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

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Contribution by C. Raison

Pugh (2017) has written a very interesting and informative paper that serves as a timely reminder of the risks to floor slabs carried on stone columns in very soft clays. The paper provides two extremely important conclusions: (*a*) that there is an upper limit to the degree of improvement feasible using vibro stone columns in very soft clays and (*b*) that it is essential to consider not only primary consolidation of soft clays, but also the potential for large secondary consolidation (creep) settlement. The discusser believes that some specialist ground improvement contractors fail to understand or properly consider primary consolidation, let alone the potential for large secondary creep settlements. There is also a risk in applying design methodologies based on an extreme simplification of the ground improvement system and soil properties without fully understanding the influence of the treatment process on the final performance.

Pugh (2017) focused on design methodologies in common usage in the ground improvement industry (Baumann and Bauer, 1974; Priebe, 1976, 1995). Both are based on the stone replacement and stress concentration ratios, as defined in the paper. The author attempted to compare field measurements for a handful of published case histories with theoretical improvement, and used these historic examples to argue an upper limit to the achievable degree of improvement and reduction in settlement.

In the discussion section of the paper, the author attributes the upper limit to the achievable reduction in settlement in soft clays to the development of pore pressures within clay soils during installation. Closer spaced columns result in higher pore pressures and a consequential reduction in the stress concentration ratio. However, this seems counterintuitive when considering the potential for more closely spaced stone columns to increase the available drainage to the surrounding clays and to act in a similar manner to vertical drains (McCabe *et al.*, 2009). The discusser believes that a more likely cause of the observed upper limit to the settlement reduction is the effect of ground disturbance caused by the installation of the stone columns.

It is well known that the initial penetration of a depth vibrator into clay soils can result in significant ground heave (McCabe *et al.*, 2013). This also occurs with large-displacement driven piles. During construction, soft clay acts as an undrained material with very little volume change possible. The initial penetration of a depth vibrator displaces the soft clay in a radial direction, then upwards. Because of the large displacement and high strains, this must result in disturbance to clay soils. A comparison with theoretical bearing capacity failure mechanisms would suggest that the ground displacement would be limited to an annular zone about one diameter wide around the stone column position. Thus, widely spaced stone columns would result in less disturbance than closely spaced columns. The effect of ground disturbance is more difficult to determine, but experience suggests that clay soils can be ‘over-worked’, leading to remoulding and softening. It is also intuitive that this would result in a proportional increase in compressibility (reduction in stiffness).

The method of construction must also be significant. The wet top-feed system uses a depth vibrator fitted with water jets for flushing the bore, maintaining stability and ensuring that stone supplied to the top of the bore can successfully reach the base of the bore. Intuitively, a jetting system should reduce the potential for disturbance around the stone column as compared with a dry bottom-feed system where the depth vibrator is ‘forced’ into the ground under its own weight or by pull-down from the vibro rig. However, the water itself can result in softening. Subtle differences in construction would be expected to result in significant variations in the degree of disturbance and could explain much of the scatter in the case history measurements.

As a further observation, it is disappointing to note that, for such an important ground improvement technique, reliable historical data are almost non-existent and the most recent case histories were published more than 25 years ago. Generally, these case histories relate to embankments, highly loaded test slabs or storage tanks, and all were large-diameter stone columns constructed using the wet top-feed process. This lack of reliable case history data is an indictment of the current state of the UK ground improvement industry and possibly the construction industry itself, and demonstrates a complete lack of any significant research and development. Perhaps more foundation failures will provide the incentive to improve this situation.

The author presented more recent data for two serviceability failures for floor slabs. In contrast to the historical data, both of these serviceability failures concerned smaller diameter stone columns installed using the dry bottom-feed process. In both cases, the stone replacement ratios and stone column diameters were significantly smaller than those reported in the case histories. For both projects, the author concluded that serviceability failure was a result of an underestimate of the primary consolidation settlement for the untreated ground and failure to even consider secondary consolidation. However, the author noted that the Priebe (1976, 1995) design methodology correctly predicted both the settlement reduction and stress ratio achieved by the stone columns.

