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Dynamic displacement of sheet pile walls adjacent to the railway track

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HIGHLIGHTS

- Examined density, distance, and load's effects on wall response and rail settlement
- Subgrade density increase leads to lower displacement ratios: 53% then 31%
- Displacement ratio drops with greater wall-rail distanc
- Higher live load amplitudes increase displacement ratios in the sand
- Denser soil and smaller loads reduce wall displacement and track settlement

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ABSTRACT

Due to the scarcity of experimental laboratory research on the effect of repetitive stress resulting from the railway on retaining walls, this study presents an investigation of an experimental laboratory model to study the effect of repetitive loads resulting from the railway on the adjacent retaining wall through several factors. The results of an experimental investigation of horizontal displacements of steel sheet pile walls behind excavations in the sand adjacent to railway tracks are presented. A series of model tests have been carried out in which the effect of sand density, horizontal distance between the railway and the sheet wall, and dynamic load amplitude on the wall horizontal dynamic displacement and its relationship to the railway dynamic vertical settlement were investigated with a load frequency equal to 2 Hz. The study examines various parameters, including different relative densities (30% loose, 55% medium, and 75% dense sand), different distances between the railway and retaining wall (0.5 H, 1 H, and 1.5 H), and variations in burden amplitudes (0.22, 0.44, and 0.66 tons). The most important factor that affects the dynamic displacement ratio (D/H) value is the relative density of the soil. The dynamic displacement ratio inversely correlates with the horizontal distance separating the railway and the retaining wall. The displacement ratio experienced a reduction of approximately 30% and 23% when the railway location relative to the retaining wall shifted from 0.5H to 1H and from 1 H to 1.5 H, respectively. The displacement ratio is directly proportional to the amplitude of cyclic live loading. Ultimately, using dense backfill soil enhances efficiency, resulting in decreased settlement of the railway and improved performance of the nearby retaining walls. It should be noted that there is a direct correlation between the horizontal movement of the wall and the vertical settlement of the rail. In the case of dense soil, these values are closely aligned.

1. Introduction

Various studies have examined the live load of trains and its effect on adjusted walls. This live load includes the heaviness of the moving train, travelers, and freight. As a train crosses the track, it bestows dynamic powers on the nearby holding wall because of its speed, speed increase, and slowing down [1]. A review conducted by Ou et al. [2] using limited component investigation to evaluate the primary reaction of adjacent walls to change detected that the concentrations of featured critical pressure are close to the foundation of the walls due to train-induced vibrations. One more study by Vadavadagi and Chawla [3], utilized field estimations and mathematical reenactments to assess the effect of train live loads on adjacent designs. This study explored and underscored the significance of considering dynamic impacts and soil-structure communication while surveying wall reactions to prepare prompted loads.

Moreover, a study by Mandloi and Hegde [4] used progressed demonstrating procedures to examine the deformation and the horizontal displacement in adjoining walls via train traffic. The cyclic stacking test on a railway evaluates its stability, solidity, twisting qualities, and, in general, primary uprightness. This testing is essential for guaranteeing railroad tracks well-being and life span [5]. To give an extensive assessment, the segment tested should include commonplace track parts, like rails,

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sleepers, counterbalance, and subgrade [6]. Ground movement induced by excavation is a challenging problem in geotechnical engineering. Deep excavation in granular material can cause severe ground movement and subsequent damage to adjacent structures.

Estimating retaining wall displacement and railway settlements near supported excavations presents a real challenge to all geotechnical engineers and requires sound engineering judgment. Most published works are concentrated on predicting ground surface settlements behind reinforced retaining walls, strutted excavations, and anchored diaphragm walls. In contrast, the available information on settlements of railways behind excavations supported by sheet pile walls is very limited [7]. In addition, most previous studies have focused on examining ground movement induced by deep excavation in clay, emphasizing soft clay material. However, studies related to excavation in sandy soil are limited to a few case histories [8].

A field study was done by Feng et al. [9] to investigate the vibration response of the railway track backfill and adjacent retaining wall. The properties of the materials substantially impact the transmission of vibrations to the structures, in contrast to the influence of speed.

Several case histories have been analyzed by Moormann [10], and the results showed that for non-cohesive soil, the average values of the normalized horizontal deflection ($\delta_{h\text{-}max}/H\%$) and vertical displacement at the ground surface ($\delta_{v\text{-}max}/H\%$) are about 0.87% and 1.1%, respectively.

In Dijckmans [11], field data and computer models were employed to investigate whether a sheet pile wall reduced vibration transmission from railway operations. The sheet piles are 12 m deep, and for every fourth pile, they extend to 18m. Assuming sufficient depth, the results show that sheet pile walls can effectively act as wave barriers in situations with soft soil.

The most classical work on the subject is that of Peck [12], which summarizes a measurement of the ground surface settlements behind braced excavations in various types of soil and relates them to the distance behind the wall. The work findings indicate that ground settlements extend behind the braced wall to a distance of 3 to 4 times the excavation depth, and the ground settlement adjacent to the braced wall is on the order of 1% of the excavation depth. As pointed out by Fujita [13], the development of new design and construction technologies led to drastic reductions of the ground settlements to values approximately equal to the lateral braced wall movement. Several investigations have approved that the ground surface settlement depends on the stiffness of the wall-support system and the preloading applied to the struts or tie-backs [14] and that even variations in the wedging techniques between the wall and struts can double the wall and soil movements.

The ground settlement behind cantilever-type walls is considerably larger than that behind strutted or anchored walls. Finite element analyses of sheet pile walls in clay, performed by Cloughand and Denby [15], showed that the ground surface settlement behind cantilever walls was six times larger than that behind horizontally braced walls.

This research aims to evaluate the performance of retaining walls adjacent to the railway in sandy soil by studying the effect of the density of the subgrade, the horizontal distance between the rail and the wall, and the dynamic load amplitude. In general, these examinations highlight the need for an exact demonstration of the factors mentioned above in understanding the effect of train live loads on the relationship between the lateral displacement of the wall and railway vertical settlement.

2. Experimental work

To study the response of the sheet pile wall, 27 model tests were conducted for up to 4000 loading cycles with a frequency equal to 2 Hz. According to the requirements for each test, the tests used different relative densities (Dr) of sand (30, 55, 75%), cyclic load amplitudes equal to (2.2, 4.4, and 6.6) kN, and distance between railway and retaining wall (X) equals (0.5, 1, and 1.5) H, where H is the excavation depth.

2.1 Soil and ballast

The soil was dried and sieved on sieve No. 10 (2.0 mm), and then the physical properties of the soil were determined per the standard specifications, as shown in Table 1. The values of friction angle (measured in shear box tests, ϕ), dry unit weight (γ_d), void ratio (e), and relative density (Dr) of the loose, medium, and dense sand beds used in model tests are shown in Table 2.

