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# EFFECTIVENESS OF COMPACTION GROUT PILES IN IMPROVING FOUNDATION SOILS OF EXISTING RUNWAY

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## ABSTRACT

Compaction grout piles were used to minimize the liquefaction potential of the foundation soils of Tokyo International Airport at the intersection area of the two runways A and B. The compaction grout piles were intermittent to treat only the liquefiable soil layers and of varying diameter to account for the variable condition of the treated soils. This paper describes the performed grouting works and presents improvement results for one of the grouting stages. The presented results reveal the effectiveness of the adopted design and procedure in improving the liquefiable soils. The paper also discusses the improvement results with emphasis being on the obtained improvements at the vertical boundaries of the treatment zones. The discussion suggests that there is a loss of improvement at the boundaries and this loss is attributed to the boundary effect and the effect of variation of soil compressibility around the boundary of treatment zone. A correlation between a newly presented index called relative compressibility index (*RCI*) and the improvement at the boundary is identified. This correlation is useful in planning the intermittent treatments by compaction grout piles and implies that the loss of soil improvement at the boundary of treatment zone increases as *RCI* decreases.

## INTRODUCTION

The foundation soils of B-runway of Tokyo International Airport were assessed to be potentially liquefiable during earthquakes. Sand compaction piles were used to improve these soils and minimize their liquefaction potential. However, at the intersection area of A-runway with B-runway, it was required to keep on the normal operations of the airport with minimum disruption during the treatment period. Therefore, an alternative ground improvement method was needed for treating the soils at the intersection area. Compaction grout piles were decided for this purpose. Unlike the common compaction grout piles that are continuous and of theoretically uniform diameter, intermittent compaction grout piles of varying diameter were considered. The intermittent procedure was employed to treat only the liquefiable soil layers. The objective of varying the diameter was to approach given target improvements with accounting for the variable condition of the treated soils.

The grouting works were performed in five stages. In the first part of this paper, the performed compaction grouting works are described and the design of piles is summarized for the fourth stage. The second part presents improvement results and discusses the effectiveness of treatment in improving the liquefiable foundation soils with emphasis being on the improvement obtained at the vertical boundaries of treatment zones and the effect of variation of the initial soil properties, in terms of soil compressibility, on the improvement.

## PROJECT DESCRIPTION AND GROUTING PROCEDURE

Sand compaction piles were used to improve the foundation soils of B-runway of Tokyo International Airport against liquefaction during earthquakes. However, it was required to keep the intersection part of B-runway with A-runway in use during the treatment period, and therefore it was necessary to consider another ground improvement method. Among the potential methods, compaction grouting was decided as the appropriate alternative, because of the following factors:

- The possibility of keeping its large-size equipment away from the treatment area and the easy handling of its injection pipes, hoses and accessories to and from the treatment area.
- The drilling radius is small and thus causes minimal disturbance to the runway pavement that can be easily restored during the working hours.
- The possibility of treating only the liquefiable soil layers and leaving the others.
- The possibility of varying the injected volume of grout to account for the variation of soil properties throughout the treatment zone.

The daily compaction grouting works were performed in only seven hours in the night. This allowed for keeping on the normal operations of the airport with minimum disruption.

Figure 1 shows a plan view of the airport at the intersection of the two runways and the location of the compaction grouting treatment zone. Compaction grouting was performed in five

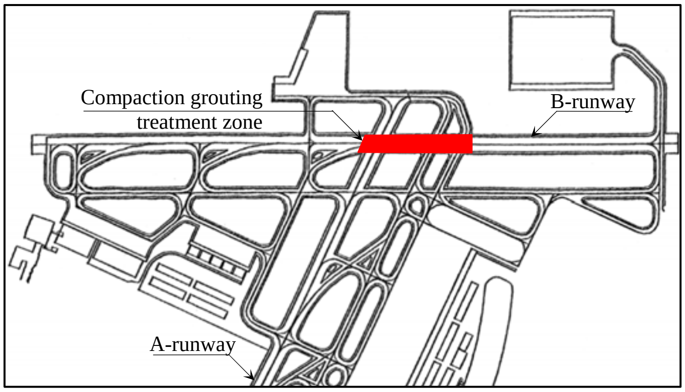



*Fig. 1. Zone of treatment by compaction grout piles at the intersection of A- and B-runways of Tokyo International Airport.*

