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Vehicle velocity effect on the structural response of buried flexible pipe: experimental study

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HIGHLIGHTS

- The effect of vehicle velocity on the response of a buried flexible pipe was investigated.
- As velocity increased, both pipe displacement and strain were reduced. Where apex strain dropped by 26.9% from 5–10 km/h and 3.3% from 10–15 km/h.
- Apex displacement decreased by 29.5% from 5–10 km/h and 12% from 10–15 km/h.
- When speed dropped from 15–10 km/h, spring line displacement and strain rose by 28.58 and 2.05%.
- From 10–5 km/h, spring line displacement and strain increased by 18.17 and 11.36%, respectively.

Keywords:
Vehicle velocity
Flexible pipe
Moving load
Pipe displacement
Pipe strain

ABSTRACT

An urgent need to investigate the effects of the vehicles' characteristics on city infrastructure has arisen as a result of the development of roads and transportation, including the construction of new roads and the rise in vehicle numbers brought about by global population growth. In this research, an experimental study is performed to examine the effect of vehicle velocity on the behavior of buried Polyvinyl Chloride (PVC) pipe under traffic load (moving load). The moving-wheel load has been exerted using a small-scale model with three velocities (5, 10, and 15 km/hr) to compare the strains and deformations occurring at the apex of the buried pipe. The pipe was instrumented with the data acquisition system, including installing the strain gages to read the strains at the pipe circumference as well as Linear Variable Differential Transformers (LVDTs) to read the displacement in the same locations. It was revealed that as the velocity rises, the displacement and strain fall. When the velocity increased from 5 to 10 km/hr and from 10 to 15 km/hr, the decrease percentage in the pipe's apex strain was 26.9 and 3.3% respectively, while the decrease percentage in the pipe's apex displacement was 29.5 and 12% respectively. In addition, as the velocity rose from 5 to 10 km/hr and from 10 to 15 km/hr the decrease percentage in the pipe's spring line displacement was 18.17 and 28.58% respectively, while the decrease percentage in the pipe's spring line strain was 11.36 and 2.05% respectively. As a result, it is not necessary to restrict vehicle speed on roads including buried structures to prevent damage, as occurs in traffic accidents caused by excessive speed.

1. Introduction

The impact of vehicle velocity on underground pipelines is a major concern in infrastructure management and civil engineering, particularly in metropolitan settings where traffic loads impose significant stress on subsurface utilities [1]. A buried pipe may affect the road structure through structural interaction, weakening the foundation support if it ruptures and leaks. As a result, there may be significant disruptions to the road's traffic flow [2,3]. Roadway traffic above underground pipelines generates dynamic forces that increase soil stress and strain, potentially compromising the structural integrity of the pipes. Notably, there has been less research on the interaction between roadways and buried flexible pipes [2]. Flexible pipes are defined with subtle differences by various authorities. According to AASHTO, a flexible pipe can deform under load without incurring significant structural failure, relying on the interaction with the surrounding soil to distribute loads and limit deformation [4]. In contrast, Moser and Folkman define a flexible pipe as one that can deflect at least 2% without suffering structural distress, emphasizing not only the pipe's inherent stiffness but also the quality of the backfill material [5]. This juxtaposition illustrates that while AASHTO offers a broader conceptual framework centered on soil-pipe interaction, Moser and Folkman provide a more quantifiable criterion for performance. Moreover, the high ratio of diameter to wall thickness causes buried pipes with a large diameter to behave flexibly often [6].

According to bending stiffness (EI) and axial stiffness (EA), flexible pipes have low flexural rigidity and circumferential stiffness. The main issue with flexible pipes is that they are more likely to deform when subjected to external loads. Flexible pipes experience considerable deformation in contrast to rigid pipes, which retain their structural integrity under load. The

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displacement of the crown is a key factor in changing the cross-sectional shape [7-9]. The relative stiffness between the pipe and the surrounding soil particularly influences this behavior. Since the stiffness of flexible pipes is lower than that of the soil, they exhibit a phenomenon known as negative arching,' wherein the surrounding soil does not provide the structural support typically observed in rigid pipe systems [10].

