International Conference on Soft Ground Engineering (ICSGE2015)
3-4 December 2015, Singapore

IMPROVEMENT OF SOFT SUBGRADE SOIL USING STONE COLUMNS FOR HIGH-SPEED RAILWAY TRACK

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High-speed railway infrastructure demands a high level of performance in terms of settlements and the stability of the railway track. However, constructions of roads, railways and other engineering structures in areas where loose or soft cohesive deposits are found usually involve with problems such as excessive settlements, deformations and stability problems. Several remedies have been proposed to avoid or reduce those problems, for instance, replacement of soft soil, constructing piles or stone columns.

Stone columns represent the most well-known column-type technique for improving soft soil, and enables it to withstand low to moderate loading conditions. The performance of the treated ground depends on various parameters such as the strength of the natural deposits and backfill materials, together with the spacing, length and diameter of the columns. Stone columns possess high compressive strength and stiffness relative the soft soil. Moreover, they increase the bearing capacity and reduce the settlement of the soft ground. In practice, stone columns are frequently used for settlement control.

This study aims to expand the knowledge of improving ballasted railway track subgrade by making use of stone columns. For that reason, a FE model of an embankment, which is overlying soft soils has been simulated. The results from the analysis are presented and compared in two circumstances; one considering the embankment without any subgrade improvement, and the other by enhancing the subgrade through constructing stone columns.

INTRODUCTION

Ballasted railway tracks are one of the most common structures traveled by high-speed trains (HST). The high speeds of these trains lead to increased vibrations in the tracks and nearby structures, which can affect the serviceability and maintenance costs of the tracks. Ballasted track includes continuously welded rail laid on concrete sleepers with an intervening rail pad that are supported by ballast and subgrade.

The purpose of the track structure is to gradually distributes the loads from the rolling stock to the subgrade.

The subgrade provides a stable support for the track, while the stresses on the subgrade should be kept minimize to prevent non-recoverable deformations. Increase the level of stresses and deformations cause progressive degradation of the track geometry, and decrease the safety and ride quality.

Improvement of the subgrade depends on the enhancement of the underlying weak natural ground formation. This improvement reduces the rate of track geometry degradation and lower maintenance cost.

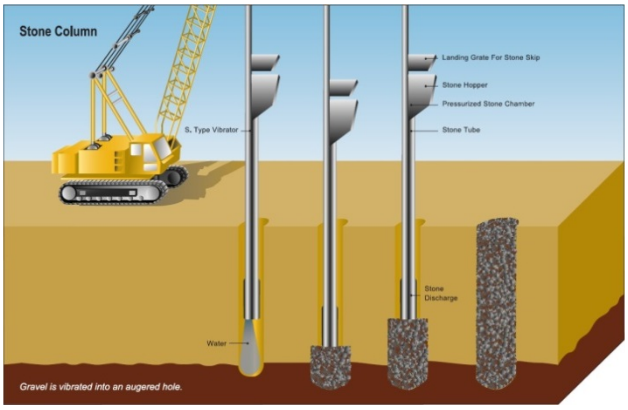
Ground treatment is required at poor ground areas where the natural sub-soils are unable to support the embankment and rail system without exceeding the requirements of the design.
Ground improvement with stone column is a cost-effective method made of the granular material components with high permeability. The use of stone columns as a method of soft soil improvement has been successfully implemented around the world to increase the load carrying capacity of the soil, reduce the excessive settlement, improve the stability, and increase the rate of consolidation and resistance to liquefaction. Stone columns may be provided in areas where subsoil consists of more than about 5 m thick soft cohesive soil.
Poorooshasb and Meyerhof (1997) have introduced elastic analyses to study the settlement reduction of a raft foundation resting on reinforced soft soil with end bearing stone columns. They have shown that the spacing and degree of compaction of the material in the columns control their strength and stiffness.
Important factors in design of the stone columns are the grain size of the stone column's material and the stiffness of the stone column. Seeing that many works have been conducted to study the stone column materials; for example, Isaac and Girish (2009) have studied stones, gravel, river sand, sea sand and quarry dust through laboratory experiments as column's material installed in clay. They have found that stones are the most effective material, and gravel is more effective than other materials. Moreover, many researchers, including Tan et al. (2008) have been tried to model the behavior of soft soil and its interaction with loaded columns.
In general, soft soil is a common problem in many projects in Europe, and it is one of the main concerns before construction, especially for the high-speed railway tracks. Applying a proper approach to improve the soft subgrade for these projects needs good knowledge about available remedies and design approaches. Besides, embankments overlying soft soils are being considered with high train velocities, and very strict requirements on residual settlements being important factors in the design of the works. Therefore, the main objective of this study is to expand the knowledge of improving soft subgrade of the railway track under passage of various train speeds by making use of stone columns.

