Limitation in Conventional Oedometer Consolidation Test for Deep Layered Soil

Adhya Nanda Kumara, Widjojo Adi Prakoso and Tommy Ilyas
Department of Civil Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia

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Abstract: Consolidation test for soil is a very common test to find compression parameter in geotechnical investigation. Terzaghi invented the theory of consolidation in 1925 and the test became geotechnical standard in 1945. Since then, the theory and mechanical in this test has no meaningful improvement, whereas due to the rise in numbers of high-rise buildings, the foundation depth requirements are increasing. In consolidation test, deeper foundation means higher pressure required to find the preconsolidation pressure (pc). Meanwhile, the conventional equipment is still very popularly used in commercial geotechnical laboratories causing the result from consolidation less accurate. This paper will discuss the impact in consolidation test using conventional equipment for deep- layered soil and how to improve the result of consolidation test.

1 INTRODUCTION

Consolidation test is one of the most common and important test in geotechnical investigation. Its purpose is to find the compression parameter from soil, so that soil engineer can predict soil settlement caused by the additional load from the construction or structure. The theories of consolidation was proposed by Terzaghi in 1925 and by 1945 this test has become standard test in geotechnical society (Head, 1998).

When the theory of consolidation was developed, geotechnical world was still very young and complex computer computations were still in early stage, so like any other theory in its time, Terzaghi developed the theory of consolidation with some assumptions to simplify the mathematical calculations. He developed testing apparatus called Oedometer that only allowed the soil specimens to move in one direction or also known as One-Dimension Test (1D). But due to its simplicity and accuracy, Terzaghi's consolidation testing method can easily be accepted in geotechnical society and largely used in geotechnical practices all over the world.

The oedometer consolidation apparatus works by molding an undisturbed soil specimen inside a thin-steel ring (1-inch) to confine the soil, then the soil will be loaded with loading mechanism to simulate the overburdened soil pressure. The steel ring is then placed inside a watertight steel cell filled with water to fully saturate the soil. By applying some load to the soil with loading mechanism and monitoring the deformation of the soil using a dial gauge, soil settlement or consolidation could be observed from this test. Later, the load will be added step by step to observe the soil behavior to different loads, therefore the apparatus is known as Incremental Loading (IL) apparatus.

As technology development increases, consolidation test was also developed further, but the basic concept is still using the same principle. Additional data acquisition and automatic loading mechanism using step-motor or pneumatic pressure only to simplify and automate the testing, but the main concept is still based on Terzaghi's theory of consolidation. There are several new developments in consolidation testing such as Constant Rate Strain (CRS) and rowe cell, but they are not as popular as Terzaghi's Oedometer and not widely accepted in geotechnical community.

When the apparatus become world standard, the load requirement was not high. Back then, the final set load for incremental loading is 800 kPa for normal range of soil, and it could be extended to 1600 and 3200 kPa for stiff or overconsolidated clays. These pressure equal to weight set of 64kg as

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standard weight when someone purchase the normal oedometer equipment.

With the development of high-rise buildings, deeper foundation is required, so the geotechnical investigation which used to be only 20-30m depth, is now required to be deeper to 50-80m, some even requires more than 100m depth. With this additional depth, it means the load requirement for the geotechnical test also increases (BS1377:5, 1990).

With the increase in load requirement to simulate the overburden pressure, this gives new challenges for geotechnical testings, especially in laboratories. The equipments being used in the laboratories also needed to be checked for its specifications, since most laboratory equipments has their limitations. These laboratory equipment limitations never became a problem for geotechnical laboratories in Indonesia, since typically in Indonesia the soil consist of soft soil, but now with the increase in load requirement, it becomes a new challenge for geotechnical laboratories in Indonesia.

This paper will discuss about the background theory of load requirement for the consolidation test. Then, then this paper will discuss equipment limitations and what might happen when the soil tested with less than load requirement. At the end, we will discuss how to increase test accuracy in consolidation testing.

2 PRECONDOLIDATE PRESSURE

In 1920, Terzaghi introduced principle of effective stress, where he demonstrate an apparatus filled with water and on the bottom filled with cohesive soil (Figure 1), by measuring the height of water (hw) and unit weight of water, pressure applied to the soil by the water could be measured. This principle is called neutral stress (Terzaghi, 1943).

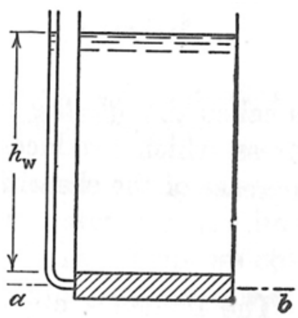

Figure 1: Terzaghi’s apparatus to simulate neutral stress.

