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Geosynthetic reinforced column supported embankments with defective columns

Remblais renforcés par des géosynthétiques sur des sol ameliorés par inclusions rigides défectueuses

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ABSTRACT: Geosynthetic reinforced columns supported embankments generally require the installation of a large number of ground improvement columns, such as drilled displacement columns. Defects within such ground improvement columns can arise due to several reasons during construction, which may compromise the load-settlement response of the columns, and as a result, may adversely affect the performance of the embankment. The load transfer platform overlying ground improvement columns distributes embankment loads towards column heads through soil arching and membrane actions. Small scale model tests were conducted to understand how soil arching develops above a defective column. Imaging of the small-scale models indicated that for tall embankments, a plane of equal settlement may still develop above a defective column. However, the defective column was shown to increase the height at which a plane of equal settlement formed, and as such, shallow embankments may be susceptible to differential settlements if columns with defects are installed.

RÉSUMÉ : Les remblais renforcés par géosynthétiques nécessitent généralement l'amelioration du sol sous-jacent par l'inclusion d'un nombre important d'inclusion rigides. Des défauts dans de telles inclusions peuvent survenir pour plusieurs raisons lors de leurs construction, compromettant ainsi leurs portance et, par conséquent, le comportement du remblai. La plateforme de transfert de charge recouvrant les inclusions répartit les charges de remblai vers les têtes des inclusions par le biais de l'effet de voûte du sol et des actions de membrane. Des essais ont été menés sur des modèles physiques pour comprendre comment l'effet de voûte se développe au-dessus d'une inclusion défectueuse. L'imagerie de ces modèles a montré que pour les remblais hauts, un plan de tassement égal peut encore se développer au-dessus d'une inclusion défectueuse. Cependant, il a été aussi démontré que l'inclusion défectueuse augmentait la hauteur à laquelle un plan de tassement égal se formait, et à ce titre, les remblais peu profonds peuvent être sujets à des tassements différentiels si des inclusions présentant des défauts sont installées.

KEYWORDS: ground improvement, displacement columns, column supported embankments, soil arching.

1 INTRODUCTION

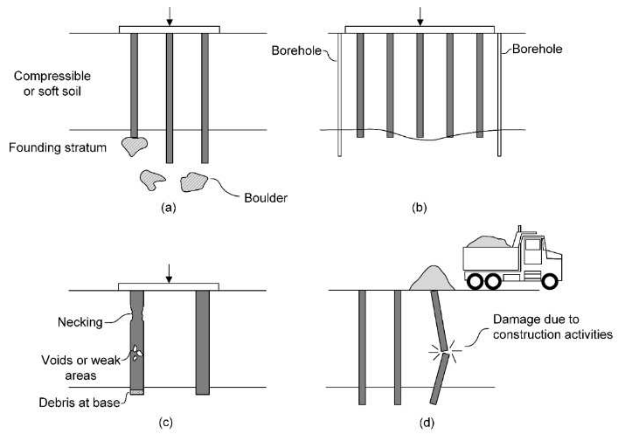
A geosynthetic reinforced column supported embankment (GRCSEs) is a form of ground improvement that is commonly adopted to provide ground support for infrastructure underlain by soft soils. In recent years drilled displacement columns (DDCs) have been increasingly adopted as a semi-rigid form of ground support for GRCSEs due primarily to the rapid installation rates that can be achieved with modern piling rigs. DDCs go by a number of other names including; auger pressure-grouted displacement piles, drilled displacement piles or Controlled Modulus Columns. Where ground conditions are suitable, DDCs have many advantages over conventional deep foundations however there are a number of disadvantages and risks associated with their usage in practice. These include; 1) DDCs are typically designed as unreinforced elements, and 2) DDCs are a full-displacement technique that are generally installed at rapid rates. While providing commercial benefits in terms of cost and time these two factors increase the potential risk for quality control issues, which may result in defective columns that fail to achieve their design requirements or at least columns whose integrity and load-settlement response is open to question.

When piles are connected by a rigid structural element such as a pile cap, the structural connection redistributes loads away from any defective piles towards the surrounding non-defective piles (Poulos 1997). However, when defective ground improvement columns are installed within a large group of columns beneath a load transfer platform (LTP), the redistribution of stresses is not as well understood, e.g., how does the overlying LTP utilise soil arching and membrane actions to distribute loads away from the defective column.