STONE COLUMNS

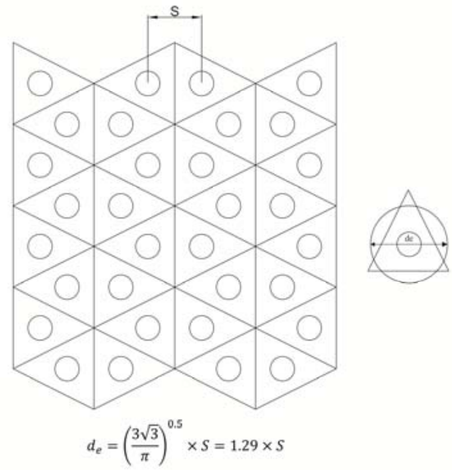
Back ground and installation

The stone column technique is one of the economical and environmentally friendly treatments for the weak grounds. Stone columns are being constructed to control the settlement, and they enable the surrounding soil to withstand low to moderate loading conditions. Wide range of the soils, from soft clays to loose sands, can be treated by constructing stone columns.
Stone columns enhance the density, strength and deformation properties of the soil in the constructed area. Moreover, they rapidly dissipation of the excess pore water pressures, accelerate consolidation and minimize post-construction settlement.
Effectiveness of this treatment depends on the strength of the soft soil layers, backfill materials, length, diameter and space between the columns.
In this method, crushed rocks with particles size less than one-seventh of the stone column diameter installed in the soil by the help of special depth vibrators.
The dry or wet method of installation can be used depending on the existing railway track and water sources. The dry bottom feed causes the minimum change of consistency of cohesive soils, and for the railway tracks, has less risk of unacceptable settlements compare to the wet method. Nevertheless, additional ballast and sub-ballast material should be available in case leveling of the track is required.
Stone columns can be installed in different patterns; triangular, squared or hexagonal. Figure 1

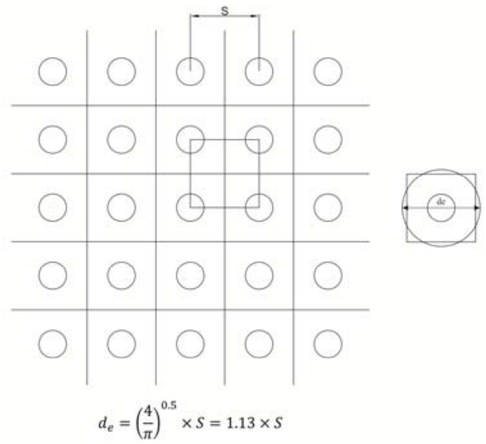
shows these three types of installation as well as the influence area of a unit cell of stone columns. The selection of column type is most often based on workability, load capacity and cost.



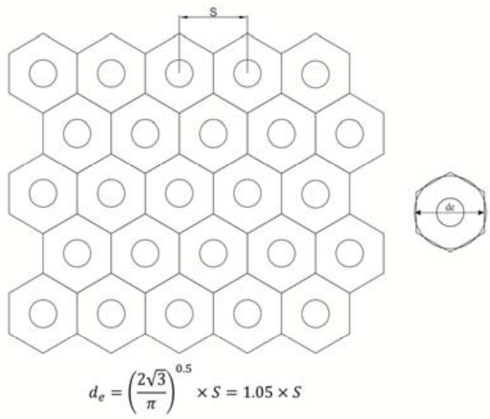
(a) Schematic installation procedure (wet method)



(b) Hexagonal orientation



(c) Square orientation



(d) Triangular orientation

Figure 1. Installation and orientation of stone columns, after (Weber, 2007)

GEOMETRY AND MATERIAL PROPERTIES

Background

Conventional ballasted railway track consists of rail, pad, sleeper, ballast and sub-ballast. These layers are lying at the grade level or embankment to provide a smooth path for a train to travel. In this study, three models of whole track structure have been prepared, one an embankment on the soft soil without any improvement and others with utilizing stone columns.