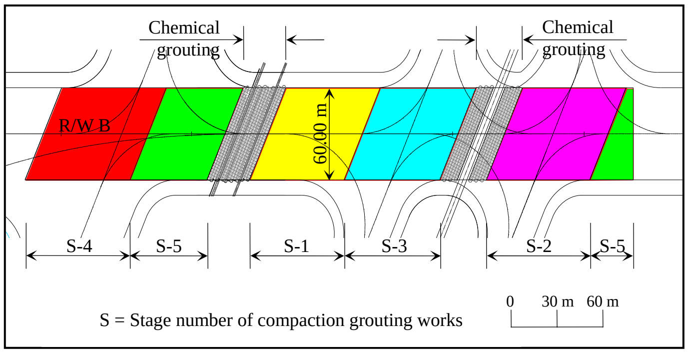



*Fig. 2. Locations and areas of compaction grouting stages.*

stages, S-1 through S-5. Figure 2 shows the locations and the areas of these stages. This paper describes the grouting works of the fourth stage (S-4). At the intersection part, chemical grouting was used to improve the soils at two areas because of existing underground ducts and pipelines. The areas treated by chemical grouting are also shown in Fig. 2.

A pre-treatment soil investigation and an assessment of the liquefaction potential of the soils revealed that the foundation soils are highly variable and consist of alternate layers of liquefiable and non-liquefiable soils. For this condition, the compaction grout piles represent an effective and economically feasible solution, where only the liquefiable layers can be treated. In addition, the compaction grout pile can be injected with a varying diameter, and can thus be designed to account for the variation of soil properties. Therefore, unlike the common compaction grout piles that are continuous and of uniform diameter, intermittent compaction grout piles of varying diameter were considered to improve the foundation soils of B-runway.

To minimize the disturbance of the runway pavement during the drilling and grouting works and during the normal airport operations, a specially manufactured steel casings (190 mm in outside diameter) with two internally welded rings (100 mm in inside diameter) and bolted caps were installed in the top 0.16 m of the pavement at the locations of the grout holes. The annular space (5 mm) between the casing and the pavement was filled with cement-bentonite milk. The drilling/injection pipe (73 mm in outside diameter) was guided by the casing during both drilling and injection. After completion of drilling and until starting injection, the casing was capped to allow for the normal operations of the airport. After completion of injection and pulling the injection pipe, the casing was extracted and the hole was filled with cement paste.

The compaction grout piles were injected by staging upward. Each pile comprised a number of grout bulbs that were successively injected into the treatment layers with a depth interval of 0.33 m. Upon completion of a given bulb injection, the injection pipe was raised to the depth of the next one by means of a hydraulic jacking system. For the untreated soil layers, during raising the pipe, the grout was being pumped to fill the space left behind the pipe until reaching the lower boundary of the next treatment zone or the pavement surface.

The used grout was a mixture of fines-containing aggregate, cement and water. The grout had a slump of less than 5.0 cm and was injected under an average rate of 0.04 $m^3$/min. The injection of a given grout bulb was limited by injecting a pre-determined grout volume corresponding to a given assumed uniform diameter of the grout pile or reaching an injection pressure of 6.0 MPa. Flow-pressure recording units connected to the delivery lines were used to monitor the injected grout volume and the attained injection pressure and to suspend the injection process upon reaching a limiting criterion. A cumulative pavement upheave value of 7.0 cm was also considered as a limiting criterion. The grout was mixed on site using auger mixers and pumped by high pressure positive displacement piston-type pumps. The grout plants were mounted on trucks for easy shifting as the work progresses.

## GROUND CONDITIONS AND GROUTING DESIGN

Twenty pre-treatment SPT tests (B-1 to B-20) with recovered soil samples were conducted at the area of S-4. Figure 3 shows the area of S-4 and the locations of the SPT tests. The recovered SPT samples indicated highly variable soils. The general strata of soil profile are summarized as follows:

- Pavement: dark gray to dark brown crushed stone overlain by asphalt of approximately 0.30 m thick, extends from the surface to a depth of approximately 0.90 m; brown gray to dark gray fine sand, extends from approximately 0.90 m to 3.00-3.75 m.
- Bs: highly heterogeneous layer made of construction waste, extends from approximately 3.00-3.75 m to 5.80-7.00 m, fine content ($F_c$) of 20-60%.
- Cs: dark gray to black gray sandy silt.
- As0: dark gray fine sand, $F_c$ of 30-50%.
- Ac1: black gray to dark gray silt to clayey silt.
- As1: dark gray silty sand to sand, $F_c$ of 10-40%.
- Ac2: dark gray silt to sandy silt.
- As2: dark gray silty sand, $F_c$ of 10-25%.
- Ac3: dark gray silt to sandy silt.