The ballast is one-seventh of the original size and is made of white-colored pieces with angular shapes produced by stones breaking into bigger sizes. The maximum particle size, D_{max}, was 11 mm; the average particle size, D_{50}, was 6 mm; and the uniformity coefficient, C_u, was 1.71. Per the USCS, the ballast utilized is poorly graded ballast. Figure 1 shows the particle size distribution curves for soil and ballast used in this study.

2.2 Railway and sheet pile wall used

The railway and sheet retaining wall model were manufactured; a scale of 1/7 of the realistic measurement is used [16], which consists of a pair of steel rails with a 70 cm length and seven wooden sleepers to simulate the real railway, per European and Iraqi specifications [17]. The steel pile wall was made with a thickness of 2 mm, a height of 600 mm, and a length of 600 mm, which was formed to simulate the type PZ40 [18]. The figure 2a and 2b show the rail track and sheet wall used in the investigation, respectively. Before testing can begin, the model must be prepared by placing the retaining wall and sandy soil in the container according to the relative densities and distances mentioned earlier. The last step is to add the ballast layer and the railway, as shown in Figure 2c.

The sand deposit is prepared using a tamping rod. Initially, the soil was placed at a height of 150 mm according to the specified density, and then the retaining wall was placed according to the distance required for each test. As stated in this paper, three cases of relative densities are chosen (30% for loose sand, 55% for medium sand, and 75% for dense sand). This means that the weight required to achieve the relative density is pre-determined since the unit weight and the volume of the sand are pre-determined. Also, the weight is divided into six equal weights, each representing the weight required for each layer, which has a 100 mm thickness for the active and passive sides. The soil in each layer is compacted to a pre-determined depth. After completing the final layer, the top surface is scraped and leveled by a sharp-edged ruler to get as close as possible to a flat surface.

Following the same procedure as the soil preparation, the required quantity of ballast was calculated for a single layer whose thickness wasn't greater than 50 mm. The ballast was then spread over the soil surface to achieve the dry unit weight required for every case. The layer is carefully compressed using a tamping rod. The railway was subsequently laid on top of the ballast and slopped down on either side at a ratio of around 1.25:1. Lastly, the retaining wall's required height was achieved by excavating the soil's passive side.

Table 1: Physical properties of sand used

Property	Value	Standard Specifications
Specific gravity (Gs)	2.66	ASTM D854 [19]
D_{60}, mm	0.53	ASTM D422 [20]
D_{30}, mm	0.26	ASTM D422 [20]
D_{10}, mm	0.15	ASTM D422 [20]
Coefficient of uniformity, C_u	3.53	ASTM D422 [20]
Coefficient of gradation, C_c	0.85	ASTM D422 [20]
Minimum dry unit weight, kNm^3	15.2	ASTM D4253 [21]
Maximum dry unit weight, kNm^3	18.0	ASTM D4254 [22]
Soil classification	SP	ASTM D2487 [23]
Maximum void ratio	0.75	………
Minimum void ratio	0.48	………

Table 2: Sand bed cases

Sand case	(γ_d) kN/m^3	(ϕ), deg	(Dr)%	(e)
Loose	15.94	30.5	30	0.67
Medium	16.62	35.5	55	0.60
Dense	17.20	39	75	0.55

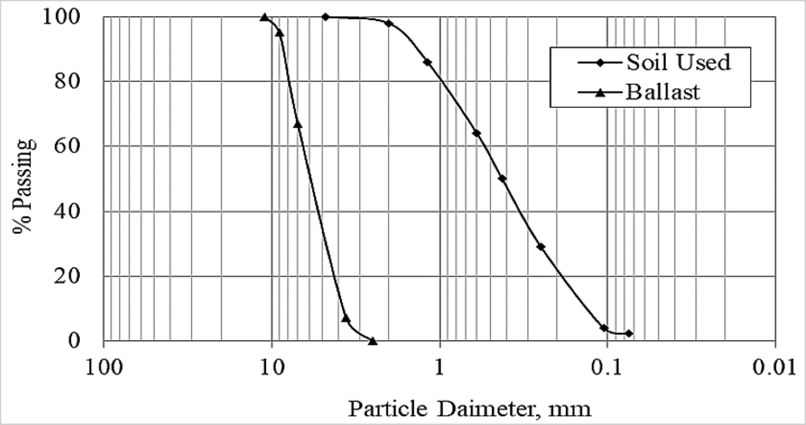


Figure 1: Grain size distribution curve for sand and ballast

a. railway **b. sheet wall** **c. experimental test model**

Figure 2: Laboratory models; a. the rail track, b. the steel sheet wall, and c. experimental test model with sandy soil.

2.3 Load setup and model tests

2.3.1 Load setup

A vibratory impact device was manufactured in the soil laboratory of the University of Technology, as shown in Figure 3, and a series of dynamic tests were performed on the model. The lateral movements in the middle of the wall were recorded with displacement transducers at three different levels, as shown in Figure 4. The vertical settlement of the railway is measured by the device via the shaft encoder. It is an electromechanical device that converts shaft movement into a digital code, which is processed into information such as displacement, revolutions per minute, and speed. The programmable logic controller (PLC) is employed for data acquisition, registering information, and detecting settlements and displacements during tests, enabling the analyst to quickly get tremendous information from the readings. It is also employed to select a pre-determined frequency used in the test. It is an emerging innovative training unit, a computerized computer for electromechanical computing procedures. This type of data acquisition examines information accurately. The PLC instrument includes an LCD communication scanner board to view and obtain information from promoted stepwise motion logic.

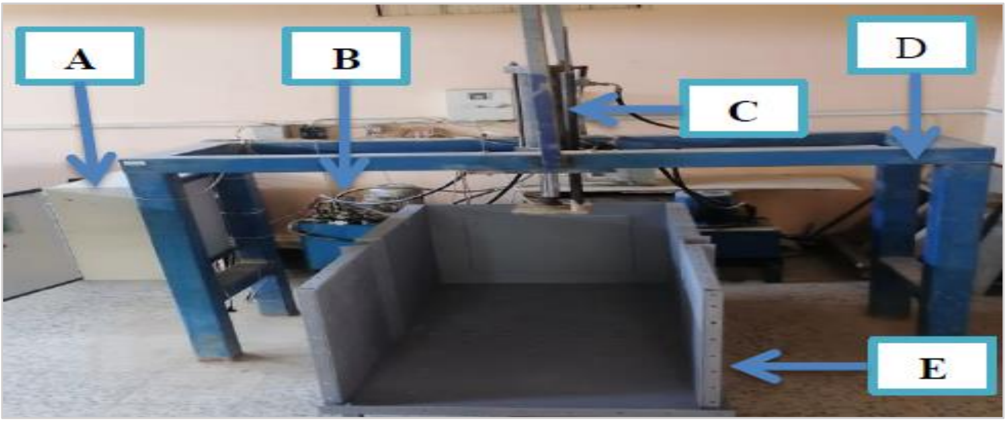


Figure 3: Device for vibratory impact: A. Data acquisition, B. Electro-hydraulic apparatus, C.Shaft encoder, D. Steel frame loading, and E. Steel container