The section is a double track railway embankment overlying on three layers subgrade. The superstructure of the models includes rails, pads, and sleepers. Normal UIC 60 rail has been modified to rectangular section, dimensions selected in the way to maintain the properties of the original rail satisfactory (Shahraki et al., 2015). This modification reduces the computation time, and minimizes result's error due to the meshing of a complex geometry.

The rail pads with 10 mm thickness are provided between the sleepers, and rails. The total length of each model is 120 m, including 200 standard concrete sleepers (B70), and center to center distance of 60 cm. The sleeper cross-section is rectangular 20*20 cm, and 2.5 m length, which is the modification of the standard sleeper according to Witt (2008).
Figure 2 illustrates the depth and the position of each layer of ballasted track. Tracks have been supported by three layers soil at the bottom. Depth of the first and the second layers are 3 m and 1 m respectively while the last layer has 20 m depth. The total depth of 24 m and implementation of the elastic/viscous boundary elements as ground surface springs (MIDAS, 2014) ensure that no wave reflection happens at the boundaries in the dynamic analysis.

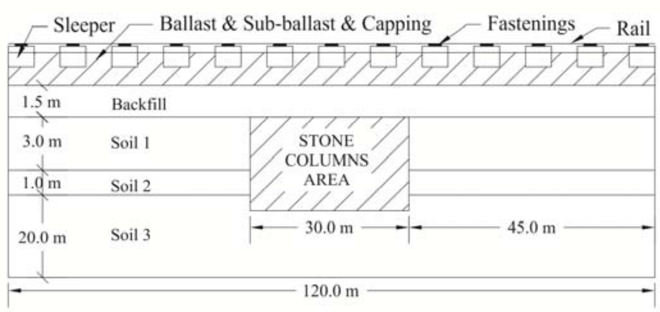


Figure 2. Geometry of the model and location of stone columns

Geometry and material properties of all models are the same except the arrangement of the stone columns and their dimensions. The geometry of the superstructure and all dimensions can be seen in Figure 3.

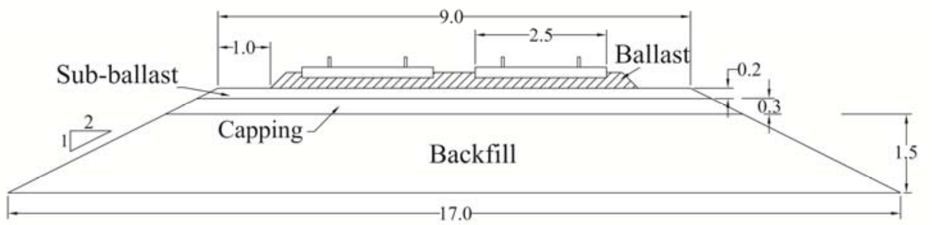


Figure 3. Cross-section of the superstructure [m]

In the modeling of the railway track, it is profitable for the researchers not to consider the non-linear behavior. The reason for this is limited applicability of non-linearity in many real engineering works. Moreover, it can drastically increase the computational time and needs of physical memory of the computers. Seeing that, all layers have been modeled as continuous media with elastic linear behavior, as it can give a good sight to the behavior of an embankment under passage of high-speed trains. Material properties of all soil layers that have been used for modeling are mentioned in Table 1 (Berggren et al., 2012, Truty and Obrzud, 2011, Mohamed Basheer Dardeer Elsawy, 2010).

