Influence of underground excavation on compensation grouting in clays; small-scale laboratory experiments

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ABSTRACT: This study aims to improve long-term compensation efficiency by grouting within the exclusion zone of underground excavation. The study proposes the existence of a neutral zone where the negative excess pore pressure generated during excavation can be used to significantly reduce the positive excess pore pressure generated during grout injection and hence counter consolidation. Small-scale laboratory testing is performed to verify the hypothesis. Results show that long-term compensation efficiency for normally consolidated and lightly overconsolidated clays can be improved by grouting closer to an excavation. The major concern on grouting closer to an underground excavation is the possibility of excavation face instability due to stresses exerted by grouting. Results indicate that no additional stresses are exerted on the excavation face if grouting is performed simultaneously with the excavation.

1 INTRODUCTION

Compensation grouting is gaining popularity in the construction industry as a method of settlement control to limit ground settlement due to underground excavation in soft ground. This method is based on the idea of replacing volume of ground loss with an equal volume of grout (Mair and Hight, 1994).

The major problem of compensation grouting in soft clay is that the amount of soil heave is significantly less than the amount of grout injected, particularly in normally consolidated clays. This low compensation efficiency is mainly attributed to consolidation settlement where the clay around the grout consolidates with time due to dissipation of excess pore pressure generated during the injection (Au et al., 2003). There is a preference for fracture grouting because it is considered to generate smaller excess pore pressure compared to compaction grouting. Improvement on compensation efficiency through use of different grout compositions, grouting methods (e.g. multiple simultaneous injection) and varying grouting geometries (e.g. closer injection spacing) have been studied (Soga et al., 2004). These studies are able to control the magnitude of excess pore pressure and hence the consolidation settlement. However, excess pore pressure will develop and consolidation settlement will prevail as long as grout is injected into saturated clay.

In the past, the efficiency of compensation grouting has been debated from a myopic viewpoint where the influence of excavations on compensation grouting is excluded. During excavation, the soil surrounding the excavation undergoes stress relief and results in a zone of negative excess pore pressure. If compensation grouting is performed within this zone of negative excess pore pressure, a zone of neutral stresses may exists where the negative excess pore pressure generated during excavation can significantly reduce the positive excess pore pressure generated during grouting. By overcoming the dominance of consolidation settlement, the efficiency of compensation grouting can be improved leading to cost savings in the construction industry.

There are major concerns over the face stability of open excavation when grout is injected too closely to the excavation (e.g. Friedman et al., 1996; Ikeda et al., 1996; Essler et al., 1999). Hence, the hypothesis on improving long-term compensation efficiency by grouting closer to an excavation requires justification. The possible risks of grouting too closely to an excavation needs to be examined.

This study aims to improve long-term compensation efficiency by grouting within the exclusion zone of underground excavation as shown in Fig. 1. Small-scale laboratory testing was performed to verify this hypothesis. The effects on soil deformation and stress development surrounding the excavation due to grouting closer to an excavation are investigated. The experiment aims to provide insights on the

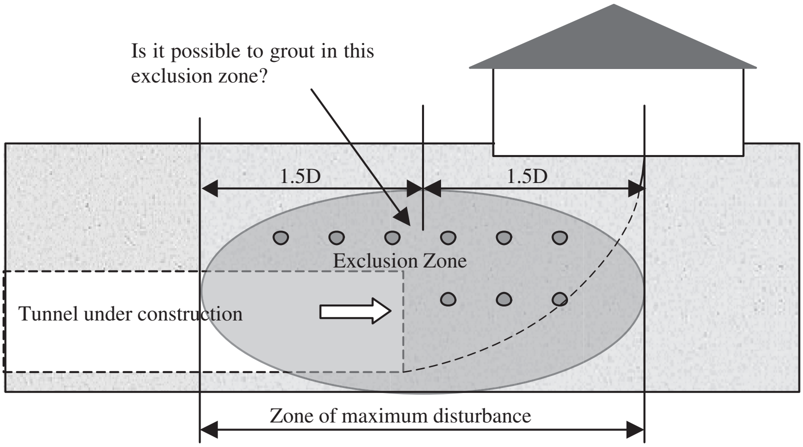

Figure 1. Grouting in exclusion zone in compensation grouting.

excess pore pressure development due to interactions between excavation and grouting in clays of different overconsolidation ratios.