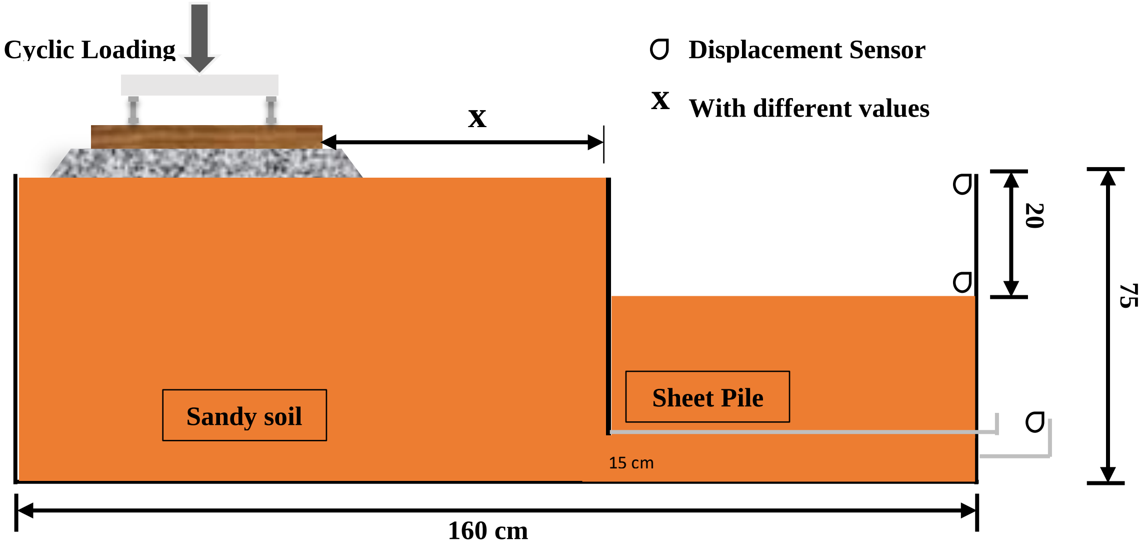


Figure 4: A side view of the experimental model showing the railway, the retaining wall and the sandy soil.

2.3.2 Model tests

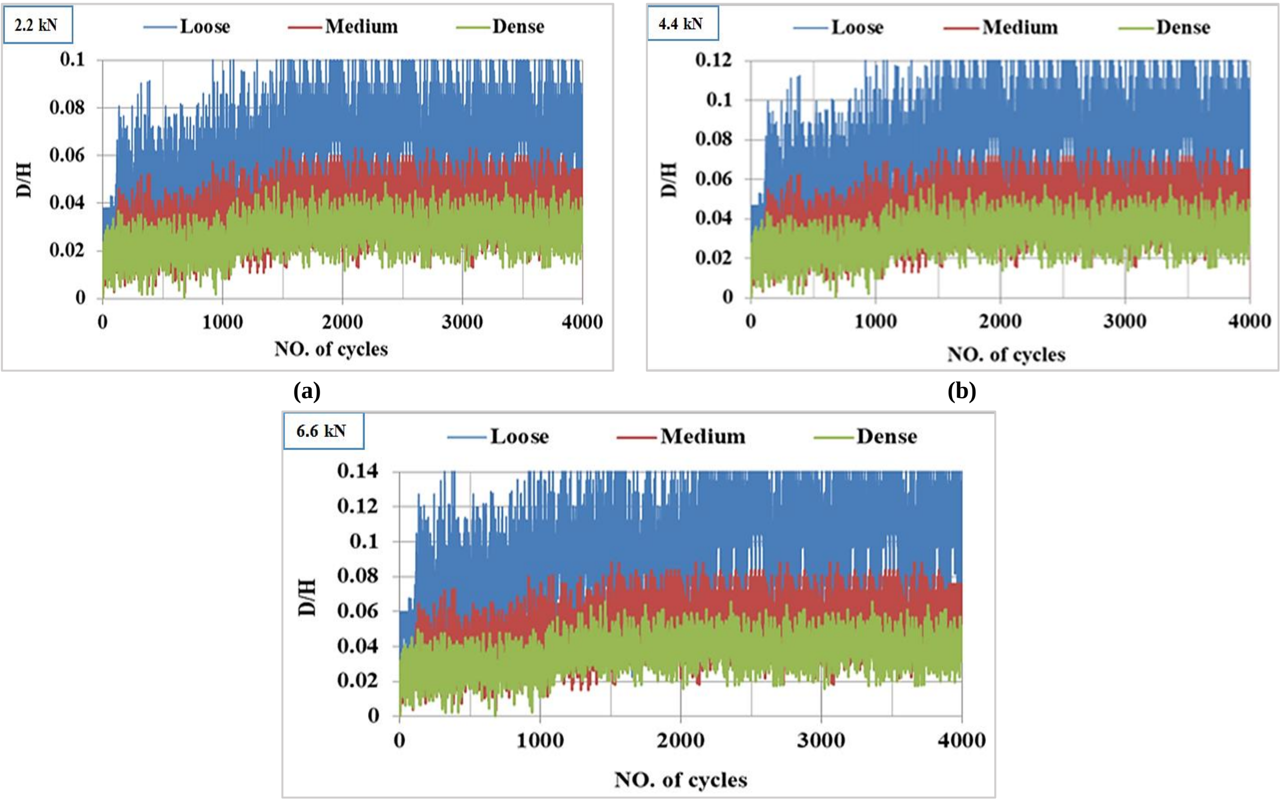
The model is prepared for testing, which consists of placing the sandy soil with the retaining wall according to the relative density and distance mentioned previously in a 1600 × 750 × 750 mm container, whose three sides and base were constructed of 5 mm thick steel except the front face, which is made of toughened Plexiglas plate glass with a thickness of 15 mm. The side tip and the base of the wall were allowed to move freely, affecting the side of the container and the base of the sand bed, respectively. The ballast layer is placed on top of the sand according to the required density and the railway to start the test. Figure 4 shows the model used in the laboratory. Finally, the railway is placed on the ballast to start the test. A series of 27 dynamic tests were performed on the model using different values of sand density. Railway live load with a frequency of 2 Hz and different distances between the railway and sheet wall (X). The sleepers were subjected to rectified sine wave loading to simulate traffic loads [17], [24], who proposed this loading method. The resilient properties of granular materials were not significantly affected by the duration or frequency of the load, according to numerous researchers, including [25]. Accordingly, the effect of the load frequency is small compared to the other variables mentioned previously. It was a hydraulic loading system with a frequency of 2 Hz, which was dependent on the pressure and flow capacity of the system. This is a relatively low frequency compared to the track's typical range of about 10 Hz.