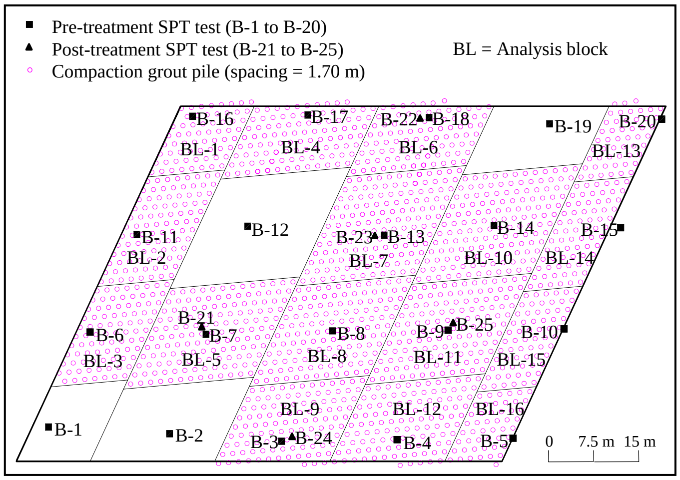



*Fig. 3. Fourth stage (S-4) of treatment by compaction grout piles: locations of pre- and post-treatment SPT tests and areas of analysis blocks.*

To assess the liquefaction potential of the foundation soils with accounting for the variation of soil properties, the area of S-4 was divided into blocks, the borders of which were determined at the mid-distances between the pre-treatment SPT borings. The blocks of the liquefiable soil layers are numbered in Fig. 3 (BL-1 to BL-16). The depth intervals of these soil layers are summarized in Table 1. For these layers, target N-values that minimize the liquefaction potential were back-calculated and the corresponding replacement ratios ($a_S$) of the compaction grout piles (that result in these target N-values) were estimated. $a_S$ is defined as the ratio of effective cross-sectional area of compaction grout piles to the area of treated soils. The piles were laid out on a triangular pattern of 1.70 m in spacing (see Fig. 3). For a given soil layer, the grout volume corresponding to the estimated $a_S$ was calculated assuming a uniform pile diameter ($\phi$) throughout the layer depth. In Table 2, $a_S$ and $\phi$ are summarized for the treatment layers. A total of 1,595 intermittent compaction grout piles were injected in S-4.

Because of the intermittent grouting procedure and the small thickness of some treatment layers, there was an uncertainty about the effectiveness of treatment near the vertical boundaries; whether the improving effect is local to the soils being treated or it is significantly lost into the adjacent untreated soils. Therefore, as a precaution against the questionable improvement at the boundaries, an additional grouting, henceforth called auxiliary grouting (A), was considered by extending the piles by 1.0 m in the sandwiched soil layers that were assessed as non-liquefiable; no auxiliary grouting was considered for the Bs layer.

## IMPROVEMENT RESULTS

To evaluate the improvement due to treatment, five post-treatment SPT tests (B-21 to B-25) were conducted at the locations shown in Fig. 3. In this section, the improvement results are presented and discussed for BL-5 and BL-11 of S-4. Figure 4 shows a comparison between the pre- and post-treatment SPT N-values through the foundation soils of the two blocks. Also shown in the figure are the target N-values, the fines content ($F_c$) of the pre-treatment SPT samples, the depth intervals of the liquefiable soil layers, and the depth intervals of the treated (T) and untreated (U) zones, as well as

