A Numerical Assessment of GRPS Foundations for High-Speed Railways on Soft Ground

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ABSTRACT

The development of high-speed railway lines in Vietnam is facing major challenges due to the prevalent presence of soft ground in many delta and coastal areas, necessitating effective ground improvement solutions to ensure the stability and longevity of these infrastructures. This study focuses on evaluating the effectiveness of Geosynthetic-Reinforced Pile-Supported (GRPS) foundation systems through numerical simulations using the Finite Element Method (FEM) with Plaxis 3D software. The study constructs models based on realistic parameters representative of the soft ground conditions in Vietnam, and provides a detailed analysis of key technical indicators, such as stress, displacement, settlement, and deformation of each component within the GRPS system. The simulation results quantify the effectiveness of the GRPS system in reducing overall settlement (average U_z reaching -109.27 mm), controlling displacement (average U at 143.38 mm), and maintaining tensile force and deformation within safe limits. These findings demonstrate that the GRPS solution significantly enhances the stability of high-speed railway foundations, while also being well-suited to the complex geological conditions typical of Vietnam, thus offering wide potential for application in modern transportation infrastructure projects.

Keywords-soft ground; GRPS; Finite Element Method (FEM); high-speed railway

I. INTRODUCTION

The construction of high-speed railway lines has become a key objective for Vietnam, which aims to meet the demands of a modern, sustainable, and internationally integrated transport system. The North–South high-speed railway, with a total length of approximately 1,541 km, has become urgent to implement. This railway line plays contributes not only to connecting the country's major socio-economic centers but also in meeting the growing demand for passenger and freight transport, thereby helping to alleviate the heavy pressure placed on the road and air transport systems. However, one of the greatest challenges in implementing these projects is the prevalence of soft ground, which is common in many deltaic and coastal areas [1]. The characteristics of soft soil include large settlements, low bearing capacity, and slow consolidation rates, making structures prone to uneven settlement, cracking, and even instability during operation. The selection of appropriate ground improvement solutions not only determines the lifespan and safety of the structure but also greatly affects investment costs and construction schedules.

In response to this situation, various ground improvement methods have been applied, such as sand piles, cement-soil columns, sand cushions, vertical drains, and controlled embankment construction [2]. However, these traditional methods still have limitations in terms of economic efficiency, their effectiveness in reducing settlement, and their suitability for the complex soft soil conditions typical of Vietnam. The utilization of geosynthetic materials in combination with pile foundation systems—exemplified by GRPS foundation systems—has attracted attention in modern transportation infrastructure construction [3-5]. The GRPS system optimally utilizes the advantages of both concrete piles and geosynthetic materials: piles transfer loads to deeper, more stable soil layers, while the geosynthetics enhance the arching effect, distributing loads more evenly, reducing localized settlement, and improving the overall stability of the embankment [6, 7].

Nevertheless, there is a lack of quantitative research on the effectiveness of GRPS systems on soft soils typical of Vietnam, especially of detailed numerical simulations to provide a basis for selecting and optimizing designs suitable for real-world conditions. Therefore, this paper focuses on simulating and analyzing the behavior of the GRPS system on soft ground using FEM with Plaxis 3D software, aiming to quantify settlement reduction, control displacement, and assess component performance limits. Through specific technical indicators, this study provides scientific evidence as a foundation for selecting advanced ground improvement solutions for high-speed railway projects in Vietnam.

II. MATERIALS AND METHODS

In this study, the material properties and input parameters of the model were derived from field tests and supported by laboratory results, ensuring that the simulation accurately reflects the typical soft ground conditions in Vietnam and the structure of the GRPS system as applied to high-speed railway construction. The soil strata in the model consist of three main layers: soft clay, clay, and silty sand, as shown in Figure 1. These soil layers are simulated using the Modified Cam-Clay model to accurately represent the mechanical behavior and consolidation process of soft soils under large embankment loads [8, 9], as presented in Table I.

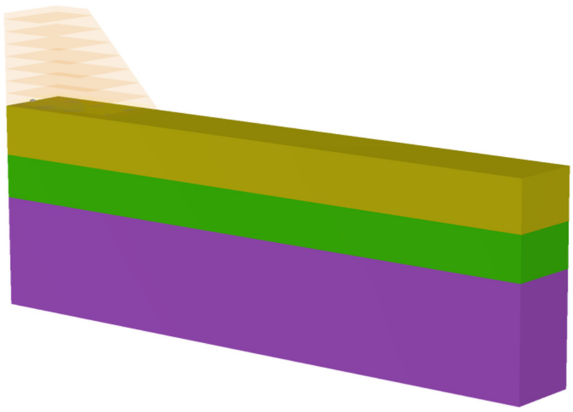

Fig. 1. Soil stratification of the model with soft clay, clay, and silty sand layers.