Vehicle-induced pressure waves, especially from trucks, trains, and military vehicles, can propagate through the Earth. In softer soils, these waves apply dynamic stresses on underground structures, which may lead to wear or deformation over time. Dynamic loads, vibrations, and soil-structure interactions (affected by factors such as the vehicle's weight, speed, soil type, and structural design) create variable stresses on buried pipelines [11,12]. The rapid loading conditions can alter the soil's stress-strain properties, which can compromise its ability to support pipelines, resulting in greater displacements and reduced stability of the pipeline system [13]. Many previous studies have shown that there are different opinions about the effect of vehicle speed on the behavior of buried pipes. According to Alzabeebee et al. [14], slower-moving loads result in higher stress levels because the time of load application on the pipe reduces with increasing vehicle speed. Their results show that the load stays in touch with the soil-pipe system longer at lower speeds, which permits extra stress to develop. In a similar vein, Neya et al. [15], noticed that greater velocities lessen the sustained stress on the pipe because of the transient character of the applied load in their three-dimensional numerical simulation of subterranean steel pipes under moving loads. However, field studies that investigated the structural behavior of buried steel and concrete culverts under traffic load revealed that there are various results on the effect of truck's speed on the structural behavior of buried structures, with some showing an increase in stresses and cross-sectional deformations of pipes when vehicle speed decreases [16,17] while others show the opposite [18].

In summary, the influence of vehicle velocity on underground pipelines is a multifaceted field of study, encompassing various factors affecting the structural stability of subterranean utilities. As urban traffic patterns evolve, engineers must consider the complex soil-pipe interactions under moving loads when constructing and maintaining underground infrastructure. Continued research is crucial to ensure the security and reliability of vital utility networks. To further explore this relationship, a decision was made to use moving loads in a controlled laboratory setting through a small-scale model to simulate vehicle loading on a buried flexible pipe. This approach differs from previous studies, which have primarily used in situ or numerical methods to study the behavior of rigid pipes. This approach will allow for a more controlled analysis of the specific effects of vehicle speed on buried pipes, ultimately contributing to safer and more durable infrastructure. This research specifically aims to investigate the influence of vehicle speed on the structural response of the buried flexible pipe by carrying out a series of experimental tests using a small-scale model, considering changes in pipe crown deformation and pipe spring line deformation.

2. Experimental work

2.1 Small-scale model

To investigate the behavior of pipes buried in soil under a moving wheel load, it is required to imitate the conditions as closely as possible to those occurring in the field. A special testing model (small-scale model) and its accessories have been designed and manufactured to fulfill this task. During the design process, the limited budget, the size of the sections used, and the availability of devices in the market were taken into account. Figure 1 illustrates the formulation of the model setup. It is noteworthy that the testing duration ranged between 15 seconds and 5 seconds.

