P_L\) and L/D with effective overburden stress, as both quantities are related by the probe-soil interface friction angle. Larger \(q_t/P_L\) and L/D ratios are required for initiation of self-penetration in materials with larger stiffness and strength, characterized by negative state parameters (Figures 7a, 7b, and 7c). This trend is likely due to the contribution of soil dilation and the associated changes in the state of stresses to penetration resistance (e.g. larger increase in effective stresses during cavity expansion and penetration in denser soils).

The undrained simulations indicate an increase in \(q_t/P_L\) with decreasing soil state for silica flour and with increasing OCR for Boston blue clay (Figures 7c and 7d). These results indicate a greater effect on \(q_t\) than on \(P_L\) by the increase in strength and stiffness associated with decreases in \(\xi\) and increases in OCR. The L/D ratios from undrained silica flour simulations, obtained using the total stress formulation for the probe-soil interface strength in Equation (3), indicate an increase in L/D with increasing soil state. This is due to the larger excess pore pressures generated during the simulation with \(\xi = 0.0\), which cause a decrease in the radial effective stress acting on the probe-soil wall. The L/D ratios obtained for Boston blue clay using the total stress formulation in Equation (3) indicate an increasing trend as OCR is decreased. This trend highlights the increase
in undrained shear strength with increases in OCR, which yields a greater shear resistance force along the expanded section of the probe.

The trends in self-penetration potential as a function of soil type, described by the $q_t/P_L$ or $L/D$ ratios, broadly follow the trends expected for penetration resistance based on the vast published experience obtained from field tests. This experience has led to the understanding that soil penetration resistance is larger for dense gravelly and sandy soils, followed by loose sands and sand/silt mixes, and then by overconsolidated and normally consolidated clays (see, for instance, Robertson et al. 1986; Robertson et al. 1990). Table 4 presents a summary of the $q_t/P_L$ and $L/D$ ratios obtained from drained and undrained cavity expansion analyses, field and calibration chamber tests, and theoretical relationships. The predictions of $q_t/P_L$ from the simulations, soundings, and agree with each other, with values between 3.0 to 11.0 for sands and 1.4 and 6.5 for silts and clays. The results also indicate a similar decrease in $q_t/P_L$ as the soil transitions from coarse-grained to fine-grained. The $L/D$ values from cavity expansion analyses and field tests on sands agree with each other, with values between 1.5 and 6.5. The $L/D$ ratios from cavity expansion in silts and clays are also in agreement with those predicted from field tests, with values between 1.5 and 3.5 and 2.8 and 4.2, respectively. The range of $L/D$ values obtained from cavity expansion analysis is relatively constant for the soil types examined. The results indicate that dense sands (in drained conditions) and soft clays (in undrained conditions) will likely represent the most challenging self-penetration conditions due to the former’s large penetration resistance and the latter’s low undrained shear strength available to produce reaction forces.

**Comparison to Razor Clam, Caecilian, and Earthworm Dimensions**
To evaluate the L/D ratio results presented in the previous section, which provide an estimation of the relative dimensions required by a self-penetrating probe to overcome the soil penetration resistance, the values can be compared to the equivalent ratios for burrowing organisms that use the similar types of locomotion. Organisms like razor clams, caecilians, and earthworms are analogically similar to the probe analyzed in this paper. A razor clam uses its internal muscles to separate its shell to generate reaction forces during burrowing. Simultaneously, the clam expands its foot from its anterior end, which is required to overcome the soil penetration resistance (Winter et al. 2014), as shown schematically in Figure 8a. These animals have an elongated cross-sectional area that can be approximated as an ellipse. Therefore, the ratio of the animal’s shell length, L, to width, D, can be used to estimate L/D ratios for comparison to the proposed probe’s L/D values obtained via cavity expansion analysis.