For the pile material, reinforced concrete was selected with a modulus of elasticity $E = 3.50 \times 10^7$ kN/m², unit weight $\gamma = 25$ kN/m³, Poisson's ratio $\nu = 0.2$, and compressive strength of up to 36,000 kN/m². These parameters ensure that the pile can transfer large loads from the superstructure to the deeper, more stable soil layers. The embankment soil was modeled using the Mohr-Coulomb criterion with the following main parameters: modulus of elasticity E_{ref} = 50,000 kN/m², γ = 20 kN/m³, cohesion C_{ref} = 10 kN/m², and internal friction angle $\varphi' = 35°$, which meet the requirements for the bearing capacity and slope stability. The geosynthetic material used in the model had a longitudinal tensile stiffness of EA_1 = 100 kN/m, playing an essential role in distributing horizontal loads between pile heads and controlling localized settlements in the subgrade.

The numerical model was built using Plaxis 3D software with a configuration closely matching actual construction practice [10-12]. The GRPS structure consists of six prestressed spun concrete piles, each with a diameter of 500 mm and a length of 6 m, arranged in a rectangular grid with a spacing of 3 m in both directions. At the top of the piles, a concrete pile cap of 1 m × 1 m × 0.3 m is designed to ensure the proper application and distribution of loads to the pile system. The geosynthetic layer is placed continuously between the pile heads to enhance the arching effect during embankment filling, as depicted in Figure 2. The embankment itself is constructed in 8 layers, with a total thickness of 7.5 m, simulated in stages to accurately reflect the accumulation of stress and strain in the soil and foundation system over time.

TABLE I. DESCRIPTION PARAMETERS OF SOFT CLAY, CLAY, AND SILTY SAND LAYERS

Parameter	**Soft clay layer**	**Clay layer**	**Silty sand layer**
Soil	Soft clay	Clay	Silty sand
Soil model	Modified cam-clay	Modified cam-clay	Modified cam-clay
Drainage condition	Drained	Undrained A	Undrained A
Unsaturated unit weight (kN/m³)	18.2	17.1	18.5
Saturated unit weight (kN/m³)	18.2	17.1	18.5
Initial void ratio	1.055	1.464	1.032
Final void Ratio	0.5134	0.5942	0.5079
λ	5.70E-03	0.04	2.40E-03
κ	2.00E-03	4.00E-03	3.00E-04
Poisson's ratio (ν)	0.3	0.3	0.3
MCSL	1	1	1
K_0	0.6986	0.7358	0.7325
Permeability (K_x, K_y, K_z)	4.32E-03	8.64E-05	8.64E-04
Porosity (n_{init})	0.5134	0.5942	0.5079
Crefinter	62.3	17.8	53
Φ	15.8	9.4	13.8
Ψ	1	1	1
Particle size distribution			
< 2 μm	10	10	10
2 μm - 50 μm	13	13	13
50 μm - 2 mm	77	77	77

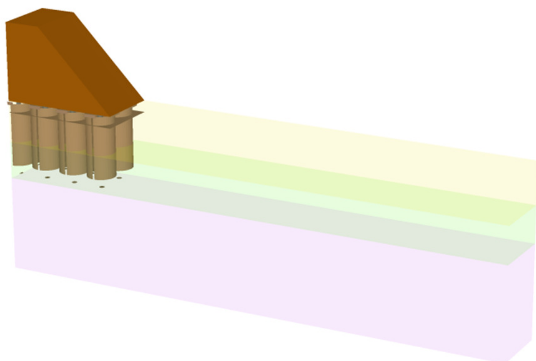

Fig. 2. GRPS system simulation in Plaxis 3D.

The simulation process begins with the initial phase, establishing the initial stress equilibrium in the soil. This is followed by simulating the pile construction and sequential embankment filling, interspersed with the placement of the geosynthetic layer, allowing a detailed evaluation of stress and deformation development at key stages [13, 14]. In particular, long-term consolidation analysis was conducted at time intervals of 90, 120, 180, and 500 days to assess the long-term effectiveness of the GRPS system in reducing settlement and maintaining structural stability.