Table 1. Material properties

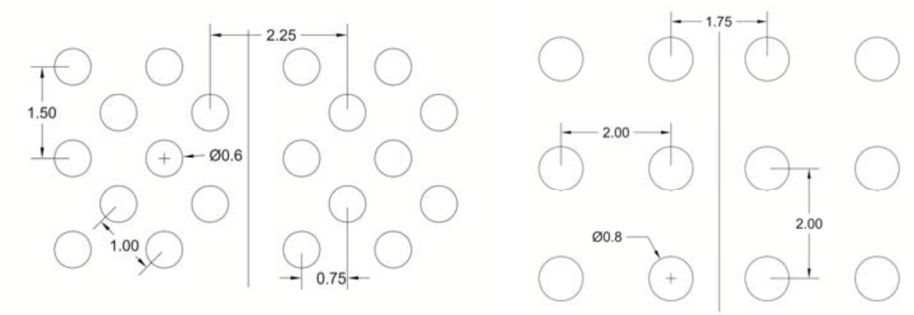
Track's elements	Parameters		
	γ [kN/m^3]	ν[-]	E[kN/m^2]
Rail	61.86	0.30	210000000
Rail pads	19.5	0.30	210000
Sleeper	20.5	0.20	30000000
Ballast	18.0	0.20	80000
Sub-ballast	19.0	0.25	60000
Capping layer	20.0	0.25	60000
Backfill	19.0	0.20	26000
Soil 1	17.5	0.20	10000
Soil 2	16.0	0.35	5000
Soil 3	19.5	0.30	210000
Stone column	19.0	0.30	55000

Embankment on triangular orientation

A combination of four columns that are oriented triangularly support each of tracks on the embankment. Column's diameter is 60 cm with the horizontal space of 1.5 m and diagonal distance of 1.0 m. The span between two adjacent inner columns of two tracks is 2.25 m. Figure 4 (a) is illustrated all the dimensions and the location of columns.

Embankment on square orientation

Stone columns have been arranged in the square form to improve the behavior of an embankment on the soft soil. For this reason, stone columns with the diameter of 80 cm have been used. Each of double tracks has been supported by two columns with the center to center of 2 m. Distance between adjusted columns in the middle of tracks are 1.75 m. Figure 4 (b) shows the arrangement of the columns under the embankment.



(a) Triangular arrangement (b) Square arrangement

Figure 4. Distances between stone columns arrangements [m]

Loading procedure

In order to analyze the embankment and their behavior after improvement, one of the main purposes is to provide the train moving load. Here, ability of midas GTS NX has been used to simulate the train load, and one of the available pre-defined train load has been chosen. The loading configuration is KTX Korean high-speed trains with the axial load of 170 kN (MIDAS, 2014). This train consists of 46 wheels and total length of 380 m. Simulations have been carried on for three different speed scenarios. First, passage of a train with speed of 300 km/h on one track. Second, trains with speed of 300 km/h travel on both tracks in different direction at the same time.

Third, one train travels with speed of 300 km/h while in the other direction a train with speed of 180 km/h enters the model in the exact same time.

RESULTS AND DISCUSSION

The results of three models with three different train's speed scenarios are presented and compared in two circumstances; one by considering vertical deformation of the model along the length and also perpendicular to tracks, and the other by considering two directions (X and Z) deformations of a specific stone column in both improved models.
The vertical deformation at the top of the first soft soil layer (soil1) in a line exactly in the middle of two tracks are presented. Figure 5 shows the effect of passage of two trains with the same speed of 300 km/h, but in different directions, and Figure 6 belongs to the travel of two trains with speed of 300 and 180 km/h in opposite directions. In both figures, it can be seen that the deformation in the area of stone columns is much less than an embankment without columns. Either arrangements decreases the vertical deformation in the same rate. However, triangular arrangement with more number of columns and smaller diameters shows less fluctuation of deformation in the area.

