New approach of laboratory determination of coefficient of Earth Pressure at Rest (K_0) and its practical application

Michael Braverman, Keisuke Adachi, Caren Ackley, Bruce Polan
GHD, Waterloo, ON, Canada

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ABSTRACT
The coefficient of earth pressure at rest, K_0, is an important parameter for geotechnical calculations. The accurate determination of K_0 is critical for predicting the movement of soils under and around construction projects, such as retaining walls, tunnels, and deep excavations. Proper utilization of K_0 in construction design and execution increases ground and structure stability.
Various instrumentations for both in-situ and lab K_0 determination have been developed in recent years. Many tests developed for in-situ K_0 measurement are accompanied by serious soil disturbances, while lab testing requires equipment that is often cumbersome, which creates difficulties in the measurement and control of all test parameters. A simplified method for lab K_0 determination was developed in the GHD Waterloo High Complexity Geotechnical Laboratory. The main aspects of this new method and some practical applications are described in this paper.

RÉSUMÉ

1 EARTH PRESSURE AND COEFFICIENT OF EARTH PRESSURE AT REST

1.1 K_0 Importance

Temporary or permanent support structures are used to minimize ground movement following deep excavations. Proper engineering of these structures requires in-depth knowledge of the geotechnical properties of the site soil, including the relationship between horizontal and vertical stress and strain, changes in stress with depth and soil characteristics, and the strain path history of the ground (Burland et al, 1979).

In order to determine active earth pressure, the point at which the soil succumbs to shearing, knowledge of both vertical and lateral earth pressure at rest is required (Clayton et al. 2013).

Soil deposits are subject to vertical stress from overlying soil layers, as well as construction activities. In a stable, undisturbed soil deposit, horizontal effective stress develops without causing the deposit to experience horizontal strain. In unyielding soils, horizontal effective stress is known as earth pressure at rest. The concept of a coefficient of earth pressure at rest, K_0, was proposed by Terzaghi and Peck, 1967 and it is defined as the ratio of effective horizontal stress, $\sigma'h$, and effective vertical stress, $\sigma'v$, under conditions such that no horizontal yield occurs:

$$K_0=\sigma'h/\sigma'v$$

This fundamental definition of K_0 governs the practical use of this coefficient for in situ and laboratory testing. Today, all equipment used to determine K_0 in both the lab and the field, including commercially produced instrumentation and prototypes built in research facilities, is based on this universal principle. These approaches require horizontal stress to be measured while a known vertical stress is applied to a soil, resulting in minimal or no lateral strain.

Common in situ field methods used for measuring lateral earth pressure require the installation of equipment, such as the dilatometer test, borehole pressuremeter test, or a lateral stress measuring earth pressure cell test (Watabe et al., 2003, Coyle and Bartoskewitz, 1977). Consequently, each of these methods has limitations and shortcomings.

In 1962 Bishop and Henkel proposed the laboratory method for measuring K_0, which is performed in a triaxial apparatus. Since that time, various techniques have been developed to control axial stress and lateral strain. However, the basic elements of the test remain unchanged: the sample is subjected to increasing axial stress, while its diameter is maintained constant by adjusting triaxial cell pressure, guided by feedback from a strain measuring device. Horizontal strain is continuously monitored, and cell pressure is appropriately adjusted to increase horizontal stress with the goal of maintaining zero lateral strain. Based on this concept, various laboratory methods have been developed and employed for determining K_0 (Eliadoranu and Vaid, 2006, Goto et al., 1991, Hornig and Buchmaier, 2005, Isah et al., 2018, Laloui et al., 2006).

The most crucial, yet most problematic component of these tests is the accurate measurement and control of the sample diameter. The simplest approach is to equate the measured volume change of the water contained between the inner triaxial cell wall and the membrane surrounding the soil sample, to the volume change of the sample. With controlled vertical displacement, sample diameter can be calculated on the condition that all necessary corrections are applied, including temperature correction. Applying the appropriate and necessary corrections is critical, however they usually cannot be consistently and accurately accounted for. For example, during pressurization, the triaxial cell bulges slightly, and the latex membrane and O-rings undergo compression. These same issues arise with other methods of measuring the lateral strain of a soil sample, such as horizontal LVDTs, or so-called non-contact measurement devices, such as proximity transducers and Hall Effect gauges (Hornig and Buchmaier, 2005). In addition to the uncertainties discussed above, the compression test produces non-uniformity of sample shape due to the end restraint effect, (Amšiejus J et. al 2009), making strain measurements at the centre of the sample, where measuring equipment is mounted, likely not representative. In addition to soil density inconsistencies induced by testing procedure, soil mixtures exhibit natural variability, sometimes between seemingly minor depth changes. For example, Fig 1. shows two samples after an Unconfined Compression Test. While sample a. visually exhibits uniform density, sample b has a softer and most likely less dense upper half, which resulted in uneven compression and bulging in this half of the sample.