After completing the simulation, key technical indices were extracted and analyzed to quantify the performance of the GRPS system. Key geotechnical performance indicators—including soil and structural stresses, displacement measures, and tensile–shear forces in the geosynthetic layer—were analyzed to evaluate the operational safety and deformation behavior of the GRPS system [15]. These indicators were statistically processed (maximum, minimum, mean, and standard deviation) to provide an objective and comprehensive assessment of the system's effectiveness under typical soft ground conditions in Vietnam.

III. RESULTS

The simulation results, presented in Table II, indicate that the stresses in the ground are strongly influenced by the embankment construction process and the interaction among the GRPS system components. According to statistical data, the horizontal stress component σ_{xx} ranges from a minimum value of -5,620 kPa to a maximum of 3,610 kPa, with an average value of -90.57 kPa and a standard deviation of 212.6, as portrayed in Figure 3. Similarly, σ_{yy} records a minimum of -4,890 kPa, a maximum of 3,460 kPa, and an average of -103.41 kPa, as presented in Figure 4. The vertical stress σ_{zz} has a minimum of -8,270 kPa, a maximum of 5,600 kPa, an average of -445.99 kPa, and a standard deviation as high as 1,033.05.

These results confirm that the stresses generated in the soil are mainly concentrated in the vertical direction, reflecting the effect of embankment loading on soft soils. The large distribution of vertical stress further demonstrates the efficiency of the GRPS system in distributing loads, which helps reduce local settlement and improves the overall stability of high-speed railway structures.

TABLE II. STATISTICAL SUMMARY OF TOTAL STRESS (σ)

Metric	Minimum	Maximum	Mean	Std. deviation
σ_{xx}	-5.62E+03	3.61E+03	-9.0574E+01	2.12574E+02
σ_{yy}	-4.89E+03	3.46E+03	-1.0341E+02	2.06835E+02
σ_{zz}	-8.27E+03	5.60E+03	-4.4599E+02	1.03305E+03
σ_{xy}	-1.00E+03	9.63E+02	-3.0251E-02	3.28947E+01
σ_{yz}	-2.33E+03	2.29E+03	8.0516E-01	7.14596E+01
σ_{zx}	-1.49E+03	2.47E+03	1.6502E+01	1.18514E+02

The tensile and shear forces in the geosynthetic layer were analyzed to assess the working capacity and safety margin of the material in load transfer and distribution. The main tensile force N1 in the geosynthetic layer varies from -0.678 kN/m to 5.810 kN/m, with an average value of 1.68 kN/m and a standard deviation of 1.05, as shown in Figure 5. The secondary force component N2 ranges from -0.564 kN/m to 1.577 kN/m, with an average of just 0.055 kN/m, as illustrated in Figure 6. For the shear force Q_{12}, the results show a range of -1.564 kN/m to 1.349 kN/m, and a very small mean of 0.00097 kN/m, as shown in Figure 7. Overall, the geosynthetic material primarily bears tension along the main direction, with secondary and shear forces remaining at low levels, demonstrating that the geosynthetic material performs safely and effectively in distributing horizontal loads and controlling local ground deformation.

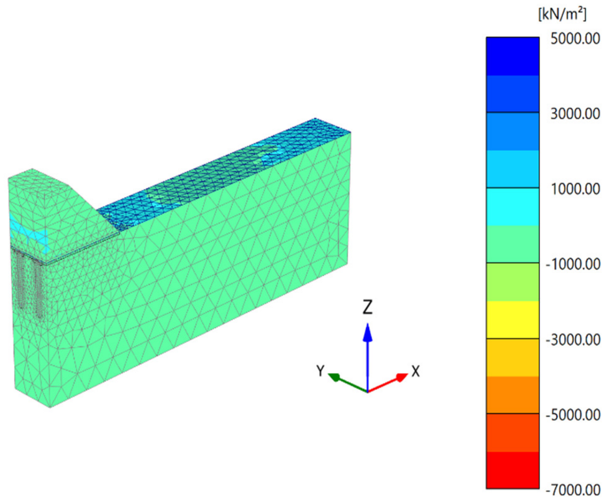

Fig. 3. Distribution of total stress in the xx direction (σ_{xx}).

