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An analytical investigation of soil disturbance due to sampling penetration

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Abstract. It is well known that the quality of sample significantly determines the accuracy of soil parameters for laboratory testing. Although sampling disturbance has been studied over the last few decades, the theoretical investigation of soil disturbance due to sampling penetration has been rarely reported. In this paper, an analytical solution for estimating the soil disturbance due to sampling penetration was presented using cavity expansion method. Analytical results in several cases reveal that the soil at different location along the sample centerline experiences distinct phases of strain during the process of sampling penetration. The magnitude of induced strain is dependent on the position of the soil element within the sampler and the sampler geometry expressed as diameter-thickness ratio D/t and length-diameter ratio L/D. Effects of sampler features on soil disturbance were also studied. It is found that the induced maximum strain decreases exponentially with increasing diameter-thickness ratio, indicating that the sampling disturbance will reduce with increasing diameter or decreasing wall thickness of sampler. It is also found that a large length-diameter ratio does not necessarily reduce the disturbance. An optimal length-diameter ratio is suggested for the further design of improved sampler in this study.

Keywords: sampling penetration; soil disturbance; cavity expansion; analytical solution; sampler features

1. Introduction

The engineering properties of soils, such as permeability, compressibility, and shear strength characteristics, are required to be measured either in situ or in laboratory (Shang *et al*. 2009, Calik and Sadoglu 2014, Voottipruex and Jamsawang 2014). As the precision of testing instruments in situ is limited, laboratory testing is widely applied to estimate the soil properties by sampling. Therefore, high quality samples are required for laboratory testing to obtain accurate soil parameters. However, one of the most important restrictions of laboratory testing results is sampling disturbance. Over the last decades, many studies on sampling disturbance have been

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carried out with several aspects. Georgiannou and Hight (1994), Santagata and Germaine (2002) and Rocchi *et al*. (2013) have conducted laboratory or numerical simulations of the sampling process to study the effects of sampling disturbance on laboratory testing results. To quantitatively analyze the effects, the methods of sample quality evaluation and definitions of the degree of sample disturbance using different indexes were proposed (Tanaka 2000, Nagaraj *et al*. 2003, Hong and Han 2007). The procedures to modify the laboratory results on "nominally undisturbed" samples to estimate the behavior of "ideal" samples were also reported (Nagaraj *et al*. 2003, Hong and Han 2007). In addition, the effects of sampler features and of field or laboratory techniques on disturbance degree were investigated (Tanaka *et al*. 1996, Wu and van Staveren 2005, Horng *et al*. 2010). Having realizing the effects of sampler features on sample quality, the conventional samplers were improved and new samplers were developed (Andresen and Kolstad 1979, La Rochelle *et al*. 1981, Lunne and Long 2006).

It is well known that the disturbance is inevitably induced during sampling penetration, extraction of the sampler from the ground and subsequent extrusion of the sample from the tube (Chung *et al*. 2004). As discussed by Clayton *et al*. (1995), the disturbance during sampling penetration is the most important. Baligh *et al*. (1987) presented analytical result for the strains imposed on a soil sample during the process of sampling penetration. It was based on the strain path method by superimposing a ring source on a uniform incompressible, inviscid, irrotational fluid flow. Clayton *et al*. (1998) examined the use of Baligh's strain path method and established additional analytical solutions based on a Bessel functions solution. Although these studies provide an important tool by which our understanding of sampling disturbance can be improved, the analytical solutions are too complicated and further investigations may be needed.

Cavity expansion method was developed with the theoretical study of changes in stresses, pore water pressures and displacement caused by the expansion and contraction of cavities. It has been used for the study of a wide variety of geotechnical problems since its early application to pressuremeter test interpretation by Gibson and Anderson (1961). These include the study of in situ soil testing (Mo *et al*. 2014), pile foundations (Randolph *et al*. 1994), and underground excavations and tunnelling (Mair and Taylor 1993). A thorough review of the method and its various applications have been given by Yu (2000). These previous researches provide us with theoretical bases and confidence to investigate soil disturbance induced by sampling penetration using cavity expansion method.

In this study, cavity expansion method was applied to investigate the effects of sampling penetration on soil disturbance. The solution of strain components imposed on a soil sample was developed. Vertical strain at the centerline of sample was chosen and its analytical results in several cases were presented and discussed. The effects of different factors of sampler features on sampling disturbance were also analyzed.

