THE DEVELOPMENT OF SHEAR STRENGTH FOR SEDIMENTARY SOFT CLAY WITH RESPECT TO AGING EFFECT

Discussion by JOHN H. SCHMERTMANN

The authors performed interesting experimental work involving the consolidation and shear strength index testing of initially destructured soft clays at very low effective overburden pressures. They then interpreted aging strength-gain behavior as the sequential sum of secondary compression and "cementation," and also to fit their results into the models represented by their Eqs. (1) and (3). As their principal conclusion they found that the rate of aging strength increase varied with the square root of the vertical effective stress during the aging.

The writer appreciates the apparent high quality of the authors' experimental work, but disagrees with their interpretation of the results—particularly with respect to "cementation." The continual use of "cementation" throughout the paper, together with associated words such as "bonding" and "thixotropy," implies to the writer and perhaps also to other readers that the aging effects they associated with these words describe a cohesive shear enhancement behavior that mobilizes independent of effective stress. If they intended this implication, the writer disagrees. Their own principal conclusion about "cementation" in the rate of aging indicates the importance of effective stress in the process.

As shown in part by the listed additional references perhaps not known to the authors, the writer has devoted a large amount of time to the investigation of soil structure and the "basic" effective stress dependent and independent components of shear strength, including how they relate to the aging of soils. These include soft clays. Like in so many other papers, the authors appear to have only assumed that effective-stress-independent "cementation, bonding or thixotropy" occurred and have tried to fit it into their own work and work of others, who may also have only assumed that it occurred.

As shown in detail in the additional 1976 (p. 93), 1981 (p. 468), and 1991 (p. 1312) references, all the writer's attempts to determine what actually occurs during aging have resulted in the finding that the additional stiffness and strength developed during aging seems almost entirely effective stress dependent and frictional. Thus, it seems reasonable that the authors also found an effective stress dependence for the rate of aging strength increase, especially when one realizes that the work imposed on a soil's structure to produce the changes that result in stiffening and strengthening can result primarily from the effective stress induced volume decreases occurring over time. At constant effective stress this volume decreases approximately linearly with the log of time and therefore the work done and perhaps the resulting aging shear enhancements increase approximately linearly with the log of time.

The writer found Fig. 9 particularly interesting because it shows the typical linear strength increase versus log time behavior found in many soil aging investigations, including the side shear setup of piles. However, he has never before seen it demonstrated at the very low effective stresses used in the authors' tests. Note in Fig. 9 how the points before EOP fit with the linear behavior of the many points after EOP. The writer has also seen such a before-after EOP fit with piles driven into clays. All these data support the concept of a relatively seamless process of soil structure stiffening and strengthening during primary, then during secondary, and then continued over longer aging times. The consolidation curves in Fig. 5 also suggest such relatively seamless behavior—particularly between secondary and aging. Although dividing the process into components, as done by the authors, may prove convenient for discussion or mathematical purposes, the writer believes that from a physical behavior standpoint it may eventually prove artificial and misleading.

However, it remains possible that special conditions exist in the high void ratio, very low effective stress, after slurry sedimentation and consolidation experiments described by the authors. True thixotropic behavior during slurry sedimentation and subsequent testing, as discussed in Schmertmann (1991, p. 1319), may have unexpected
importance in the clay structure changes occurring during aging. If so, the authors have not shown the connection. Also, the importance of strong Mohr envelope curvature at very low effective stresses may confuse the interpretation of aging on index tests for shear strength. The authors did not document or otherwise discuss envelope curvature.

Despite the above critique, the writer believes that the experiments described in this paper have contributed significantly to our further appreciation and understanding of soil aging effects with very low effective stress conditions.

**References**

**Table 5. Differences between the authors’ and the discusser’s studies**

<table>
<thead>
<tr>
<th>Object</th>
<th>Authors</th>
<th>Discusser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary soft clay</td>
<td>Sand, compacted soils, pile resistance etc.</td>
<td></td>
</tr>
<tr>
<td>Stress level</td>
<td>Very low effective stress (extended to normal state)</td>
<td>Ordinary stress level</td>
</tr>
<tr>
<td>Shear strength</td>
<td>Undrained shear strength ( \tau_{yr} = c' )</td>
<td>Effective stress analysis ( \tau_f = c' + (\sigma - \Delta u_r) \tan \phi' )</td>
</tr>
<tr>
<td>Viewpoint</td>
<td>Change in void ratio</td>
<td>Change in effective stress</td>
</tr>
</tbody>
</table>

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**Closure by Yi Xin Tang** and **Takashi Tsuchida**

The discusser has given precious comments and important information in his discussion, which will encourage those who are interested in the strength gain with time and try to crack the riddle of aging.

Though there are so many differences between the present study and the works by the discusser as compared in Table 5, their conclusions seem to agree with each other. That is, the effective stress plays an important role during the secondary process. Hence, the authors believe that “the strength gain with time is an effective stress dependent process,” in the discusser’s expression, is the truth.

As is usually accepted, the shear strength can be interpreted into two basic contributions; primarily coming from the effective stress induced volume decreases, and secondarily coming from the volume decreases occurring over time (strictly, effective stress is not essentially at constant). These two contributions can be estimated as expressed in Eq. (1) by assuming \( \beta = 1 \). Such an expression is able to estimate the shear strength by the point C shown in Fig. 3. However, it is repeatedly reported that soils experienced the secondary process is likely to yield at point D, not at point C. This means that the estimation based on the volume decreases could not evaluate shear strength perfectly. The remainder of \((p_r - p_i)\) in Fig. 3, e.g., \( \beta > 1 \) in Eq. (1), must be taken into consideration. This remainder does not relate to the volume decreases explicitly, and the void reduction between points C to D is neglected in Fig. 3.

Since this remainder enhances the shear strength without associating with the volume changes, the word of “cementation” is introduced to express this phenomenon. The authors are regretted that “cementation” is misunderstood to be “effective stress independent” or “of essentially constant effective stress.” This goes beyond the authors’ intend.

Whether “cementation” should be used in the particular situation stated above is still an arguable issue, indeed. By the authors’ understanding, the word “cementation” best describes the remainder, which enhances the shear strength over time and does not relate to the volume changes. When the researches in this field progress, and technical words are agreed to specify such a phenomenon, the authors are ready to use the new expressions.

Analyses in terms of effective stress will, of course, yield the theoretical results. If one wants to analyze shear strength in effective stress, he has to determine the cohesion \( c' \), the internal friction angle \( \phi' \) and the increment of pore water pressure \( \Delta u_r \) at failure when the stress state applied is totally understood. There are evidences (Mitachi and Fujiwara, 1987; Schmertmann, 1991) showing that the Skempton’s coefficient of pore water pressure, \( A_j \) decreases significantly with the duration of secondary process, so it seems acceptable to interpret that a part of the undrained shear strength gain is deduced from the decrease of \( A_j \) and subsequently the decrease of pore water pressure \( \Delta u_r \). However, the authors are wondering about the quantitative distinction between cohesion and internal friction, because of less information to draw a reliable envelope from Mohr’s circles. For example, Mitachi and Fujiwara (1987) have reported that the