2 LABORATORY EXPERIMENTS

Small-scale laboratory testing is undertaken using E-grade kaolin samples and the system layout (Fig. 2) is based on works by Au (2001). E-grade kaolin is mixed with de-aerated water according to a weight ratio of 1:1 using a mechanical mixer under vacuum condition to prevent development of air pockets in the clay sample. Normally consolidated and overconsolidated E-grade kaolin samples are prepared in a steel modified consolidometer and loaded with iron weights to the required consolidation ratios between 1 to 3.

Underground excavation and grouting operations are simulated using latex balloons at 50 mm height from the base of the consolidometer. Simulation of excavation is achieved by inflating one of the latex balloons (excavation balloon) before the clay slurry is poured into the consolidometer. The sample and the inflated excavation balloon are then consolidated together at different overconsolidation ratios. The final confining pressure before excavation and/or grouting operations was set to be 50 kPa. Upon completion of consolidation, the excavation balloon was deflated to a specific volume to a create volume loss in the clay sample resembling an underground excavation. The excavation balloon had an inflated volume of 15000 mm^3 and was deflated to 10000 mm^3 to generate a 5000 mm^3 volume loss. The second latex balloon (grouting balloon) was inflated to simulate ideal compaction grouting. The grouting balloon was generally inflated to a volume equalling the 5000 mm^3 volume loss. The radius of the model (50 mm) is

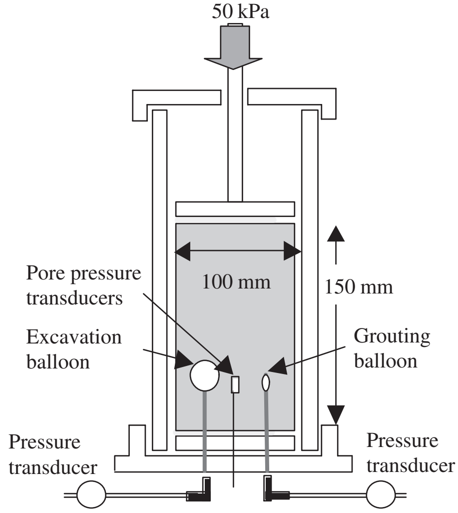

Figure 2. Schematic diagram of consolidometer.

relatively small compared to that of the excavation balloon (15 mm), which raises a concern of the boundary effect. A finite element analysis was conducted by Cheong (2003) and results show that the stress contours around the excavation balloon is indeed influenced by the boundary. However, when the FE analysis was performed with a model with greater boundary distance, the result still showed similar trends, which was in line with what was observed qualitatively in the laboratory. It should be noted that the buoyancy effect induced by the density difference between soil and grout is ignored in this experimental investigation.

The surface displacements of the sample are recorded throughout the experiment using a linear

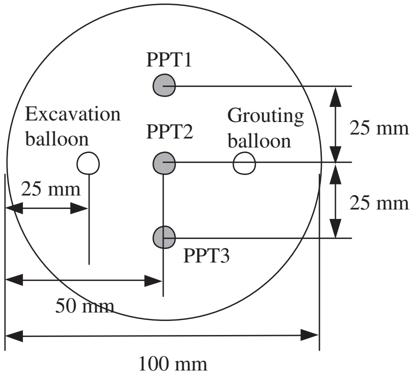

Figure 3. Locations of PPTs and balloons.

variable differential transducer (LVDT) to evaluate the immediate and long-term compensation effect. Displacements are measured with respect to a datum, which is the surface level of the sample after completion of consolidation and before the commencement of balloon deflation or inflation. The final sample height before injection is maintained at approximately 150 mm for all testing. Three pore pressure transducers (PPT) positioned at different locations in the sample are used to monitor the development of excess pore pressure in the sample during testing (see Fig. 3). Finally, pressure transducers (PT) installed at the bases of the injection needles are used to monitor the pressure changes in the excavation and grouting balloons.

Five different tests are performed as follows in E-grade Kaolin samples:

(a) *Isolated grouting* – only the grouting balloon is inflated to determine the net surface heave.
(b) *Isolated excavation* – only the excavation balloon is deflated to determine the net surface settlement.
(c) *Sequential grouting within exclusion zone* – the grouting balloon is inflated immediately within the exclusion zone after the excavation balloon is completely deflated.
(d) *Pre-conditioning within exclusion zone* – the excavation balloon is immediately deflated after the grouting balloon is fully inflated within the exclusion zone.
(e) *Simultaneous grouting within exclusion zone* – the grouting balloon is inflated and the excavation balloon deflated concurrently.