2. Analytical solution of strain component induced by sampling penetration

Fig. 1 shows a typical problem of cavity expansion in semi-infinite soil. Zhu (2005) deduced the displacement components induced by cavity expansion using the approach of Kassir and Sih (1975), taking the boundary condition without restraint on the surface into account. In his study, the soil was assumed as a saturated, isotopic and elastic material, obeying Hooke's law. Considering a soil element located at an arbitrary point *A* in Fig. 1, the solution of displacement components is found to be (Zhu 2005)

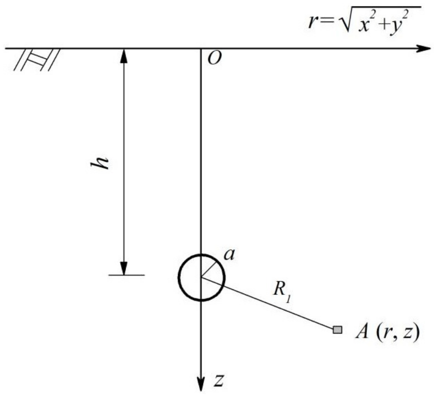


Fig. 1 Cavity expansion in semi-infinite soil

$$u_r = \frac{a^3}{3}\left(\frac{r}{R_1^{\ 3}} + (3-4\nu)\frac{r}{R_2^{\ 3}} - \frac{6rz(z+h)}{R_2^{\ 5}}\right) \tag{1}$$

$$u_z = \frac{a^3}{3}\left(\frac{z-h}{R_1^{\ 3}} - (3-4\nu)\frac{z+h}{R_2^{\ 3}} + \frac{2z}{R_2^{\ 3}} - \frac{6z(z+h)^2}{R_2^{\ 5}}\right) \tag{2}$$

where u_r and u_z are the radial and vertical displacement of soil element A, respectively; r and z are the radial and vertical distance between the soil element and origin, respectively; h is the vertical distance from the surface to cavity center; R_1 is the distance between the soil element and cavity center, $R_1 = \sqrt{r^2+(z-h)^2}$; R_2 is a variable equaling to $\sqrt{r^2+(z+h)^2}$; a is the radius of cavity; and v is Poisson's ratio of soil.

Fig. 2 illustrates twin symmetric and identical cavities expand simultaneously in semi-infinite soil. The coordinates of the two cavity centers are (-D/2, h) and (D/2, h), respectively. D is identical as the diameter of sampling tube. As the penetration process occurs quickly, undrained condition is also considered and Poisson's ratio equals to 0.5. Thus, the displacement components of an arbitrary point A due to the twin symmetric cavities could be derived from Eqs. (1)-(2) by the principle of superposition as follows

$$u_r = \frac{a^3}{3}\left(\begin{array}{l}\dfrac{r+D/2}{R_1^{\ 3}} + \dfrac{r+D/2}{R_2^{\ 3}} - \dfrac{6(r+D/2)z(z+h)}{R_2^{\ 5}} \\ + \dfrac{r-D/2}{R_1'^{3}} + \dfrac{r-D/2}{R_2'^{\ 3}} - \dfrac{6(r-D/2)z(z+h)}{R_2'^{\ 5}}\end{array}\right) \tag{3}$$

$$u_z = \frac{a^3}{3}\left(\frac{z-h}{R_1^{\ 3}} + \frac{z-h}{R_2^{\ 3}} - \frac{6z(z+h)^2}{R_2^{\ 5}} + \frac{z-h}{R_1'^{3}} + \frac{z-h}{R_2'^{\ 3}} - \frac{6z(z+h)^2}{R_2'^{\ 5}}\right) \tag{4}$$

where R_1 and R'_1 are the distance between soil element A and the center of twin cavities, respectively, i.e., $R_1 = \sqrt{(r+D/2)^2+(z-h)^2}$, $R_1' = \sqrt{(r-D/2)^2+(z-h)^2}$; $R_2 =$

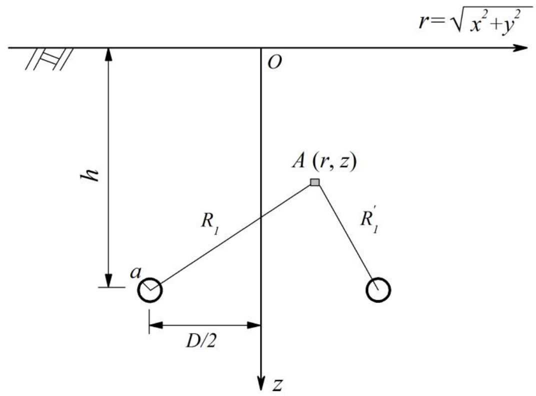


Fig. 2 Twin symmetric and identical cavity expansions in semi-infinite soil

$\sqrt{(r+D/2)^2+(z+h)^2}$ and $R_2'=\sqrt{(r-D/2)^2+(z+h)^2}$ as explained above.