The discusser's own experience suggests that the Baumann and Bauer (1974) method applied to very soft clays appears much more optimistic than the Priebe (1976, 1995) method and would probably have overestimated the settlement reduction. If the contractors for the two serviceability failures had used this design method, it may have resulted in a false sense of security.

The author attributed the serviceability failures to poor site investigation and a lack of information necessary for the design. However, the discusser believes that an additional contributing factor is the change in the way vibro stone columns are specified and procured by the construction industry. In the 1970s–1990s, vibro stone column ground improvement was considered to be a highly specialist 'black art' and, in the UK, was offered by only a small handful of contractors. The specialists were careful to fully 'understand' the ground and not to be too optimistic in what could be achieved. However, stone columns are now offered by a much wider range of ground improvement contractors with far less experience and perhaps more optimism. Vibro stone columns are now considered to be a 'product' comparable to a pile foundation. Most contracts are now let under competitive tender, which favours 'risk takers' and the cheapest proposal. In the discusser's view, this must lead to pressures on contractors to reduce costs, reduce engineering and increase risks.

The paper by Pugh (2017) needs to be carefully read and understood by specialist ground improvement contractors, consulting engineers and potential clients who may be considering stone column ground treatment to improve the performance of floor slabs on very soft clays. If nothing else, they must realise that the degree of settlement reduction will almost certainly be limited to less than 40% for most practical situations, and that there is still a significant geotechnical risk from both primary and secondary consolidation that needs to be addressed.

Author's reply

The author is grateful to the discusser for this positive and thought-provoking contribution which, as with previous discussions, has contributed to the understanding of the issues raised in the paper.

The author agrees with the discusser's view that increased soil displacement/disturbance is the fundamental cause of the decrease in initial stress concentration ratio with decreasing column spacing/diameter ratio. Displacement of very soft clay during column installation leads to yielding and excess pore pressures, which in turn results in reduced effective stresses as well as contributing significantly to a reduction in the undrained shear strength (from in situ to remoulded values) and undrained stiffness – all of which combine to reduce the initial lateral support to the columns and hence the initial stress concentration ratio. The basis of the author's opinion on installation disturbance was simply that the magnitude and extent of the increased pore pressures recorded during column installation were indicative of the magnitude and extent of the causal disturbance and yielding of the very soft clay.

Using bearing capacity theory, the discusser suggests that significant ground displacement during column installation would be limited to an annular zone about one diameter wide. On this basis, the disturbed annuli would touch tangentially at a spacing/diameter ratio of 3, which coincides with the divergence of the proposed settlement reduction curve (Figure 7(b)) from that of Priebe (1995).

A further discussion on the original paper (Pugh and Serridge, 2017) suggests that soil disturbance reaches a critical level with respect to column efficiency at about 15% stone replacement. This corresponds to a spacing/diameter ratio of about 2·5, at which point the annuli would overlap to within half the diameter of the adjacent columns.

Figure 7 indicates that any benefit provided by increasing stone replacement is entirely offset by increased soil disturbance when the spacing/diameter ratio falls to about 2. At this point the annuli would extend to the perimeters of the adjacent columns, indicating all of the soil surrounding the columns to be disturbed.

The discusser's suggested zone of annular disturbance thus appears to the author to sit very well with the observed decreases in stress concentration ratio and column efficiency with decreasing spacing/diameter ratio for both wet top-feed and dry bottom-feed installations. On the contrary, the discusser's view that closely spaced columns (with spacing/diameter ratios of 2 or less) would result in rapid dissipation of excess pore pressures and that wet top-feed installation should generate less soil displacement/disturbance is at odds with both the foregoing and the data presented in Figure 7. The latter suggests that, irrespective of installation method and variations in workmanship, the controlling factor with respect to the stress concentration ratio, settlement reduction and stone column efficiency for very soft clays is the column spacing/diameter ratio.

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