It has been shown that soil arching and membrane actions within an LTP progressively mobilise as the soft subsoil undergoes consolidation. Similar to the progressive mobilisation of arching and membrane actions, the settlement of a defective column will also develop as loads are progressively applied to it through both of these actions. Thus, the transfer of loads towards and away from a defective column within a group of columns overlain by an LTP will depend on complex soil-structure-geosynthetic interaction mechanisms, which are settlement dependent and will progressively develop over time.

This paper focuses on DDCs and describes situations that occur in practice where a potentially defective ground

Figure 1. Defects arising due to (a) geological sources; (b) inadequate



ground investigation; (c) construction techniques; and (d) construction actives, modified from Poulos (2005).

improvement column may occur. This is supported by a series of small-scale model tests that were undertaken to further understand the impact that a defective column may have on the performance of a GRCSE.

2 DEFECTIVE GROUND IMPROVEMENT COLUMNS

Defects within piles, or ground improvement columns, may arise due to a number of imperfections or conditions, which Poulos (2005) broadly grouped as geological imperfections, inadequate ground investigation, pile construction, loading during construction and loading during operation, as shown in Figure 1.

DDCs are often installed through soft clay and found in an underlying stiffer stratum. While site investigation may be undertaken to nominate DDC toes levels based on the required embedment into a founding stratum, the amount of site investigation required to define relatively shallow embedment lengths with confidence over a large embankment footprint is often prohibitive. As such, it is common practice to define the top of the DDC founding stratum, and start of embedment into the founding stratum, based on a site-specific correlation that usually involves assessing piling rig torque outputs, penetration rates and pull-down forces during column installation to enable construction phase verification. This approach requires careful calibration of the piling rig instrumentation to site investigation data, preferably by installing trial columns within close proximity of a cone penetrometer test (CPT). However, this approach at times is not without its limitations. For example, Michalowski et al. (2018) reported an embankment in Poland that was supported on 13,670 DDCs that were designed to be terminated at no less than 0.5 m into a founding stratum. The depth of this founding stratum was determined during DDC installation by a significant increase in piling rig torque. Some of these columns experienced an increase in rig torque prior to reaching the founding stratum due to thin lenses of stronger soil and were prematurely terminated, i.e., floating columns were installed without any embedment into the founding stratum. It was shown that the premature termination of DDCs in some locations contributed to excessive embankment surface settlements, which among other factors, played a role in the serviceability failure of this embankment.

Structural defects of DDCs are associated with the column structure itself and may include the column size (diameter or length) not being as per the design requirements or the column integrity being compromised. DDCs are typically unreinforced, and as a result, prone to a number of defects that arise due to their limited bending moment capacity. In addition to their unreinforced nature, DDCs are a full displacement column, displacing the soil laterally when the auger head penetrates into the ground. King et al. (2018), showed that it is inevitable that the installation of a large group of DDCs will cause flexural cracking of DDCs. While the vertical load-settlement response of a DDC is unlikely to be affected by flexural cracking, the lateral resistance of a cracked DDC is likely to be compromised. Nguyen et al (2019) simulated this installation sequence numerically using 3D FLAC analysis and arrived at a similar conclusion.

The installation of DDCs adjacent to recently completed DDCs (less than 24 hours) can cause the squeezing of fresh concrete from adjacent columns due to the lateral displacement of soils during DDC auger penetration. This squeezing can result in a reduction in DDC diameter and impact a columns verticality, both of which may reduce a DDCs axial stiffness. It is common practice to adopt a “hit 1 miss 1” installation sequence where adjacent DDCs are not installed within 24 hours of each other. Adopting such a sequence may reduce the risk of columns squeezing, however, it does introduce the requirement to track back over recently completed DDCs with a piling rig. As such, it may be necessary to introduce additional temporary works or careful sequencing to reduce the risk of damaging unreinforced DDCs due to the loading of piling rigs and other construction plant.

3 SMALL-SCALE MODEL TESTS

King et al. (2019a) presented a series of small-scale column supported embankment model tests that were conducted and imaged using synchrotron X-ray CT. In these experiments, a settlement plate was displaced vertically downwards to simulate subsoil settlement (δ_{sp}). Imaging of the specimens was undertaken at increments of subsoil settlement and digital volume correlation (DVC) techniques were applied to calculate total and incremental displacements of the embankment granular material at various stages of settlement plate displacement. This paper presents a series of additional tests that were undertaken using the model set up described in King et al. (2019a) where a single column was driven vertically downwards relative to the surrounding stationary columns to simulate the additional settlement that may arise due to a defective column.