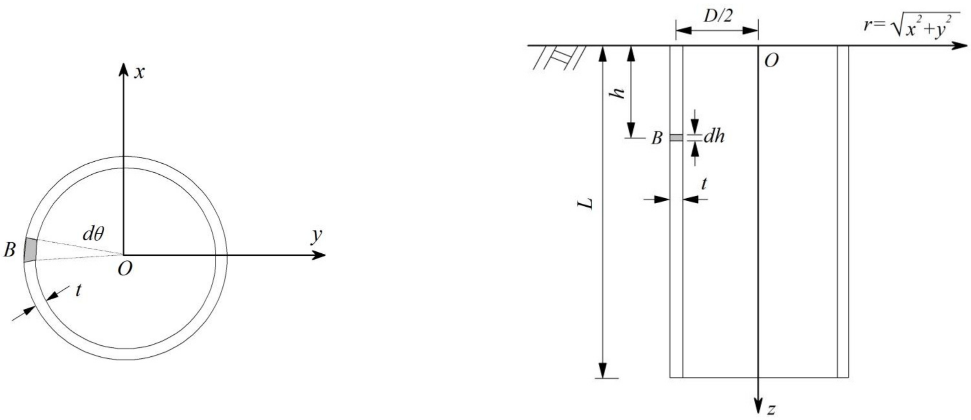
From Eqs. (3)-(4), the corresponding radial and vertical strain defined in Yu (2000) can be expressed as

$$\varepsilon_r=\frac{\partial u_r}{\partial r}=\frac{a^3}{3}\left(\begin{array}{l}\dfrac{(z-h)^2-2(r+D/2)^2}{R_1^{\,5}}+\dfrac{(z+h)^2-2(r+D/2)^2}{R_2^{\,5}}\\ -6z(z+h)\dfrac{(z+h)^2-4(r+D/2)^2}{R_2^{\,7}}+\dfrac{(z-h)^2-2(r-D/2)^2}{R_1'^5}\\ +\dfrac{(z+h)^2-2(r-D/2)^2}{R_2'^5}-6z(z+h)\dfrac{(z+h)^2-4(r-D/2)^2}{R_2'^7}\end{array}\right) \tag{5}$$

$$\varepsilon_z=\frac{\partial u_z}{\partial z}=\frac{a^3}{3}\left(\begin{array}{l}\dfrac{(r+D/2)^2-2(z-h)^2}{R_1^{\,5}}+\dfrac{(r+D/2)^2-2(z+h)^2}{R_2^{\,5}}\\ -6(z+h)\dfrac{(3z+h)(r+D/2)^2+(z+h)^2(h-2z)}{R_2^{\,7}}+\dfrac{(r-D/2)^2-2(z-h)^2}{R_1'^5}\\ +\dfrac{(r-D/2)^2-2(z+h)^2}{R_2'^5}-6(z+h)\dfrac{(3z+h)(r-D/2)^2+(z+h)^2(h-2z)}{R_2'^7}\end{array}\right) \tag{6}$$

Fig. 3 shows the plan view and elevation view of sampling tube in semi-infinite soil. As suggested by Chow and Teh (1990), an assumption is made that any infinitesimal portion of sampling tube can be equivalent to cavity with the same volume. Considering an infinitesimal portion *B* of sampling tube with a wall thickness of *t* as shown in Fig. 3, its radian and height are *dθ* and *dh*, respectively. The magnitude of its volume could be computed as (*Ddθ·t·dh*)/2. The equivalent cavity with a radius of *a* is thus given by

$$\frac{4}{3}\pi a^3=\frac{Dt}{2}d\theta\cdot dh \tag{7}$$



(a) Plan view (b) Elevation view

Fig. 3 Sampling tube in semi-infinite soil

Due to the geometric symmetry of sampling tube, the process of sampling penetration can be treated as a series of twin symmetric cavity expansions along the tube. Substituting Eq. (7) into Eqs. (5)-(6) and integrating over the whole tube, the soil strain imposed on the sample due to sampling penetration could be calculated as the following dual integral equations

$$\varepsilon_{rr} = \int_0^L \int_0^\pi \varepsilon_r \tag{8}$$

$$\varepsilon_{zz} = \int_0^L \int_0^\pi \varepsilon_z \tag{9}$$

where ε_{rr} and ε_{zz} are radial and vertical strain of the soil sample, respectively; L is the length of sampling tube.

