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Train Live Load Effects on the Subsidence of the Backfill Behind the Sheet Retaining Wall

Kather A. Naji *, **Mohammed A. Al-Neami**, **Mahmood R. Mahmood**
Civil Engineering Department, University of Technology, Baghdad, Iraq.

Keywords:
Backfill Soil; Sheet Retaining wall; Train loads; Vibration Recurrence; Settlement.

Highlights:

- *The effect of relative density, separation distance, and live load on railway settling.*
- *Increasing subgrade density lowered the dynamic settlement ratio from 59.9% then 35%.*
- *The dynamic settlement ratio decreased with wall-track distance.*
- *High live load and low frequency increased the backfill dynamic settlement ratio.*
- *The relationship between dynamic settlement and cycles was nonlinear.*

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****Corresponding author:***
Kather A. Naji
Civil Engineering Department, University of Technology, Baghdad, Iraq.

Abstract: Live loads generated by trains are a significant load in lateral pressure and settlement calculations. Studies emphasize the meaning of "accurately calculating live loads" to ensure the initial straightness of retaining walls. So, overestimating the effect of live loads generated by trains will lead to an overdesign of retaining walls and the surrounding soil and increase the cost of shoring. However, calculating these loads accurately will result in sufficient reinforcement without the need for excessive design of the retaining walls, leading to a durable design of the train system at a lower cost. In the present work, a laboratory model of a 1/7 scaled railway track was manufactured and employed. The influence of the live load induced by the trains passing on the cumulative settlement of backfill soil behind the sheet retaining walls was studied. Many parameters were studied, consisting of different burden amplitudes (0.22, 0.44, and 0.66 tons), vibration frequencies (2, 4, and 6 Hz), relative density (30% loose, 55% medium, and 75% dense sand), and different distances between the railway and retaining wall (0.5H, 1H, and 1.5H). The results showed that under the same cyclic burden amplitude, increases in the backfill relative density significantly impacted the dynamic settlement of the railway. The cumulative dynamic settlement ratio decreased as the horizontal distance between the railway and the retaining wall increased. The cumulative dynamic settlement ratio decreased by about 27.8% and 18.3%, as the railway location relative to the retaining wall changed from 0.5H to 1H and 1H to 1.5H, respectively. Dynamic settlement decreased as frequency increased when the conditions were kept constant. The settlement ratio increased with the live loading amplitude. Finally, dense backfill soil acted more efficiently than the medium soil, reducing the railway settlement and improving the overall behavior of the railway track adjacent to retaining walls.

تأثير الحمل الحي للقطار على هبوط الردم خلف الجدار الساند الصفائحي

كثير أ. ناجي، محمد النعيمي، محمود ر. محمود
قسم الهندسة المدنية/ الجامعة التكنولوجية / بغداد – العراق.

الخلاصة
أصبحت الأحمال الحية التي تولدها القطارات هي الحمل المهم في حسابات الضغط الجانبي والهبوط. تؤكد الدراسات على معنى "حساب الأحمال الحية بدقة" لضمان الاستقامة الأولية للجدران الساندة. لذا فإن المبالغة في تقدير تأثير الأحمال الحية التي تولدها القطارات ستؤدي إلى الإفراط في تصميم الجدران الساندة والتربة خلفها وزيادة تكلفة التدعيم. ومع ذلك، فإن حساب هذه الأحمال بدقة سيؤدي إلى تعزيز كافٍ دون الحاجة إلى تصميم مفرط للجدران الساندة، مما يؤدي إلى تصميم متين لنظام القطار بتكلفة أقل. في العمل الحالي، تم تصنيع نموذج مختبري لمسار سكة حديدية بمقياس ٧/١ واستخدامه لدراسة تأثير الحمل الحي الناجم عن مرور القطار على الهطول التراكمي للتربة خلف الجدران الساندة الصفائحية. تمت دراسة العديد من المعلمات، والتي تتكون من سعات حمل مختلفة (٠,٢٢ و٠,٤٤ و٠,٦٦ طن)، وترددات الاهتزاز (٢ و٤ و٦ هرتز)، والكثافة النسبية (٣٠٪ رمل سائب و٥٥٪ متوسطو٧٥٪ رمل كثيف)، ومسافات مختلفة بين السكك الحديدية والجدار الساند (H٠,٥ وH١ وH١,٥). أظهرت النتائج أنه تحت نفس سعة الحمل الدوري، فإن الزيادة في الكثافة النسبية للردم لها تأثير كبير على الهطول الديناميكي للسكك الحديدية. تنخفض نسبة الهطول الديناميكي التراكمية مع زيادة المسافة الأفقية بين السكك الحديدية والجدار الساند. انخفضت نسبة الهطول الديناميكي التراكمية بنحو ٢٧,٨٪ و١٨,٣٪ مع تغير موقع السكك الحديدية بالنسبة للجدار الساند من H٠,٥ إلى H١ ومن H١ إلى H١,٥. ينخفض الهطول الديناميكي عمومًا مع ارتفاع التردد عندما تبقى الظروف ثابتة. تزداد نسبة الهطول مع زيادة سعة التحميل الحي. وأخيرا، تعمل تربة الردم الكثيفة بكفاءة أكبر من التربة المتوسطة، مما يقلل من هطول السكك الحديدية ويحسن السلوك العام لمسار السكة الحديدية المجاورة للجدران الاستنادية.

الكلمات الدالة: تربة الردم، الجدار الساند الصفائحي، أحمال القطار، تكرار الاهتزاز، التسوية.