3 RESULTS

3.1 *Normally consolidated clay (OCR = 1)*

3.1.1 *Grouting far from exclusion zone*

For isolated grouting, the surface heaved when the grouting balloon was inflated by 5000 mm^3 as shown

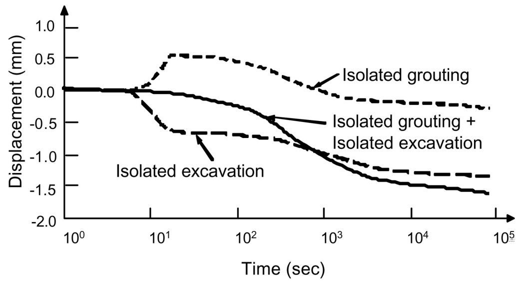

Figure 4. Consolidation settlement with time (OCR = 1).

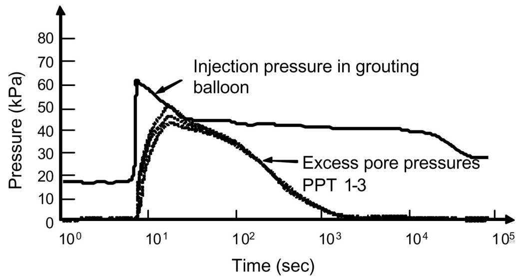

Figure 5. Injection and pore pressures for isolated grouting.

in Fig. 4. However, the surface settled with time and the final settlement is below the datum, which indicates that the excess pore pressures were generated by shearing associated with grouting. This is shown by the measured excess pore pressures and injection pressure in Fig 5. The surface heaved when the grouting balloon is inflated and the injection pressure reached a sharp peak in less than 2 seconds. The peak reflects the resistance experienced by the grouting balloon to initiate surface heave. The injection pressure decreased gradually as the surface continued to heave during the 10 s course of injection, which suggests soil softening and continuous shearing during heaving. Pore pressure measurements in the clay shows that positive excess pore pressures developed concurrently with the injection pressure. These excess pore pressures reduced to zero as the soil consolidated.

In Fig. 4, isolated excavation shows that the surface settled immediately in response to a 5000 mm^3 volume loss but consolidation caused further settlement due to dissipation of excess pore pressures generated by excavation-induced soil shearing.

Surface settlement due to grouting performed far from the underground excavation was obtained by superimposing the settlement due to isolated grouting onto the settlement due to isolated excavation as shown in Fig. 4. Superimposing is possible as the two settlements are regarded to be mutually exclusive and do not

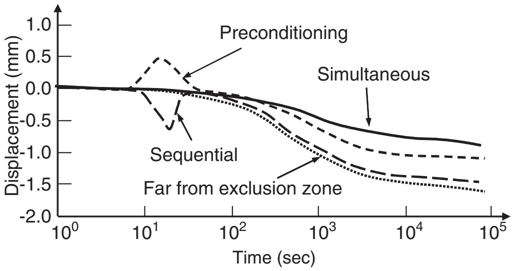

Figure 6. Settlements by different grouting methods.

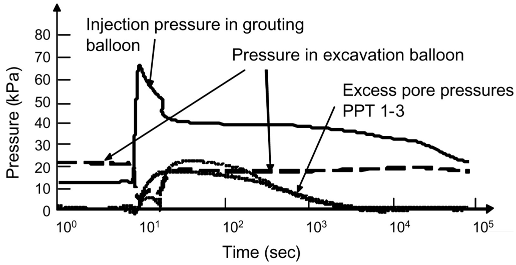

Figure 7. Injection and pore pressures in simultaneous grouting.

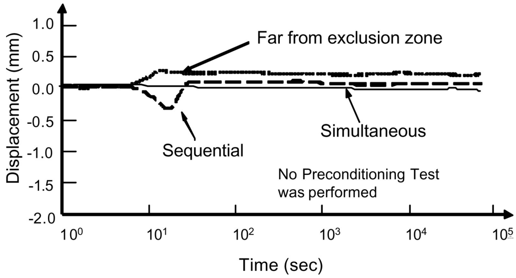

Figure 8. Settlement by different injection methods.

influence one another. The final settlement obtained by superposition is 1.7 mm below the datum with onset of creep.