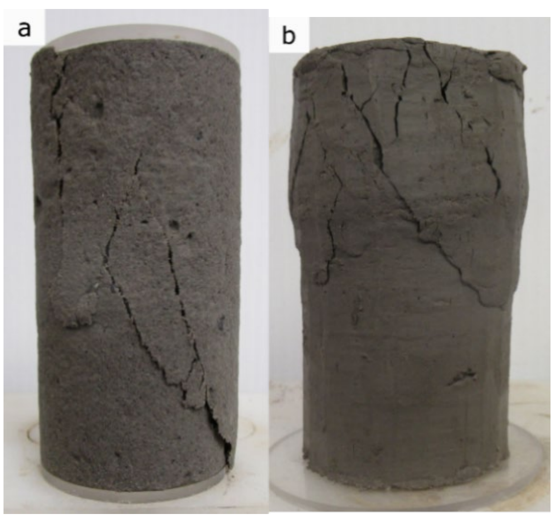


Figure 1 Post-test samples demonstrate the effects of density differences. Samples exhibit a) uniform density throughout sample used for unconfined compression test, compared to b) non-uniform density where the top of the sample used for extension test is less dense.

In clay soils specifically, which tend to be anisotropic, some layers of the sample may exhibit higher vertical as well as horizontal strains, compared to others. Due to these factors, using volume change as a proxy, lateral strain cannot be accurately assessed. Therefore, theoretical approaches to control and maintain constant sample volume do not necessarily translate into constant sample diameter.

Without modifications to this setup, the sources of error described above prevent accurate horizontal strain detection. To overcome these challenges, a new laboratory method for measuring K_0 was developed in the GHD Waterloo High Complexity Geotechnical Laboratory.

2 TEST METHOD AND TEST APPARATUS

2.1 Triaxial Test Modifications and Test Setup

For the reasons discussed above, measurement and control of vertical strain in triaxial compression appears to be simpler than measurement and control of sample diameter. To take advantage of this phenomenon, we explored a modified triaxial test setup that can uphold the condition of zero lateral strain with increasing vertical stress. This new method replaces the test condition of "zero lateral strain" with that of "zero axial strain". To satisfy this condition, a soil sample was placed in a triaxial cell at 90° to the axial direction of the sample as obtained in the field, achieved by the preparation of a cylindrical soil specimen extracted in the horizontal direction from the core sample. The main elements of this novel method are presented in Figure 2.

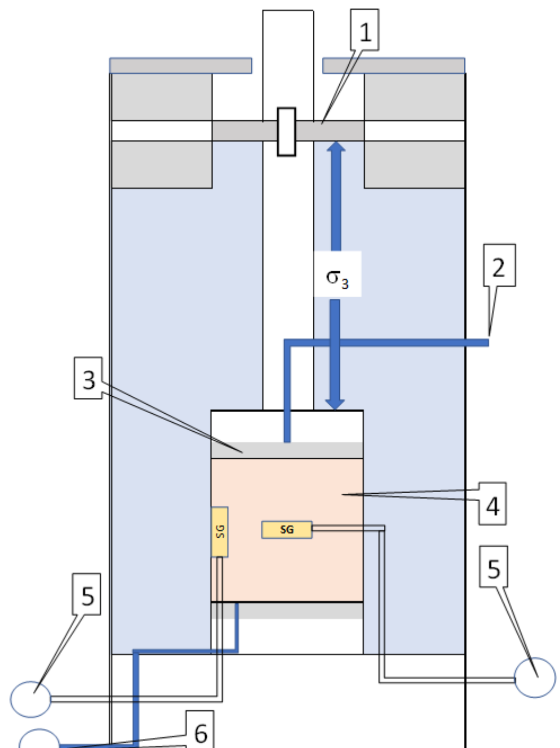


Figure 2. Triaxial cell showing equipment components and K_0 test setup. Bellofram® membrane (1) is open to the atmosphere to negate downward pressure applied to the sample from the pressurized cell. Vertical and horizontal strain gauges guide horizontal pressure (stress) adjustment to maintain zero strain. The top of the sample (2) is connected to the atmosphere to equalize pressure under the top cap and above the Bellofram® membrane; (3) - porous stone, (4) – soil sample, (5) – strain gauge readout, (6) - pore pressure readout.

