On the Nature of Secondary Compression in Soils

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ABSTRACT

Classic theories of secondary compression in clays are reviewed. Inferences are drawn as to why the computed values of secondary settlements might differ from those computed from the traditional Buisman’s approach. It is suggested that a practicing engineer may be able to discern in advance when a difference in the two values would arise for a given problem. Accordingly, corrections in the computed values may be introduced.

1. INTRODUCTION

It was in 1936 when Buisman reported that in one dimensional oedometer test, the secondary compression in clays followed approximately a linear relationship when plotted against the logarithm of time (Buisman 1936). This linear relationship then became a basis for computing long term settlements in structures founded on soils exhibiting a secondary compression behavior (Fig.1).

Fig. 1: Secondary Compression, the Buisman’s Approach (Duncan & Buchignani 1976)

Since Buisman’s ground breaking work, much has been added to understanding the causes and mechanics of secondary compression and the various factors, man made or environmental, which affected them. But, insofar as the practice of soil mechanics is concerned, even today the use of Buisman’s linear relationship continues (Duncan & Buchignani 1976).

To prepare a state of the art report on secondary compression would be a difficult undertaking as investigators are far from agreement. Whereas it has been hypothesized that it is the viscous behavior of the aqueous double layer in a soil water system which is primarily responsible for secondary settlements in clays, and thus, variations in temperature should play a dominant role in such a process, an investigation indicates that “the coefficients of secondary compression from normally loaded and overconsolidated specimens are independent of testing temperatures” (Mesri 1973).

This paper presents only a generally accepted viewpoint.

2. MECHANICS OF SECONDARY COMPRESSION

In 1941, Terzaghi published a general hypothesis concerning the combined process of primary and secondary consolidation. Terzaghi said, “Every soil particle is surrounded with a very viscous film of adsorbed water the presence of which delays the establishment of a direct contact between the solid soil constituents.” (Terzaghi 1941)

Figure 2 is a graphic representation of Terzaghi’s conception regarding the interaction between adsorbed layers. It represents a magnified view of sections through the vicinity of a point of contact between two soil particles. In the immediate vicinity of the surface of the solid particle, the viscosity of the adsorbed water is extremely high and its density is far above normal. With increasing distance from the particle surface, both the viscosity and the density of water decrease. Beyond a certain distance, d, the properties of the water become normal. According to Terzaghi, “The distance d depends both on the chemical properties of the solid and those of the substances other

![Fig. 2: Graphic Representation of Terzaghi’s Conception](image-url)
than water which are present within the zone of adsorption. Thus, for instance, if the water in the voids of a bentonite specimen contains sodium salts in solution, the adsorbed layers are very much thicker than those in one saturated with pure water.”

![Fig. 2: Terzaghi’s Conception of Interaction Between Adsorbed Layers](image)

Upon application of a load $Q$, a saturated soil mass first passes through a phase of primary consolidation wherein the total stress is shared by the pressure in the normal pure water (called pure pressure), by the viscous resistance of the adsorbed double layer (called film bond stress) and by the grain to grain contacts represented by the merging of virtually solid portions of the adsorbed layers. The sum of film bond stress and the solid bond stress constitutes the effective stress in the soil water system.

After primary consolidation is complete, i.e., when pore pressures have dissipated, the applied pressure is borne by the film bonds and the solid bond. This phase of consolidation is referred to as secondary compression — a process where deformation continues within a soil mass under a constant applied stress (which is also the effective stress, since pore pressures are negligible). Thus, during the phase of secondary compression there takes place a gradual transfer of stress from film to solid bond which is accompanied by a very slow viscous flow or creep of a soil mass. As the clay particles approach one another, the effective viscosity increases (indicating a nonlinear behavior), and the adjustments in the grain position proceed at a rapidly decreasing rate.

Finally, all the applied stress is taken by solid bonds and the system reaches a state of equilibrium.

A firm foundation to Terzaghi’s hypothesis was later provided by Lambe (1953) who employed the principles of colloidal chemistry to demonstrate that “the most important consideration of soil structure is the nature and magnitude of forces between the soil particles and between soil and water.” (Fig. 3)

![Fig. 3: Lambe’s Conception of Diffused Double Layer](image)

Lambe argues that since clay particles have high specific surface (surface area per unit mass or volume) because of their size and shape (usually plate, needle or rod shaped), they are colloidal in nature. There is ample experimental evidence to suggest that a soil colloid when suspended in water carries a net negative charge. “Since the net electrical charge on the entire soil-water suspension must be zero, the charge on each colloid must be neutralized by ions from the water which swarm round each soil colloid. These ions are called ‘counterions’ or ‘exchangeable ions.’…The counterions constitute the ‘diffuse double layer’ of the colloid; the surface charge of the colloid is the other layer of the double layer.” (Lambe 1953)

![Fig. 4: Correlation Between $C_\alpha$ and Natural Water Content (Mesri 1973)](image)

Since Terzaghi and Lambe theories attribute part of the secondary compression to the presence of adsorbed water layer, the thickness of this layer must necessarily have a dominant effect on the magnitude of secondary compression. Thickness of the adsorbed layer, in general, is proportional to the liquid limit of the soil. Liquid limit is in turn related to the primary compressibility of soils represented by $C_C$, the coefficient of primary compression. Thus, soils possessing large values of $C_C$ also exhibit large amounts of secondary compression. It has been observed that the ratio of $C_\alpha/C_C$ is a constant for most soils (Mesri & Vardhanabhuti 2005).

A more convenient property of natural soil deposits is their natural water content. As a general rule, higher natural water content indicates higher liquid limit in normally consolidated deposits. That indeed the value of $C_\alpha$ is
proportional to the natural water content has been shown by Mesri (1973) and based on his collection of data on soil deposits from different parts of the world (Fig. 4).