3.1.2 *Sequential grouting*

Sequential grouting in Fig. 6 shows that the surface settled in response to a 5000 mm^3 volume loss created by the deflation of excavation balloon. The surface then responded immediately to the 5000 mm^3 inflation of grouting balloon and heaved. The surface settlement worsened with consolidation but the final settlement is less than that of grouting far from the underground excavation as shown in Fig. 6. Small creep settlement is observed.

3.1.3 *Pre-conditioning grouting*

Pre-conditioning of ground prior to underground excavation is simulated when grouting balloon is inflated followed by the deflation of the excavation balloon. Fig. 6 shows the surface heaved 0.5 mm due to the 5000 mm^3 inflation of grouting balloon and settled 0.5 mm back to the datum level when the excavation balloon is deflated 5000 mm^3. The final settlement is 1.1 mm below the datum and small creep settlement is observed.

3.1.4 *Simultaneous grouting*

In Fig. 6, simultaneous excavation and grouting (TA4) shows no sudden changes in surface level during excavation and grouting but gradual consolidation settlement. This is an ideal outcome of compensation grouting because surface structures would not experience sudden distortions. The final settlement is 0.9 mm and creep is observed.

Fig. 7 shows a significantly smaller magnitude of excess pore pressure (PPT2) of 20 kPa for simultaneous grouting compared to other tests, which explains the small final settlement. The increase in injection pressure and the decrease in excavation face pressure happened concurrently with no surface level change. The injection pressure is the same as other tests where the pressure peaked and gradually decreased, followed by a sudden drop to 45 kPa when injection is stopped. The pressure in the excavation balloon decreased from an initial pressure of 20 kPa to 5 kPa followed by a sudden jump to 15 kPa, which is less than the initial pressure (20 kPa). Hence, the excavation balloon did not experience additional stresses due to the inflation of the grouting balloon.

3.2 *Overconsolidated clay (OCR = 3)*

3.2.1 *Grouting far from exclusion zone isolated grouting*

Surface displacement due to grouting performed far away from the underground excavation is obtained by superimposing the settlement due to isolated grouting onto the settlement due to isolated underground excavation as shown in Fig. 8. For isolated grouting, the surface heaved when the grouting balloon was inflated and the final settlement achieved was 0.4 mm above the datum. Positive excess pore pressure developed concurrently with the increase in injection pressure to 25 kPa, which is lower than the excess pore pressure generated in OCR 1 (52 kPa) and OCR 1.5 (35 kPa). For isolated underground excavation, the surface settled in response to a volume loss of 5000 mm^3. The long-term settlement improved and heaved due to swelling of soil and final settlement was 0.15 mm below the datum. Hence, by summing the two processes, the ground heaved 0.25 mm and no long-term settlement was observed as shown in the figure. The small swelling in isolated excavation cancelled out the small consolidation observed for isolated grouting.

3.2.2 *Sequential grouting*

Sequential grouting in Fig. 8 shows the surface settled 0.3 mm in response to a 5000 mm^3 volume loss created by the deflation of excavation balloon. The surface responded immediately to the 5000 mm^3 inflation of grouting balloon and heaved by 0.4 mm resulting in a final heave of 0.1 mm above the datum. No long-term settlement was observed in the test.

3.2.3 *Simultaneous grouting*

Simultaneous grouting shows no sudden surface level change during excavation and grouting and no long-term settlement as shown in Fig. 8. The increase in injection pressure and the decrease in excavation face pressure happened concurrently with no surface level change. Significantly smaller excess pore pressure of 5 kPa in PPT3 was recorded compared to other tests (15 kPa), which verifies the small final settlement. This is an ideal outcome of compensation grouting because surface structures will not experience sudden stresses and distortions.

The pressure in the excavation balloon decreased from an initial pressure of 25 kPa to 5 kPa followed by a sudden jump to 10 kPa, which is less than the initial pressure of 25 kPa. Hence, the excavation balloon did not experience additional stresses due to the inflation of the grouting balloon.

Apart from the results presented in this Section, injection tests were performed on OCR = 1.5 specimens. Further details of the experiments can be found in Cheong (2003).