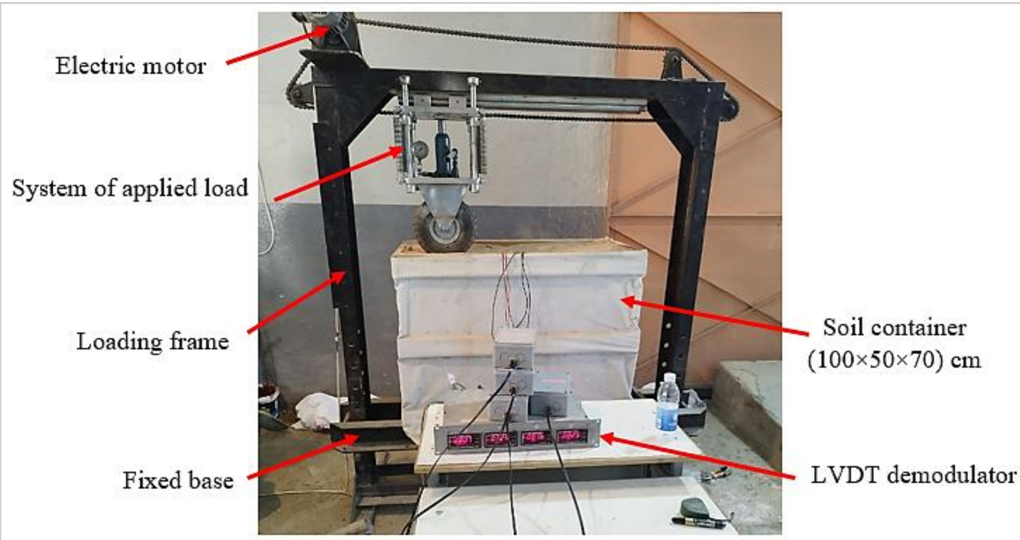


Figure 1: Model setup implementation

2.2 PVC pipe

In this study, a PVC pipe is provided in the experimental work. The outer diameter of the pipe is 110 mm, and the wall thickness is 2 mm, while the length is 450 mm to avoid attaching to the sides of the soil box. The tensile tests were carried out in the Materials Department of the University of Technology as shown in Figure 2. The tests have complied with BSI [19], for (Underground sewer and Drainage services). The properties of PVC pipe are illustrated in Table 1.

Figure 2: Pipe testing machine

Table 1: Pipe properties

Tensile yield strength	20 MPa
Modulus of elasticity (E)	3 Gpa
Density	1250 kg/m^3
Poisson's ratio (υ)	0.35

2.3 Soil

The PVC pipe was embedded in suitable soil that had been provided. The following soil tests were carried out to ascertain its characteristics: modified proctor compaction test, specific gravity, grain size analysis, direct shear test, maximum and minimum dry density, and relative density. The University of Technology's Soil Mechanics Laboratory was the venue for the soil testing program. It should be noted that the soil passes through sieve No. 4 and is classified as poorly graded sand (SP) according to the USCS (Unified Soil Classification System). According to the ASTM D422 [20], the mechanical grain size analysis was carried out and illustrated in Figure 3. The considered soil density in the research was 1600 kg/m^3 and determined by the raining technique method which was developed by Koulbuzewski [21]. The modulus of elasticity (E) of the soil was 15 MPa, whereas the Poisson's ratio (υ) and friction angle Ø were 0.3 and 35, respectively.

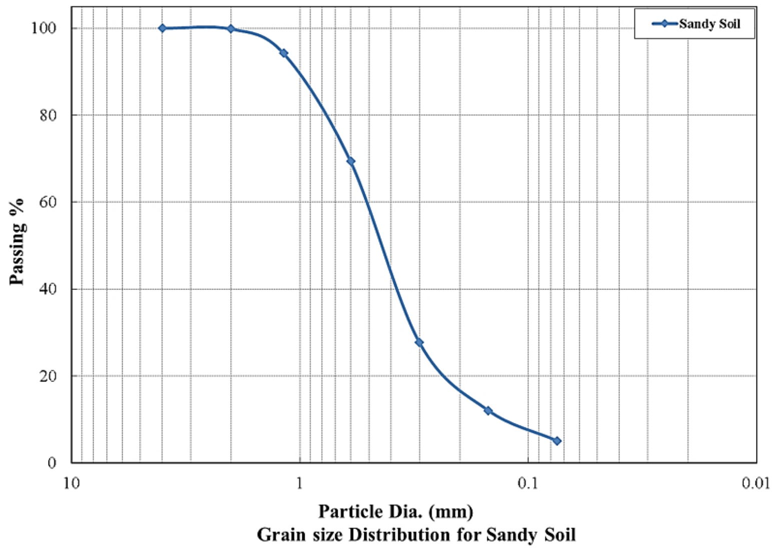
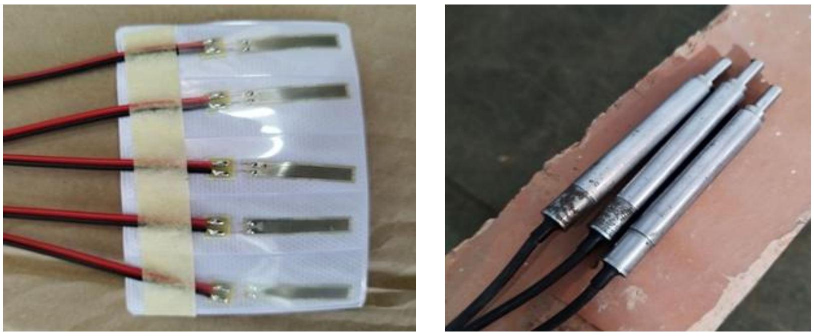