1.INTRODUCTION

Retaining wall construction is one of the most important geotechnical engineering structures for retaining soil. It is widely used to conserve railway tracks, highways, mines, tunnels, underground construction, and soldier protection. As it is mainly composed of backfill soil and a retaining wall, the engineering purpose of the retaining wall is to maintain the retaining soil in a certain condition and prevent it from settling and collapsing (stability) [1]. Therefore, the distortion of the wall and its horizontal and vertical displacements must be minimized to preserve the elements (serviceability). The construction and sustainability of railways require a high degree of reliability for all elements of the chain, including railways, trains, locomotives, and the retaining walls in particular [2]. For the appropriate management of railway structures, it is crucial to address deformations of the structure at an early stage [3]. The live loads applied via trains on the railway and nearby holding walls are a basic calculation of the railroad framework plan and security [4]. Various studies have examined this powerful load and its effect on holding walls. The live load includes the weight of the moving train, passengers, and goods. As a train crosses the track, it bestows dynamic powers on the ballast, the subgrade, and the nearby holding wall due to its speed, acceleration, and deceleration [5]. Powers shift given variables, for example, train speed, weight, track bend, and angle. Studies emphasize the importance of “accurately calculating live loads” to ensure the initial straightness of retaining walls. The idea of a load-initiated train requires consideration of impact factors, including wheel loads and their spread, to survey rail and wall stability and stress rotation. Further assessments focused on the need to address train live loads in the present day and plan ways to ensure the adaptability and security of the railway components and adjacent walls [6]. Understanding the live load and its consequences for retaining walls is essential to enhance the sustainability of railway retaining walls [7], the selection of reasonable materials, and the execution of shoring methodologies that can upgrade the general safety and solidity of rail line foundations. Trains apply the consequences of dynamic live loads to adjacent rails and walls, which leads to various difficulties in the basic design. These loads result from the entry of heavy moving stock and the initiation of vibrations, both vertical and lateral, requiring careful consideration of the plan, such as wall support, to ensure the basic stability of adjacent designs [8]. Retaining wall structures are often designed with a factor of safety higher than necessary due to limited knowledge of their serviceability and field performance [9]. In the field study by Ref. [10], i.e., a concrete pile wall adjacent to the train track, it has been confirmed that in all operating conditions, the displacement of the concrete pile wall decreased with increasing distance between the railway and the wall. Ref. [11] studied the dynamic analysis of railways using the finite element method. It was noticed that the maximum settlement occurred in the center of the sleeper, especially in the case of low-frequency. The frequency of loading varies for different researchers; [12] utilized 0.16 Hz for 50 cycles and 0.5 Hz for the remainder of the test. In 1974, Ref. [13] changed the loading frequency from 0.1 to 30 Hz. All of the tests started at 0.1 Hz for the first eight cycles. The reason for applying low frequency during the test's initial few cycles is that the deformations are usually substantial and may surpass a testing machine's hydraulic oil flow capacity. The deflection pattern of the track under wheel weight showed that just three sleepers sustained the load, while the others stayed suspended [14]. Additionally, Ref. [15] found that the sleeper below the wheel supported 40% to 60% of the wheel weight. While Ref. [16] recommended distributing the point wheel load over five adjacent sleepers, with the most significant stress on the sleeper below the wheel, since the maximum rail seat load fluctuates based on track conditions, there is no correct assumption for designing ballasted railway track foundations. The effect of train live loads on the subgrade and neighboring retaining walls has been the subject of examination in structural design writing, as has the conveyance of these accumulation effects and their impact on various parts of the sheet retaining wall, particularly at critical points. However, specialists have used limited component investigation and field estimates to view and predict pressure failures and live load effects of trains. Refs. [17, 18] used a limited component investigation to evaluate the primary reaction of adjoining walls to changing train loads. Their discoveries featured critical pressure concentrated near the foundation of the walls because of train-induced vibrations. One more study by [19] utilized field estimations and mathematical reenactments to assess the effect of train live loads on adjacent designs. Their findings underscored the significance of considering dynamic impacts and soil-structure communication while surveying wall reactions to prepare for prompt loads. Previous studies demonstrated that tests with a (1/n) scale model induced a resistance close to the results of a full-scale test with a ($1/n^3$) scale [20, 21]. The conditions and results of the test offered herein are from a scale model (1/7 scale). The similitude was considered for full-scale implementation. The validity of scaled railway models and a scaled ballast to portend full-scale behaviors was investigated by [22-24] through experiments. Previous studies did not consider the soil density factor in the strategic plan for track vibration and its negative impact on adjacent walls. Also, repeated load factors at different frequencies were not accounted for earlier. So, in this study, these parameters were considered to determine the extent of their impact on the outcomes obtained. A few past examinations have explored the impacts of train live loads on railway subgrade and some of these studies on nearby walls; therefore, this experimental study highlights the significance of fathoming the impact of train experience burdens on neighboring walls and their relationship to the backfill soil behind these retaining walls.

2.EXPERIMENTAL WORK

2.1.Soil Properties

The soil used in this study was poorly graded sand, taken from Diyala City, Iraq. It might be possible for designers to produce a safer and more affordable model by gathering data on soil factors like grain size and relative unit weight [25]. The soil was dried and sieved on sieve No. 10 (2.0 mm). Then, the physical properties of the soil were determined per the standard specifications, as shown in Table 1. The grain size distribution of the sand is plotted in Figure 1.

Table 1 Physical Properties of Sand Used.

Property	Value
Specific gravity (Gs)	2.66
D60, mm	0.53
D30, mm	0.26
D10, mm	0.15
Coefficient of uniformity, Cu	3.53
Coefficient of gradation, Cc	0.85
Minimum dry unit weight, kNm3	15.2
Maximum dry unit weight, kNm3	18.0
*Soil classification, USCS- ASTM D2487	SP
Maximum void ratio	0.75
Minimum void ratio	0.48

