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Research on the sampling performance of a new bionic gravity sampler

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S1 Disturbance analysis of the soil sample

The sampling process of the sampler tube can be regarded similar as the spherical cavity expansion under undrained conditions. The mechanism analysis in this paper is based on the following assumptions: (1) the soil is the ideal elastic-plastic material, which is uniform and isotropic; (2) the soil in the plastic zone should obey the Mohr-Coulomb yield criterion; (3) the cavity expansion is regarded as an undrained process, and the soil in the plastic zone is compressible, but the compressed volume is zero; (4) regardless of the body force in plastic zone, and the ultimate radius of the cavity is equal to that of the sampler tube.

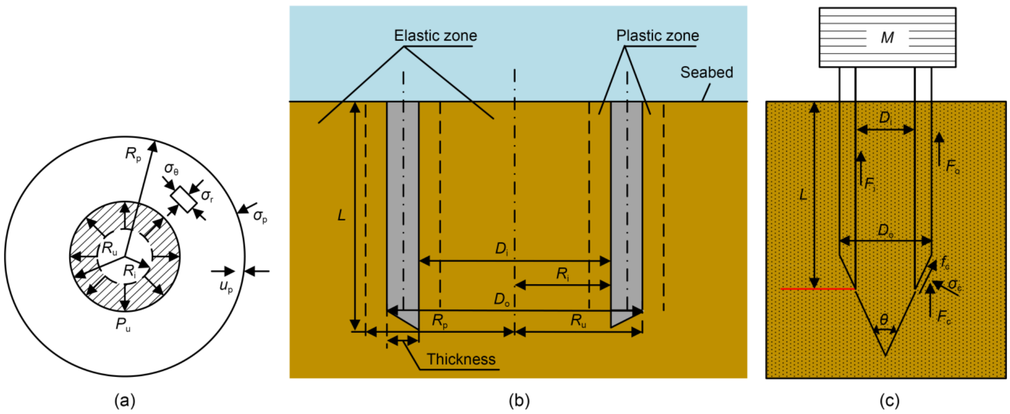

Fig. S1 (a-b) Diagram of spherical cavity expansion model; (c) friction resistance analysis of sampler tube. R_i is the initial radius of the hole, R_u is the ultimate radius after cavity expansion,

p_u is the reaming pressure around the cavity, R_p is the radius of the plastic zone, p_p is the reaming pressure around plastic zone, u_p is the radical displacement after cavity expansion, σ_r is the radial stress, σ_θ is the circular stress, L is the penetration depth, D_i is the inner diameter of the sample tube, D_o is the outer diameter of the sample tube, F_i is the friction resistance of the inner wall, F_o is the friction resistance of the outer wall, F_c is the resistance of the knife edge, and θ is inclination angle of the knife edge

The boundary conditions are given as below:

$$\begin{aligned} r = R_u, \sigma_r = P_u \\ r = R_p, \sigma_r = P_p \end{aligned}. \tag{S1}$$

In the centrosymmetric spherical cavity expansion, the equilibrium equation in the spherical coordinates can be expressed as:

$$r\frac{d\sigma_r}{dr} + 2\times(\sigma_r - \sigma_\theta) = 0, \tag{S2}$$

Where r is the distance between any point and the center of the cavity, σ_r is the radial stress, σ_θ is the circular stress.

As for elastic material, the elastic strain can be expressed as (Timoshenko and Goodier, 2007):

$$\varepsilon_r = \frac{1}{E}[\sigma_r - 2\mu\sigma_\theta], \tag{S3}$$

$$\varepsilon_\theta = \frac{1}{E}[-\mu\sigma_r + (1-\mu)\sigma_\theta], \tag{S4}$$

where ε_r is the radial strain, ε_θ is the circular strain, E is the elastic module and μ is the Poisson's ratio.

The general solution of the radical and circular stress can be expressed as

$$\sigma_r = A + \frac{B}{r^3}, \tag{S5}$$

$$\sigma_\theta = A - \frac{B}{2r^3}, \tag{S6}$$

where A and B are constant. Considering the boundary condition $r = R_u$, $\sigma_r = p_u$ and $r = R_p$, $\sigma_r = p_p$, the two constant can be obtained:

$$A=\frac{p_pR_p^3-p_uR_u^3}{R_p^3-R_u^3}, \tag{S7}$$

$$B=\frac{R_u^3R_p^3\left(p_u-p_p\right)}{R_p^3-R_u^3}. \tag{S8}$$

Thus the radical and circular stress can be expressed as

$$\sigma_r=\frac{p_pR_p^3-p_uR_u^3}{R_p^3-R_u^3}+\frac{1}{r^3}\frac{R_u^3R_p^3\left(p_u-p_p\right)}{R_p^3-R_u^3}, \tag{S9}$$

$$\sigma_\theta=\frac{p_pR_p^3-p_uR_u^3}{R_p^3-R_u^3}-\frac{1}{2r^3}\frac{R_u^3R_p^3\left(p_u-p_p\right)}{R_p^3-R_u^3}. \tag{S10}$$

In practical engineering, soil is considered to be a semi-infinite space, thus, $b\gg a$ and $p_p=0$, and the above two formulas can be simplified as

$$\sigma_r=\frac{R_u^3p_u}{r^3}, \tag{S11}$$

$$\sigma_\theta=-\frac{R_u^3p_u}{2r^3}=-\frac{1}{2}\sigma_r. \tag{S12}$$

The radical displacement can be expressed as

$$u_p=\frac{1+\mu}{2E}\cdot\frac{R_u^3p_u}{r^2}. \tag{S13}$$

To obtain the stress and strain of the soil in plastic zone, the Mohr-Coulomb yield criterion is applied, which can be expressed as

$$\sigma_1=\frac{\sigma_3\left(1-\sin\varphi\right)-2c\cdot\cos\varphi}{1+\sin\varphi}, \tag{S14}$$

where σ_1 and σ_3 is the First and third Principal Normal Stresses, and c is the cohesion and φ is the angle of internal friction.