Figure 3: Grain size distribution for the soil

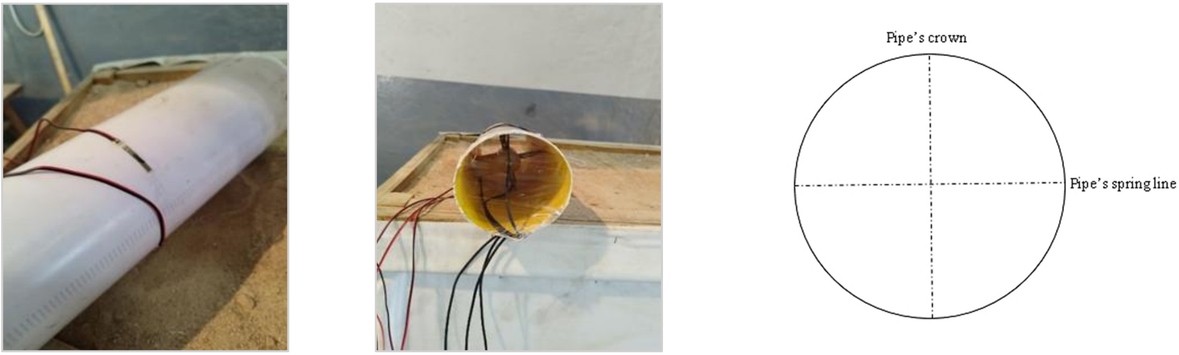
2.4 Data acquisition system

The pipe was instrumented with three strain gages and three LVDTs (Linear Variable Differential Transformer) to read the strains and deformations, respectively, as shown in Figure 4 (a and b respectively). The strain gages were mounted on the external surface of the pipe at the crown, spring line, and invert, while the LVDTs were installed on the internal surface of the previous locations of the pipe as shown in Figure 5 (a and b). The terminology used to define the pipe section is shown in Figure 5 (c). The system can read data from 24 channels simultaneously using LabVIEW software, which is sufficient for collecting and storing test data. The data is stored automatically in text files. Spreadsheets and application programs were used to post-process the output voltages that made up the measured data to identify design parameters.



(a) (b)

Figure 4: a) Strain gages, b) LVDTs



(a) (b) (c)

Figure 5: a) Installation of strain gauges, b) Installation of LVDTs, c) Terminology of the pipe section [22]

3. Testing procedure

In this research, the PVC pipe is designed without taking into account the presence of the pavement because the pavement's beneficial impact in decreasing the induced soil pressure on the pipe will diminish over time as a result of pavement deterioration, so there will be a greater chance of pipe failure due to the significantly increased pressure of the soil [23, 24]. Moreover, the most critical condition for the pipes during the numerical analysis has been adopted, which includes the absence of fluids inside the pipes, as these fluids generate a load that balances the external load resulting from the internal pressure of the fluids, thus reducing the stresses and deformations of the pipe [25].