For most soils the value of \( \alpha \) lies between 0.1% to 10%. The range being quite high, a classification has been proposed by Mesri (1973) (Table 1). For example, the value of \( \alpha \) for San Francisco Bay Mud has been found to be .01 to .02 (Bonaparte and Mitchell 1979), and therefore, based on Mesri's classification the secondary compressibility of Bay Mud should be referred to as “high”. With a natural moisture content of 90% Bay Mud plots slightly above -moisture content line in Fig. 4.

Table 1: Classification of Soils Based on Secondary Compressibility (Mesri 1973).

<table>
<thead>
<tr>
<th>Coefficient of Secondary Compression, ( C_\alpha ) %</th>
<th>Secondary Compressibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.2</td>
<td>Very Low</td>
</tr>
<tr>
<td>0.4</td>
<td>Low</td>
</tr>
<tr>
<td>0.8</td>
<td>Medium</td>
</tr>
<tr>
<td>1.6</td>
<td>High</td>
</tr>
<tr>
<td>3.2</td>
<td>Very high</td>
</tr>
<tr>
<td>&gt; 6.4</td>
<td>Extremely high</td>
</tr>
</tbody>
</table>

3. FIELD VERSUS LABORATORY

In 1953, Terzaghi put forward a hypothesis explaining why the observed secondary settlements in the field could differ from those indicated by laboratory experiments. According to Terzaghi, secondary compression effects in the field are induced by at least two independent processes, governed by different laws.

“One of them is the secondary time effect which follows the primary consolidation of laterally confined soil samples in the laboratory. The secondary compression of such specimens increases approximately with the logarithm of time. If the thickness of the layer or layers of clay responsible for the settlement of a structure is small compared to the horizontal dimensions of the loaded area, the secondary settlement is likely to proceed in accordance with a similar law. It represents the result of grain adjustment under lateral confinement. However, if the clay strata are thick the secondary settlement due to grain adjustment combines with another one due to lateral displacement of the clay, because the application of the load subjects the clay to what can be compared to a squeeze test and the shearing stresses produced by this type of loading are associated with creep, unless they are very low.” (Terzaghi 1953)

Thus, long term settlements in field are a function of the ratio \( H/2B \), where \( H \) is the thickness of the clay stratum and \( 2B \) is the foundation width. If it is assumed that a laboratory specimen with height/diameter ratio of 0.4 will yield reasonable predictions for field settlements at a site with \( H/2B = 0.4 \), then, a settlement forecast for sites with \( H/2B > 0.4 \) should be multiplied by a factor, where

\[
\alpha = \alpha \left( \frac{H}{2B} \right)
\]

Since Terzaghi’s hypothesis indicates that settlements in the field must always be greater than those predicted from laboratory tests, the value of \( \alpha \) is necessarily greater than one.

A verification to Terzaghi’s hypothesis was provided by Bjerrum (1964) who compared the secondary settlements of normal buildings with those of structures like tanks and silos which possess high \( H/2B \) ratio, and experience large variations in live loads. Noting the importance of lateral yield component of secondary compression, he concluded that secondary settlements in such structures occur in direct proportion to time \( t \), contrary to \( \log t \) as observed in the laboratory.

Terzaghi’s hypothesis does explain the phenomenon when the field settlements are greater than laboratory, but, quite often it has been found that field settlements are smaller than those predicted from experiments. This is because of smaller rate of loading in the field than what is followed in the laboratory. Thus far in this report, mention has been made only of one type of compression curve (type I curve in Fig. 5), wherein a well defined primary consolidation curve is followed by a straight line of secondary compression on a semi-log plot. As Ladd and Preston (1965) indicate, this type of curve is obtained only when the soil is subjected to large pressure increment ratio. Small load increment ratios produce a curve of Type III, whereas for intermediate ratios a transition curve of the Type II is obtained. Terzaghi’s theory of primary consolidation, and the Buisman’s approach to secondary compression only apply to Type I curve. Also, the \( \log t \) fitting method for determining the end of primary consolidation is not applicable to Type II and Type III curves.

![Fig. 5: Settlement vs Log time from Oedometer Test on Saturated Clay (Ladd & Preston 1965)](image-url)
There is conclusive evidence that a smaller load increment ratio produces smaller secondary compression. In fact, with very small load increment ratios, a soil behaves as if it were over consolidated. Perhaps it is due to the strengthening of internal bonds by pressures, not large enough to cause any disruptions in the soil mass.

In the field, the pressure increment ratio is usually very small since the in situ stresses are very high as compared to the applied pressure increments. And, rarely does this ratio equal unity, as is usually the case in the laboratory.

There is limited evidence that the rate of secondary compression, indicated by , is independent of sample thickness. An increase in sample thickness simply results in an increase in the duration of primary consolidation. For a very large thickness of consolidating medium, as is normally the case in the field, it is quite probable that a substantial portion of secondary compression would have already occurred by the time the excess pore water pressures are dissipated, i.e., the primary consolidation is over. This suggests that in the field, the primary and secondary compressions proceed together.

In cases where the field records match excellently with the predictions of laboratory, it would seem natural to postulate that an increase in long term settlement due to a lateral yield of soil in the field compensates the increase in settlement due to a large pressure increment ratio in the laboratory.

4. CONCLUSIONS

The paper attempts to explain to a practicing geotechnical engineer why the measured values of secondary settlements differ from, or sometimes match with the predicted values using the classical Buisman’s method. Some classic works on secondary compression are used as a starting point for the arguments made. It is inferred that the discrepancies between the predicted and computed values can be surmised and accordingly corrections can be introduced in the computed values.

REFERENCES