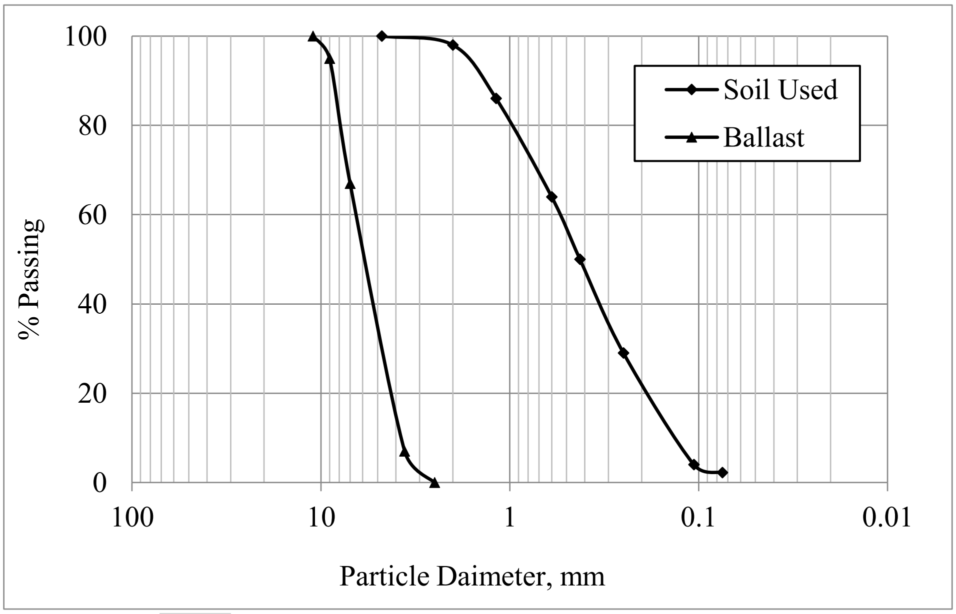


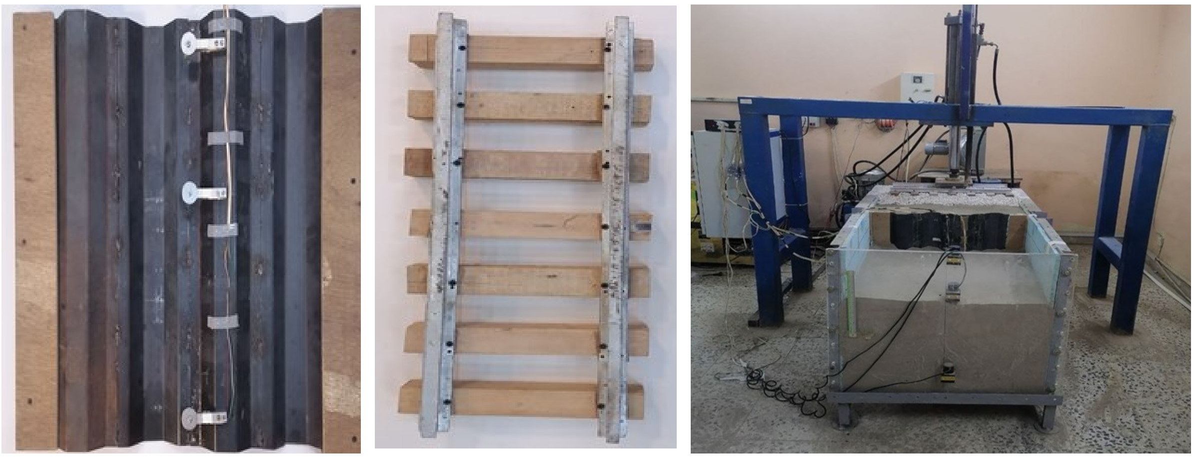
Fig. 1 Sand and Ballast Grain Size Distribution Curve.

2.2.Ballast Used

To prepare the (1/7) scale track ballasted, ballast particles at one-seventh of the original size were prepared from crushed stone, white-colored pieces with angular shapes produced by breaking stones of bigger sizes. Figure 1 shows the particle size distribution curve. 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- ASTM D422, the ballast utilized was poorly graded (GP) according to USCS- ASTM D2487.

3.SHEET RETAINING WALL MODEL AND RAILWAY MODEL

To prepare the sheet retaining wall and railway track model, a scale of 1/7 of the realistic measurement was used [26]. A steel sheet retaining 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 [27], as shown in Figure 2(a). The railway truck was also manufactured and installed for testing, which consisted of a pair of steel rails with a 65-cm length and seven wooden sleepers to simulate the real railway, per European and Iraqi specifications [24], as shown in Figure 2(b). The model was prepared for testing. The preparation consisted of placing the sandy soil with the retaining wall according to the relative density and distance mentioned previously in the container, and finally placing the ballast layer and the railway to start the test. Figure 2(c) shows the model used in the laboratory.



(a) Steel sheet wall. **(b)** Railway truck. **(c)** Laboratory model.

Fig. 2 Parts of a Railway Track Model.

4.MODEL TEST

4.1.Load Setup

To investigate the dynamic burden of the live load generated by trains on a sandy layer behind the wall, a special pressure apparatus was designed and assembled to achieve this aim. This device can apply different dynamic loads at various frequencies [24], as shown in Figure 3. This apparatus consisted of the following parts:

1. Loading frame, 2. Electro-hydraulic system, 3. Data acquisition, 4. Column encoder, and 5. Steel container (160×75×75) cm.

- **Loading frame**
  To ensure that the imposed load is applied vertically and centrally in the laboratory model used, a steel beam was manufactured that includes a steel edge, essentially consisting of four bars and four parts. Each part and column had a square cross-sectional area of 100mm × 100mm, made from a steel material with a thickness of 4mm. The steel frame components were 170 × 170 × 170 cm (length × width × height).
- **Electro-hydraulic system**
  The system consisted of a hydro-powered steel tank with a 70-liter maximum capacity. The tank had two holes; the top one was used to fill oil, while the other one was used to release it. The tank included an oil-operated mechanical assembly-type siphon with a fixed geometric volume, providing a release of approximately 720 liters/hr, with a maximum pressure of 150 bar. A programmable logic controller (PLC) was used to restrict pressure-driven frames. The monitoring unit opened and closed the valve associated with the oil-powered accessory, thus generating a half-full stack wave. The stacking interval was set before each test, creating a stacked wave at a specific frequency.
- **Data acquisition, obtaining, and registering information**
  It was employed to measure and detect settlements during tests, enabling the analyst to obtain valuable insights from the readings in a short period. It was also employed to select a predetermined

frequency used in the test. Information acquisition work has a programmable logic controller (PLC), which is described as a computerized control unit utilized for electromechanical computing procedures and an emerging innovative training unit. This type of data acquisition examines information accurately. The PLC instrument included an LCD communication scanner board to view and obtain information from the promoted stepwise motion logic.

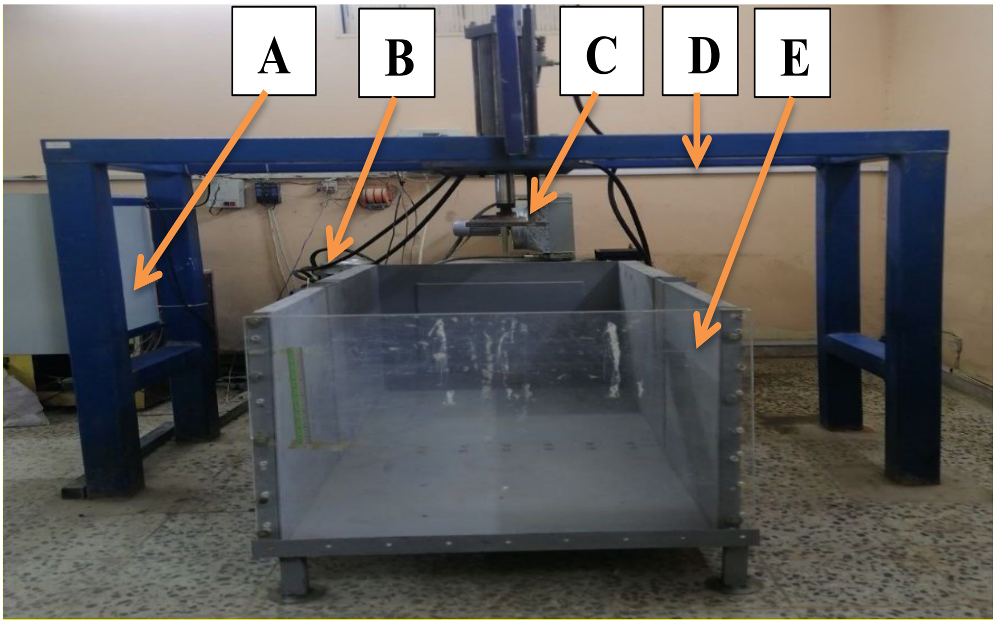


Fig. 3 Vibratory Impact Device: (A) Data Acquisition, (B) Electro-Hydraulic System, (C) Shaft Encoder, (D) Loading Steel Frame, and (E) Steel Container.

The settlement value data was transferred accurately and directly by connecting the system to the computer using a USB cable. Then, the required relationships were drawn using Microsoft Word and Excel.

- **Column encoder**
  It is an electromechanical device used to convert column movement into a digital code. The incremental encoder output provides information about the shaft movement, which is processed into information, such as settlement, revolutions per minute (rpm), speed, and position.
- **Steel container**
  The testing model consisted of a steel container with dimensions of 160 cm long, 75 cm wide, and 75 cm high, with a 5 mm-thick steel plate. The container consisted of five well-welded parts, one for the base and one for the four sides of the container, except the front face. It was made of toughened Plexiglas plate glass with a thickness of 15 mm. The edges of the long sides were strengthened by external steel angles, while the base was externally reinforced with three channels (50 mm mesh × 25 mm) with 8 square steel legs of 5×5 cm section and 25 cm height. Each leg had a circular steel base 7 cm in diameter.