3. Results and discussion

The relationship between the horizontal displacement of the retaining wall and the number of cycles is demonstrated in Figures 5 to 9. The results are shown as follows:

3.1 Effect of relative density of the subgrade

As shown in Figure5(a, b, and c) for load amplitude 2.2, 4.4, and 6.6 kN, respectively, nine cyclic tests were conducted under a 2 Hz frequency of the cyclic load with the railway resting on loose, medium, and dense sand. The cumulative dynamic horizontal displacement ratio (D/H) of the top sheet pile wall gets smaller by increasing the relative density of the sandy soil. As the relative density of the subgrade changes from 30% to 55% and from 55% to 75%, respectively, the average decreases in the rate of displacement ratio (D/H) are approximately 53% and 31%. This occurs because soils with low relative densities tend to have large spaces between their particles, which causes them to redistribute and eventually compact under the increasing burden amplitudes. The process reduces the soil matrix voids, causing the soil to settle. The larger wall and foundation displacements in the loose sand bed agree with the findings reported in [26] and corroborated by Al-Neami et al., [27].



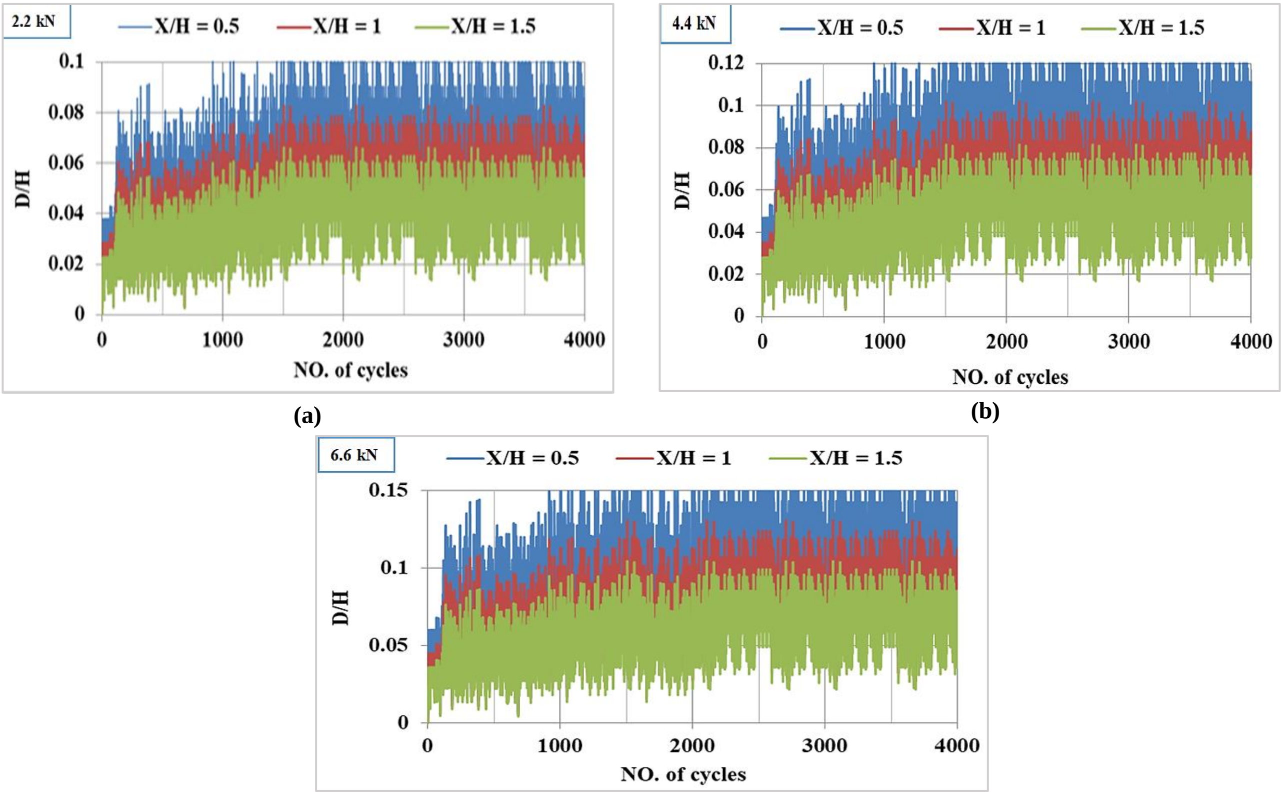
(a) **(b)**

(c)

Figure 5: Cyclic number versus lateral wall displacement ratio D/H with different relative densities, load amplitude at 2 Hz frequency, and X = 0.5 H; a., b, and c for load amplitude 2.2, 4.4, and 6.6 kN, respectively.