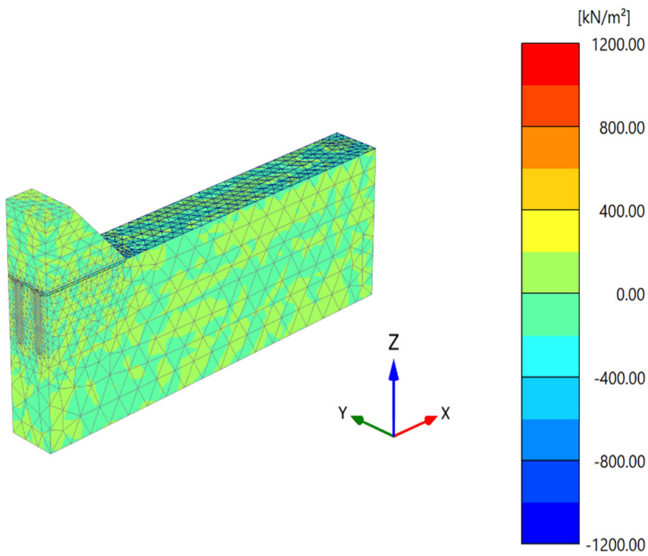

Fig. 4. Distribution of total stress in the xy direction (σ_{xy}).

The ground displacement under the effects of embankment loading and the GRPS structure is reflected through U_x, U_y, U_z, and the overall displacement U, as presented in Table III. Specifically, horizontal displacement U_x ranges from -22.41 mm to 243.37 mm, with an average value of 72.24 mm, as portrayed in Figure 8, while U_y varies within a smaller range, from -40.22 mm to 45.23 mm, and its mean value remains nearly unchanged at 0.002 mm, as shown in Figure 9. For vertical displacement U_z, which represents ground settlement, the recorded minimum settlement is -275.09 mm, the maximum is 200.90 mm, and the mean is -109.27 mm (Figure 10). The overall displacement U ranges from 0 to 275.09 mm, with an average value of 143.38 mm. These data indicate that, although some areas still exhibit relatively large settlement and ground movement, the GRPS system effectively controls the displacement distribution and minimizes differential settlement, ensuring the stability of the overlying structure.

TABLE III. STATISTICAL SUMMARY OF GROUND DISPLACEMENT

Displacement (mm)	Minimum	Maximum	Mean	Std. deviation
U_x	-22.4100	243.374	72.23607	46.313089
U_y	-40.2180	45.2300	0.002040	1.838420
U_z	-275.085	200.899	-109.26604	68.847113
U	0.00000	275.085	143.37508	59.066885

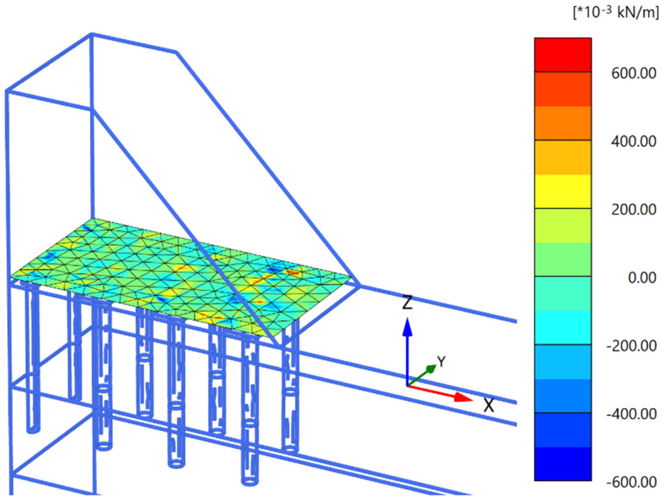

Fig. 7. Distribution of Q_{12} force in the geosynthetic layer.

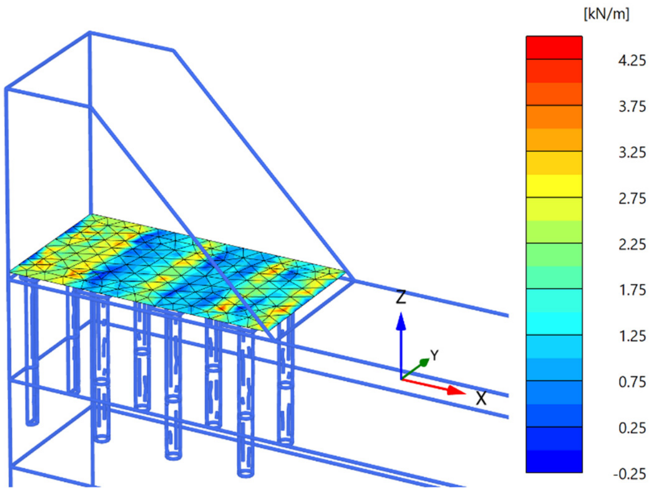

Fig. 5. Distribution of N_1 force in the geosynthetic layer.