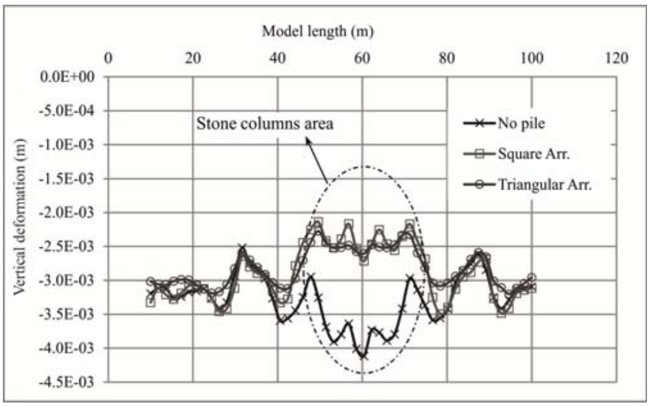


Figure 5. Vertical deformation along the middle tracks for two trains with speed of 300 km/h

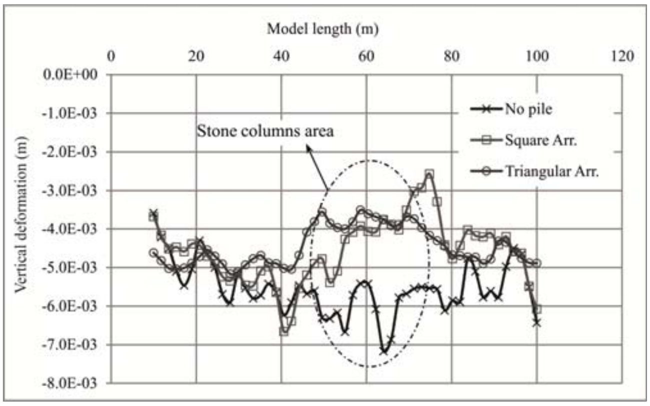


Figure 6. Vertical deformation along the tracks for two trains with speed of 300 and 180 km/h

Figure 7, 8 and 9 show three different scenarios for the vertical deformation exactly in the middle of the model, but perpendicular to the direction of the train passage.
Figure 7 shows the effect of the installing stone columns when only one train is passing the track with the speed of 300 km/h, and there is no train on the second track. It can be seen that the maximum deformations appear to be on the left side where the track has been loaded by passing train. Here, stone columns in the triangular and square arrangement cause respectively, 51% and 35% reduction in the vertical deformation compared to the embankment without any improvement.

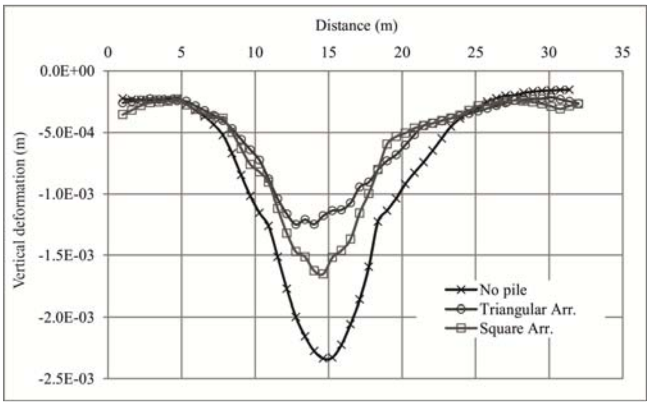


Figure 7. Vertical deformation for a train with speed of 300 km/h

Figure 8 shows the result of passage two trains with the same speed of 300 km/h at the same time on the model, but in different direction. Again, stone columns drastically decrease the deformation at the top of the first soft soil layer. Seeing that both trains are moving at the same speed and time, symmetrical deformation pattern can be seen and the maximum developed in the middle where two trains cross pass each other.