For convenience of expression, the following functions are defined

$$f(x) = \frac{1}{(\sqrt{x^2+1})^3} \tag{10}$$

$$g(x) = \frac{1}{\sqrt{x^2+1}} \tag{11}$$

$$h(x) = \frac{x^5}{(\sqrt{x^2+1})^5} \tag{12}$$

$$l(x) = \frac{x^3}{(\sqrt{x^2+1})^3} \tag{13}$$

Then, Eqs. (8)-(9) are calculated to be

$$\varepsilon_{rr}=\frac{Dt}{8}\left[\begin{array}{l}\dfrac{1}{(r+D/2)^2}\begin{pmatrix}f(\dfrac{r+D/2}{L\pm z})\\-2g(\dfrac{r+D/2}{L\pm z})\end{pmatrix}-\dfrac{z}{(r+D/2)^3}\begin{pmatrix}\dfrac{18}{5}h(\dfrac{r+D/2}{L+z})-\dfrac{18}{5}h(\dfrac{r+D/2}{z})\\+2l(\dfrac{r+D/2}{L+z})-2l(\dfrac{r+D/2}{z})\end{pmatrix}\\+\dfrac{1}{(r-D/2)^2}\begin{pmatrix}f(\dfrac{r-D/2}{L\pm z})\\-2g(\dfrac{r-D/2}{L\pm z})\end{pmatrix}-\dfrac{z}{(r-D/2)^3}\begin{pmatrix}\dfrac{18}{5}h(\dfrac{r-D/2}{L+z})-\dfrac{18}{5}h(\dfrac{r-D/2}{z})\\+2l(\dfrac{r-D/2}{L+z})-2l(\dfrac{r-D/2}{z})\end{pmatrix}\end{array}\right] \tag{14}$$

$$\varepsilon_{zz}=\frac{Dt}{8}\left[\begin{array}{l}\dfrac{1}{(r+D/2)^2}\begin{pmatrix}g(\dfrac{r+D/2}{L\pm z})-f(\dfrac{r+D/2}{L-z})\\-\dfrac{4}{3}f(\dfrac{r+D/2}{L+z})+f(\dfrac{r+D/2}{z})\end{pmatrix}\\-\dfrac{z}{(r+D/2)^3}\begin{pmatrix}h(\dfrac{r+D/2}{L+z})-h(\dfrac{r+D/2}{z})\\-l(\dfrac{r+D/2}{L+z})+l(\dfrac{r+D/2}{z})\end{pmatrix}\\+\dfrac{1}{(r-D/2)^2}\begin{pmatrix}g(\dfrac{r-D/2}{L\pm z})-f(\dfrac{r-D/2}{L-z})\\-\dfrac{4}{3}f(\dfrac{r-D/2}{L+z})+f(\dfrac{r-D/2}{z})\end{pmatrix}\\-\dfrac{z}{(r-D/2)^3}\begin{pmatrix}h(\dfrac{r-D/2}{L+z})-h(\dfrac{r-D/2}{z})\\-l(\dfrac{r-D/2}{L+z})+l(\dfrac{r-D/2}{z})\end{pmatrix}\end{array}\right] \tag{15}$$

For further simplicity and clarity, several functions are defined as

$$F_r(x)=\frac{1}{x^2}\left[f(\frac{x}{L\pm z})-2g(\frac{x}{L\pm z})\right] \tag{16}$$

$$G_r(x)=\frac{1}{x^3}\left[\frac{18}{5}h(\frac{x}{L+z})-\frac{18}{5}h(\frac{x}{z})+2l(\frac{x}{L+z})-2l(\frac{x}{z})\right] \tag{17}$$

$$F_z(x)=\frac{1}{x^2}\left[g(\frac{x}{L\pm z})-f(\frac{x}{L-z})-\frac{4}{3}f(\frac{x}{L+z})+f(\frac{x}{z})\right] \tag{18}$$

$$G_z(x)=\frac{1}{x^3}\left[h(\frac{x}{L+z})-h(\frac{x}{z})-l(\frac{x}{L+z})+l(\frac{x}{z})\right] \tag{19}$$

Hence, strain components imposed on the sample due to sampling penetration could be written as a simplified form as

$$\varepsilon_{rr} = \frac{Dt}{8}\left[F_r(r \pm D/2) - zG_r(r \pm D/2)\right] \tag{20}$$

$$\varepsilon_{zz} = \frac{Dt}{8}\left[F_z(r \pm D/2) - zG_z(r \pm D/2)\right] \tag{21}$$