The wheel is placed on to the soil at the beginning of the soil box, and the load is then manually supplied using the hydraulic jack after the pipe has been buried in the soil, as shown in Figure 6. Make sure that all connections to the data acquisition system have been made. The start button on the control board initiates the horizontal movement once the load is increased to 5 kN. The wheel continues to move until it reaches the end of the soil box, approximately a distance of 85 cm at a speed of 5 km/h. Throughout this time, the displacements and strains are measured and stored in the laptop. The burial depth of 1D has been considered (where D is the pipe diameter) in this test. Also, the previous procedure was repeated using the velocities of 10 km/h and 15 km/h instead of 5 km/h, respectively. The chosen velocities (5, 10, 15 km/h) ensure sufficient interaction time between the wheel and the buried pipe, allowing accurate measurement of strain and displacement. Higher speeds are making it difficult to capture reliable data and potentially causing unrealistic shock loading.

Figure 6: Burying the pipe with the soil

4. Results and discussion

Figure 7 demonstrates the displacement curves vs normalized time (each value of time divided into a total time) respectively for the PVC pipe's crown under the moving loading for three wheel velocities (5 km/hr, 10 km/hr, and 15 km/hr) at a burial depth of 0.5D (where D is the diameter of the pipe). It can be noticed from Figure 7 (at a velocity of 5 km/hr) when the wheel reaches about 20% of the normalized time (17 cm from the start of the movement) the crown of the pipe begins to move upward (positive sign) and continues to rise (increase in displacement) until the wheel reaches about 40% of the time (34 cm from the start of the movement) and then a sharp reversal occurs in the value and direction of the displacement of the crown when the time reaches about 50%, meaning that the wheel is directly above the pipe. At a velocity of 10 km/hr, the maximum positive displacement occurs at approximately 35% of the normalized time. Following this, the curve undergoes a steep reversal, and the maximum negative displacement occurs at a normalized time of 46%. When the wheel velocity is 15 km/hr, the peak positive displacement is obtained at 37% of the normalized time, while the peak negative displacement is obtained at 50% of the normalized time.

The reason for these curves' behavior is that when the wheel moves, it pushes the soil forward. This effect becomes stronger as the wheel approaches the pipe because the soil pushes the pipe from the side. The pipe's flexibility causes the horizontal diameter to decrease and the vertical diameter to increase, which increases the displacement in the pipe crown upward (positive displacement). When the wheel is directly above the buried pipe, its load will be concentrated on the tip of the pipe to a greater extent, thus obtaining the highest displacement. It was observed that the maximum displacement occurs at a minimum velocity (5 km/hr), while the minimum displacement occurs at a maximum velocity (15 km/hr). Figure 8 displays the strain at the pipe crown vs the normalized time. The pipe's behavior under strain is relatively similar to its behavior under displacement. At a velocity of 5, the peak positive strain is observed at 40% of the normalized time, while the highest value of positive strain is at 50%. For the remaining two velocities, the strain curves exhibit a high degree of similarity. The peak positive strain occurs at approximately 44% of the normalized time, while the maximum negative strain is observed at around 50%. It is important to highlight that a negative strain curve signifies a compressive state, whereas a positive strain curve indicates a tensile state.

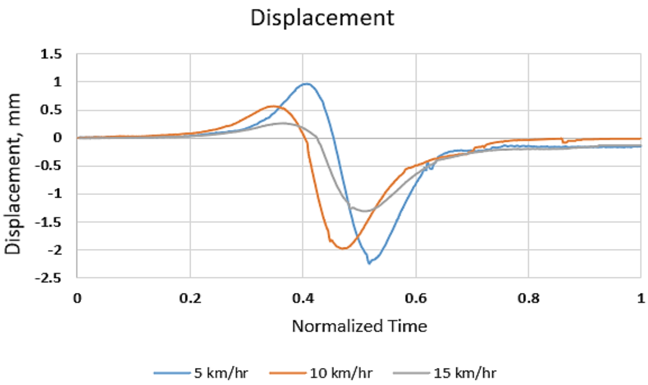


Figure 7: Displacement vs normalized time of pipe crown under moving load at velocity equal to 5 km/hr, 10 km/hr, and 15 km/hr