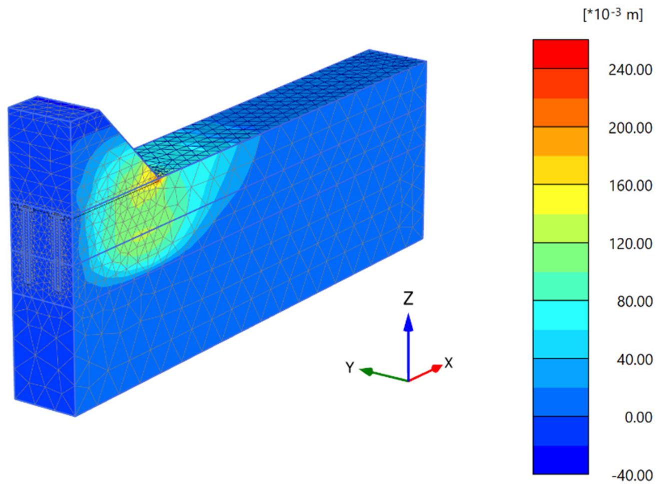

Fig. 8. Overall horizontal displacement U_x (mm).

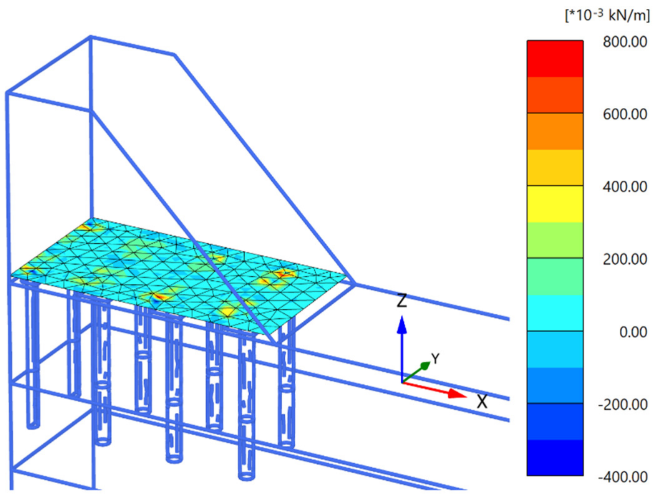

Fig. 6. Distribution of N_2 force in the geosynthetic layer.

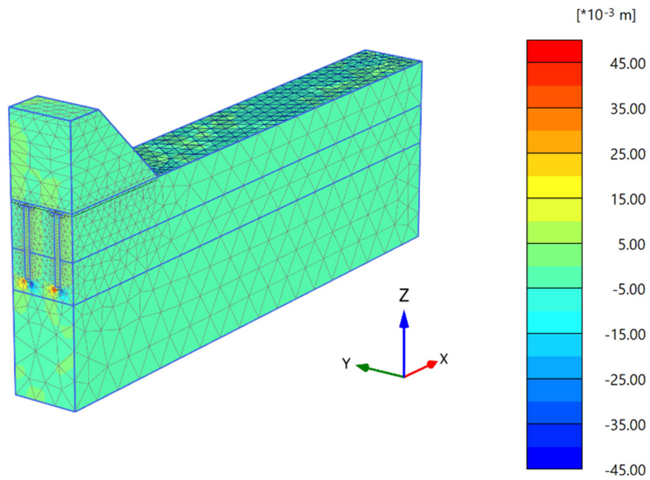

Fig. 9. Overall horizontal displacement U_y (mm).