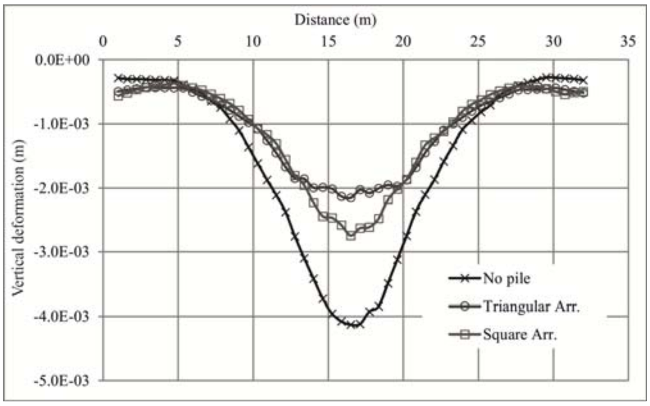


Figure 8. Vertical deformation for two trains with speed of 300 km/h

The third scenario considered the passage of two trains with speed of 300 and 180 km/h in opponent direction.

Figure 9 has no symmetry in the results, and the maximum deformation turns up to go to the right side where the train with lower speed passes. However, triangular arrangement of columns provides a smoother pattern of deformation compared to others.

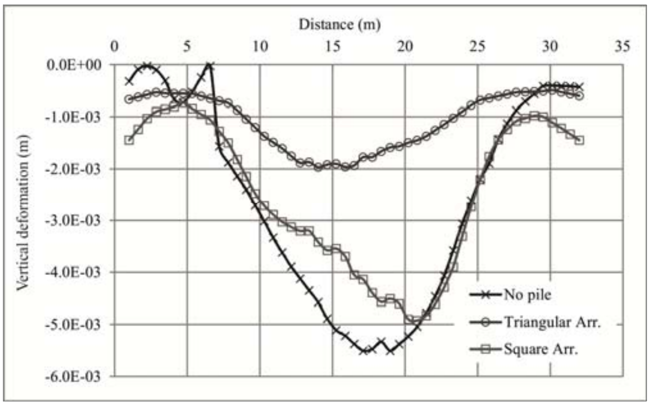
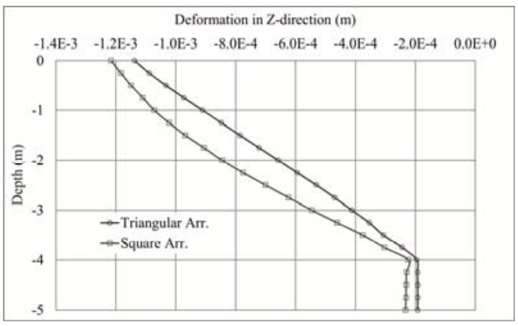


Figure 9. Vertical deformation for two trains with speed of 300 and 180 km/h

A specific column has been considered for comparison of deformations (Z and X direction) along the length of the column due to the passage of high-speed trains. For both improved embankments, the selected column is located in the middle of the improved area, under the left-hand side track. Figure 10 shows the deformation in Z-direction for two columns in the same location but in different arrangement, including the diameter and spacing between the adjacent columns. Here, the left-side track has been loaded by passage of a train with speed of 300 km/h. It can be noted that the unite column in the triangular arrangement shows less deformation compare to the triangular arrangement. Same behavior in X-direction can be seen with more intense variation, especially in the middle of the first soft layer. This deformation gap between two models tends to be minimize for the last one meter of columns where they are penetrated into the stiff layer (Soil 3).
Another point is the movement of columns in X-direction is toward the adjacent track that has no train load on it.



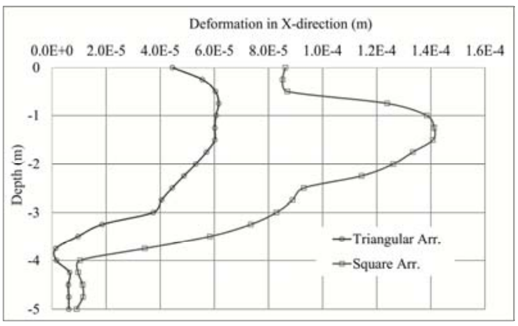


Figure 10. Deformation in X and Z-direction for a train with speed of 300 km/h

Results of the passage of two trains with speed of 300 km/h in opponent directions are shown in

Figure 11. Triangular arrangement of columns leads to smaller deformation in both Z and X-direction. Although, the maximum deformation of columns in X-direction is toward the shoulder of embankment.