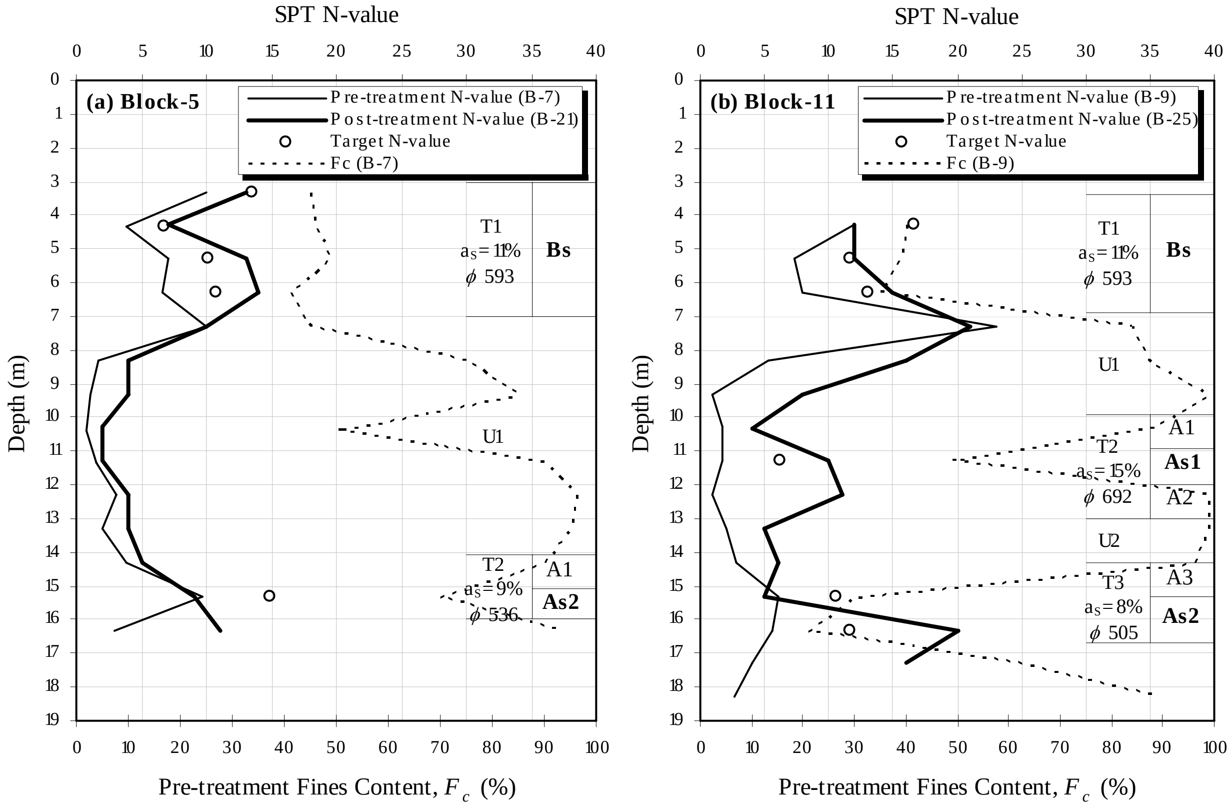
Table 1. Depth intervals of liquefiable soil layers (m).

| Block # | Bs | As0 | As1 | As2 |
|---|---|---|---|---|
| BL-1 | 3.60-6.80 | 8.00-8.90 | - | - |
| BL-2 | 3.95-6.50 | - | - | 15.95-17.40 |
| BL-3 | 3.75-6.55 | 7.85-8.20 | - | - |
| BL-4 | 3.15-7.00 | - | 11.70-13.80 | 15.75-16.90 |
| BL-5 | 3.00-7.00 | - | - | 15.10-15.95 |
| BL-6 | 3.40-6.15 | - | 10.60-11.70 | 13.30-13.70 |
| BL-7 | - | 8.25-8.75 | 9.80-13.25 | 13.90-14.70 |
| BL-8 | 3.20-7.00 | - | 11.80-13.80 | 15.20-16.95 |
| BL-9 | 3.40-6.60 | - | 11.70-12.90 | 14.90-16.85 |
| BL-10 | 3.91-6.66 | - | 10.45-12.70 | 13.75-14.80 |
| BL-11 | 3.40-6.90 | - | 10.90-12.00 | 15.30-16.70 |
| BL-12 | 2.80-6.80 | - | - | 15.35-16.90 |
| BL-13 | 4.00-6.80 | - | - | 12.40-16.90 |
| BL-14 | - | - | 9.40-12.60 | 13.80-17.70 |
| BL-15 | 3.40-6.80 | - | 10.80-12.70 | 15.30-16.90 |
| BL-16 | - | - | - | 15.10-17.15 |