Table 5 presents typical values of length and width for several clam species. As shown, lengths can vary between 40 and 250 mm and diameters vary between 16 and 76 mm (Mühlenhardt-Siegel et al. 1983; Hiebert et al. 2015; Aitken and Knott 2018; Fraser et al. 2018). The computed L/D ratios are presented in Figure 8b, indicating values between 7.5 and 9.0 for the more slender Sword razor clam, and smaller values between 1.0 and 1.5 for the stouter Pacific razor clam. Figure 8b also includes the range of L/D ratios obtained from cavity expansion analysis in sands and clays, which go from 2.0 to 4.5 and 2.8 to 4.2, respectively. As shown, the L/D ratio of the Atlantic jackknife clam, Sickle razor clam, and Pacific razor clam fall within the range predicted by the cavity expansion analysis, in agreement with observations by Tao (2018). This may indicate that the cavity expansion analysis presented herein reasonably captures the physical mechanisms involved in self-penetration of organisms such as clams. The agreement in L/D values may also
indicate that the morphology of several clam species has been optimized in consideration of the mechanics of soil burrowing to allow for efficient self-penetration.

Caecilians and earthworms also locomote through soil using variations of the radial expansion – axial penetration mechanism. Caecilians can be as long as 1500 mm (Sherratt 2012), while certain species of earthworms can reach lengths of up to 3000 mm (Blakemore et al. 2002; Blakemore et al. 2007). Typical diameters for caecilians are between 6 and 25 mm (Hofrichter 2000), while diameters for earthworms are slightly smaller, from 1 to 20 mm (Laird et al. 1981; Coleman et al. 2017). The form of locomotion used by both of these types of organisms, internal concertina by caecilians like *Dermophis mexicanus* and peristalsis in earthworms like *Lumbricus terrestris*, involves radially expanding one or more sections of their body to increase the radial pressure against it. Therefore, the relevant length for estimation of L/D ratios in both of these organisms is the length of the animal’s body section that is expanded, as opposed to the overall body length. Unfortunately, the authors are not aware of any dataset describing this dimension, making computation of L/D ratios for these organisms for comparison with the cavity expansion predictions unfeasible at this point.

**Practical Implications**

The self-penetration potential analysis presented in this paper provides insights for the development of a bio-inspired self-penetrating probe. In particular, the calculated L/D ratios are related to the geometry required for a probe to generate enough reaction force to initiate self-penetration in a given soil. Cavity expansion analyses, as well as results from analytical relationships and calibration chamber and field soundings, indicate that self-penetration potential is high in overconsolidated clays and loose sands, characterized by small L/D ratios. These small
ratios suggest that in such soils, self-penetration may be realized by a probe with an expanding section that is two to three times longer than the probe’s diameter. The biggest challenge for field tests will be dense sands, where the larger L/D ratios suggest that the expanding section would need to be greater than four to six and a half times the probe diameter. In addition, the larger limit pressures mobilized by the dense sands will also require higher hydraulic or pneumatic pressures during the cavity expansion process, impacting the choice of equipment for field testing. Other factors will also influence the probe’s self-penetration potential, including changes in the state of stresses caused by both the expanding cavity and the penetrating probe, which other authors have studied and shown to be important when both probe components are in close proximity (e.g. Dorgan et al. 2007; Savioli et al. 2014; Ruiz et al. 2015; Huang and Tao 2018; Cortes et al. 2018). The results and trends presented herein should be further evaluated using numerical simulations such as finite elements or discrete elements (e.g. Khosravi et al. 2018) as well as using prototypes tested in the laboratory and field.

Conclusions

The self-penetration potential of a bio-inspired probe consisting of an expanding cylindrical shaft and a penetrating tip was investigated in terms of the relative geometry and pressure that the probe would require to generate enough reaction force to facilitate self-penetration. This geometry is expressed as the ratio of expanding shaft length to the penetrating tip diameter (L/D). The analysis framework is based on the balance of forces acting along the longitudinal axis of the probe, consisting of the shear force generated along the expanding cavity as the reaction force and the tip penetration resistance as the penetration force. Results from cavity expansion analyses on clean sand, silty sand, silt, and clay at different initial states provided total and effective stress
components, as well as shear stresses, excess pore pressures, and void ratio, all as a function of cavity radial strain.

The results indicate that the required L/D ratios to initiate self-penetration are smaller in silts, loose sands, and overconsolidated clays. In contrast, dense-of-critical sands and normally consolidated soft clays require larger L/D ratios due to the penetration resistance being proportionally higher than the frictional resistance that can be generated at the expanded anchor. Data from cavity expansion analyses, theoretical relationships, calibration chamber tests, and field tests indicate that larger L/D ratios are required in sands as the state parameter decreases. In clays, the required L/D ratio increases as the OCR decreases. A comparison of the predicted L/D ratios using cavity expansion with L/D ratios of several species of razor clams indicates a close agreement, suggesting that the numerical simulations presented herein reasonably capture the soil burrowing mechanisms of these organisms. The evaluation of self-penetration potential presented here, in terms of \( q_t/P_L \) and L/D ratios, will aid in the design and development of prototypes of self-penetrating probes that may reduce the need for rigs with a large reaction mass for performance of site characterization soundings to desired depths.