5.MODEL PREPARATION

The soil anisotropy is considered a critical issue in the construction and design of the railways, particularly in the subgrade and the behavior beneath. Railway tracks are exposed to the dynamic loads generated by passing trains, and any anisotropic behavior in the soil may affect the overall performance of the railway system [28]. Therefore, to achieve this, the sand deposit was prepared using a hand-tamping rod for loose sandy soils, and a modified compactor was used for dense and medium sandy soils, as shown in Figure 4. A total of 81 models were examined under cyclic loading using different relative densities of sandy backfill of 30, 55, and 75% representative of loose, medium, and dense sand, respectively, i.e., the weight required to achieve the relative density is predetermined since the unit weight and the volume of the sand are predetermined. The total weight was divided into six equal weights, each one representing the weight required for a single layer, which had a thickness of 10 cm for the active and passive sides. The soil in each layer was compacted to the required depth. After completing the final layer, the top surface was scraped and leveled with a sharp-edged ruler to achieve a flat surface. Following the same procedure as the soil preparation, the required quantity of ballast was calculated for a single layer whose thickness was not greater than 6 cm. The retaining wall was placed according to the required distance for each test. After completing the sanding process, the top surface of the soil was leveled. Then, a 2.5 cm thick sub-ballast layer was placed, followed by a 5 cm thick ballast layer. During this process, the railway model was placed on top to overlap with the ballast according to the required dimensions. Finally, the device was prepared for the cyclic test in a specific order. The benefit from the cyclic load continues until four thousand cycles. Figure 5 shows the plane and section of the laboratory model. Corrected sine wave loading was applied to sleepers [29], who proposed this loading method to produce traffic loads. Numerous studies, including [30], found that frequency has a negligible effect on granular material resilience. Thus, load frequency has a minimal influence compared to other factors. The flow and pressure capacity of the hydraulic loading system specified its frequencies by (2, 4, and 6) Hz, which is close to the train railway track's typical frequency value, which ranges up to 10 Hz [24]. The live load used in the lab model (2.2) kN simulated the train's axle live load according to [31]. The simulated live load (2.2) kN was doubled to (4.4 and 6.6) kN to assess the impact of increasing the live load on the railway system's performance.

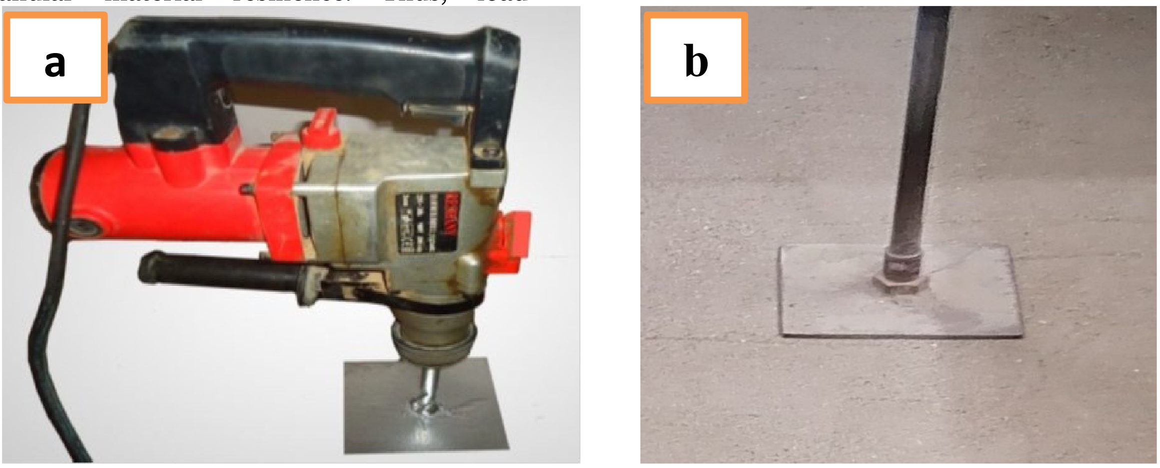


Fig. 4 (a) Modified Compactor, (b) Tamping Rod.

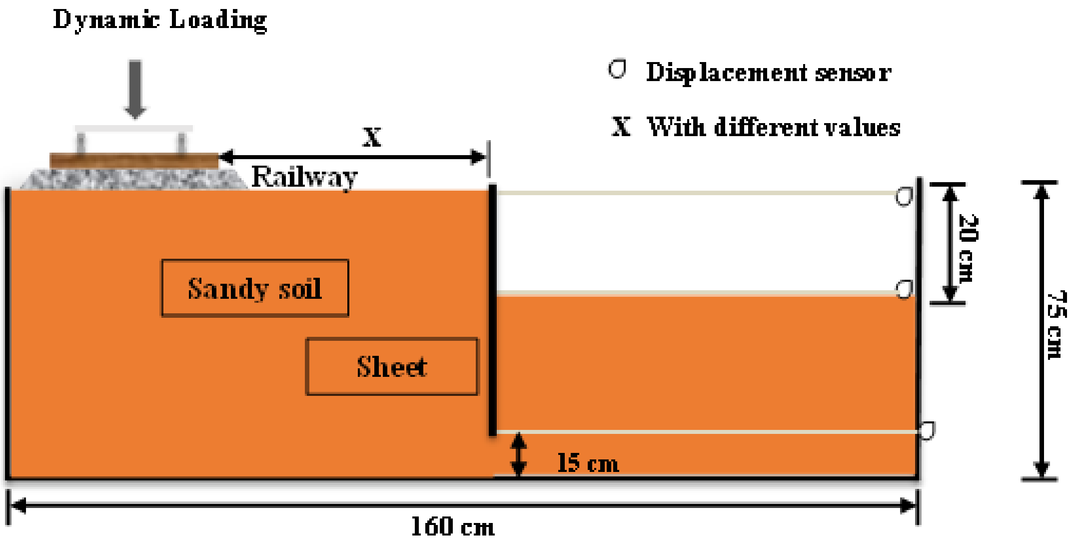


Fig. 5 The Plane and Section of the Laboratory Model.

6.RESULTS AND DISCUSSION

Eighty-one tests were conducted for up to 4,000 loading cycles to study the effect of the factors listed below on the cumulative dynamic settlement of the railway model adjacent to the retaining wall. According to the requirements for each test, all tests used load amplitudes equal to (2.2, 4.4, and 6.6) kN. Also, tests were performed on a railway with a position at a distance (X = 0.5, 1, and 1.5 H) from the retaining wall, where H is the excavation depth, and the frequency of the cyclic load was equal to (2, 4, and 6) Hz.