Table 2. Replacement ratios ($a_S$) and diameters ($\phi$) of compaction grout piles.

| Block # | $a_S$ (%) | | | | $\phi$ (mm) [1] | | | |
|---|---|---|---|---|---|---|---|---|
| | Bs | As0 | As1 | As2 | Bs | As0 | As1 | As2 |
| BL-1 | 11 | 11 | - | - | 593 | 593 | - | - |
| BL-2 | 11 | - | - | 9 | 593 | - | - | 536 |
| BL-3 | 11 | 11 | - | - | 593 | 593 | - | - |
| BL-4 | 11 | - | 16 | 9 | 593 | - | 715 | 536 |
| BL-5 | 11 | - | - | 9 | 593 | - | - | 536 |
| BL-6 | 11 | - | 16 | 9 | 593 | - | 715 | 536 |
| BL-7 | - | 11 | 16 | 9 | - | 593 | 715 | 536 |
| BL-8 | 11 | - | 16 | 9 | 593 | - | 715 | 536 |
| BL-9 | 11 | - | 16 | 9 | 593 | - | 715 | 536 |
| BL-10 | 11 | - | 16 | 9 | 593 | - | 715 | 536 |
| BL-11 | 11 | - | 15 | 8 | 593 | - | 692 | 505 |
| BL-12 | 11 | - | - | 8 | 593 | - | - | 505 |
| BL-13 | 11 | - | - | 8 | 593 | - | - | 505 |
| BL-14 | - | - | 15 | 8 | - | - | 692 | 505 |
| BL-15 | 11 | - | 15 | 8 | 593 | - | 692 | 505 |
| BL-16 | - | - | - | 8 | - | - | - | 505 |

[1] *Pile spacing = 1.70 m (triangular pattern)*




Bs, As1, As2 = soil layers; T = treated zone; U = untreated zone; A = auxiliary grouting; $a_S$ = replacement ratio; $\phi$ = diameter of compaction grout pile

*Fig. 4. Comparison between pre- and post-treatment N-values of SPT test: (a) BL-5; (b) BL-11.*

$a_s$ and $\phi$. The difference in depth between a given liquefiable soil layer and the corresponding treatment zone represents the length of the auxiliary grouting. For example, A1 and A2 (each of 1.0 m in length) in Fig. 4-b represent the auxiliary grouting above and below As1, respectively; T2 represents the treatment zone of As1.

The comparison shown in Fig. 4 reveals that the liquefiable soils were significantly improved. For most of the liquefiable soil layers, the attained improvements are larger than the target ones. Considering the actually obtained improvements, an assessment of the overall condition of the foundation soils indicated satisfactory results and effectiveness of the considered treatment against liquefaction.

For a given treatment zone, the attained improvement as shown in Fig. 4 is variable throughout the depth interval of treatment. The improvements at the upper and lower boundaries of treatment zones are small or very small compared to the improvements attained within the treatment zones (except for As2 layer; this exception is discussed below). It is also seen that significant improvements were attained for the untreated soils (U1 of BL-5, and U1 and U2 of BL-11) that are sandwiched between the treatment zones. Such improvements are large and comparable with the improvements of the treated soils. These observations indicate that the treatments at the boundaries of treatment zones significantly improved the adjacent untreated soils and that the improving effect was not only local to the soils being treated, but extended considerably beyond the vertical boundaries of treatment zones within the adjacent untreated soils. The improvement below As2 corroborates this conclusion. The loss of improvement at the boundary of treatment zone and the improvement of the adjacent untreated soils is defined herein as the boundary effect. Therefore, had not the auxiliary grouting been considered, the treatment of the liquefiable soil layers should have contributed more to the adjacent soils beyond the boundary of treatment and thus resulted in smaller improvements of the soils required to be improved.

## EFFECT OF SOIL COMPRESSIBILITY

The results in Fig. 4 indicate that the variation of initial soil properties around the boundary of treatment zone is likely a factor contributing to the loss of improvement at the boundary. In this section, the effect of variation of soil properties in terms of $F_c$ is discussed. $F_c$ is an intrinsic soil parameter and is used herein as a representative of the soil compressibility; the larger the $F_c$, the more compressible the soil.