3.2 Influence of railway's placement on retaining wall

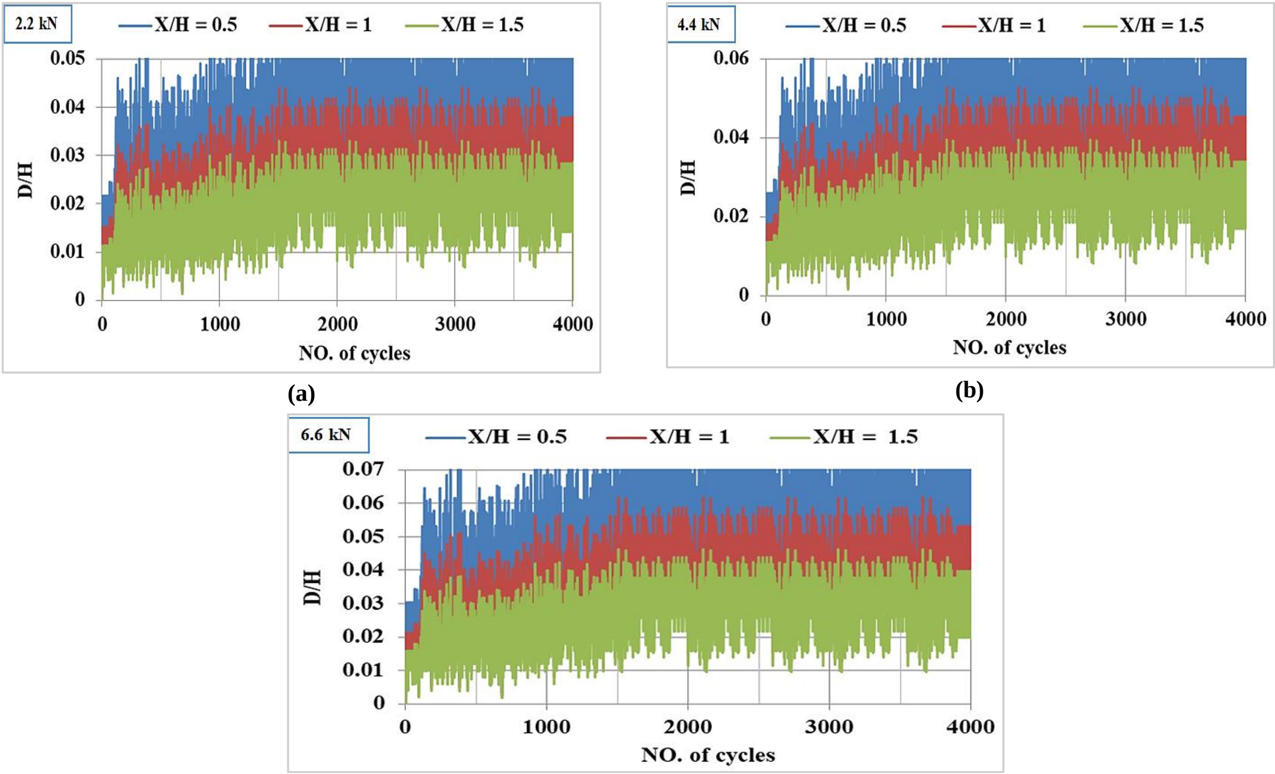
To clarify the impact of the location, nine series of tests were carried out on a railway placed at a distance (X = 0.5 H, 1 H, and 1.5 H) from the retaining wall. The railway was resting on loose, medium, and dense sand, where all the tests were using a load amplitude equal to (2.2, 4.4, and 6.6) kN. All the tests were performed with a frequency of 2 Hz for the cyclic load. From figures 6 to 8 (a, b, and c) for load amplitude 2.2, 4.4, and 6.6 kN, respectively, demonstrate that the top retaining wall's dynamic horizontal displacement ratio (D/H) was lessened as the distance between the railway and the wall increased. Moving the railway from 0.5 H to 1 H and then from 1 H to 1.5 H reduces the rate of displacement ratio by approximately 30% and 23%, respectively. This variation in the displacement values returns to the difference between the active and passive earth pressure resultants at the front and back of the retaining wall, which differed according to the distance between live loads and the retaining wall. This agrees with the findings of [28], which demonstrated that, under all operating circumstances, the lateral displacements of the pile walls decreased with distance from the pile wall.



(a) **(b)**

(c)

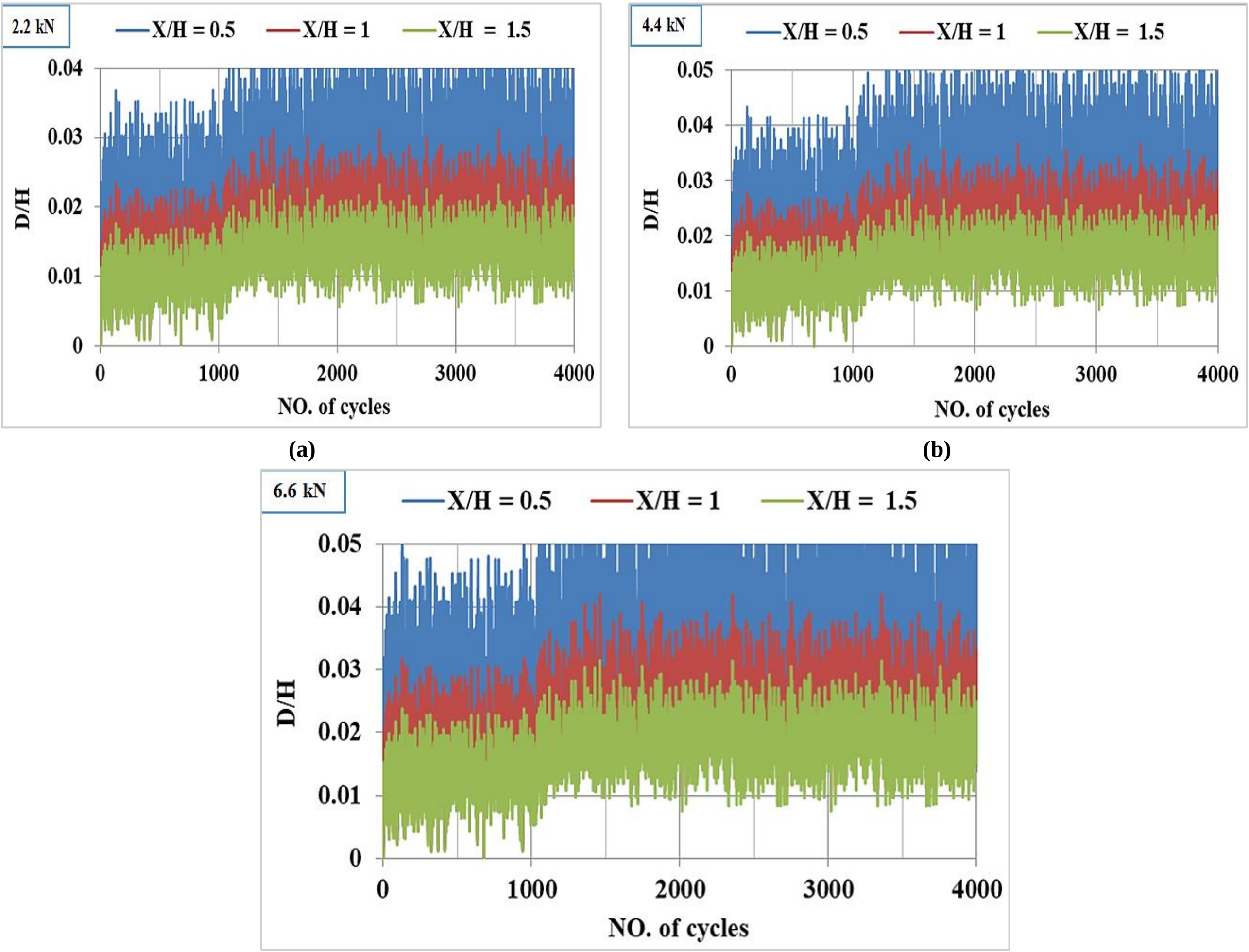
Figure 6: Cyclic number versus lateral wall displacement ratio D/H with different X/H for loose sand, under 2 Hz frequency; a., b, and c for load amplitude 2.2, 4.4, and 6.6 kN, respectively.



(a) **(b)**

(c)

Figure 7: Cyclic number versus lateral wall displacement ratio D/H with different X/H for medium sand, under 2 Hz frequency; a., b, and c for load amplitude 2.2, 4.4, and 6.6 kN, respectively.