Model tests were performed using an apparatus with columns arranged on an equilateral triangular grid. Sand was used to simulate the load transfer platform (LTP) granular material and was prepared using air pluviation in both dense and medium dense states. The model comprised circular columns with a centre-to-centre spacing (s) of 40 mm and a column diameter (d) of 12.6 mm, resulting in a replacement ratio (α) of 0.09. The central column was driven downwards in these tests at a ratio of central column displacement to settlement plate displacement of approximately 1:3.6, simulating a defective column that settles relative to the surrounding non-defective columns but remains stiffer than the subsoil. For the following discussion, the central column will be referred to as the defective column and settlement plate displacements have been normalised by the equivalent axisymmetric columns clear spacing (b'), where $b' = 1.05s - d$ for columns on an equilateral triangular grid.

3.1 *Results*

Incremental displacements and strains have been used to show the mechanisms governing soil arching and load transfer at specific increments of settlement plate displacements, meaning that displacement vectors are calculated between specific increments of settlement plate displacement.

The incremental normalised vertical displacements are presented in Figure 2 for model tests comprising a central defective column at two increments of normalised settlement plate displacement for both dense and medium dense sand. The symmetrical nature of the slices means that slices can be divided in two about a central line of symmetry, with the model tests comprising dense and medium dense sand displayed in the left and right half of each slice, respectively. The normalised displacements in Figure 2 show the additional settlement that the soil directly above the central column underwent compared to the surrounding non-defective columns. However, even with this additional settlement experienced by the defective column at the base of the embankment sand, differential settlements reduced with height above the column heads, such that a plane of equal settlement developed. Thus, for the arrangement modelled, a critical height still formed in the presence of the central defective column. Again, it is also evident that with increasing settlement plate displacement, greater amounts of settlement propagated to the sand/embankment surface above the critical height for samples of dense sand, while medium dense samples did not experience much of a change.

The incremental maximum natural shear strains are shown in Figure 3 for models comprising a central defective column at the same, with scans taken at the same location of the model and displacement increments as presented in Figure 2. It is evident in Figure 3 that the same failure surfaces as observed by King et al. (2019a) for models without a defective column, still developed above the non-defective column heads.

There are two distinct sets of failure surfaces, or shear bands, that develop from the interface between the column heads and the settlement plate. The first set of shear bands form and propagate above the column heads at an angle to the horizontal of approximately 55° to 65° and are referred to as Type 1 shear bands. The second set of shear bands form and propagate away from the column heads at an angle to the horizontal of approximately 25° to 35° to the horizontal. Both Type 1 and Type 2 failure surfaces developing above the non-defective column heads appear to be relatively unaffected by the presence of an adjacent defective column and exhibit similar magnitudes of shear strain to what was observed in tests without a central defective column by King et al. (2019a). In both models comprising dense and medium dense sand, the Type 1 shear bands above the defective column did not mobilise as much shear strain as the corresponding Type 1 shear band above the adjacent non-defective column. In the dense sand above the defective column, the extension of the Type 1 shear band that bounds the radial shear zone, mobilised only a small amount of shear strain compared to the same shear band above the non-defective column. The only shear band propagating from the defective column head in the dense sand that mobilised significant shear strain is the Type 2 shear band, which appears to be interacting with the shear band propagating from the adjacent non-defective column head. The differential settlement between column heads and settlement plate (or subsoil settlement) is responsible for mobilising shear bands that propagate into the granular material overlying column heads. In model tests comprising a defective column, the differential settlement between the defective column head and settlement plate ($\delta_{sp,def}$) is less than the differential settlement between non-defective column heads and the settlement plate, i.e., $\delta_{sp,def} < \delta_{sp}$. This reduction in differential settlement is why it was observed in Figure 3 that generally less shear strain was mobilised within the shear bands developing above the defective column head compared to the non-defective column heads. In mobilising less shear strain above the defective column head, less load would be transferred towards this column through soil arching compared to non-defective columns. This was also observed in centrifuge experiments undertaken by King et al. (2019b) where defective columns were seen to carry less load than the surrounding non-defective columns.