The consolidated K_0 introduced here, utilizes a typical triaxial cell. To compensate for the cell pressure applied to the sample in a vertical direction, the triaxial cell's top cap was equipped with a Bellofram® membrane, a flexible seal with a unique configuration that permits relatively long piston strokes while completely eliminating sliding friction (Marsh Bellofram website). The Bellofram® membrane was attached to the underside of the cap and connected to the loading rod (Figure 2). This configuration formed a watertight seal. The loading rod was screwed in to the triaxial top cap. The diameter of Bellofram® membrane is equal to the diameter of the sample, thus compensating for cell pressure applied to the sample in the axial direction and creating conditions for anisotropic consolidation by allowing independent control of axial and lateral stresses.

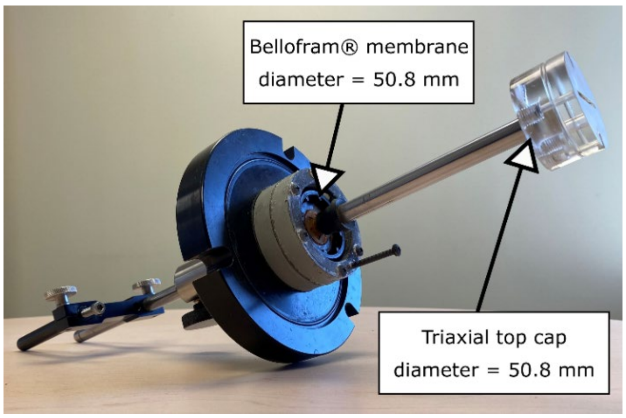


Figure 3. Top of triaxial cylinder modified with Bellofram® membrane and an affixed triaxial top cap, both measuring 50.8 mm diameter.

In the proposed setup, cell pressure can be directly interpreted as "axial" stress applied to the sample in situ, so the sample's "in situ diameter" becomes height in the triaxial cell. The sample is bound by the porous stones and can be controlled via the load frame, given that there are means of measuring it. According to Equation 1, where K_0 is the relationship between σ'h and σ'v, this unconventional sample setup still satisfies the definition of earth pressure at rest with zero lateral strain. It should be noted that all calculations of K_0 values were done in terms of in-situ stress direction. Where σv is vertical (normal) stress in-situ, even if it is applied in a horizontal direction in the proposed test setup, and σh is horizontal (lateral) stress in-situ, respectively. For the duration of this paper, "axial" and "lateral" refers to the direction of the prepared sample placed at 90° within the triaxial cell, while "in situ axial" and "in situ lateral" refers to the original direction of the sample, i.e. axial is parallel with soil layers.

The successful application of strain gauges for measurement of very small strains in soil samples analysed in a triaxial setup was described by Adachi et al. (2019). It was demonstrated that strain gauge technology can be used in soil testing under certain conditions. The main advantage of using strain gauges in soil samples is that strain is measured directly at the surface of the sample, eliminating all complex and unreliable volume change corrections that are required in typical test procedures. To measure lateral strain, strain gauges were affixed to the outer surface of the soil sample, one in each of the vertical and horizontal centres. A 3-cm strip of Teflon© tape was glued to the sample to increase the surface area of the strain gauge, thereby increasing the durability of the attachment to the sample, and the strain gauge was subsequently glued to the Teflon© tape.

With strain gauges attached, the sample was set up using the standard procedure for triaxial soil testing: the sample was placed on the triaxial pedestal, confined on the top and bottom by porous stones, and enclosed by a latex membrane. Once the sample and equipment were set up, the cell was pressurized to 5 kPa and the sample was left overnight to allow for pressure equilibration and stabilization of strain gauge readings. To execute the test and determine K_0, the cell pressure was incrementally increased by 5-10 kPa, reaching 100-300 kPa. An increase in cell pressure results in axial elongation, which is followed by compression. At each stage of compression, changes in the sample height were detected by the strain gauges and sample height was kept constant for the duration of the test. Cell pressure, pore pressure and force were continuously recorded throughout the test.