4 DISCUSSION

4.1 *Long-term compensation efficiency*

The effectiveness of compensation grouting is quantified by the "compensation efficiency η", which is the ratio of volume heaved (V_H) to initial grout volume (V_{inj}) (i.e. $\eta = V_H/V_{inj}$). In clay, η in short term is 100% as injection is done rapidly in undrained conditions. However, η decreases with time toward the long term compensation efficiency value η_{final} due to consolidation settlement. Negative efficiency values have been reported both field and laboratory experiments on very soft clays (Au et al., 2003).

The measured settlement data by different grouting methods was used to compute the final compensation efficiency in clay samples of OCR = 1, 1.5 and 3 as shown in Fig. 9. The results support a hypothesis that long-term compensation efficiency in normally consolidated and lightly overconsolidated clay can be improved by grouting closer to an underground excavation.

For OCR = 1, simultaneous grouting within exclusion zone achieved the highest long-term compensation efficiency (−40%) while grouting far from exclusion zone achieved the lowest efficiency of −160%. Grouting simultaneously within exclusion zone improved the long-term settlement by four times in normally consolidated clay. The highest long-term compensation achieved in lightly overconsolidated clay (OCR = 1.5) is also from simultaneous grouting within the exclusion zone (86%). This is a five times improvement in efficiency compared to the lowest efficiency of (−20%) due to sequential grouting. For heavily overconsolidated clay (OCR = 3), simultaneous grouting achieved 100% long-term compensation efficiency.

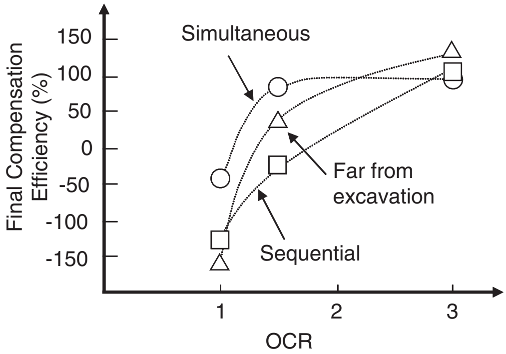

Figure 9. Final compensation efficiency obtained by different grouting methods for different OCRs.

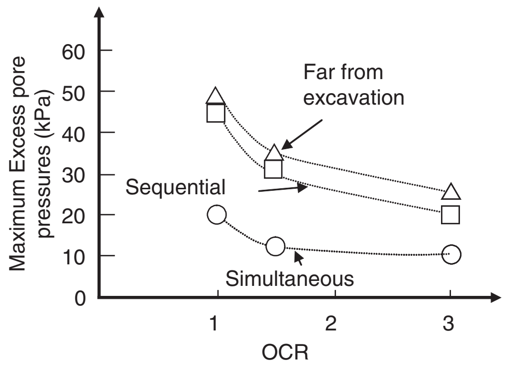

Figure 10. Maximum excess pore pressures recorded by PPT3 for different grouting methods.

Results verified that negative excess pore pressure generated during excavation significantly reduces positive excess pore pressure generated during grouting. Fig. 10 shows the excess pore pressure generated by different grouting approaches in samples of OCR 1, OCR 1.5 and OCR 3 at PPT3 in Fig. 2. Results show that excess pore pressure is influenced by the grouting approach. In normally consolidated clay, simultaneous grouting within exclusion zone resulted in the lowest excess pore pressure. The highest excess pore pressure was generated by grouting far from the exclusion zone. Same observations were made in lightly and heavily consolidated clays. Excess pore pressure in normally consolidated clay is almost double that in heavily consolidated clay. However, this high excess pore pressure in normally consolidated clay can be decreased by almost 2.5 times if simultaneous grouting is applied within exclusion zone.

The results show that sequential grouting is inferior in improving long-term settlement despite grouting within the exclusion zone. An insight into the excess pore pressure development of the different grouting approaches may provide explanations on the effectiveness of simultaneous grouting approach over sequential grouting. The development time for negative excess pore pressure due to excavation balloon deflating is observed to be very short in normally consolidated (3 s) and lightly overconsolidated clay (10 s). Hence, most of the negative excess pore pressure generated during balloon deflation may have dissipated should the grouting balloon be inflated after the completion of balloon deflation (sequential grouting). However, if balloon inflation is performed simultaneously with balloon deflation the negative excess pore pressure is fully utilised to reduce the positive excess pore pressure generated during balloon inflation. Ideal compensation grouting should therefore result in minimal change in surface level, which is consistent with Komiya et al. (2000).