Since the gravity coring process is very short, the soil can be regarded as undrained, and the seabed soil is mostly saturated soft clay with high water content, thus, Eq. (S14) can be simplified as (Yu, 2000)

$$\sigma_1-\sigma_3=\sigma_\theta-\sigma_r=2c_u, \tag{S15}$$

where $\sigma_1=\sigma_\theta$, $\sigma_3=\sigma_r$, and c_u is the undrained shear strength.

Substituting Eq. (S14) into Eq. (S2), the equilibrium equation of the soil in the elastic-plastic boundary can be expressed as

$$r\frac{d\sigma_r}{dr}+4c_u=0.\qquad \text{(S16)}$$

As for the plastic zone, considering the boundary condition $r=R_u, \sigma_r=P_u$, the stress in the plastic zone can be expressed as

$$\sigma_r=P_u-4c_u\cdot\ln\frac{r}{R_u},\qquad \text{(S17)}$$

$$\sigma_\theta=P_u-2c_u-4c_u\cdot\ln\frac{r}{R_u}.\qquad \text{(S18)}$$

Considering the boundary condition $r=R_p, \sigma_r=P_p$ and equation (S17) and (S13), the radial displacement in the elastic-plastic interface can be obtained:

$$u_p=\frac{(1+\mu)}{2E}R_p\left[P_u-4c_u\ln\frac{R_p}{R_u}\right].\qquad \text{(S19)}$$

Combining Eqs. (S15), (S3), and (S4), the reaming pressure in elastic-plastic interface ca be expressed as

$$\sigma_p=\frac{4c_u}{3}.\qquad \text{(S20)}$$

The volume change of the elastic zone can be expressed as

$$\Delta V=\frac{4}{3}\pi\left(R_u^3-R_i^3\right)=\frac{4}{3}\pi R_p^3-\frac{4}{3}\pi\left(R_p-u_p\right)^3.\qquad \text{(S21)}$$

Regardless of the higher-order quantities (e.g., R_i^3 and u_p^3) and the compression of the soil in the plastic zone. According to Eqs. (S19) and (S20), the relative radius of the plastic zone can be expressed as

$$\frac{R_p}{R_u}=\sqrt[3]{\frac{G}{c_u}},\qquad \text{(S22)}$$

where G is the shear module.

Thus, combining Eqs. (S17), (S20), and (S22), the ultimate reaming pressure can be expressed as

$$P_u=\frac{4c_u}{3}\left(1+\ln\frac{G}{c_u}\right).\qquad \text{(S23)}$$

The friction resistance between the sampler tube and soil can be expressed as

$$dF_i=\alpha_f P_u dA_s=\frac{4\alpha_f c_u}{3}\left[\ln\frac{E}{2(1+\mu)c_u}+1\right]dA_s,\qquad \text{(S24)}$$

where α_f is the coefficient of friction, A_s is the contact area between sampler tube and soil.

S2

The calculation results of the cavity expansion model based on Mohr-Coulomb yield criterion are list in Table S1, and the ultimate reaming pressure is 22.1 kPa.

In numerical simulation analysis in Section 4.3.1 (Table S1), the ultimate reaming pressure on the outer and inner wall of the sampler tube are 20.6 and 18.4 kPa, respectively.

Table S1 Characteristic of the soil used in tests

Parameter	Symbol	Value
Cohesion (kPa)	c	2.94
The angle of internal friction (°)	φ	0
Young's modules (kPa)	E	1160
Poisson's ratio	μ	0.32
Thickness of ST (mm)	h	7.5
Inner radius of ST (mm)	R_{i}	80
Ultimate radius of cavity (mm)	R_{u}	3.75
Radius of the plastic zone (mm)	R_{p}	15.4
Ultimate reaming pressure (kPa)	p_{u}	22.1

S3

The theoretical analysis is consistent with the parameters set in the numerical simulation, and the initial penetration velocity, weight (whole model tube) and inclination angle of knife edge of the sampler tube are 6 m/s, 30.18 kg, 30°, respectively. The coefficient of friction, the enhancement factor of shear strength and the coefficient of viscosity are 0.4, 1.1 and 0.1, respectively.

Thus, Eqs. (S25), (S26) and (S27) can be obtained:

$$F_{\mathrm{i}} = 51.2\pi\left(L + 0.65L^2\right), \tag{S25}$$

$$F_{\mathrm{o}} = 66.88\pi\left(l + 0.65l^2\right), \tag{S26}$$

$$F_{\mathrm{c}} = 3.89\pi\left(1 + 1.3l\right). \tag{S27}$$

In the numerical calculation, and the friction resistance on the inner and outer wall of the sampler tube are 334.94N and 581.59N, respectively. While in the theoretical calculation, the friction resistance on the inner and outer wall are 525.01N and 685.80N, respectively.