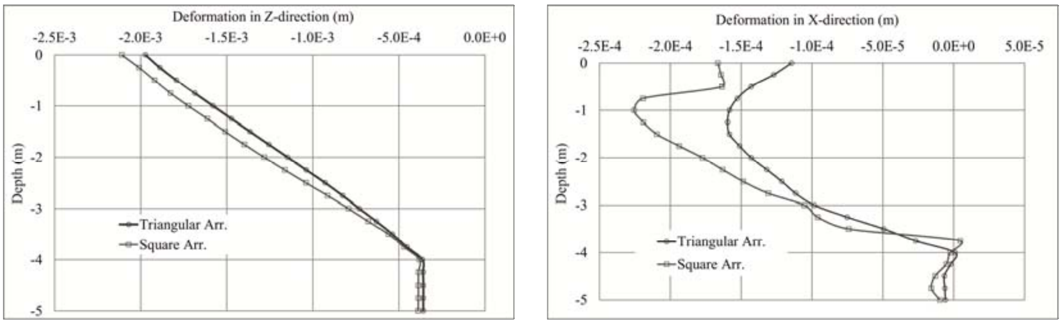


Figure 11. Deformation in X and Z-direction for two trains with speed of 300 km/h

Figure 12 has been obtained from the passage of two trains with speed of 300 and 180 km/h in different directions. In comparison to the last two scenarios, broader difference between triangular and square arrangement in both directions can be seen. Especially, in Z-direction triangular arrangement leads to much lower deformation; while same as previous, the maximum difference in X-direction happens in the middle of the first soft soil layer. Once more, the column tends to deform in the direction of shoulder where there is no load.

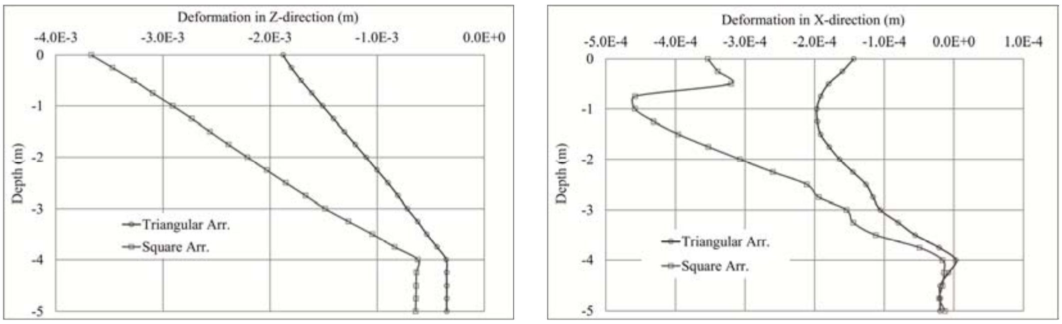


Figure 12. Deformation in X and Z-direction for two trains with speed of 300 and 180 km/h

CONCLUSION

Three 3D finite-element models have been developed to study the effect of constructing stone columns for an embankment overlaying on the soft soil layers under passage of high-speed trains. One model without any improvement and the others improved by stone columns' properties. These two improved models are different in arrangement, spacing and diameter of the stone columns and all the material properties stayed the same.

Moreover, three different scenarios of train passage have been applied to each of the models. In the first scenario only one train with speed of 300 km/h passes the model. In the next scenario, two trains with speed 300 km/h pass the model at the same time but in opponent directions, and as a

result both train cross pass exactly in the middle of the model. Third scenario considered passage of two opponent trains with speed of 300 and 180 km/h.
In general, installation of the stone columns with triangular orientation shows smaller deformations compare to square arrangement. Although, in comparison to no improved model, both types of arrangements lead to much less deformation in vertical direction. Besides, it shows that the passage of two trains are more crucial than only one train. Furthermore, travel of two trains with the same speed of 300 km/h is less crucial than when one of two trains have lower speed. The latest causes the most critical situation for the track and it led to the maximum deformations in all three models.

ACKNOWLEDGMENTS

The authors would like to thank 'midas GTS NX' for the technical support, and providing the opportunity to conduct this paper.

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