6.1.Effect of Relative Density of Subgrade

To study the effect of relative density (RD) on railway performance, cyclic tests were conducted under various (X/H) ratios and several dynamic load amplitudes at different vibration frequencies with the railway resting on loose, medium, and dense sand. Figure 6 shows the relationship between the cumulative dynamic settlement ratio S/B and the relative density (RD) of the bed soil. S/B decreased with increasing relative densities, regardless of the other parameters, because loose sandy soil contains high voids in contrast to dense sandy soil. As a result of the railway dynamic burden amplitudes, the soil particles started to redistribute and come closer together. Increases in the backfill relative density significantly impacted the dynamic settlement ratio of the railway. The average decreases in the rate of S/B were about 59.9% and 35% as the relative density of subgrade changed from 30% to 55% and from 55% to 75%, respectively. This result is coupled with the results indicated by [32], who conducted a series of vibration experiments on a shallow foundation based on sandy soil with different relative densities to calculate foundation settlement. The results showed that settlement decreased when the relative density of sand increased.

6.2.Influence of the Dynamic Load Amplitude on the Settlement

The vertical settlement of the sandy backfill soil behind a sheet retaining wall is significant to consider under dynamic burdens with different vibration frequencies and burden amplitudes, relative densities, and different distances between the railway track and the retaining wall. Figure 7 depicts the effect of cyclic load amplitude on S/B for the rail model resting on loose, medium, and dense sand. The tests were conducted to clarify the effect of the live load train amplitude on railway performance. Three load amplitudes (2.2, 4.4, and 6.6) kN were applied to the model with frequencies of (2, 4, and 6) Hz of cyclic load. The increase in the amplitude of cyclic loads directly caused track settlement to increase for all soil densities. Also, the effect decreased with increasing the distance between the wall and rails, i.e., the railway was affected by a variety of dynamic burdens. The change in live load amplitude from 2.2 kN to 4.4 kN and from 4.4 kN to 6.6 kN led to an increase in the rate of cumulative dynamic settlement ratio S/B of approximately 29.8% and 35% for loose sand, 26.8% and 23.2% for medium, and 20.3% and 17.4% for dense, respectively. This behavior happened because the dynamic load amplitude increased, and the active thrust on the wall generated a lateral displacement. Increasing this thrust will cause the backfill soil to settle vertically. The lateral active earth pressed against the divider as the relative density of the backfill soil increased, resulting in a decrease in lateral displacement and a subsequent reduction in soil settling. This outcome is in line with a laboratory study by [33], who examined the impact of increasing the cyclic loads on the foundation next to the gravity retaining wall. It was found that the foundation settlement increased with the amplitude of the applied load.

6.3.Railway Location's Impact on the Retaining Wall

A challenging and important component of structural engineering is understanding how retaining walls behave under dynamic loads, especially in locations of dynamic forces. The dynamic forces that trains cause as they move impact the earth and the nearby infrastructure. To clarify the impact of the location, nine series of tests were conducted 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. Figure 8 shows the (S/B) variation with the X/H ratios. (S/B) significantly increased as the locations moved toward the wall, and the distance between the wall and the live load decreased. The maximum settlement occurred at a distance of 0.5H, and for the same railway location, the soil density significantly impacted the decrease in railway settlement. Also, the figure shows that when the railway location moved away from the wall, the rate of decrease in S/B decreased. The rate of S/B decreased by about 27.8% and 18.3% as the railway location relative to the retaining wall changed from 0.5H to 1H and from 1H to 1.5H, respectively. This variation in the settlement 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. As well, these results align with the research of [34], which was conducted to examine the settlement of a strip foundation on sandy soil located next to excavations supported by a sheet pile wall. Their results indicated that most settlements occurred when the building was closest to the excavation.

6.4.Effect of Frequency Vibration of the Cyclic Load on the Backfill Settlement

Knowing the influence of the frequency is essential to preventing resonance amplification, which may cause wall damage and excessive movement. Therefore, in this study, three frequencies (2, 4, and 6) Hz with nine cyclic tests were performed on the railway model resting on loose, medium, and dense sand. Three burden amplitudes (2.2, 4.4, and 6.6) kN were considered, with one unique distance equaling 0.5H between the railway and the retaining wall. Figure 9 shows the relationship between the settlement ratio and burden amplitude for the three relative densities. It can be observed that the cumulative dynamic settlement ratio S/B was inversely proportional to the burden amplitude; the higher the frequency, the less the settlement. Also, more effects can be marked when the sand is in a loose state.