An examination of the results in Fig. 4 reveals that the soils at the upper boundaries of A1 of BL-5 and A3 of BL-11 are less compressible than the adjacent upper soils and more compressible than the adjacent lower soils. It is seen that the corresponding improvements at the upper boundaries of A1 of

BL-5 and A3 of BL-11 are smaller than those of the adjacent upper soils and larger than those of the immediately adjacent lower soils. It is also seen that the initially less compressible soils at the upper boundary of As2 (for both BL-5 and BL-11) did not experience significant improvements, while the upper and lower adjacent soils that are relatively more compressible experienced significant ones. These observations suggest that the treatment at the boundary was improving more in the direction of the relatively more compressible soils and imply that the loss of improvement due to the boundary effect will be larger if the treated boundary soils are less compressible than the adjacent untreated soils. In accordance with this, it is worth mentioning that the post-treatment SPT borings included grout recovered from the depth intervals 6.70-7.80 m and 6.90-8.70 m of BL-5 and BL-11, respectively. This indicates that the grout injected at the bottom of the Bs layer should have traveled into the soils below the Bs layer; in terms of $F_c$, the soils below the Bs layer are more compressible than the Bs layer.

As for the intermediate treatment zone of BL-11 (T2), it is seen that the improvements at the upper and lower boundaries are relatively larger than those at the lower boundary of T1 and the upper boundary of T3. The larger $a_S$ of T2 was essentially a factor contributing to this larger improvement. However, by carefully examining the results in Fig. 4-b, it is seen that the variation of soil compressibility around the boundaries of T2 is not as large as those around the lower boundary of T1 and the upper boundary of T3. This suggests that the smaller variation of soil compressibility around the boundaries of T2 most likely resulted in a smaller loss of improvement at the boundaries; and therefore, relatively larger improvements were attained at the boundaries of T2.

A rigorous analysis of the effect of variation of soil compressibility around the boundary of treatment zone on the loss of improvement at the boundary is difficult owing to several factors including the natural variability of the treated soils, the variation of the thicknesses of treated and sandwiched untreated soils, the variation of $a_S$, and the inclusion of grout in the recovered samples. However, this effect may be understood, if the attained improvement (or loss of improvement) at the boundary can be correlated to an index representing the compressibility or the relative compressibility of both the treated and the adjacent untreated soils. For this purpose, an index called Relative Compressibility Index (*RCI*) and defined as the ratio of the fines content of the treated soil, $F_{c(T)}$, to that of the immediately adjacent untreated soil, $F_{c(U)}$, is presented herein. Figure 5 shows a correlation between *RCI* calculated for the soils around the boundary lines and the corresponding improvement. In calculating *RCI*, the values of $F_{c(T)}$ and $F_{c(U)}$ were interpolated at 0.5 m from the boundary line for the treated and untreated soils, respectively; $F_c$ at 0.5 m is assumed to reasonably represent the corresponding soil. For the treatment layers of less than 1.0 m in thickness, such as As2 of BL-5, $F_{c(T)}$ is calculated at the mid-thickness of the layer. The improvement represented in Fig. 5 is the difference between the pre- and post-treatment N-values that are interpolated at the boundary line.

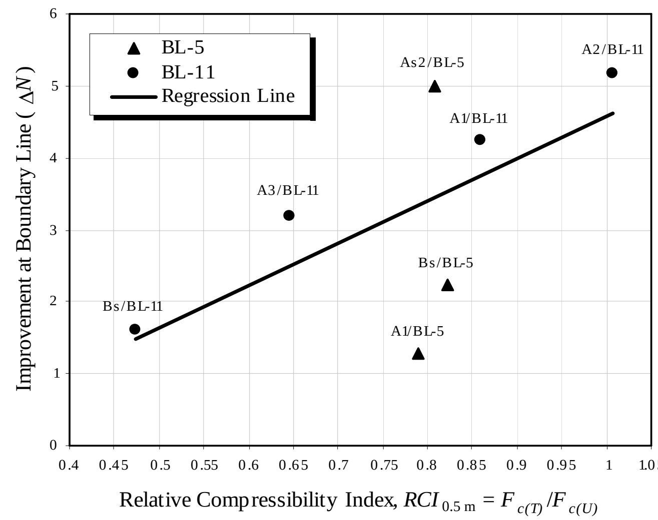



*Fig. 5. Correlation between improvement at boundary of treatment zone and relative compressibility index.*