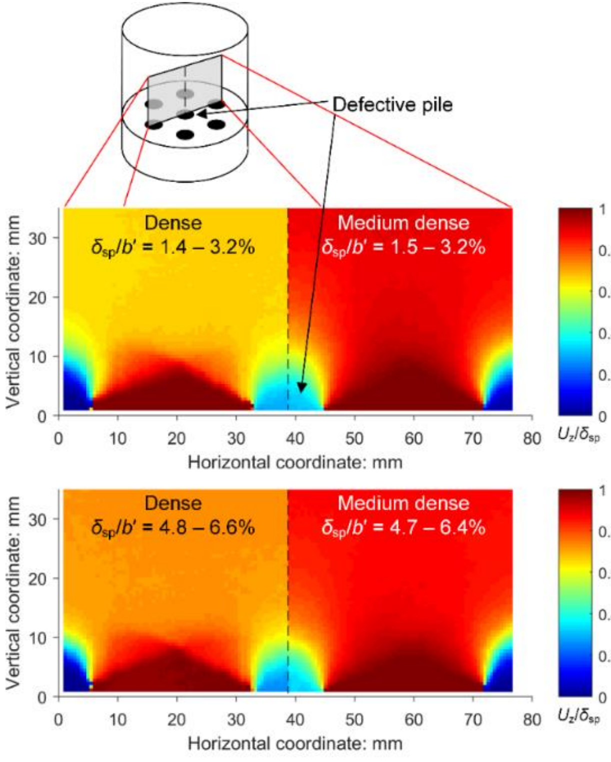


Figure 2. Slices of incremental normalised vertical displacements with dense sand on the left and medium dense sand on the right of each slice for triangular model comprising defective column.

As shown in Figure 2, a plane of equal settlement still developed within the sand mass when a defective column was present. This is further demonstrated in Figure 4 where the incremental normalised vertical displacements taken throughout the height of the sand mass are presented for three locations, amid columns, above the non-defective columns and above the central defective column. It is evident from the incremental displacements in Figure 4 that at some height above the non-defective column heads the vertical displacements within the sand mass approach become approximately equal, and hence, form a plane of equal settlement. The height at which this occurs is termed the defective column critical height ($h_{cr,def}$).

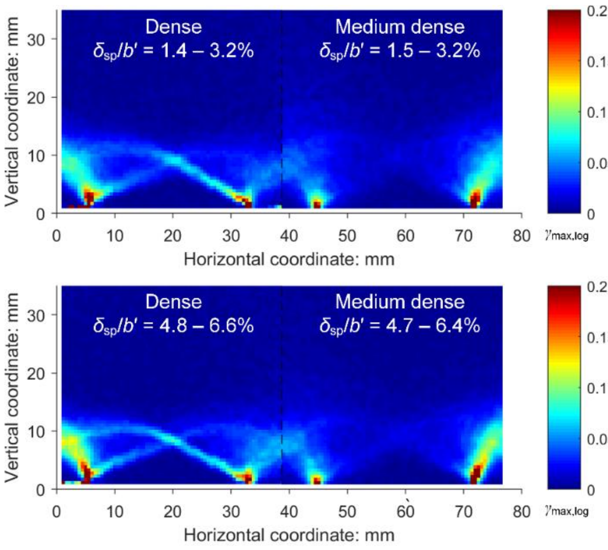
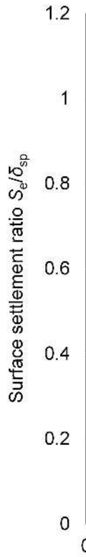


Figure 3: Slices at equivalent position as Figure 2 of incremental maximum shear strain for triangular model comprising defective column.