With the same principle, this principle also applied to the soil specimen beneath the earth, but for the soil, there are overburden soil above the soil specimen, so that by measuring the soil depth and unit weight of overburden soil, pressure applied to the soil specimen could be achieved. This pressure known as total stress.

The difference between pressure caused by overburden soil (total stress) and the pressure caused by water (neutral stress) is known as effective stress. This effective stress is a very important principle in geotechnical testing, because soil deformation is not affected by total stress, but only by effective stress (Budhu, 2010).

Soil has a unique characteristic, where the soil could maintain memory of the past maximum effective stress (Budhu, 2010). This is known as soil loading history and this value could be determined from the consolidation test. In consolidation test, the past maximum vertical effective stress that soil has experienced is known as preconsolidation pressure (ASTM D653-03, 2003). If the preconsolidation pressure is less than the overburden effective stress, it is known as normally consolidated soil, if the preconsolidation pressure is more than the overburden effective pressure, it is known as overconsolidated soil.

According to ASTM D2435 (2011), to find preconsolidation pressure the final pressure should be minimum four times the preconsolidated pressure. This means that the loading requirement is four times the overburden effective stress from soil specimen (ASTM D2435-11, 2011).

For example, to perform consolidation test for soil with 77m-depth, the overburden effective pressure would be around 600 kPa. The final pressure for the consolidation test should be around 2400 kPa. Now, if the soil specimen taken from 140m-depth, the overburden effective pressure would be around 1050 kPa, and the final pressure for consolidation test should be minimum 4200 kPa.

What would happened if the final pressure is less than four times the overburden pressure? For example, this test was conducted for 139.5-meter-depth soil specimen. The test was conducted in Japan up to 10240 kPa. As discussed before, for 140m-depth specimen, final pressure required is 4200 kPa, so the final pressure for this test is more than four times the overburden pressure. As shown from Figure 2, the preconsolidation pressure of the sample is 1900 kPa, which shown that the soil is overconsolidated soil.

If the test stops at 2560 kPa which is more than overburden pressure, but it does not reach four times

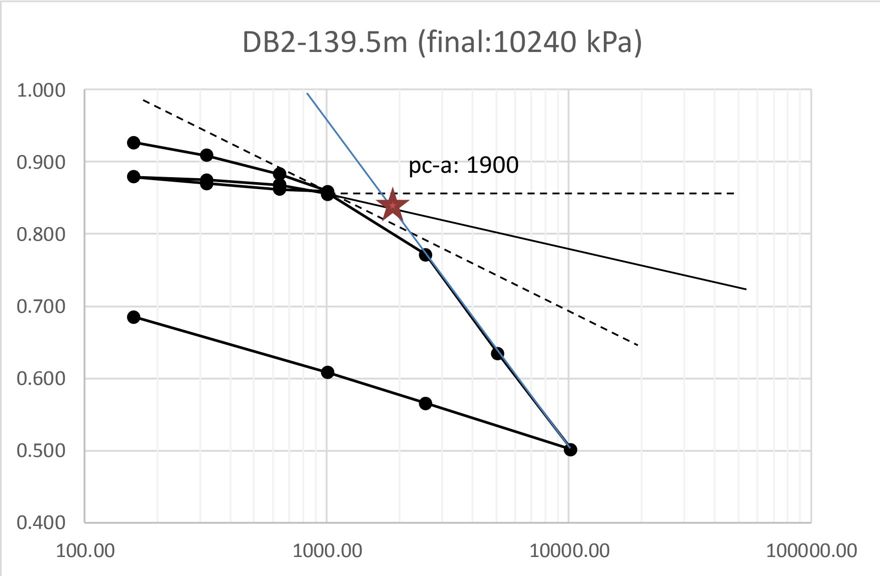

Figure 2: Consolidation result of Stress vs Void Ratio Graph for soil specimen with 139.5m-depth. (Data from Pondasi Kisocon tested in Japan).

Figure 4: Maximum weight set up to 128 kg (2560 kPa). And not possible to add more weight.

Figure 5: Counterweight to prevent equipment from tilting.

the overburden pressure, the preconsolidation pressure is only 750 kPa as Figure 3 shows and the soil becomes normally consolidated. This would make an error in the result of the consolidation test.

Another difference is in Compression Index Value (Cc), where if the final load is properly set up the Cc value is around 0.52, but if the final load only stops at 2560 kPa the Cc becomes 0.78. Not only Compression Index, Recompression Index (Cr) will also be different.

From this exercise, the decision for final pressure in consolidation testing is very important.