3. Effects of sampler features on sampling disturbance

From Eqs. (16)-(21), it can be found that the vertical strain of a given element (r, z) is mainly dependent on four parameters, i.e., tube diameter D, wall thickness t, tube length L and depth of soil element z. As discussed by previous investigations (Horng *et al*. 2010, Baligh *et al*. 1987, Clayton *et al*. 1998), it is also reasonable to denote them as three dimensionless parameters: diameter-thickness ratio D/t, length-diameter ratio L/D and vertical element location z/D. As it has been concluded that soil disturbance decreases towards the center of the sample and soil elements located at the sample centerline suffer the least disturbance, soil specimens at or nearby the centerline of sample are generally adopted for laboratory testing (Baligh *et al*. 1987). Hence, it is reasonable and necessary to investigate the disturbance of soil elements located at the centerline of sample.

3.1 Effects of diameter-thickness ratio on vertical strain at the sample centerline

To study the effects of diameter-thickness ratio on vertical strain at the centerline of sample, three cases labeled as C1-C3 were considered as listed in Table 1. In these cases, the length-diameter ratio L/D was constant as 10, whereas the diameter-thickness ratio D/t was taken as 10, 20 and 40, respectively. 20 and 40 of diameter-thickness ratio are the typical value of an universal Shelby tube as specified by American Society for Testing and Materials (ASTM D1587-94) (Santagata and Germaine 2002) and the value of 10 is taken for comparison.

Fig. 4 shows the analytical results obtained from the proposed solution. The horizontal axis represents vertical strain of soil element along the sample centerline. The positive value implies extension and the negative value implies compression. The vertical axis represents the location of soil element along the centerline, expressed as vertical element location z/D. For convenience of analysis, the schematic diagram of all variables used to describe the sampler is also illustrated in

Table 1 Basic parameters of sampling tube in different cases

Case	Diameter-thickness ratio (D/t)	Length-diameter ratio (L/D)	Remarks
C1	10	10	To study the effects of D/t on sampling disturbance
C2	20	10	
C3	40	10	
C4	10	5	To study the effects of L/D on sampling disturbance
C5	10	10	
C6	10	20	

Fig. 4. It can be observed that the centerline element experiences distinct phases of strain. The general trend of the profile of vertical strain is noted to be similar with that of Baligh *et al*. (1987). Along the lower portion of sample, compression is observed to develop at phase a-b and the strain decreases obviously with decreasing *z*/*D* until extension develops at phase *b*-*c*. For soil at the middle phase *c*-*d*, compression is resulted from the compaction imposed by sampler. For the upper phase *d*-*e*, the soil is subjected to extension, meaning that heaves are induced on the surface. This is likely due to the fact that the surface is free from restriction and displaced upwards due to

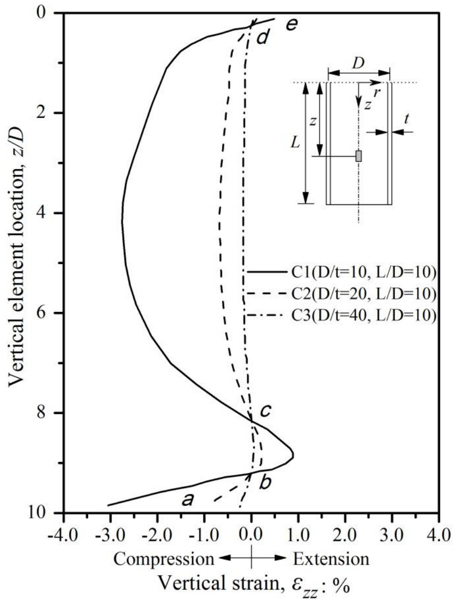


Fig. 4 Effects of diameter-thickness ratio on vertical strain along sample centerline

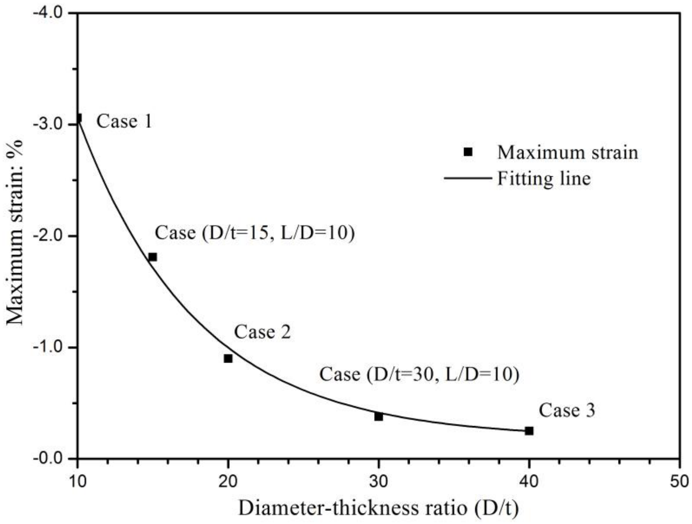


Fig. 5 Variation of maximum strain at the sample centerline versus diameter-thickness ratio