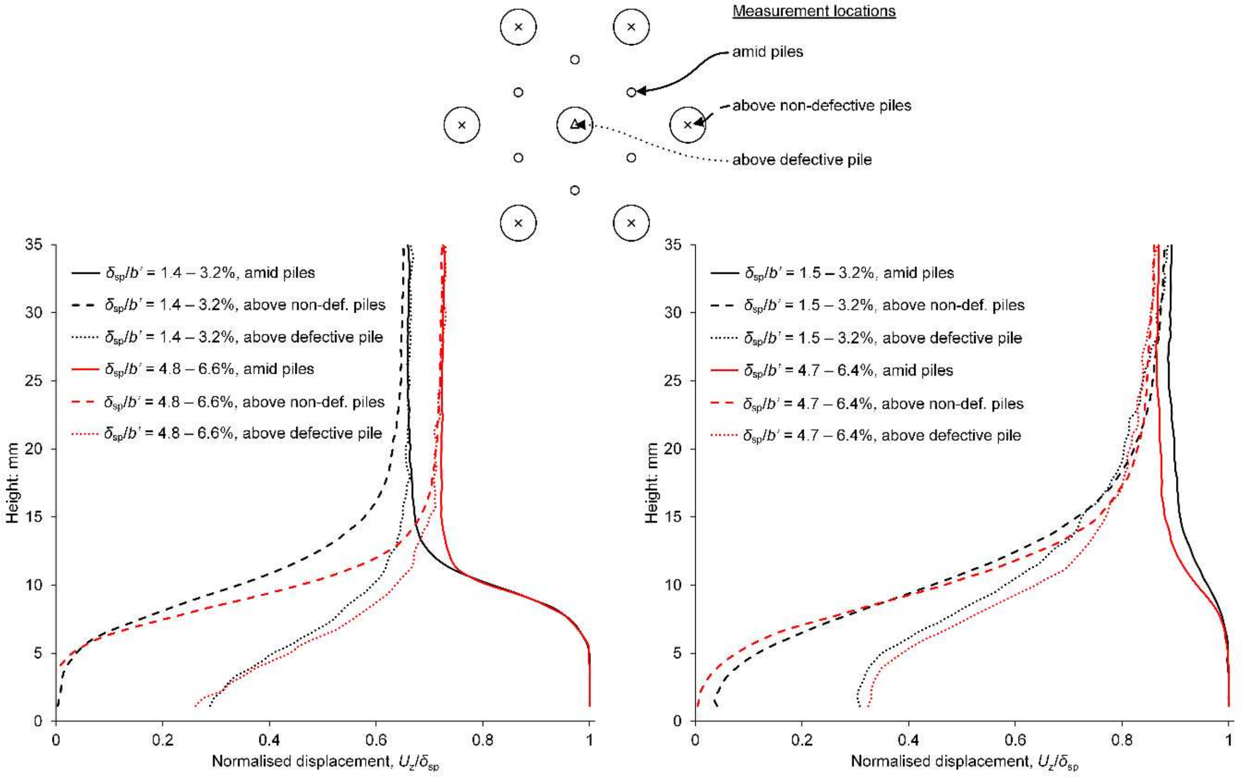


Figure 4. Displacements within model tests with defective pile comprising (a) dense sample; (b) medium dense sample.

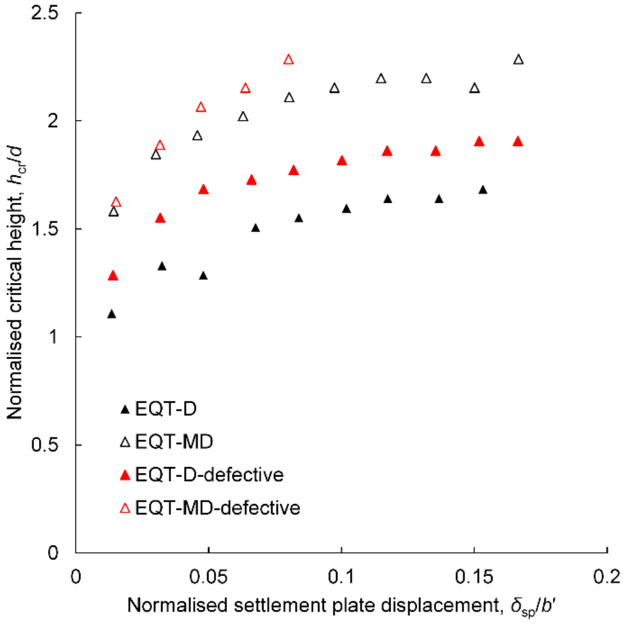
It is also shown in Figure 4a that models comprising dense sand underwent a progressive transition where an increasing portion of the settlement plate displacement propagated above the critical height to the embankment surface (total embankment settlement) with increasing increments of settlement plate displacement. Such a transition is not evident in Figure 4b for the sample comprising medium dense sand. This behaviour for both dense and medium dense samples of sand was also observed in model tests without defective columns (King et al. 2019a).

The critical height, defined as the height above the column heads where displacement amid columns and above columns becomes equal, is presented in Figure 5 for model tests comprising columns on an equilateral triangular arrangement both with and without a defective column. Unfortunately, the worm drive controlling the displacement of the central defective column failed during the test comprising a defective column and medium dense sand after a normalised settlement displacement of 8%, which meant that the test did not extend to displacements that allowed the final critical height to be determined. It is evident from Figure 5 that the defective column caused an increase in critical height for both dense and medium dense model tests.