3 EQUIPMENT LIMITATIONS

To understand how difficult it is to increase load pressure for deeper soil, we need to understand the equipment specifications. Every equipment was made with its specifications and limitations. If we over-specify the equipment, there must be some accuracy that being compromised.

Equipment specifications also depend on the year that equipment was made. As discussed before, in the old days load requirement is not as high as it is as today, so most of old equipments were not designed for very high load. This is one of the issue in geotechnical practices in Indonesia, because most geotechnical testing were done using very old equipment. For example, the equipment that the writer uses daily only have maximum weight up to 1280 kPa. We manage to add up to 2560 kPa by borrowing the weight set from other equipment. The equipment itself is not possible to be added to more than 2560 kPa, since there is no more room to add more weight (Figure 4). The CRS consolidation machine that the writer faces daily has load cell only up to 2000 lbf or 2800 kPa, but after using it for testing several samples with 2500 kPa, the motor starts to break down. The equipment from the university that the writer uses also only have weight set up to 32 kg (1000 kPa). Since the equipment from university was made from original ELE, according to the specification, the equipment has maximum load up to 8800 kPa, but in reality to set up 8800 kPa is not easy because when such a high load being used on the apparatus, the whole apparatus needs to be counterweighted to prevent the equipment from tilting (Figure 5).

As discussed before, to test 77m soil sample, minimum load for consolidation test is around 2400 kPa and for 140m depth, the minimum load is 4200 kPa. Meanwhile if the equipment maximum capacity is only up to 2560 kPa, the equipment is only accurate up to 70-80m depth and not suitable to be used for more than 80m depth. This is the reason why some geotechnical companies send their sample to Japan only for consolidation testing. The example above was tested in Japan with load up to 10.000 kPa.

The quality-made of the equipment also affecting the accuracy of the test. According to ASTM D2435-03 the loading device shall have precision of +/- 0.5% of applied load. With this precision, the quality of equipment can make a difference especially when the equipment is being pushed up to its limit. To compare between equipments, the writer compares consolidation results between several different equipments which are available (Figure 6). For information, the CRS consolidation machine was made in America, Oedometer E4 was made in Japan, and Oedometer B3 was made in Singapore. These equipments also have different models, while CRS and Oedometer E4 has typical vertical load frame, meanwhile the Oedometer B3 is typical ELE-type consolidation machine with yoke and beam mechanism. Shown in Figure 6, the CRS and Oedometer E4 give similar results, where Oedometer B3 gives a completely different result. At lower stress, Oedometer B3 still gives similar result as the rest up to 500 kPa, where the line start to separate from the other equipments.

Oedometer B3 also shows higher strain result where it could happen due to soil starts to creep out from the oedometer ring. This creep phenomenon are quite common happening in Oedometer with yoke and beam model.

When checking the equipment manufacturer's website, the specification from the equipment varies, but the latest equipment already prepared for higher load as specified in Table 1 where the latest trend of equipment has maximum load capacity above 5000 kPa.