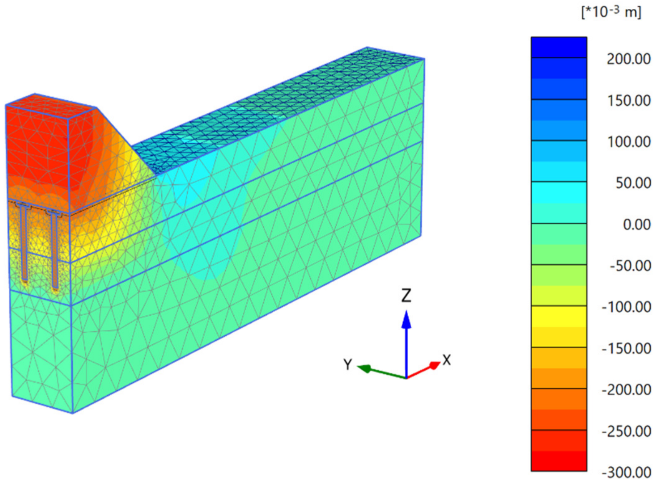

Fig. 10. Overall vertical displacement U_z (mm).

The pile foundation displacement is a key criterion for evaluating stability and the effectiveness of load transfer to deeper soil layers. According to the simulation results, the horizontal displacement U_x at the pile cap varies from 0 to 243.32 mm, with an average value of 96.27 mm, as illustrated in Figure 11. The U_y displacement at the pile cap is very small, ranging from -2.165 mm to 2.062 mm, and the average is only 0.014 mm, indicating that horizontal displacement perpendicular to the track alignment is negligible, as shown in Figure 12. Notably, the vertical displacement U_z—representing pile settlement—ranges from -236.05 mm to 25.03 mm, with a mean value of -147.27 mm, as depicted in Figure 13. These results indicate that, while the GRPS system helps to reduce differential settlement and horizontal displacement, the vertical settlement of pile foundations must still be carefully controlled in practical design to ensure structural durability.

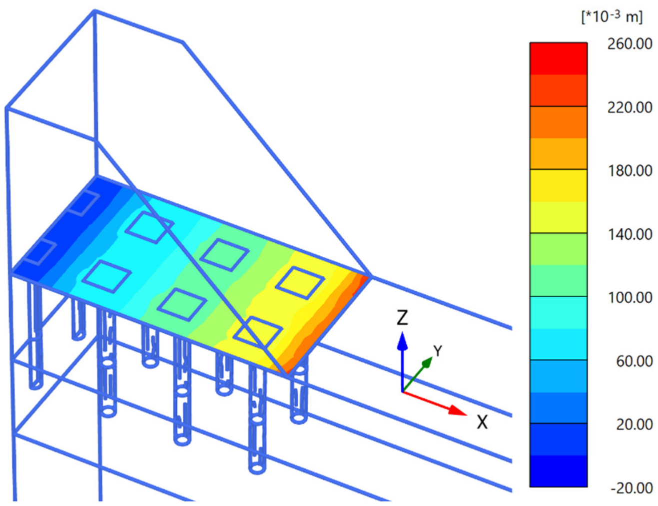

Fig. 11. Horizontal displacement U_x at the pile cap.

The deformation of the geosynthetic layer plays a crucial role in load distribution and the overall stability of the improved ground system. The horizontal displacement U_x in the geosynthetic layer varies from 0 to 180.63 mm, with an average value of 91.29 mm. U_y varies from -3.257 mm to 4.056 mm, and the mean value is only 0.048 mm. For vertical displacement U_z—reflecting the settlement of the geosynthetic layer—the results range from -242.93 mm to -19.46 mm, with a mean value of -156.93 mm. The total displacement U of the geosynthetic layer across the system ranges from 153.63 mm to 244.88 mm, with a mean value of 196.60 mm. These results demonstrate that the geosynthetic layer undergoes its greatest deformation primarily in the vertical and horizontal directions, playing an important role in distributing loads evenly to the piles, thereby helping to reduce the local settlement and maintain the stability of the entire ground improvement system.

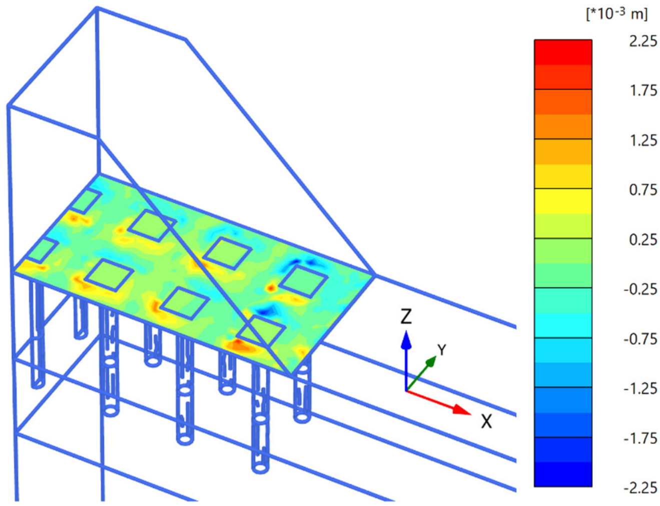

Fig. 12. Horizontal displacement U_y at the pile cap.