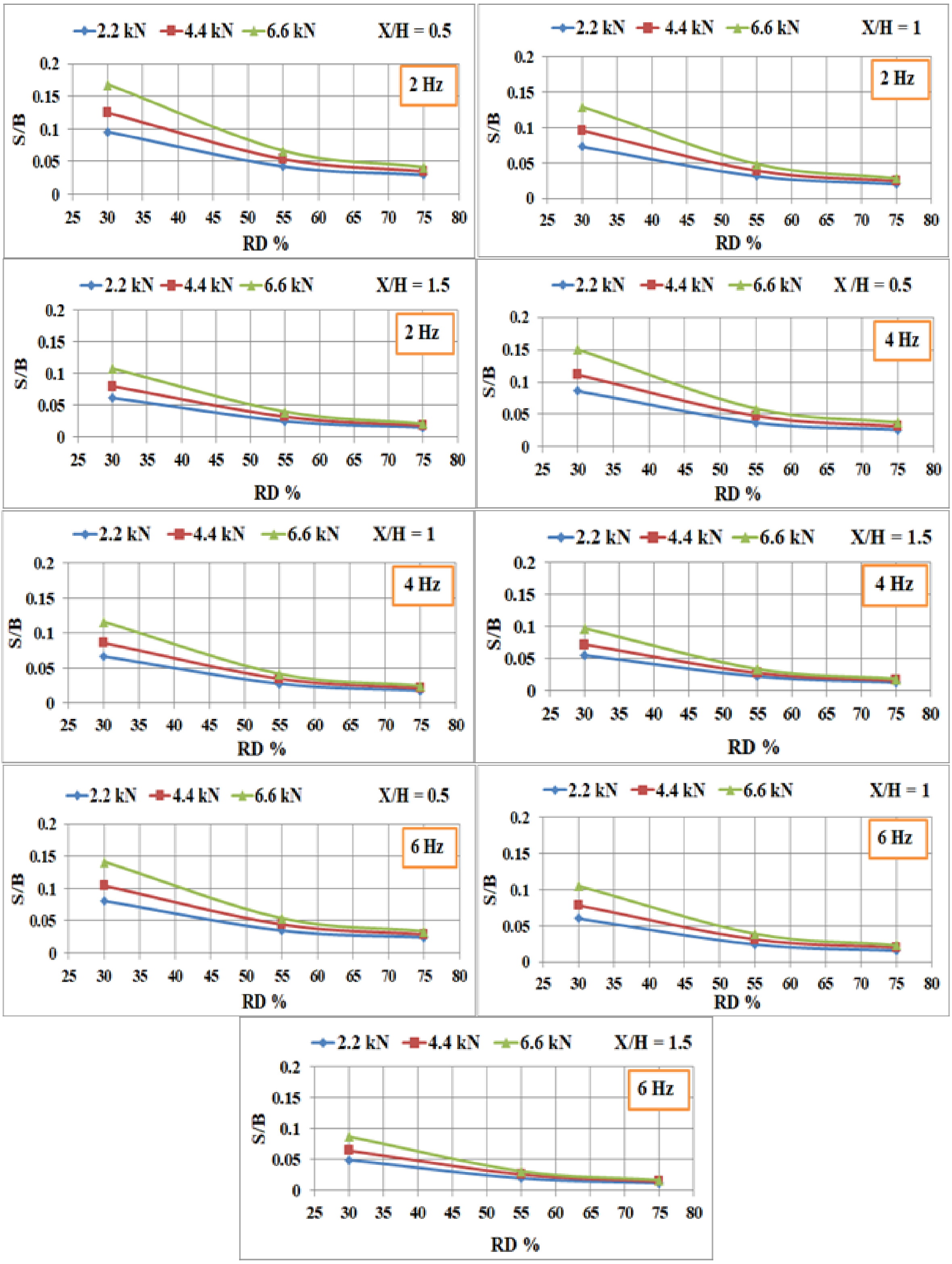


Fig. 6 (S/B) Versus (RD%) with Various (X/H) Ratios and Several Dynamic Load Amplitudes at Different Vibration Frequencies.

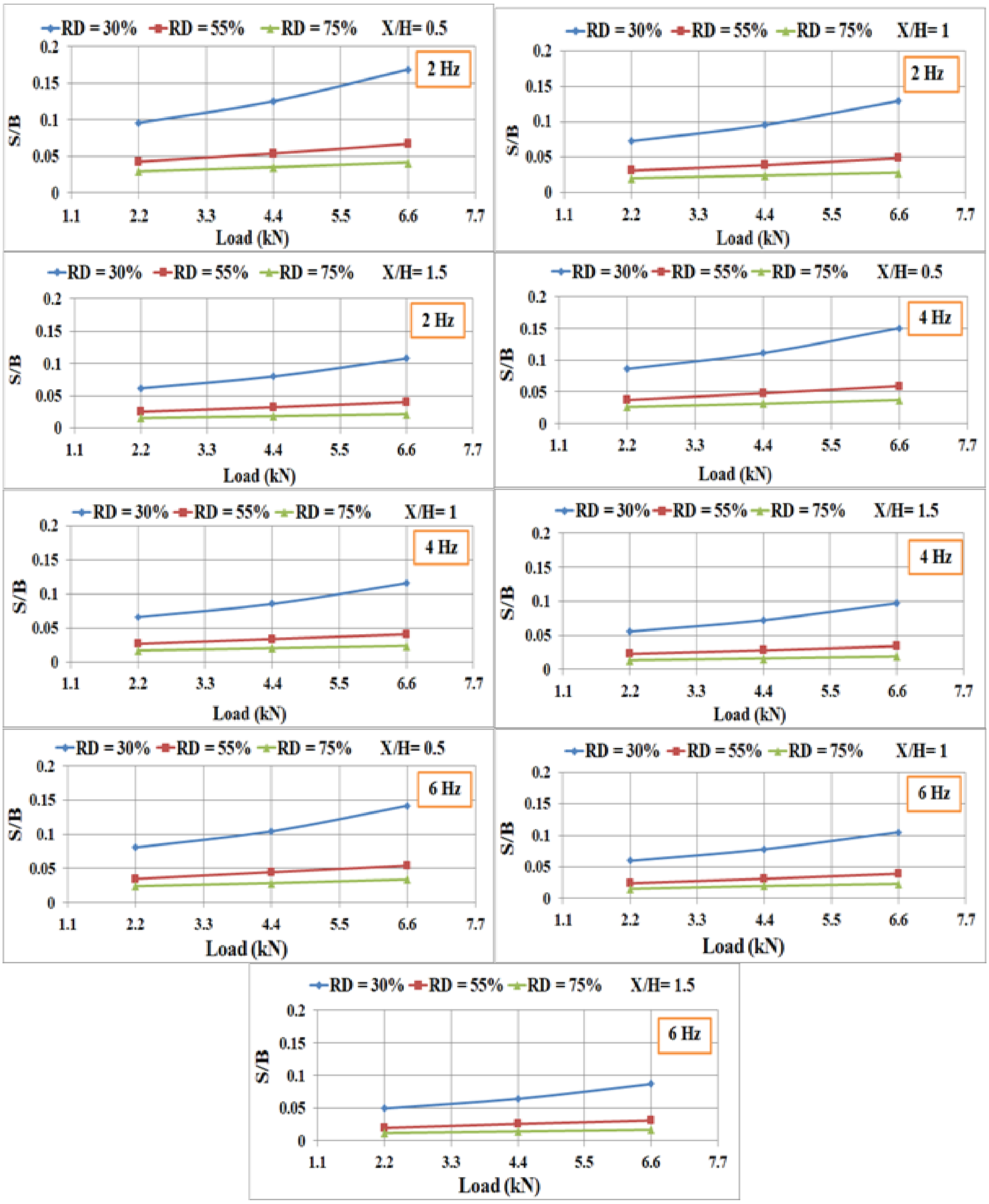


Fig. 7 Variation of (S/B) Against Dynamic Load Amplitude at (2, 4, and 6) Hz Vibration Frequency with Various (RD) and (X/H) Ratios.