2.2 Considerations for Sample Saturation

In most drained and undrained triaxial tests, the sample is saturated prior to test commencement. In a standard saturation procedure, air contained within the soil pores is dissolved in water under gradually applied pressure. However, the addition of water to clay samples may promote swelling, resulting in changes in sample size and structure compared to the in-situ sample conditions. As a result, the initial conditions for K_0 consolidation would change considerably, leading to erroneous K_0 test results. The method of sample collection also impacts the physical properties of soil. The most common method used for collection of soil samples for geotechnical testing is the Shelby tube extraction. This method is generally thought to provide undisturbed samples that are appropriate for geotechnical analysis. However, as soon as the Shelby tube is removed from the ground, the soil within experiences a release of stress which may result in uncontrolled swelling. Subsequently, when the soil sample is extracted from the tube in the lab, additional expansion often occurs. As swelling progresses and pore size increases, air is potentially introduced into the pore spaces, resulting in a lower degree of saturation.

For this research, the standard soil saturation stage was omitted to minimize structural changes to the sample that would subsequently affect the mechanical properties of the clay, specifically the K_0 value. Instead, a special procedure for sample saturation was applied prior to the K_0 consolidation test.

This saturation procedure is described by K.H Head et al., 1986. It requires that no extra water is introduced to the sample. Rather, as the sample is compressed during the test, the volume of void space is gradually reduced and the excess air within the sample void is reduced. With an increase in pore pressure, air is absorbed into pore water or expelled from the sample. This procedure cannot be utilized for initially “dry” samples where the natural degree of saturation is significantly lower than 100%. For samples with an initial degree of saturation of 90% and higher, the state of full saturation is usually achieved in the range of overburden pressure.

2.3 Sample Selection and Preparation

All samples selected for testing contained a high percentage of clay or silty clay. Six different soil samples were selected for testing this new method, four samples visually appeared anisotropic (layered), and three samples visually appeared isotropic. The physical properties of the samples are presented in Table 1. To evaluate the effects of clay anisotropy on strain measurements, two specimens were collected from each sample. Each sample was prepared and tested in both the vertical (normal) and horizontal direction, for a total of 12 tests. Cylindrical samples were prepared to 50.8 mm diameter with a 1:1 height-to-diameter ratio.

Table 1. The properties of the clays used for K_0 tests, including Atterberg limits and particle size distribution as percent by mass. Results are representative of Sample ID for both vertical and horizontal test specimens.

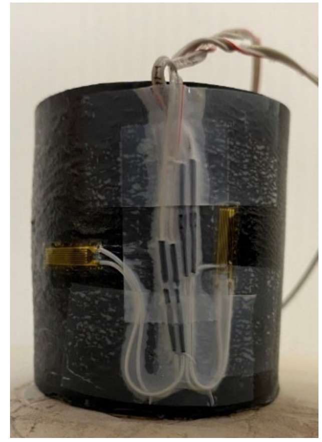


Figure 4. Rubber sample with attached strain gauges

The typical Poisson’s ratio for the rubber falls in the range of 0.46-0.5. The tested sample was loaded to approximately 115 kPa of axial stress and Poisson’s ratio was determined as 0.491 in the range of 50 and 107 kPa (see Figure 5)

Sample ID	LL	PL	PI	Gravel	Sand	Silt & Clay	Silt	Clay
1	33	15	18	2	21	77	46	31
2	37	18	19	0	2	98	60	38
3	36	18	18	0	2	98	45	53
4	28	17	11	0	1	99	68	31
5	54	21	33	0	1	99	23	76
6	23	14	9	5	18	77	52	25

3 RESULTS

3.1 Test of Rubber Cylinder as Proof of Concept

The value of K_0 is related to Poisson’s ratio (ν), based on Hooke’s law applied to materials within the range of elastic deformations (Federico and Elia, 2009):

$$K_0 = \frac{\nu}{1-\nu}$$

As a proof of concept, Poisson’s ratio of the rubber sample size of 50.8 mm diameter and 1:1 H to D ratio was determined (Figure 5.) The same sample was then tested in the K_0 apparatus with the constant height and constant diameter methods.

