DYNAMIC RESPONSE OF A SYSTEM OF 3 RIGID CONCRETE SLABS ON FOUNDATION TO A MOVING LOAD ON THE CONCRETE PAVEMENT USING FINITE ELEMENT ANALYSIS

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Abstract

The dynamic response of a concrete pavement system with load transfer dowels under the effects of moving loads is a topic of interest to many scholars. However, to fully understand the nature of the stress-strain state of the concrete slab, load transfer dowels, and the subgrade in the pavement structure, further research is needed. Using numerical methods with the commercial software ABAQUS 2020, this article thoroughly investigates the dynamic behavior of rigid pavement structures under moving loads at a constant speed. The results of this study illustrate the dynamic performance of the pavement structure in terms of vertical displacement on the pavement and vertical displacement along load transfer bars at different wheel trace locations. The research results will provide pavement and airport engineers with valuable insights into the actual working conditions of rigid pavement structures.

Keywords: *Pavement; moving load; dowel; foundation; deflection; stress; soil-structure interaction.*

1. Introduction

The dynamic response of rigid pavements to moving loads on the surface has attracted significant attention from scholars and engineers. Rigid pavements, subgrades, and dowels form a complex system that must withstand all loads from vehicles and temperature changes.

Typically, scholars propose assumptions to simplify the process of designing road pavement structures. These assumptions may include considering loads as static at certain points on the slab, slabs not accounting for the process of load transfer to adjacent slabs through dowel bars (load transfer bars), soil-structure interaction simplified as a spring system, with or without damping, and the foundation considered as an elastic spring system or an infinite elastic half-space.

To deeply understand the working nature of the pavement structure in order to improve design quality, more in-depth studies of the working process under moving vehicle loads are necessary.

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In our study, dynamic response of a system of 3 rigid concrete slabs on the foundation to a moving load on the slab surface using finite element analysis with ABAQUS in which the soil-structure interaction is taken into account. The results of the numerical modeling are in the form of pavement deflection along the slabs, the stress distribution of the dowel bar, concrete area around the dowel bar.

In our study, the dynamic response of a system consisting of three rigid concrete slabs, each measuring 5 m × 5 m × 0.4 m, supported by a soil foundation of dimensions 15 m × 5 m × 1 m, was investigated. Finite element analysis with ABAQUS was utilized to account for soil-structure interaction as the slabs were subjected to a moving load on their surface. This moving load was represented by two main wheels on an axle, which featured a circular contact area and exerted a pressure of 0.6 MPa, with varying velocities throughout the model. The results of the numerical modeling were presented in terms of pavement deflection across the slabs, as well as the stress distribution in the dowel bar and the surrounding concrete area.

2. Literature review

In designing rigid cement concrete pavements, the dimensions of the concrete slab are constrained to prevent damage from thermal stresses. Consequently, it is crucial to arrange contraction joints, expansion joints, and dowel bars effectively to transfer wheel loads between slabs through vertical shear and bending moments.

From a numerical perspective, rigid pavements can be modeled as infinitely long beams [1-3] or as infinite elastic plates [4-6] supported by a soil medium. The soil foundation can be represented as a system of elastic springs and dashpots [7, 8] or modeled as homogeneous [3], layered infinite soils [9], or layered half-spaces [10, 11]. The material properties of the pavement can vary, being elastic, viscoelastic, or elasto-plastic, while the foundation layers may exhibit elastic, viscoelastic, or even inelastic behavior.

The use of dowel bars in concrete slabs is crucial for enhancing the performance and longevity of pavement systems. According to [12], dowel bars effectively reduce faulting and pumping in concrete slabs. This is essential for maintaining smooth surfaces and preventing structural damage. While extensive research has focused on the effects of static loads on joints and dowel bars, studies addressing the dynamic response of pavement systems under moving loads are limited. Understanding how dowel bars behave under dynamic conditions is critical for predicting performance in real-world scenarios. In stresses and strains at the dowel-concrete interface, a comprehensive understanding of the stresses and strains at the dowel-concrete interface is necessary to assess their distribution around loaded dowel bars. These stress distributions play a significant role in the overall performance of the joint and can affect load transfer efficiency (LTE). As highlighted by Mackiewicz [13], the stresses at the dowel-concrete interface are vital to the load transfer efficiency at joints. Deterioration in LTE can lead to increased joint distress, contributing to pavement failure over time. A deeper investigation into the dynamic response of dowel bars and the associated stress distributions is essential for optimizing joint design and ensuring the durability of pavement systems. Continued research in this area will help develop better strategies for enhancing load transfer efficiency, ultimately leading to more resilient infrastructure