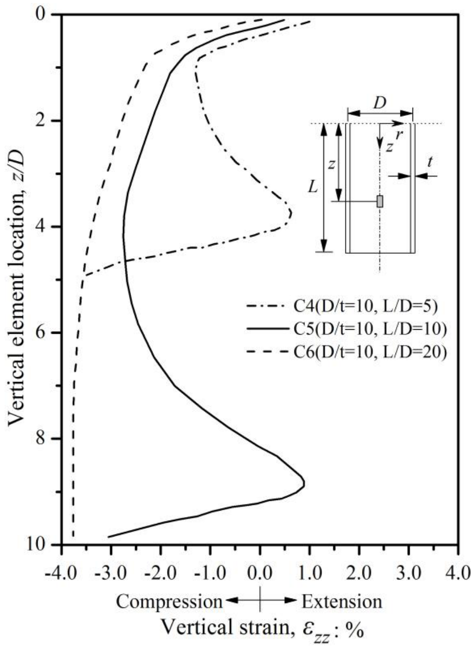


Fig. 6 Effects of length-diameter ratio on vertical strain along sample centerline

sampling penetration. In addition, it is worth noting that the profile at both ends has a great curvature, indicating that the soils at the ends are of larger nonuniform disturbance than those located at the middle portion of sample as discussed by La Rochelle *et al*. (1981) and Chung *et al*. (2004). Therefore, soil specimens located at the middle portion are suggested to be adopted for subsequent laboratory testing.

Fig. 5 summarizes the variation of induced maximum strain at the sample centerline versus different diameter-thickness ratio for the first three cases. Another two cases with 15 and 30 in diameter-thickness ratio are also included for comparison. The fitting line clearly shows that the induced maximum strain decreases exponentially with increasing diameter-thickness ratio. It means that a larger tube diameter or a smaller wall thickness will lead to a smaller disturbance, demonstrating that thin-walled sampler is superior to be used instead of thick-walled sampler. This finding is in line with that of earlier study (Clayton *et al*. 1995). Note also that the change of maximum strain is negligible as the diameter-thickness ratio becomes larger and larger. This implies that the sampler with a larger diameter does not necessarily provide soil sample of better quality as mentioned by Tanaka (2000). Only considering these cases in this study, the suggested diameter-thickness ratio is taken as 40 which is the typical value of a Shelby tube.

3.2 Effects of length-diameter ratio on vertical strain at the sample centerline

In order to evaluate the effects of length-diameter ratio on vertical strain imposed on sample along the centerline, another three cases labeled as C4-C6 were conducted as listed in Table 1. In these cases, the diameter-thickness ratio D/t was constant as 10, whereas the length-diameter ratio L/D was taken as 5, 10 and 20, respectively. The length-diameter ratio of 5 and 10 are selected as the typical value of ELE100 sampler (Tanaka *et al*. 1996) and Shelby tube (Santagata and

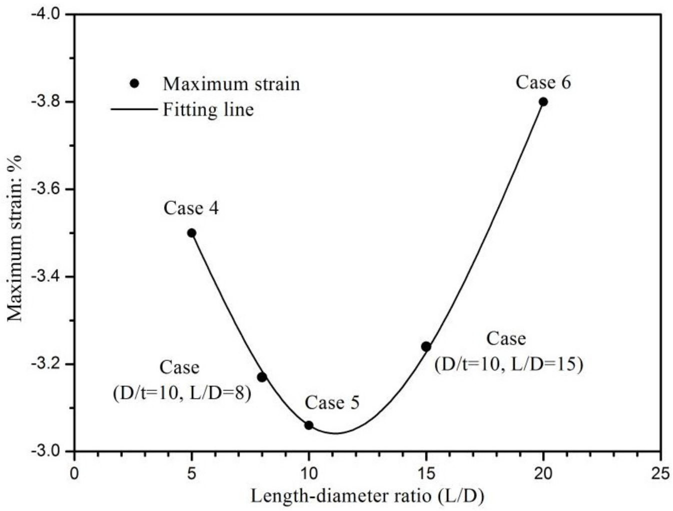


Fig. 7 Variation of maximum strain at the sample centerline versus length-diameter ratio

Germaine 2002), respectively, and the value of 20 is taken for comparison.