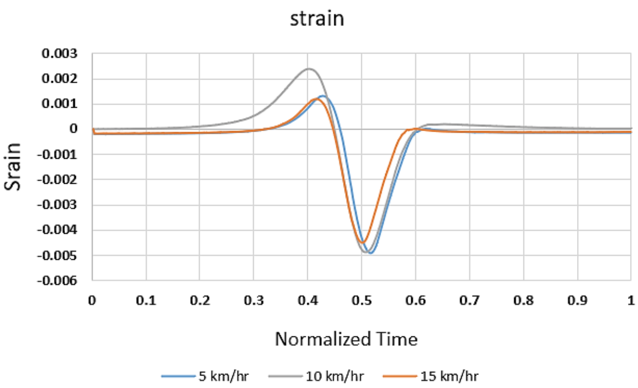


Figure 8: Strain vs normalized time of pipe crown under moving load at velocity equal to 5 km/hr,10 km/hr, and 15 km/hr

Both the beginning and end of the strain and displacement curves are linear and nearly flat, indicating that the wheel load has minimal influence in these regions due to the sufficient distance from the pipe's location. This behavior also reflects the damping effect of the surrounding soil, which absorbs and disperses a significant portion of the applied surface load before it reaches the buried pipe. Additionally, as shown in Figure 9, the maximum crown displacement decreased by about 29.5% when the wheel velocity increased from 10 to 15 km/hr, and it decreased by about 12% when the velocity changed from 5 to 10 km/hr. From Figure 10, when the velocity decreased from 15 to 10 km/hr and from 10 to 5 km/hr, the crown strain increased by about 26.9 and 3.3%, respectively.