The historical development of dowel bar and joint design has significantly evolved over the years, starting with the foundational work of key researchers. Here's a summary of the key contributions to dowel bar design. Westergaard [8] developed a mechanistic approach for analyzing dowel bars in joints then analyzed the case of a load applied on one side of the joint, positioned midway between uniformly spaced dowels. However, Westergaard [8] assumed the dowels to be infinitely stiff, leading to the conclusion that the two abutting slab ends would deflect equally then provided a method to calculate the relief of load stress at the edge of the loaded slab, which indicated a higher stress relief due to the infinite stiffness assumption. Teller [7] built on Westergaard's theory by incorporating additional factors such as slab stiffness and subgrade stiffness.

This analysis allowed for a more realistic assessment of load transfer in dowel systems.

Friberg *et al.* [14] proposed that only dowels within a certain distance from the load effectively contribute to load transfer. Modeled an effective dowel as an elastic beam embedded in an elastic medium [15]. Friberg *et al.* [14] suggested that shear stress in each dowel decreases linearly with distance from the applied load, leading to the conclusion that compressive pressure in the concrete supporting the dowel can be described by a specific Eq. (1):

$$\sigma_b = \frac{K \cdot e^{-\beta x}}{2 \cdot \beta^3 \cdot E \cdot I}\left[P_t \cdot \cos\beta x - \beta \cdot M_0(\cos\beta x - \sin\beta x)\right] \tag{1}$$

where P_t is load transmitted by the dowel to the adjacent slab, M_0 is moment applied by the dowel for a joint opening, K is modulus of dowel support, x is distance along the dowel measured from the joint face, β is relative stiffness of an elastic bar embedded in an elastic media, E and I are modulus of elasticity and moment of inertia of the dowel bar, respectively.

The stress must be less than the allowable stress of the concrete to ensure that the concrete does not crack or break.

The friction between the dowels and the concrete slab plays a crucial role in alleviating the local stress on the concrete surrounding the dowels. If the friction coefficient is excessively high, it can hinder the smooth movement of the slabs and dowels, resulting in the formation and progression of cracks in the concrete, which ultimately can damage the slab [16].

Numerical methods serve as effective tools for simulating models with various variables that are challenging to test experimentally. Many researchers have assumed that dowel bars act as beams rigidly fixed to the concrete at two slabs. However, this assumption is not accurate, as the bars must be able to move along their axis and can experience bending when the slabs undergo different displacements.

3. Finite element analysis

In this study, the dynamic response of a system of 3 concrete slabs connecting each other by a row of dowel bars on soil foundation under moving load using ABAQUS commercial package in Fig. 1 as below:

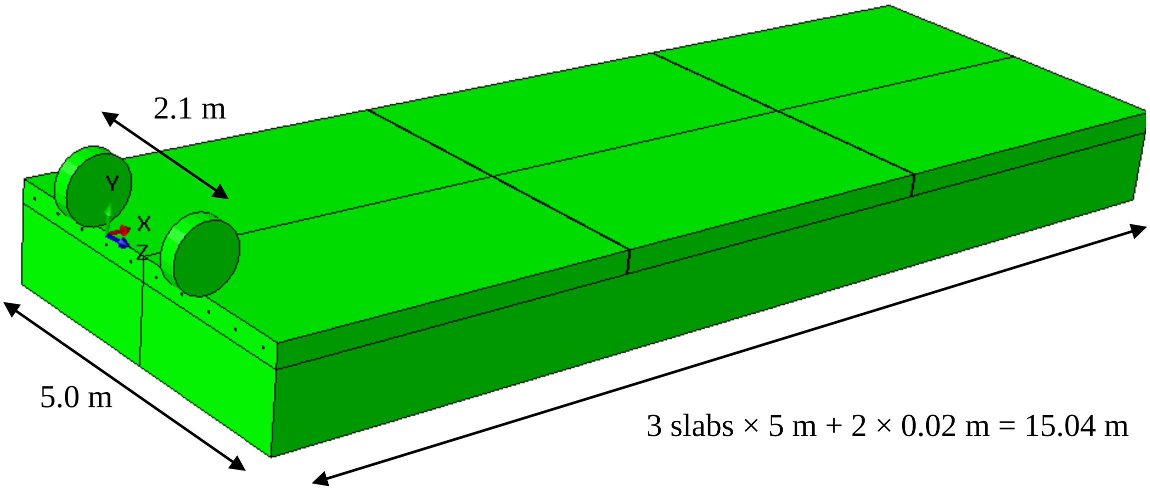

Fig. 1. Problem definition.