The scattering shown in Fig. 5 is most likely attributed to the natural variability of the treated soils, the variation of $a_S$, the variation of the thicknesses of the treated and sandwiched untreated soils, and the existence of grout in the recovered SPT samples (the data point representing the lower boundary of As2 of BL-11 showed large scattering and therefore is not included in the figure). The attained improvement at the boundary of treatment zone should be independent of the effect of variation of soil compressibility around the boundary, if *RCI* = 1.0 (i.e., both the treated and untreated soils in the vicinity of the boundary line have the same compressibility characteristics). In other words, it can be said that an *RCI* of 1.0 means that the loss of improvement at the boundary is due only to the boundary effect. The trend of the improvement loss at the boundary of treatment zone with the variation of soil compressibility around the boundary, as shown by the correlation in Fig. 5, is in accordance with the above observations and discussions. It indicates that the improvement loss at the boundary is the least for *RCI* = 1.0 and that it increases practically linearly as *RCI* decreases. The improvement corresponding to *RCI* = 1.0 takes account of the improvement loss due to the boundary effect, while the improvement corresponding to a given value of *RCI* of less than 1.0 takes account of the improvement loss due to both the boundary effect and the effect of variation of soil compressibility around the boundary. This correlation provides an important guideline that will be essentially useful in planning intermittent treatments by compaction grout piles.

Despite the highly variable nature of the treated soils, the above discussion gives insights on the soil improvement at the boundary of treatment zone, for intermittent treatment by compaction grout piles. However, further investigations are required to rigorously evaluate the relative effects of the potentially influencing parameters, such as the variation of soil compressibility around the boundary, the replacement ratio, and the thicknesses of treated and sandwiched untreated soils, on the loss of improvement at the boundary of treatment zone.

## ACKNOWLEDGEMENT

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## SUMMARY AND CONCLUSIONS

In this paper the compaction grouting works that were performed to minimize the liquefaction potential of the foundation soils of Tokyo International Airport at the intersection of the two runways A and B were described. Compaction grouting was selected for this job, because of the possibility of keeping its large equipment away from the treatment area and the minimum disturbance it causes to the runway pavement. The daily grouting works were performed in seven hours in the night. This allowed for keeping on the normal operations of the airport with minimum disruption.

The foundation soils are highly variable and consist of alternate layers of liquefiable and non-liquefiable soils. Therefore, intermittent compaction grout piles of varying diameter were considered to treat only the liquefiable layers and to account for the variable condition of the treated soils. The piles were injected in five stages. Improvement results of the fourth stage, in which 1,595 piles were injected, were presented and discussed. It was found that the treatment could effectively treat the foundation soils as targeted.

The discussion presented in the paper emphasized the obtained improvements at the boundaries of treatment zones. It was found for the treatments at the boundaries that the improving effect is not only local to the soils being treated, but extends to significantly improve the adjacent untreated soils beyond the boundary of treatment zone. As a consequence, it was concluded that considering an auxiliary grouting beyond the limits of liquefiable soils is a useful precaution to minimize the improvement losses at the boundaries of the soils required to be improved.

The discussion also revealed that the variation of initial soil compressibility around the boundary of treatment zone significantly influences the obtained improvement at the boundary. The treatment at the boundary is improving in the direction of the relatively more compressible soils, and therefore the loss of improvement at the boundary will be larger if the treated boundary soils are less compressible than the adjacent untreated ones. Based on the available improvement results and fines contents of the treated soils, a correlation was identified between an index called relative compressibility index (*RCI*) and the obtained improvement at the boundary of treatment zone. *RCI* is defined as the ratio of $F_c$ of the soils at 0.5 m from the boundary in the treated zone to that in the sandwiched untreated zone. This correlation is useful in planning the intermittent treatments by compaction grout piles and implies that the loss of improvement at the boundary of treatment zone is the least for *RCI* = 1.0 and that the loss of improvement increases practically linearly as *RCI* decreases.