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are those of the author(s) and do not necessarily reflect those of the NSF or the California Department of Water Resources, Division of Safety of Dams.

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Captions list:

Figure 1: Schematic of idealized probe during (a) initial condition, (b) shaft expansion, and (c) self-penetration. D = tip diameter, De = expanding section diameter, L = expanding section length, PL = soil limit pressure, qt = soil tip resistance, and τ = probe-soil interface shear strength.

Figure 2: (a) Theoretical correlation from Yu et al. (1996) for sands for an initial mean effective stress of 100 kPa, and (b) calculated L/D ratios required for initiation of self-penetration.

Figure 3: Reinterpreted data from calibration chamber tests on sands by Schnaid (1990) showing (a) tip resistance to limit pressure ratios (qt/PL) and (b) computed length to diameter ratios (L/D) as a function of effective horizontal stress and relative density (original data provided in Schnaid 1990).

Figure 4: Tip resistance to limit pressure ratios (qt/PL) and computed length to diameter ratios (L/D) from in-situ tests on (a) sandy soils and (b) clayey soils (data for tests on sandy soils: McDonald’s Farm and Lecdschendam from Withers et al. 1989, Middenweg from Withers et al. 1986, and TAMU NGES from Briaud 2000. Data for tests on clayey soils: McDonald Farm, Lulu Island, and Langley Lower from Hers 1986, TAMU NGES from Briaud 2000, and Opelika NGES from Mayne et al. 2000).

Figure 5: Mobilized stresses during cylindrical cavity expansion simulations of (a) drained Toyoura sand with state parameter, ξ, of 0.1, (b) drained Toyoura sand with ξ of -0.1, (c) undrained Boston blue clay with OCR of 1.0, and (d) undrained Boston blue clay with OCR of 8.0.

Figure 6: Stress paths from cylindrical cavity expansion simulations on (a) drained Toyoura sand (small dash lines ξ = 0.1, medium dash lines ξ = 0.0, solid lines ξ = -0.1) and on (b) undrained
Boston blue clay (small dash lines OCR = 1.0, medium dash lines OCR = 4.0, solid lines OCR = 8.0). Note: light gray circles indicate beginning of stress paths.

Figure 7: Tip resistance to limit pressure ratios ($q_t/P_L$) and probe length to diameter ratios ($L/D$) from cavity expansion simulations on (a) Toyoura sand, (b) FC35 sand, (c) Silica flour, and (d) Boston blue clay (note different y-axis scale on (d)).

Figure 8: (a) Schematic of stresses acting on a razor clam during burrowing and (b) comparison of $L/D$ ratio of various razor clam species with ranges obtained from cavity expansion analysis (CE) in sands and clays.
Table 1: MIT-S1 calibrated parameters.

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Table 2: Results summary from drained cavity expansion analyses.

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<td>317</td>
<td>610</td>
<td>1.9</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>400</td>
<td>194</td>
<td>625</td>
<td>1209</td>
<td>1.9</td>
<td>4.1</td>
</tr>
</tbody>
</table>

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Table 4: Summary of $q_t/P_L$ and L/D values from cavity expansion analyses and literature.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Cavity Expansion</th>
<th>Field and Calibration Chamber Tests</th>
<th>Theoretical Relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$q_t / P_L$</td>
<td>L / D</td>
<td>$q_t / P_L$</td>
</tr>
<tr>
<td>Sands</td>
<td>3.0 – 7.0</td>
<td>2.0 – 4.5</td>
<td>4.0 – 11.0</td>
</tr>
<tr>
<td>Silts</td>
<td>3.5 – 6.5</td>
<td>1.5 – 3.5</td>
<td>4.0 – 5.0</td>
</tr>
<tr>
<td>Clays</td>
<td>1.9 – 2.7</td>
<td>2.8 – 4.2</td>
<td>1.4 – 2.5</td>
</tr>
</tbody>
</table>

*Based on Yu et al. (1996) relationship, **Based on Gibson and Anderson (1961) and Ladanyi and Johnston (1974) relationships.
Table 5: Length, diameter, and L/D ratio ranges for various razor clam species.