Based on the proposed solution, the profiles of induced strain with respect to vertical element location are plotted in Fig. 6. For the case of 20 in length-diameter ratio, only half of the profile is illustrated. The schematic diagram of all variables used to describe the sampler is also included. It is evident that the profiles herein are of similar shape to these of the first three cases, indicating that the soil element experiences the similar strain path history as described in Fig. 4. The distinct difference is that the magnitude of vertical strain is clearly effected by the length-diameter ratio. Fig. 7 summarizes the variation of induced maximum strain at the sample centerline versus different length-diameter ratio for the latter three cases. Another two cases with 8 and 15 in length-diameter ratio are also included for comparison. The absolute values of induced maximum strain for these cases are 3.5%, 3.17%, 3.1%, 3.24% and 3.8%, respectively. It appears that the strain in the case of 10 in length-diameter ratio is smaller than that of another four cases. This observation reveals that a large length-diameter ratio does not necessarily reduce the disturbance. An optimal length-diameter ratio may be suggested to reduce sampling disturbance for the design of improved sampler. From the fitting line in Fig. 7, the suggested length-diameter ratio could be adopted as 11, which is close to the typical value of a Shelby tube.

4. Conclusions

This paper presents an analytical method carried out to investigate the soil disturbance due to sampling penetration. Considering the soil as a saturated, isotopic and elastic material, an analytical solution was proposed to predict the soil strain inside the sample using cavity expansion method. A series of analytical results of vertical strain imposed on soil element along the sample centerline were presented and discussed to evaluate the effects of sampler features on sampling disturbance. Based on these analyses, the following conclusions may be drawn:

- The soil at different location along the centerline is subjected to distinct phases of strain during the process of sampling penetration. Most of the middle portion of soil is subjected to compression, whereas extension is observed at the upper portion. In addition, the soil disturbances at the ends are more nonuniform than those located at the middle portion, suggesting that soil specimens located at the middle portion are prior to be adopted for laboratory testing.

- Through analyzing the effects of diameter-thickness ratio on sampling disturbance, it is found that the induced maximum strain decreases exponentially with increasing diameter-thickness ratio. This finding reveals that the sampling disturbance will reduce with increasing diameter or decreasing wall thickness of sampler. Thin-walled sampler is suggested to be used preferentially.
- Through analyzing the effects of length-diameter ratio on sampling disturbance, it is found that it is not necessary to use a large length-diameter ratio for reducing the disturbance. An optimal length-diameter ratio of 11 is suggested for the further design of improved sampler in this study.

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References

Andresen, A.A. and Kolstad, P. (1979), “The NGI 54 mm sampler for undisturbed sampling of clays and representative sampling of coarser materials”, *Proceedings of the International Symposium on Soil Sampling*, Singapore, July.

Baligh, M.M., Azzouz, A.S. and Chin, C.T. (1987), “Disturbances due to ‘ideal’ tube sampling”, *J. Geotech. Eng.*, **113**(7), 739-757.

Calik, U. and Sadoglu, E. (2014), “Engineering properties of expansive clayey soil stabilized with lime and perlite”, *Geomech. Eng., Int. J.*, **6**(4), 403-418.

Chung, S.G., Kwag, J.M., Giao, P.H., Baek, S.H. and Prasad, K.N. (2004), “A study of soil disturbance of Pusan clays with reference to drilling, sampling and extruding”, *Geotechnique*, **54**(1), 61-65.

Chow, Y.K. and Teh, C.I. (1990), “A theoretical study of pile heave”, *Geotechnique*, **40**(1), 1-14.

Clayton, C.R.I., Matthews, M.C. and Simons, N.E. (1995), *Site Investigation*, (Second Edition), Wiley-Blackwell, London, UK.

Clayton, C.R.I., Siddique, A. and Hopper, R.J. (1998), “Effects of sampler design on tube sampling disturbance-numerical and analytical investigations”, *Geotechnique*, **48**(6), 847-867.

Georgiannou, V.N. and Hight, D.W. (1994), “The effect of centerline tube sampling strains on the undrained behavior of two stiff overconsolidated clays”, *Geotech. Test. J.*, **17**(4), 475-487.

Gibson, R. and Anderson, W. (1961), “In situ measurement of soil properties with the pressuremeter”, *Civil Eng. Pub. Works Rev.*, **56**(658), 615-618.

Hong, Z. and Han, J.A. (2007), “Evaluation of sample quality of sensitive clay using intrinsic compression concept”, *J. Geotech. Geoenviron. Eng.*, **133**(1), 83-90.