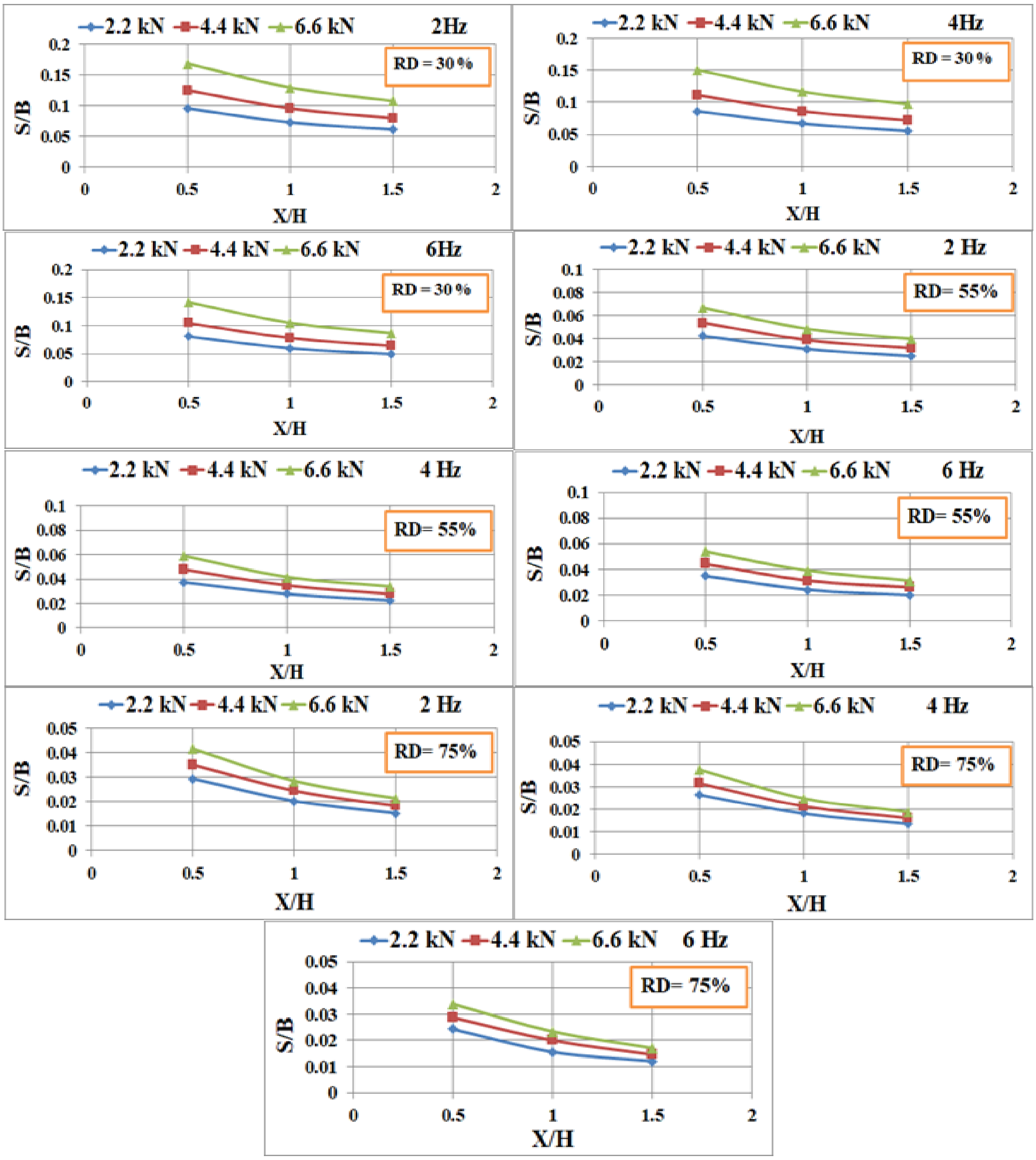


Fig. 8 Variation of (S/B) Against (X/H) Ratio with Various RD under Different Load Amplitudes at Variable Vibration Frequencies.

Under the same conditions, the average reduction in the rate of the settlement ratio was about 12% and 8%, as the frequency vibration of the cyclic load changes from 2 Hz to 4 Hz and from 4 Hz to 6 Hz, respectively. This behavior may be attributed to the fact that the loose sand has more voids than other states, and the sand particles compacted under shaking; therefore, the loose sand exhibited more settlement. The greater susceptibility to the effect at lower vibration frequencies may be because the period of load application for each cycle at low frequency was greater than at high frequency. According to the findings of [35], in their study of machine foundations, the settlement of footings decreased as the frequency increased, regardless of the relative density of sandy soil and dynamic load amplitude.

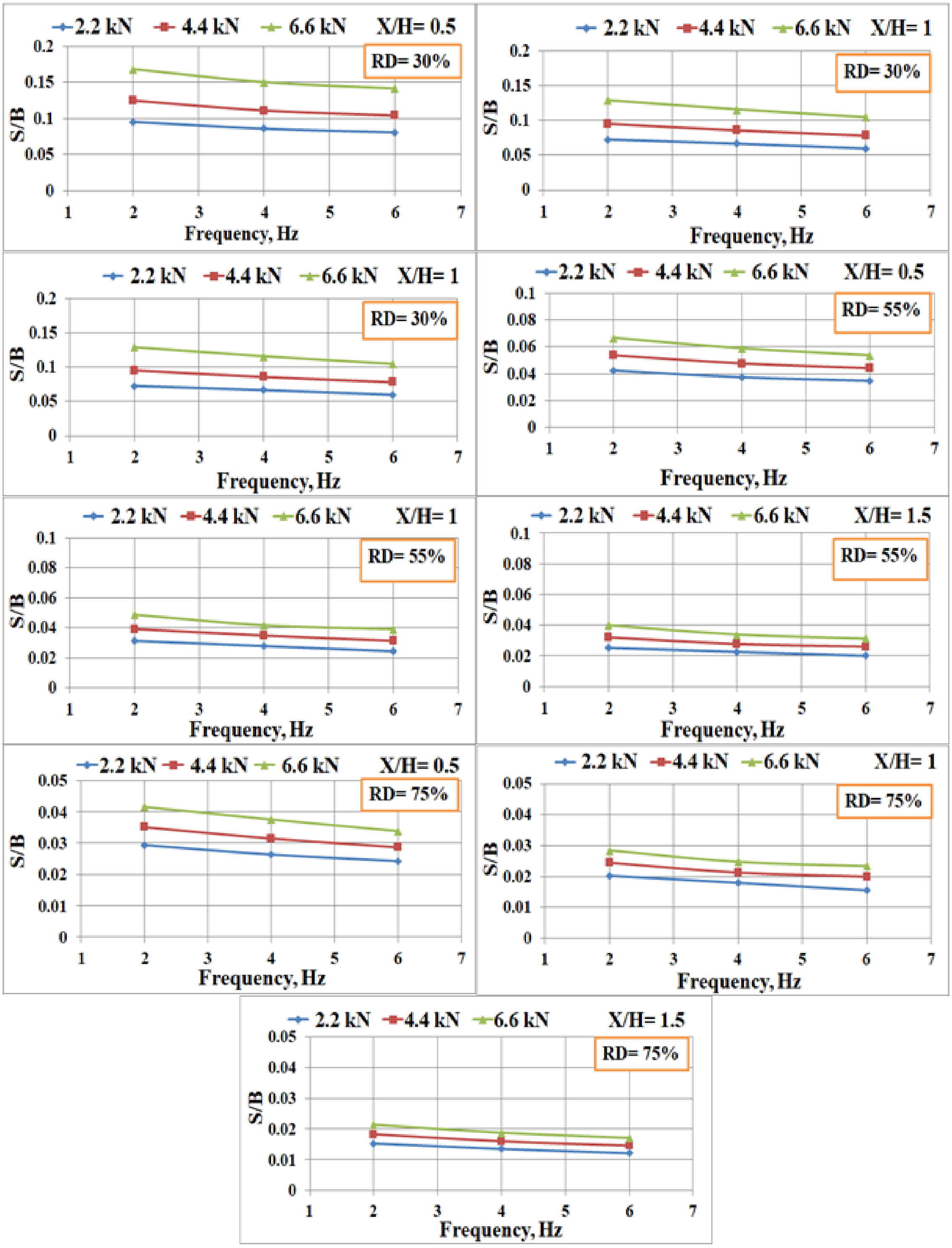


Fig. 9 Variation of (S/B) Versus Vibration Frequency with Various RD under Different Dynamic Load Amplitude and Variable (X/H) Ratios.