<table>
<thead>
<tr>
<th>Animal</th>
<th>Common name, scientific name</th>
<th>Length (mm)*</th>
<th>Width, D (mm)*</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Razor clam</td>
<td>Sword razor, <em>Ensis ensis</em></td>
<td>120-150</td>
<td>16 - 17</td>
<td>7.5 - 9.0</td>
</tr>
<tr>
<td></td>
<td>Razor shell, <em>Ensis arcuatus</em></td>
<td>150-230</td>
<td>20 - 30</td>
<td>7.5 - 8.0</td>
</tr>
<tr>
<td></td>
<td>Jackknife clam, <em>Ensis minor</em></td>
<td>170 - 250</td>
<td>24 - 41</td>
<td>6.0 - 7.0</td>
</tr>
<tr>
<td></td>
<td>Atlantic jackknife clam, <em>Ensis directus</em></td>
<td>80-150</td>
<td>15 - 28</td>
<td>5.0 - 6.0</td>
</tr>
<tr>
<td></td>
<td>Sickle jackknife clam, <em>Solen sicarius</em></td>
<td>103 -125</td>
<td>28 - 31</td>
<td>3.7 - 4.0</td>
</tr>
<tr>
<td></td>
<td>Pacific razor clam, <em>Siliqua patula</em></td>
<td>40-190</td>
<td>20 - 76</td>
<td>2.0 - 2.5</td>
</tr>
</tbody>
</table>

*Based on Mühlenhardt-Siegel et al. (1983), Hiebert et al. (2015), Aitken and Knott (2018), Fraser et al. (2018)
Figure 1: Schematic of idealized probe during (a) initial condition, (b) shaft expansion, and (c) self-penetration. D = tip diameter, De = expanding section diameter, L = expanding section length, P_L = soil limit pressure, q_t = soil tip resistance, and τ = probe-soil interface shear strength.
Figure 2: (a) Theoretical correlation from Yu et al. (1996) for sands for an initial mean effective stress of 100 kPa, and (b) calculated L/D ratios required for initiation of self-penetration.
Figure 3: Reinterpreted data from calibration chamber tests on sands by Schnaid (1990) showing (a) tip resistance to limit pressure ratios ($q_t/P_L$) and (b) computed length to diameter ratios ($L/D$) as a function of effective horizontal stress and relative density (original data provided in Schnaid 1990).
Figure 4: Tip resistance to limit pressure ratios ($q_t/P_L$) and computed length to diameter ratios (L/D) from in-situ tests on (a) sandy soils and (b) clayey soils (data for tests on sandy soils: McDonald’s Farm and Leedschendam from Withers et al. 1989, Middenweg from Withers et al. 1986, and TAMU NGES from Briaud 2000. Data for tests on clayey soils: McDonald Farm, Lulu Island, and Langley Lower from Hers 1986, TAMU NGES from Briaud 2000, and Opelika NGES from Mayne et al. 2000).
Figure 5: Mobilized stresses during cylindrical cavity expansion simulations of (a) drained Toyoura sand with state parameter, $\xi$, of 0.1, (b) drained Toyoura sand with $\xi$ of -0.1, (c) undrained Boston blue clay with OCR of 1.0, and (d) undrained Boston blue clay with OCR of 8.0.
Figure 6: Stress paths from cylindrical cavity expansion simulations on (a) drained Toyoura sand (small dash lines $\xi = 0.1$, medium dash lines $\xi = 0.0$, solid lines $\xi = -0.1$) and on (b) undrained Boston blue clay (small dash lines OCR = 1.0, medium dash lines OCR = 4.0, solid lines OCR = 8.0). Note: light gray circles indicate beginning of stress paths.
Figure 7: Tip resistance to limit pressure ratios ($q_t/P_L$) and probe length to diameter ratios (L/D) from cavity expansion simulations on (a) Toyoura sand, (b) FC35 sand, (c) Silica flour, and (d) Boston blue clay (note different y-axis scale on (d)).
Figure 8: (a) Schematic of stresses acting on a razor clam during burrowing and (b) comparison of L/D ratio of various razor clam species with ranges obtained from cavity expansion analysis (CE) in sands and clays.