Horng, V., Tanaka, H. and Obara, T. (2010), “Effects of sampling tube geometry on soft clayey sample quality evaluated by nondestructive methods”, *Soils Found.*, **50**(1), 93-107.

Kassir, M.K. and Sih, G.C. (1975), *Three-dimensional Crack Problems*, Mechanics of Fracture, Noordhoff International Publishing, Dordrecht, Netherlands.

La Rochelle, P., Sarrailh, J., Tavenas, F., Roy, M. and Leroueil, S. (1981), “Causes of sampling disturbance and design of a new sampler”, *Can. Geotech. J.*, **18**(1), 52-66.
Lunne, T. and Long, M. (2006), “Review of long seabed samplers and criteria for new sampler design”, *Mar. Geol.*, **226**(1), 145-165.
Mair, R.J. and Taylor, R.N. (1993), “Prediction of clay behaviour around tunnels using plasticity solutions”, *Predictive Soil Mechanics-Proceedings of the Wroth Memorial Symposium*, Thomas Telford, Oxford, UK, July.
Mo, P.Q., Marshall, A.M. and Yu, H.S. (2014), “Elastic-plastic solutions for expanding cavities embedded in two different cohesive-frictional materials”, *Int. J. Numer. Anal. Met.*, **38**, 961-977.
Nagaraj, T.S., Miura, N., Chung, S.G. and Nagendra, P. (2003), “Analysis and assessment of sampling disturbance of soft sensitive clays”, *Geotechnique*, **53**(7), 679-683.
Randolph, M.F., Dolwin, J. and Beck, R. (1994), “Design of driven piles in sand”, *Geotechnique*, **44**(3), 427-448.
Rocchi, G., Vaciago, G., Fontana, M. and Da Prat, M. (2013), “Understanding sampling disturbance and behaviour of structured clays through constitutive modelling”, *Soils Found.*, **53**(2), 315-334.
Santagata, M.C. and Germaine, J.T. (2002), “Sampling disturbance effects in normally consolidated clays”, *J. Geotech. Geoenviron. Eng.*, **128**(12), 997-1006.
Shang, J.Q., Tang, Q.H. and Xu, Y.Q. (2009), “Consolidation of marine clay using electrical vertical drains”, *Geomech. Eng., Int. J.*, **1**(4), 275-289.
Tanaka, H. (2000), “Sample quality of cohesive soils: lessons from three sites, Ariake, Bothkennar and Drammen”, *Soils Found.*, **40**(4), 57-74.
Tanaka, H., Sharma, P., Tsuchida, T. and Tanaka, M. (1996), “Comparative study on sample quality using several types of samplers”, *Soils Found.*, **36**(2), 57-68.
Voottipruex, P. and Jamsawang, P. (2014), “Characteristics of expansive soils improved with cement and fly ash in Northern Thailand”, *Geomech. Eng., Int. J.*, **6**(5), 437-453.
Wu, Y.D. and van Staveren, M.T. (2005), “Research on high quality continuous sampling techniques”, *Rock Soil Mech.*, **26**, 275-278.
Yu, H.S. (2000), *Cavity Expansion Methods in Geomechanics*, Kluwer Academic Publishers, Dordrecht, Netherlands.
Zhu, N. (2005), “Theoretical analysis of soil deformation due to piles jacking”, Ph.D. Dissertation; Hohai University, Nanjing, China.

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Notation

The following symbols are used in this study

A	=	any soil element in semi-infinite soil;
a	=	radius of cavity;
B	=	any infinitesimal portion of sampling tube;
D	=	diameter of sampling tube;
h	=	vertical distance between the surface and cavity center;
L	=	length of sampling tube;
r	=	radial distance between soil element A and origin;
t	=	wall thickness of sampling tube;
z	=	vertical distance between soil element A and origin;
$d\theta$	=	radian of any infinitesimal portion B;
dh	=	height of any infinitesimal portion B;
R_1	=	distance between soil element A and left cavity center;
R'_1	=	distance between soil element A and right cavity center;
R_2	=	$\sqrt{(r + D/2)^2 + (z + h)^2}$;
R'_2	=	$\sqrt{(r - D/2)^2 + (z + h)^2}$;
u_r	=	radial displacement of soil element A;
u_z	=	vertical displacement of soil element A;
v	=	Poisson's ratio of soil;
ε_r	=	radial strain of soil element A;
ε_z	=	vertical strain of soil element A;
ε_{rr}	=	radial strain of soil sample due to sampling penetration;
ε_{zz}	=	vertical strain of soil sample due to sampling penetration.