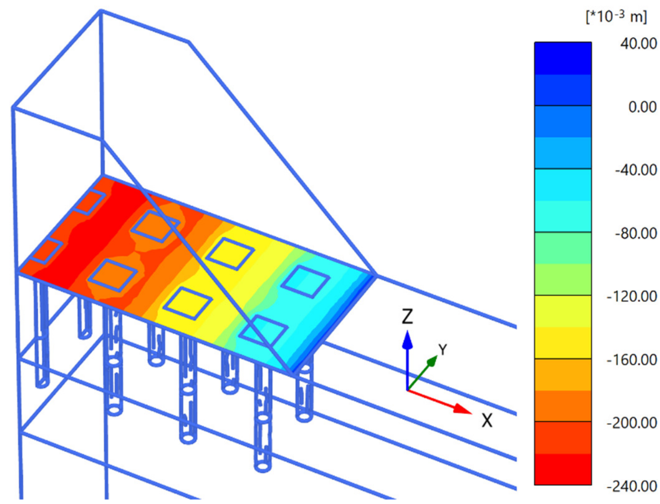

Fig. 13. Vertical displacement U_z at the pile cap.

IV. DISCUSSION

The simulation results of the GRPS system for high-speed railway foundations confirmed the advantages in settlement reduction, load distribution, and structural stability. In baseline cases without reinforcement, previous field observations have reported vertical settlements often exceeding 0.5 m under similar soft soil conditions and embankment heights [16]. In contrast, the GRPS model in this study achieved much lower values, with the average vertical displacement U_z of the subsoil recorded at -109.27 mm and at the pile cap at -147.27 mm, while the average total displacement U was only 143.38 mm under the same loading and embankment thickness of 7.5 m. These results are consistent with numerical and theoretical studies on GRPS embankments [12], further highlighting the effectiveness of the GRPS system relative to conventional solutions.

In the working mechanism of the GRPS system, concrete piles with high elastic modulus help transfer loads efficiently to deeper, more stable soil layers, reducing the stress concentration in weak zones, as indicated by the average σ_{zz} value of -445.99 kPa. The geosynthetic material plays an essential role, with an average tensile force N_1 of 1.68 kN/m—within safe limits—and a very small shear force Q_{12} (0.00097 kN/m), thereby ensuring the arching effect and effective control of differential settlement. The model also demonstrates the adaptability of the GRPS system to typical weak ground conditions in Vietnam, such as soft clay and clay with high void ratios and low permeability, while no abnormal settlement is observed in the silty sand layer. These results suggest that longer piles, smaller spacing, stronger geosynthetics, rational fill layering, and controlled load increments can further improve settlement control and stability.

V. CONCLUSIONS

The findings of the current study confirm that Geosynthetic-Reinforced Pile-Supported (GRPS) foundation systems are highly effective in controlling settlement and improving the stability of weak subsoils for high-speed railway projects in Vietnam. Through numerical simulation analysis, the displacement indicators of the ground, especially vertical settlement, were all within controllable limits, meeting technical standards and ensuring operational safety. The tensile force and deformation of the geosynthetic material were also maintained below critical thresholds, contributing to uniform load distribution, limiting differential settlement, and enhancing the service life of the structure, especially in areas with typical weak soils. However, the study still has some limitations, as it does not yet consider the impact of dynamic loading from trains—a critical factor for high-speed railway lines. Additionally, the boundary conditions in the model remain idealized and cannot fully reflect practical factors, such as fluctuating groundwater levels, soil heterogeneity, or natural environmental influences. Therefore, the results still need to be validated by field experiments and long-term monitoring to confirm the practical applicability of the solution. Future research should focus on integrating numerical simulations with additional field experiments, expanding the analysis of dynamic loading effects, and optimizing design costs by adjusting material and geometric parameters, as well as applying probabilistic evaluation methods. These research directions will not only enhance the effectiveness of GRPS systems in transportation infrastructure projects in Vietnam but may also provide valuable scientific and technical foundations for other regions with similar weak ground conditions.

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