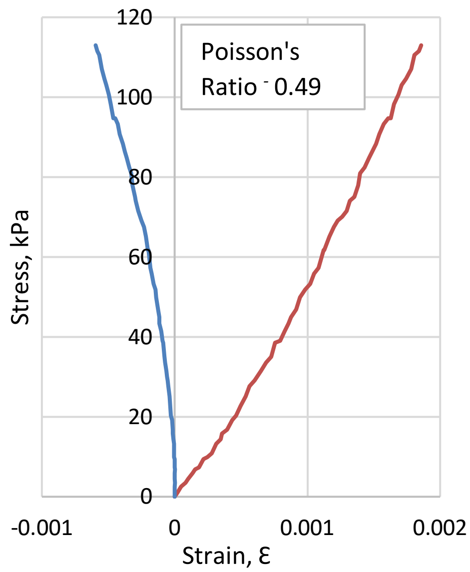
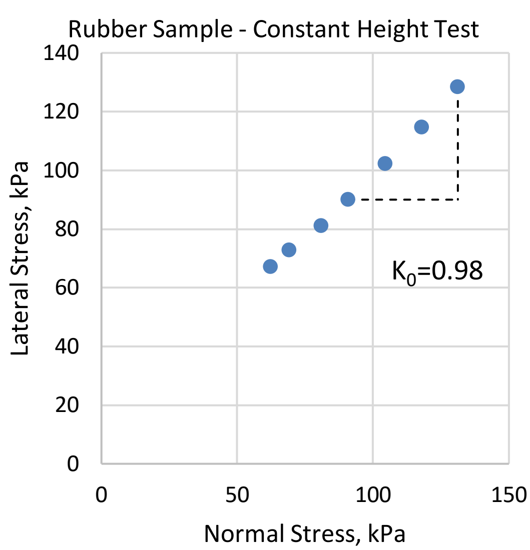


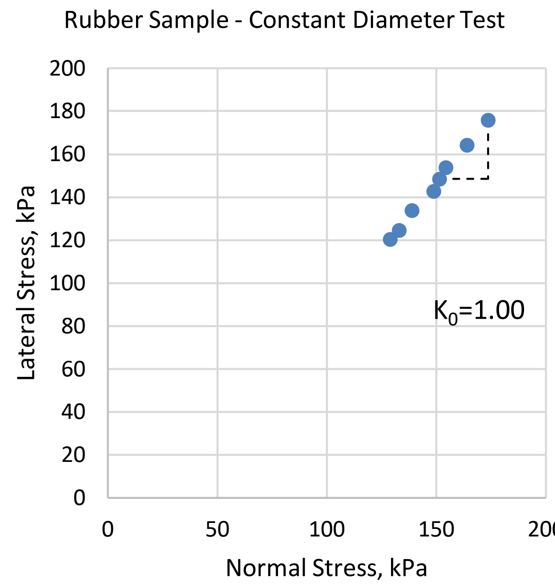
Figure 5. Elastic Deformation of the rubber sample. Red line represents vertical strain vs stress. Blue line represents lateral strain vs stress.

Thus, the measured value of Poisson's ratio of 0.491 theoretically should give us K_0=0.96.

The K_0 test results for this rubber sample are shown in Figure 6. Figure 6a represents the constant height and Figure 6b the constant diameter tests. The measured K_0 value from the constant height method is slightly closer to the theoretical value than the one obtained by the constant diameter method. This can be explained by some variations in diameter along sample height. Nevertheless, both results were considered satisfactory in their first approximation: K_0 Theoretical = K_0 (constant height) = K_0 (constant diameter) = 1.0



a.



b.

Figure 6. Rubber sample test results: a - constant height, b - constant diameter.