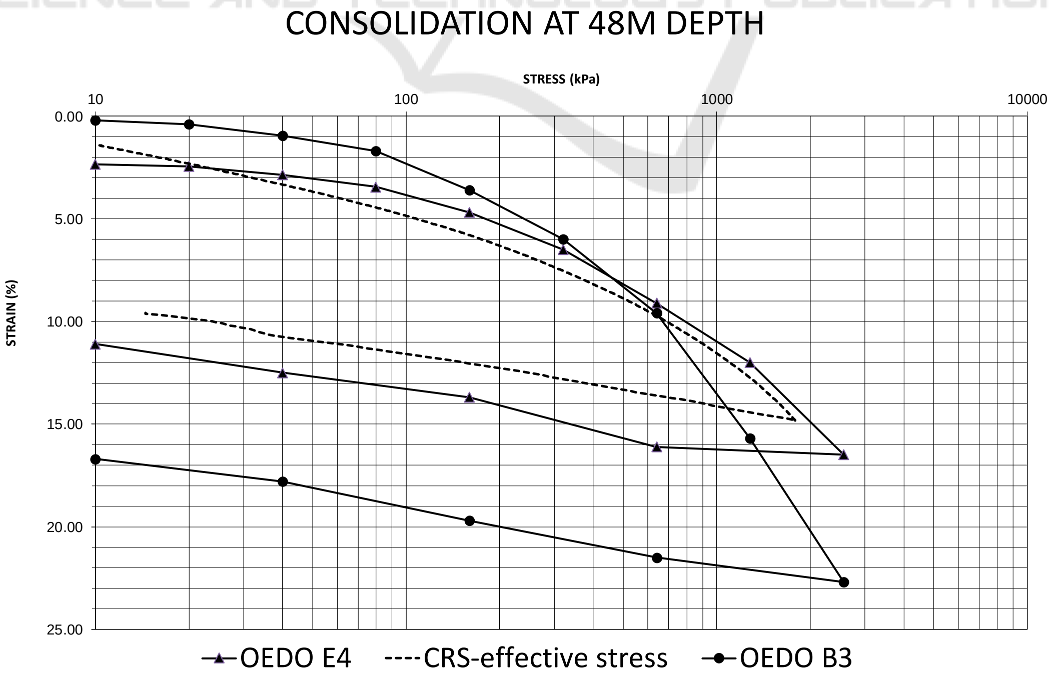

Figure 6: Graph of comparison between different equipments.

Table 1: Maximum equipment specification.

Band	Type	Maximum Load	Load Applied on Sample		Note
			D: 6.35 cm/ 2.5 inch	D: 5 cm	
Hogentogler	Geostar Consolidometer	8.9 kN	2800 kPa	4500 kPa	Since 1991
GCTS	CRS-10	10 kN	3150 kPa	5000 kPa	
Controls Group	ACE-Ems	20 kN	6300 kPa	10000 kPa	
Conrols Group	Oedometer	18 kN	5700 kPa	9000 kPa	168 kg weight (11:1)
VJ Tech	ACONS	15 kN	4800 kPa	8000 kPa	
ELE	Oedometer	12.5 kN	4000 kPa	6400 kPa	128 kg weight (10:1)

For note in Table 1, these are maximum specifications for the equipment, where some equipments need extra modifications to reach these limits. For example, for ELE oedometer the standard weight is set only up to 64kg. Extra weight set needs to be purchased separately, and a special table is needed to prevent the equipment from tilting.

4 IMPROVING THE CONSOLIDATION TEST RESULT

As discussed before, incorrect use of final load could lead to inaccuracy in consolidation test result, so the decision to determine correct final load is very important in consolidation testing. There are several methods that could be applied to current equipment to increase load.

The first method is by adding the weight set to increase the load for the test. Most of geotechnical practices, usually has more than 1 consolidation equipment. To increase the load, it is very easy to add more weight by borrowing weight set from the other equipments since the weight set from the same equipment usually already calibrated and compatible with each other. Buying another weight set from manufacture also possible to add more load. But this method only applicable up to equipment specification. Making weight set is also possible, but each weight needs to be calibrated.

Second method is by increasing the beam ratio. For beam and yoke type of equipment, usually the beam ratio could be change from 10:1 to 11:1, which will increase the load applied on the sample.

The third solution is by decreasing sample diameter could increase the load applied to the sample. The standard sample diameter usually 2.5 inch (6.35 cm). According to ASTM, minimum sample diameter is 5 cm. By decreasing the sample diameter could increase the load applied to the sample. Table 1 shows comparison between samples diameter 6.35 cm to 5 cm, where the load could increase quite significantly. Changing sample from 6.35cm to 5 cm is not as easy as changing the ring, since most oedometer ring is set with its oedometer cell. So to change the sample size, the whole oedometer cell needs to be replaced as well. This becomes a problem for old equipment where the oedometer cell with 5 cm diameter is not available.

Last method is by purchasing higher capacity consolidation machine. Of course, purchasing new equipment with higher capacity will solve this problem, but with such low fee for consolidation testing in Indonesia, not everybody is able to purchase expensive equipment from well-known equipment manufacturer. It is not a secret that some geotechnical practices has equipments made in Indonesia, which is not a problem for low capacity, but by pushing the equipment above its limit would not give a good and accurate result.

5 CONCLUSIONS

In consolidation testing for deep soil, to determine final load is very important to get a reliable and accurate data. According to ASTM D2435-03, to calculate preconsolidation pressure, the final load should be minimum four times effective overburden pressure, which for deep soil sample would be very high pressure. When the final load does not meet four time the effective overburden, the preconsolidation pressure (pc), compression index (Cc), and Recompression Index (Cr) would not be accurate and could lead the overconsolidated soil to be normal consolidated soil.

To be able to achieve this high load, consolidation apparatus needs to be checked for its specification since the old model apparatus usually does not have capability for high-pressure testing. Checking for available weight set, diameter of oedometer ring, and beam ratio would show the equipment capability. Some model of consolidation apparatus could have high load pressure with some modification like changing the beam ratio, adding weight set, and reduce the oedometer ring size.

Purchasing a new equipment need to check equipment capability, although most new equipments are capable to have high load pressure, but not all equipments have similar specifications.

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