(a) **(b)**

(c)

Figure 8: Cyclic number versus lateral wall displacement ratio D/H with different X/H for dense sand, under 2 Hz frequency; a., b, and c for load amplitude 2.2, 4.4, and 6.6 kN, respectively.

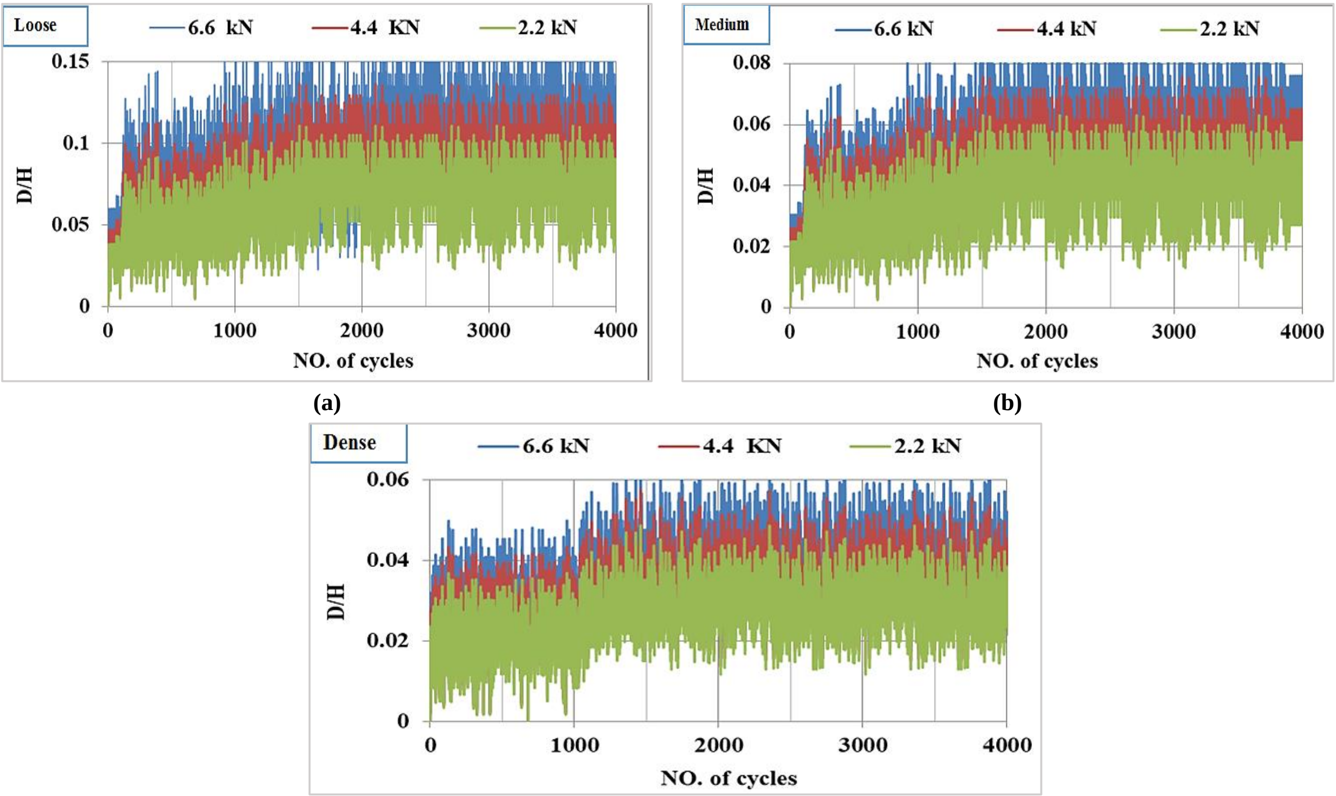
3.3 Effect of dynamic load amplitude

The horizontal displacement of the sandy backfill soil behind a sheet retaining wall is very important to consider under dynamic burdens with different amplitudes. Increasing cyclic load amplitudes caused the wall's horizontal displacement to increase; this is what was inferred from Figure 9, where all the tests were performed with a frequency of 2 Hz for the cyclic load and (0.5 H) for distances between the railway track and the retaining wall on loose, medium, and dense sand. These results were in accordance with [29, 30], where the soil lateral displacement caused by active lateral earth pressure on the wall increases as the dynamic load amplitude does.

The most significant factor affecting the dynamic displacement is the relative density of the backfill soil, as indicated in Sections 3.1, 3.2, and 3.3. This factor has a greater influence than the distance between the wall and the rail and the amplitude of the dynamic load on the railway. This can be attributed to the soil surrounding the retaining wall and supporting the track directly. However, the effect of increasing the distance between the wall and the rail is more direct on the wall than on the rail because of the time factor required for the effect of the load applied to the rail to be transmitted to the wall. In contrast, the effect of the load is direct on the rail and reaches the retaining wall after settlement occurs in the rail, which leads to its impact being the least on the wall's displacement from the density as well as the distance.