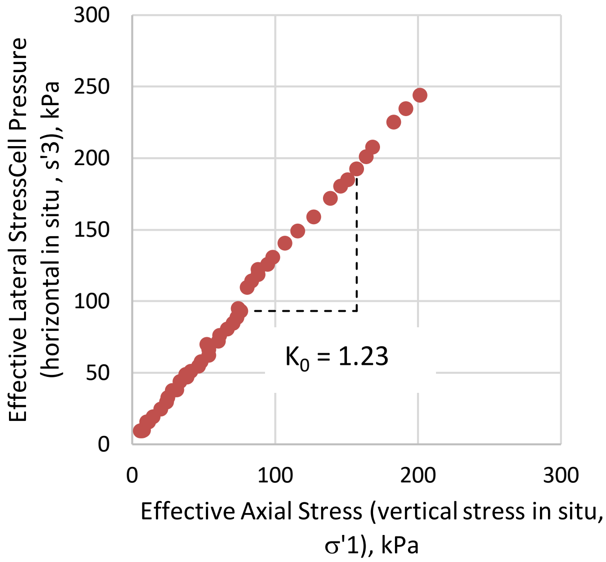
3.2 Soil Test Results

The results presented below demonstrate the experimental technique of zero vertical strain. Typical results of a K_0 consolidation test obtained with the proposed method are described below. All tests were performed in pairs of horizontally and vertically prepared samples. The K_0 value varies significantly within the pairs of the samples, which indicates a high degree of anisotropy of the tested clays.

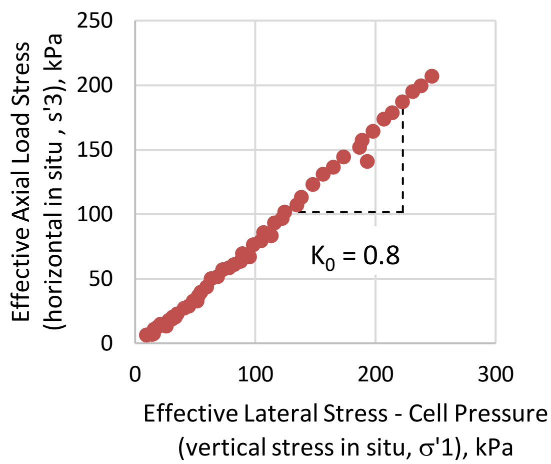
The test results are summarized in Table 2. The relationship between vertical and horizontal effective stresses is presented in Figure 7. The straight line in Figure 7 demonstrates that the K_0 value is independent of applied stress.

Table 2. K_0 Test Results

Sample ID	Sampling Direction	K_0
1	horizontal	0.60
	vertical	1.21
2	horizontal	0.82
	vertical	1.21
3	horizontal	0.63
	vertical	2.53
4	horizontal	0.51
	vertical	1.01
5	horizontal	0.71
	vertical	1.91
6	horizontal	0.80
	vertical	1.23



a.



b

Figure 7. Typical test results for vertically and horizontally obtained samples. 7a. Vertically obtained sample, 7b. Horizontally obtained sample. Note that effective axial stress refers to in situ horizontal stress (σ'3) and effective cell pressure refers to in situ vertical stress (σ'1).

The range of K_0 for both tests falls within the expected range, from 0.51 to 0.81 for horizontally oriented samples, and between 1.01 and 2.53 for vertically oriented samples. All vertically obtained samples (horizontal direction in situ) have K_0 values higher than 1, which is typical for overconsolidated clays. This can play a significant role in calculating the vertical pressure and strain at the bottom of deep excavations, where horizontal stress significantly exceeds vertical stress due to the overburden removal.

4 CONCLUSION

This new method for triaxial testing to determine the K_0 value of a sample requires that a sample is prepared and set up within the triaxial cell at 90° to the direction extracted from the earth. Using this method, the test height (sample diameter) can be controlled and monitored with greater precision and consistency. Seven samples were tested, each sample tested in both the vertical (normal) and horizontal (90°) directions. In general, the vertically tested samples showed a higher K_0 value compared to the horizontally prepared samples.

For all samples tested, the K_0 value was relatively consistent, as the vertical stress increased, suggesting that this test is reliable and repeatable. Furthermore, the simplicity of the proposed height-controlled K_0 test makes this method superior to other methods that attempt to measure and control the sample diameter during compression by adjusting triaxial cell pressure.

The presented research suggests that due to the anisotropy of clay in some cases it is beneficial to determine K_0 value in both directions: in horizontal as well as in vertical. For example, the clay behaviour in the wall of excavation where soil exposed from one side in horizontal direction will be different from clay behaviour in the bottom of excavation, where soil exposed in vertical direction.

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