The surface settlement ratio, defined as the ratio of embankment surface settlement to settlement plate displacement, for model tests both with and without a central defective column, is plotted against the normalised settlement plate displacements in Figure 6. Other than a small discrepancy between model tests comprising dense sand at small settlement plate displacements ($\delta_{sp}/b' < 5\%$), the surface settlement ratio between models both with and without a defective column match closely.

The model tests did not investigate different rates of defective column displacement, which would have simulated different severities of column defects. Different rates of defective column displacement would likely result in different outcomes. However, for the geometries and displacements tested, the results from Figure 5 and Figure 6 show that the defective column did not adversely affect the performance of the sand surface (above the critical height). It should be noted that the defective column increased the height at which the plane of equal settlement developed. As such, if a relatively shallow embankment was constructed where $h_e \approx h_{cr}$, then the presence of a defective column would likely result in differential settlements being experienced at the embankment surface.

Figure 5: Normalised critical height plotted against normalised settlement plate displacement for model tests comprising columns on a triangular grid both with and without a central defective column.



4 DISCUSSION

It has been shown that in many cases a defective column will exhibit a softer load-settlement response to non-defective columns, and as a result, may undergo additional settlement to these other non-defective columns when installed within a group supporting an overlying LTP (King et al. 2019b). In the event that a defective column does undergo additional settlement, the height required for a plane of equal settlement to develop within the embankment will be increased from h_{cr} to $h_{cr,def}$. The magnitude of this increase will primarily depend on the severity of the column defect and the additional settlement the defective column experiences because of its defect.

With the increasing demand to construct GRCSEs with shallow embankment heights, where h_e is approximately less than $1.5h_{cr}$, there is a significant risk that embankments will experience differential surfaces settlements if the underlying columns exhibit any differential axial stiffness. It is therefore essential that shallow height embankments are subjected to strict quality assurance and quality control practices to ensure that all columns exhibit consistent axial stiffness and undergo uniform settlement. In the event that a defective ground improvement column, such as a DDC, is installed within a shallow height embankment, the following remedial actions may be considered:

- Install replacement column(s). Consideration must be given to how the replacement column will behave and interact with the LTP. For example, if the replacement column is installed adjacent to the defective column, the span between the replacement column and the furthest adjacent non-defective column must be such that the critical height above these columns is less than the embankment height.
- Increase the thickness of the LTP/embankment. While it may not be possible for the finished embankment surface to extend above a certain level, there may be an opportunity to break the columns back, construct column heads and place the base of the LTP at a lower level.
- Perform site testing/trials and rigorous analysis to confirm that the defective column will not undergo additional settlement to the surrounding non-defective columns. If this can be established, then it may be possible to demonstrate that remedial actions do not need to be undertaken. However, it is noted that conventional finite element analysis alone may not be sufficient to confirm this due to the limitations with these techniques (Smith et al., 2021).

Where a defective column is present, the span between non-defective columns becomes such that the geogrid reinforcement is required to sag a relatively large displacement to mobilise sufficient strain and tensile loads to transfer loads away from the non-defective column. As such, increasing the stiffness of geosynthetic reinforcement or adding additional layers of reinforcement does not significantly reduce differential settlements between a defective and non-defective columns at the column head level or embankment surface.

There is a greater level of redundancy in taller GRCSEs, and there may be an ability for columns to exhibit differential stiffness while not affecting the performance of the embankment. This was shown in Figures 4 and 5. However, if the granular material is placed only up to a height of h_{cr} with predominantly fine-grained materials used in the embankment fill above this height, these fine-grained materials will not reduce differential settlements as efficiently as coarse-grained materials. Thus, for tall GRCSEs where a defective column is installed, it is likely to be beneficial to increase the thickness of the LTP granular material to allow for an increase in the critical height.

It is noted that the discussion presented is based on there being only one defective column installed. In the event that multiple defective columns are identified within close proximity to each other, then it is likely that the only remedial option would be to install replacement columns.

Figure 6: Surface settlement ratio versus relative displacement for models both with and without a defective column.

5 CONCLUSIONS

A series of small-scale GRCSE model tests comprising defective a column were undertaken while being imaged using synchrotron X-Ray CT. DVC techniques were applied to the CT scans to calculate full-field displacements and strains within the model embankments.

The results of the model tests showed that the presence of a defective ground improvement column increased the heigh required for a plane of equal settlement. The results suggest that shallow embankments are more susceptible to experiencing differential settlements at the embankment surface due to the presence of defective columns.

6 ACKNOWLEDGEMENTS

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