3.4 Correlation between wall's displacement and rail's settlement

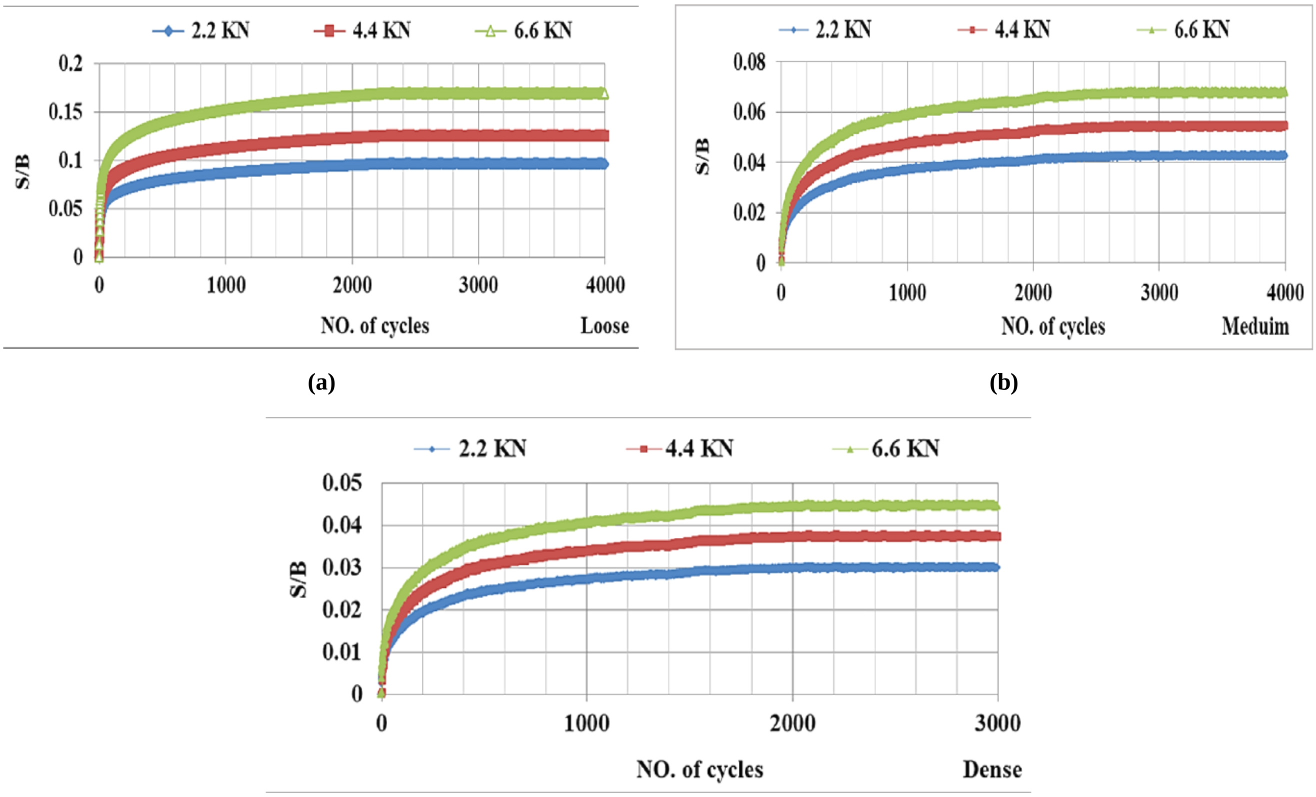
To determine how track settlement affects the wall's lateral displacement, the dynamic settlement ratio (S/B) curves (a, b, and c) for loose, medium, and dense sand, respectively were plotted in Figure 10 and compared with the displacement curves (a, b, and c) for loose, medium, and dense sand, respectively in Figure 9. It was discovered that there was a direct correlation, with a lesser average variance observed for dense soil, between the settlement and displacement. As pointed out in [11], this corresponds to reductions of the ground settlements to values approximately equal to the lateral braced wall movement as relative density increases.



(a) (b)

(c)

Figure 9: Cyclic number versus lateral wall displacement ratio D/H with different load amplitude for X = 0.5 H, under 2 Hz frequency; a., b, and c for loose, medium, and dense sand, respectively.



(a) (b)

(c)

Figure 10: Cyclic number versus settlement ratio S/B with different load amplitude for X = 0.5 H, under 2 Hz frequency; a., b, and c for loose, medium, and dense sand, respectively.

3.5 Number of load cycles' impact

According to all experimental test curves, as shown in Figures 5, 6, 7, 8, 9, and 10, horizontal displacement and vertical settlement measurements show a sharp increase up to cycle 1000 before leveling off. From 25 to 1500 cycles, there is a parameter-dependent constant increase. In line with the results of [31,32], these findings show that a limit value for accumulating permanent strain can be determined and that the permanent deformation rate in granular material will decrease under repeated loading. Railroad settlement and retaining wall displacement were mostly experienced in the initial 500 cycles due to gradual soil compaction, with only a small amount of settlement observed in subsequent cycles. Beyond that point, the rates of displacement and settlement decline and then level off.

4. Conclusion

Results from parameter-specific laboratory model tests investigating the impact of dynamic live load on the displacement of the wall in sandy soil used as backfill behind the retaining wall led to the following inferences:

- Increasing the relative density of the backfill significantly impacts the wall's dynamic displacement when subjected to the same cyclic burden amplitude. As the relative density of the subgrade changes from 30% to 55% and from 55% to 75%, respectively, at a 2 Hz frequency, the average decreases in the rate of displacement ratio (D/H) are approximately 53% and 31%.
- The dynamic displacement ratio decreases as the horizontal distance between the railway and the retaining wall increases. Moving the railway from 0.5 H to 1 H and then from 1 H to 1.5 H reduces the rate of displacement ratio by approximately 30% and 23%, respectively.
- Changing the live load amplitude from 2.2 kN to 4.4 kN and from 4.4 kN to 6.6 kN at a frequency of 2 Hz increases the rate of displacement by 23% and 29% for loose sand, 20% and 17% for medium, and 17.7% and 15% for dense, respectively, with the distance between retaining wall and railway maintained constant and the substrate's relative density unchanged.
- As the soil becomes denser and the dynamic load amplitude becomes smaller, the wall's lateral displacement (D) and the track's vertical settlement (S) decrease, and the (D/S) ratio approaches 100%.
- The displacement ratio (D/H) grows with the cyclic loading amplitude; (D/H) rises sharply up to 500 cycles, and then the displacement ratio increases at a slower, more gradual rate between 500 and 1500 cycles.
- Dense sandy backfill soil is more effective than medium sandy and loose soil.
- The most important factor that affects the D/H value is the relative density. The denser the backfill soil, the lower the value of the dynamic displacement of the retaining wall. The D/H value ranged from 0.14 in the loose soil under the highest applied load and the minimum distance between the wall and the railway to 0.017 in the dense soil under the lowest load and the largest distance between the wall and the railway.
- Under all conditions, the largest value of the dynamic horizontal displacement of the retaining wall was at the top.
- The correlation between the number of loading cycles, the wall's horizontal displacement, and the rail's vertical settlement is nonlinear.

5. Future works

- The established methodology can be applied to examine the properties of saturated cohesionless soils, focusing on their behavioral differences from dry conditions.
- The same methodology can be adapted to assess the effects of varying retaining wall heights and load amplitude frequencies, as induced by railway operations, on structural stability.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

Author contributions

Conceptualization M. Al-Neami, and M. Mahmood; data curation, K. Naji.; formal analysis, K. Naji; investigation, K. Naji; methodology, K. Naji; project administration, M. Al- Neami,, resources, K. Naji; software, K. Naji; supervision, K. Naji; validation, K. Naji, M. Al- Neami, and M. Mahmood; visualization, , K. Naji; writing—original draft preparation, K. Naji, and M. Al- Neami; writing—review and editing, K. Naji, M. Al- Neami, and M. Mahmood All authors have read and agreed to the published version of the manuscript.

