Discussion: Settlement of floor slabs on stone columns in very soft clays

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Prompted by serviceability failures of floor slabs supported by stone columns in very soft clays, Pugh (2017) has performed a very useful back-analysis of both successful case histories and serviceability failures to assess the extent of settlement reduction that columns provide for widespread loading. Importantly, the author has acknowledged that the effectiveness of stone columns in reducing settlement may not be equivalent for the primary and creep components of settlement, a distinction that has rarely been made in previous published case histories (McCabe *et al.*, 2009). In the case of the two serviceability failures presented, the author has concluded that while the primary settlements of the treated ground were in keeping with those predicted by the analytical method of Priebe (1995) (with a friction angle of 40° assumed for the column material), the reduction in creep settlement offered by stone columns was actually quite limited.

The discussion contributors have considered the potential of stone columns to arrest creep settlements in a series of recent numerical modelling papers: (a) Sexton and McCabe (2013); (b) Sexton and McCabe (2016); and (c) Sexton *et al.* (2016). The soil profile at Bothkennar, Scotland was used as representative of the soft ground conditions in which stone columns have been deployed increasingly in recent years. The soft soil creep (SSC) isotache model (Vermeer and Neher, 1999; Vermeer *et al.*, 1998) was used in papers (a) and (b), whereas the creep-SCLAY1S isotache model (Sivasithamparam *et al.*, 2015) was used in paper (c); the former is an isotropic model, while the latter is an anisotropic model that can take account of both bonding and destructuration. These models were used in conjunction with unit cell analyses of stone columns in Plaxis 2D, allowing separate primary and creep settlement improvement factors to be derived.

The improvement factors relevant to primary settlement derived from the finite-element analyses were successfully benchmarked against those predicted using up-to-date analytical models for stone columns by Castro and Sagaseta (2009) and Pulko *et al.* (2011). Creep improvement factors, while still greater than unity, were found to be considerably lower in magnitude than their primary counterparts for a given reciprocal area replacement ratio (or area improvement ratio)

A/A_c , with the difference most pronounced at low A/A_c values. An illustration of this finding, adapted from Sexton and McCabe (2016), is provided in Figure 8, in which settlement improvement factor I_f is plotted as a function of A/A_c . The columns in this case are 600 mm in diameter, 14.5 m long (full length for the depth of Carse Clay modelled), and subject to a widespread load of 100 kPa. In the analyses, the poorer settlement performance has been linked to a vertical stress transfer process from soil to column during creep leading to additional column yielding. While these findings and those of Pugh (2017) appear to be compatible, the discussion contributors acknowledge that careful research at full scale, with appropriate instrumentation, is required to confirm these findings, as advocated strongly by Serridge (2016).

Author's reply

The author is grateful to the discussion contributors for their interest in the paper and in particular for drawing attention to their recent numerical modelling papers concerning the potential for stone columns to reduce creep settlements. The numerical modelling papers are extremely enlightening in relation to not only the efficiency of stone columns with respect to creep settlement reduction but also the mechanism by which creep reduces the overall efficiency of the columns.

The analytical model used by the discussion contributors is based on creep occurring during primary consolidation. In Figure 8, however, separate improvement factors have been provided for primary and creep settlements and a reasonable comparison can thus be made between the discussion contributors' numerical analyses and the author's field observations.

In the discussion contributors' paper (Sexton and McCabe, 2016), detailed data are presented for an area improvement ratio (A_i) of 15 (equivalent to 7% stone replacement (A_r)) which is also reasonably comparable to the author's case histories ($A_r = 5\%$ and 9%). The numerical analyses indicate that with 7% stone replacement the predicted creep settlement reduction is only about 55% of that predicted for primary settlement reduction.

Applying this predicted reduction to the field observations of primary settlement reduction (which were similar to

Figure 8. Settlement improvement factors for primary and creep settlements

predictions based on Priebe (1995)) leads to equivalent respective field creep reductions of 12% and 17%. Creep reductions of this limited magnitude are consistent with the author's general conclusion regarding the efficiency of stone columns with respect to creep and also indicate good agreement between theory and practice in relation to the significant reduction in the efficiency of stone columns for creep reduction.

Most significantly, the discussion contributors' numerical analyses (Sexton and McCabe, 2016) indicate that, by imposing additional load on yielding columns, creep leads to a reduction in column efficiency. The analyses further show that creep is accompanied by decreasing radial and hoop stresses (as a result of creep-generated excess pore pressures) leading to reduced lateral restraint and a further reduction in column efficiency.

The numerical analyses thus suggest that for very soft clays with a significant organic content (for which significant creep would be expected to occur concurrently with primary consolidation) creep would also significantly reduce the efficiency of stone columns with respect to primary settlement reduction. The discussion contributors' analyses would therefore also appear to provide a theoretical explanation in support

of the experienced-based view that stone columns are not well suited for settlement reduction in highly organic clays and peats.

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