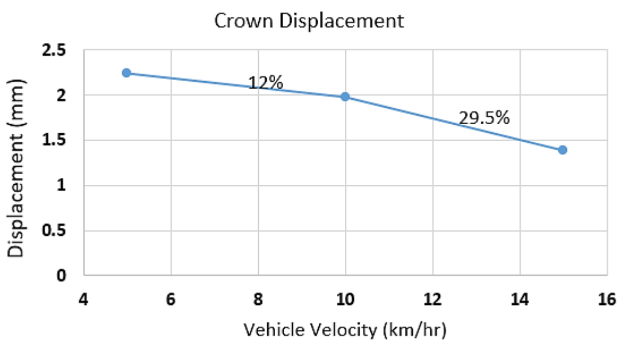


Figure 9: The impact of vehicle velocity on the pipe apex (crown) displacement

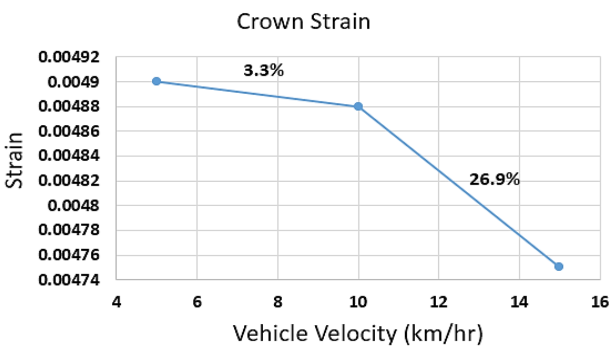


Figure 10: The impact of vehicle velocity on the pipe apex (crown) strain

Figures (11,12) illustrate the displacement and strain curves versus normalized time, respectively, for the PVC pipe's spring line under moving loads at three wheel velocities (5, 10, and 15 km/h) with a soil cover of 0.5D. It has been seen that from Figure 11, at a speed of 5 km/hr, the displacement–normalized time curve initially exhibits a slight decline and then continues to increase gradually as the wheel moves toward the pipe, up to a normalized time of 35%. At that moment, the curve begins ascending in the positive direction, reaching its maximum value at a normalized time of 43% when the wheel approaches the pipe's edge. Thereafter, a rapid drop occurs such that the highest displacement is observed at approximately normalized time 50%—that is, when the wheel is directly above the pipe. As the wheel continues moving away from the tube, the curve rises again, with the maximum positive displacement occurring at approximately a normalized time of 64% due to soil thrust resulting from the wheel's load. Subsequently, the curve gradually declines as the wheel moves further away from the tube, reflecting the diminishing effect of the load. For the curves corresponding to speeds of 10 and 15, their behavior is largely analogous to that of the previously described curve. In both cases, the maximum displacement is observed at around time 50, precisely when the wheel is directly over the tube.

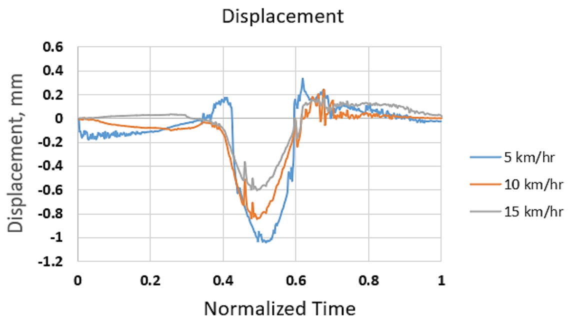


Figure 11: Displacement vs normalized time of pipe spring line under moving load at velocity equal to 5 km/hr, 10 km/hr, and 15 km/hr

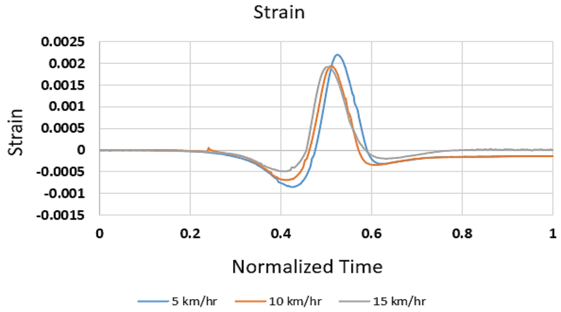


Figure 12: Strain vs normalized time of pipe spring line under moving load at velocity equal to 5 km/hr, 10 km/hr, and 15 km/hr

However, it has been noticed from Figure 12 that the behavior of these curves is analogous to that of the strain-normalized time curves for the pipe's apex, albeit with an inverted sign. Specifically, the maximum strain of the spring line is positive (indicating tensile deformation), and the peak strain occurs when the wheel is directly above the pipe, i.e., at approximately t = 50%. It is noted that, from Figure 13, the decreased percentage of spring line displacement is 18.17 and 28.58% when the wheel velocity rose from 5 to 10 km/hr and from 10 to 15 km/hr, respectively. However, the decreased percentages in the spring line strain become 11.63 and 2.05% when the velocity changes from 5 to 10 km/hr and from 10 to 15 km/hr, respectively, as illustrated in Figure 14.