6.5.Number of Load Cycles and the Settlement

The soil behavior under dynamic load depends on several factors, including the nature of the load, strain rate, strain magnitude, and the number of cycles of loading. In this section, the impact of load cycles on the settlement of the backfill sand behind the sheet retaining wall will be examined. For example, (S/B) versus the number of load cycles for a railway resting on loose, medium, and dense sand is shown in Figure 10. In these tests, the railway was placed at a distance of X = 0.5 H, and the cyclic load frequency was kept constant, i.e., 2 Hz.

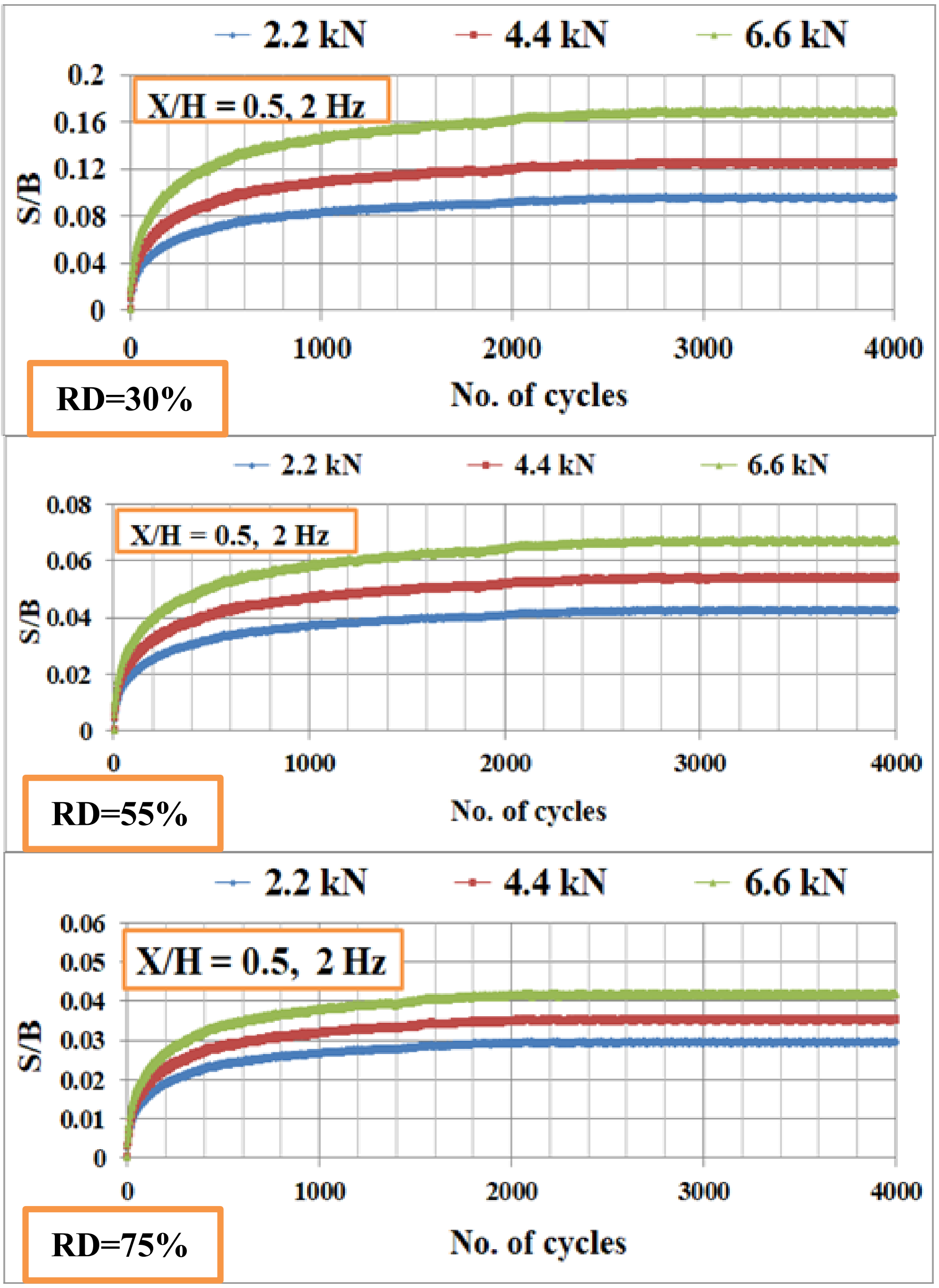


Fig. 10 (S/B) Versus No. of Cycles with Various RD, Different Dynamic Load Amplitudes at 2 Hz, and (X/H = 0.5).

It can be seen that, at the same number of load cycles, the cumulative dynamic settlement ratio, S/B, significantly decreased when the soil density increased. The settlement ratio increased gradually at the early stage of application of cyclic loading, i.e., the settlement increased very rapidly for the first 25–200 cycles. Then, the rate of increase in the dynamic settlement tended to decrease gradually until a total of 2000 cycles. After that, the rate became slower, and the trends approximately took a linear shape. The final settlement of loose soil was greater than the final settlement of dense soil. Therefore, it could be stated that dense sand works more efficiently than medium sand in reducing track subsidence and thus improving the general behavior of the railway truck adjacent to the retaining walls. These results are in line with [36, 37], who found that a limit value for accumulating permanent strain can be determined, and the permanent deformation rate in granular material will decrease under cyclic loading. Finally, the number of loading cycles was determined up to 4000 cycles based on the laboratory tests conducted, which showed that the S/B curves were remarkably stable after the 2000th cycle, consistent with findings from many studies, such as [33].

7.CONCLUSIONS

The main conclusions of the present study could be summarized as follows:

- Under the same cyclic burden amplitude, increases in the relative density of backfill significantly reduced the cumulative dynamic settlement ratio of the railway.
- The increase in the amplitude of live loads directly caused the cumulative dynamic settlement ratio to increase for all soil densities.
- The cumulative dynamic settlement ratio reduced as the horizontal distance between the railway and the steel sheet retaining wall increased.
- In general, the cumulative dynamic settlement ratio decreased as frequency increased. However, frequency has the lowest impact on the railway settlement compared to the other factors investigated in the present study.
- There was a rapid rise in S/B up to cycles 25–500, while there was a gradual decrease between 500 and 2000 cycles. After that, the trend took an almost linear horizontal shape.
- The correlation between the dynamic settlement of the track and the number of loading cycles was nonlinear.

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NOMENCLATURE

B	Sleeper length
Cc	Coefficient of gradation
Cu	Coefficient of uniformity
D_{10}	10%-passing particle size
D_{30}	30%-passing particle size
D_{50}	Average particle size
D_{60}	60%-passing particle size
D_{max}	Maximum particle size
GP	Poorly graded ballast
GS	Specific gravity
H	Excavation depth
RD	Relative density
S	Cumulative dynamic settlement
S/B	Cumulative dynamic settlement ratio
SP	Poorly graded sand
X	Wall to track distance
X/H	Horizontal distance to Excavation depth ratio

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