Heavily consolidated clays are insensitive to long-term settlement due to compensation grouting. Surface level of all samples showed either net heaves or no surface level change. When isolated excavation is performed on heavily consolidated clay, the surface level of the sample heaved with time due to soil dilation and subsequent swelling. Dilation may cause additional generation of negative excess pore pressure aside from excavation, which may have eliminated consolidation settlement in the tests.

Cheong (2003) performed finite element analysis and showed that high shear zones developed in normally consolidated clay during the simulation of sequential excavation and grouting resulting in the generation of high excess pore pressure. On the other hand, FE simulation of simultaneous grouting resulted in a less intensive development of excess pore pressure in areas between the excavation and grouting points compared to sequential grouting.

4.2 *Face pressure*

There are concerns over the face stability of open excavation when grout is injected too closely to the excavation. Fig. 11(a) & (b) show the normalised pressure in the excavation balloon before and after simultaneous and sequential grouting, respectively. For simultaneous grouting, the final pressure in the excavation balloon is lower than the initial pressure for normally consolidated and lightly overconsolidated clays. However, for sequential grouting the pressure in the excavation balloon increased. As for heavily overconsolidated clay, the change in face pressure is always negative in value. The results verified that no additional stress is imposed on the excavation balloon during balloon inflation if simultaneous grouting is performed.

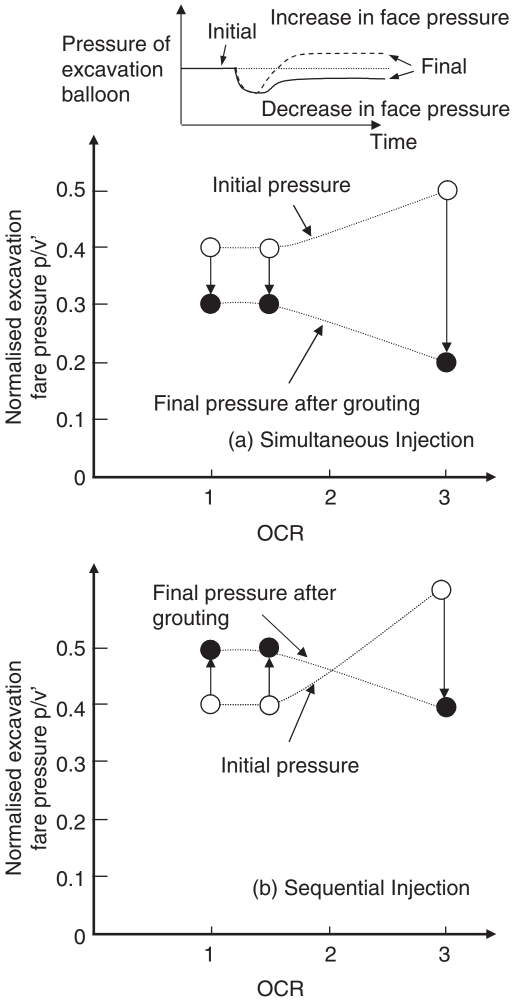

Figure 11. Pressure change in excavation balloon by simultaneous and sequential grouting.

5 CONCLUSIONS

The improvement in long-term settlement due to compensation grouting is influenced by grouting within the exclusion zone and the excavation and grouting sequences. Laboratory results show that grouting closer to an excavation can improve the long-term compensation efficiency in normally consolidated and lightly overconsolidated clays and not in heavily overconsolidated clays. The results also showed a significant reduction in the development of excess pore pressure within the sample when grouting is performed closer to an excavation. However, this reduction in excess pore pressure development is highly dependent on the elapsed time between excavation and grouting. The pressure in the excavation balloon was less than its initial value when simultaneous grouting was performed close to the excavation for normally consolidated and lightly overconsolidated clay. When sequential grouting was performed close to the excavation, the pressure in the excavation balloon increased at the end.

It should be noted that these findings are limited to the scale of the laboratory experiments. Further investigation is needed to examine whether or not these findings are applicable in the field scale.

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