References

[1] P. A. Montenegro, H. Carvalho, D. Ribeiro, R. Calçada, M. Tokunaga, M. Tanabe, W. M. Zhai, Assessment of train running safety on bridges: A literature review, Eng. Struct., 241 (2021) 112425. https://doi.org/10.1016/j.engstruct.2021.112425

[2] X. Ou, X. Zhang, J. Fu, C. Zhang, X. Zhou, H. Feng, Cause investigation of large deformation of a deep excavation support system subjected to unsymmetrical surface loading, Eng. Fail. Anal., 107 (2020) 104202. https://doi.org/10.1016/j.engfailanal.2019.104202

[3] S. S. Vadavadagi, S. Chawla, Effect of rail axle load on geosynthetic reinforced back-to-back mechanically stabilized earth walls: Experimental and numerical studies, Transp. Geotech., 38 (2023) 100907. https://doi.org/10.1016/j.trgeo.2022.100907

[4] P. Mandloi, A. Hegde, Performance evaluation of reinforced earth walls with sustainable backfills subjected to railway loading, Front. built environ., 8 (2022) 1048079. https://doi.org/10.3389/fbuil.2022.1048079

[5] D. W. Jacobs, R. B. Malla, On live load impact factors for railroad bridges, Int. J. Rail Transp., 7 (2019) 262-278. https://doi.org/10.1080/23248378.2019.1604182

[6] P. Mishra, P. Samui, E. Mahmoudi, Probabilistic design of retaining wall using machine learning methods, Appl. Sci., 11 (2021) 5411. https://doi.org/10.3390/app11125411

[7] V. K. Gade, S. M. Dasaka, Short-and long-term behavior of EPS geofoam in reduction of lateral earth pressure on rigid retaining wall subjected to surcharge loading, Geotext. Geomembr., 50 (2022) 868-880. https://doi.org/10.1016/j.geotexmem.2022.05.002

[8] M. Ramadan, M. Meguid, Behavior of cantilever secant pile wall supporting excavation in sandy soil considering pile-pile interaction, Arab. J. Geosci., 13 (2020).

[9] G. Feng, Q. Luo, P. Lyu, D. P. Connolly, T. Wang, An Analysis of Dynamics of Retaining Wall Supported Embankments: Towards More Sustainable Railway Designs, Sustainability, 15 (2023) 7984. https://doi.org/10.3390/su15107984

[10] C. Moormann, Analysis of wall and ground movements due to deep excavations in soft soil based on a new worldwide database, Soils Found., 44 (2004) 87–98. https://doi.org/10.3208/sandf.44.87

[11] A. Dijckmans, A. Ekblad, A. Smekal, G. Degrande, G. Lombaert, Efficacy of a sheet pile wall as a wave barrier for railway induced ground vibration, Soil Dyn. Earthq. Eng., 84 (2016) 55-69. https://doi.org/10.1016/j.soildyn.2016.02.001

[12] R. B. Peck, Deep excavations and tunnelling in soft ground, 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico, 1969, 225-290.

[13] K. Fujita, Soft ground tunnelling and buried structures, 13th International Conference on Soil Mechanics and Foundation Engineering, New Delhi, 5, 1994, 89-108.

[14] G. W. Clough, T. D. O'Rourke, Construction induced movements of in situ walls, Specially Conference on Design and Performance of Earth Retaining Structures, New York, 1990, 439-470.

[15] G. W. Cloughand, G. M. Denby, Stabilising term design for temporary walls in clay, J. Geotech. Eng. Division, 103 (1977) 75-90. https://doi.org/10.1061/AJGEB6.0000386

[16] V. N. M. Gilani, M. Habibzadeh, S. M. Hosseinian, R. Salehfard, A Review of Railway Track Laboratory Tests with Various Scales for Better Decision-Making about More Efficient Apparatus Using TOPSIS Analysis, Adv. Civ. Eng., (2022). https://doi.org/10.1155/2022/9374808

[17] M. Y. Fattah, M. R. Mahmood, M. F. Aswad, Stress Distribution from Railway Track over Geogrid Reinforced Ballast underlain by Clay, Earthq. Eng. Eng. Vib., 18 (2019) 77-93. https://doi.org/10.1007/s11803-019-0491-z

[18] Das, B. Principles of Foundation Engineering; D. B. M. Contractors, Inc., Federal Way, Washington, USA, 2011.

[19] American Society of Testing and Materials, Standard test method for specific gravity, ASTM D 854, West Conshohocken, Pennsylvania, USA, 2010.

[20] American Society of Testing and Materials, Standard test method for particle size-analysis of soils, ASTM D422-63, West Conshohocken, Pennsylvania, USA, 2010.

[21] American Society of Testing and Materials, Standard test method for maximum index density and unit weight of soils using a vibratory table, ASTM D4253, West Conshohocken, Pennsylvania, USA, 2006.

[22] American Society of Testing and Materials, Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density, ASTM D4254. West Conshohocken, Pennsylvania, USA, 2006.

[23] American Society of Testing and Materials, Standard practice for classification of soils for engineering purposes (united soil classification system), ASTM D2487, West Conshohocken, Pennsylvania, USA, 2006.

[24] E. O. A. Awoleye, Ballast type - ballast life predictions, Derby, British rail research LR CES 122, 1993.

[25] N. H. Thom, S. F. Brown, Effect of moisture on the structural performance of a crushed-limestone road base, Transp. Res. Rec., (1987) 50-56.

[26] M. Georgiadis, C. Anagnostopoulos, Displacement of Structures Adjacent to Cantilever Sheet Pile Walls, Soils Found., 39 (1999) 99-104. https://doi.org/10.3208/sandf.39.2_99

[27] M. A. Al-Neami, F. H. Rahil, A. F. Hussain, Settlement of Shallow Foundation in Dry Sand under the Earthquake, Eng. Technol. J., 39 (2021) 1206-1215. http://doi.org/10.30684/etj.v39i8.527

[28] W. Zhao, X. Wu, X. Ma., Model Test Study of the Synergistic Interaction between New and Existing Components of Sheet Pile Walls, Appl. Sci., 13 (2023) 1557. https://doi.org/10.3390/app13031557

[29] R. E. Hamdi, M. Y. Fattah, and M. Y. Aswad, Studying the Settlement of Backfill Sandy Soil Behind Retaining Wall Under Dynamic Loads, Eng. Technol. J., 38 (2020) 992-1000. https://doi.org/10.30684/etj.v38i7A.528

[30] M. A. Al-Neami, H. H. Baqir, S. H. Hameed, Behavior of Single Micropile Under Different Lateral Load Rates, Eng. Technol. J., 39 (2021) 167-179. https://doi.org/10.30684/etj.v39i2A.654

[31] J. L. Paute, P. Hornych, J. P. Benaben, Repeated load triaxial testing of granular materials in the French network of laboratories des ponts et chausse´es, Flexible Pavements, proceedings of the European Symposium Euroflex, Gomes Correia, editor, Balkema, 1996, 53–64.

[32] A. Asakereh1, S. N. Moghaddas Tafreshi, M. Ghazavi, Strip footing behavior on reinforced sand with void subjected to repeated loading, Int. J. Civ. Eng., 10 (2012) 140-152.