The above results were consistent with the findings of the researchers, Beben [16], Neya et al. [15], Alzabeebee S. et al. [14], and Yeau et al. [17], who demonstrated that increasing vehicle speed reduces deformations and stresses in the pipe perimeter for several types of pipes that have been studied experimentally or numerically. However, this phenomenon occurs for several reasons. Firstly, when trucks travel at low speeds, their tires remain in contact with the soil over any given point for a longer period. This results in a longer duration for the load delivered to the earth, which is then transferred to the buried pipe. Due to the extended load duration, the buried pipe and the nearby soil have more time to deform. Conversely, at faster speeds, the load is applied for a shorter amount of time, reducing the time before the pipe experiences noticeable deformation. Secondly, under continuous stresses, soil (especially cohesive soil) may exhibit creep or a viscous response. The extended load application at lower velocities can cause more substantial soil settlement, or "creep," leading to greater buried pipe deformation. In contrast, at higher speeds, the load is removed more quickly, giving the soil less time to deform to the same extent. Lastly, because the soil has dampening characteristics, energy is absorbed and eventually released. The amount of applied energy that is absorbed and transferred to the buried pipe increases with decreasing velocities. Higher velocities, however, cause the dynamic load to be transmitted more quickly, which may not provide the soil enough time to absorb and transfer all of the load energy to the pipe, thereby minimizing the amount of deformation.

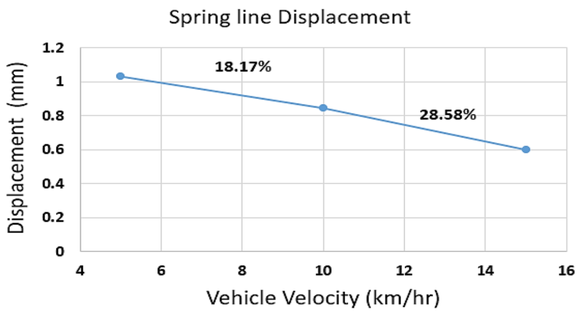


Figure 13: The impact of vehicle velocity on the pipe spring line displacement

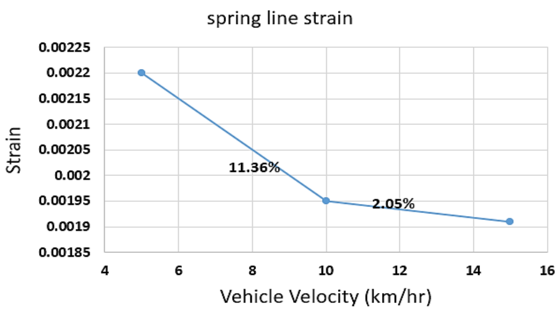


Figure 14: The impact of vehicle velocity on the pipe spring line strain

5. Conclusion

In this study, the influence of vehicle speed on the structural performance of buried flexible pipe under traffic (moving wheel) load has been investigated. The considered moving load is imposed using a small-scale model (in the laboratory), as the past studies related to moving loadings were either numerical or in situ (full-scale). However, the following conclusions are drawn from this study:

1) As the vehicle velocity increases, the displacement and strain at the pipe apex and spring line decrease.
2) The displacement and strain at the pipe's apex decreased by about 12 percent and 3.3 percent respectively as the vehicle velocity increased from 5 to 10 km/hr and by about 29.5 percent and 26.9 percent respectively as the vehicle velocity increased from 10 to 15 km/hr.
3) When the velocity decreased from 15 to 10 km/hr, the pipe spring line displacement and strain rose by about 28.58 and 2.05% respectively, while the increasing percentage was 18.17 and 11.36% when the velocity changed from 10 to 5 km/hr.

Author contributions

Conceptualization, **A. Habeeb, E. Sayhood**, and **S. Al-Wakel**; data curation, **A. Habeeb**; formal analysis, **A. Habeeb**; investigation, **A. Habeeb**; methodology, **A. Habeeb**; project administration, **A. Habeeb**; resources, **A. Habeeb**; software, **A. Habeeb**; supervision, **E. Sayhood**, and **S. Al-Wakel**; validation, **E. Sayhood**, and **S. Al-Wakel**; visualization, **E. Sayhood**, and **S. Al-Wakel**; writing—original draft preparation **A. Habeeb**; writing—review and editing, **E. Sayhood**, and **S. Al-Wakel**. All authors have read and agreed to the published version of the manuscript.

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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.

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