3.1. Concrete slabs

There are three concrete slabs with the dimensions of 5 m × 5 m × 0.4 m staying 20 mm apart from each other in the moving direction. To accurately and dynamically model the pavement system, the material properties and dimensions of the concrete slab must closely correspond to those of the actual slab, as demonstrated in Table 1.

Since this is a dynamics problem, the concrete slab needs to have Rayleigh damping characteristics. Classical Rayleigh damping is the viscous damping that is proportional to a linear combination of mass and stiffness. In Rayleigh damping, the damping matrix C is given by $C = \mu M + \lambda K$ where M and K are the mass matrix and stiffness matrix, respectively, and μ and λ are proportional constants. Using the tool to determine the eigenmodes of the system, we can find the coefficients $\mu = 0.488$ and $\lambda = 0.0048$.

The holes for dowel bars at the two opposite sides of the slab are cylinder with the depth of 250 mm, and diameter of 30 mm. The holes were placed at the neutral surface of the slabs with the spacing of 500 mm.

Table 1. Summary of materials

		Properties	**Notation**	**Unit**	**Value**
Concrete slab	1	Slab thickness	h_s	m	0.4
	2	Slab length	l_s	m	5.0
	3	Slab width	b_s	m	5.0
	4	Density	ρ	Kg/m^3	2400
	5	Young’s modulus	E	GPa	35
	6	Poisson’s ratio	μ	-	0.2
Dowel bar	1	Diameter	R	mm	29
	2	Length	L_b	mm	520
	3	Density	ρ	Kg/m^3	7800
	4	Young’s modulus	E	GPa	200
	5	Poisson’s ratio	μ	-	0.2
Soil foundation	1	Density	ρ	Kg/m^3	1470
	2	Young’s modulus	E	kPa	60242
	3	Poisson’s ratio	μ	-	0.35
Rubber wheel	1	Density	ρ	Kg/m^3	2200
	2	Young’s modulus	E	GPa	28.6
	3	Poisson’s ratio	μ	-	0.4

3.2. Dowel bars

The load transfer bars (dowel bars) between the concrete slabs is a smooth round steel bar with a diameter of 29 mm and a length of 520 mm. The case study assumes that the dowel bars have a diameter 1 mm smaller than the diameter of the hole in the concrete slab because there is a layer of bitumen that allows the load transfer bar to move easily within the hole of the concrete slab. The material properties of the steel used for the load transfer bar are in Table 1. Numerically, P. Mackiewicz [13] and K. Kim *et al.* [17] have investigated the effect of dowel bar dimension and arrangement on the performance of concrete pavement under the statics loading in different positions. In our case study, only one dowel bar configuration is taken into account but the performance of the pavement structure is investigated numerically under the moving of a truck with two heavy wheels in an axle load.

3.3. Soil foundation

The soil foundation in this case study is assumed to be a thick layer of homogeneous soil with the properties in Table 1. The soil foundation is described as materials calculated for strength according to the Mohr-Coulomb failure criteria, with characteristics of cohesion c = 30 kPa and internal friction angle, $\phi = 43°$. These are important properties of granular materials for numerical modelling.

3.4. Interaction

In the simulation problem, there are interactions between the wheel and the concrete pavement; the concrete pavement and the foundation; and the concrete pavement with the dowel bars. The interaction properties are represented by two characteristics in the tangential and normal directions.

- *The wheel - concrete pavement, dowel bar - concrete pavement interactions*

In the normal behaviour, these two interactions ensure that the elements of the two surfaces do not penetrate each other. The gap between those surfaces is equal to zero when there is pressure between those surfaces and the gap differs from zero when there is no pressure. In the tangential behaviour, the friction coefficients are 0.2 and 0.1, respectively.

- *The soil foundation - concrete pavement interactions*

The shear strength of the interfaces between the soil foundation and the concrete pavement was defined by the Mohr-Coulomb failure criterion (based on two soil properties, namely friction angle, φ, and cohesion, *cu* and the tensile strength of the interfaces is set to zero in order to allow gapping between the foundation and the pavement. The FORTRAN user subroutine, called fric_coef which has been developed by Nguyen *et al.* [18], has been used to include interface elements between the parts in this study.

Surface-to-surface contact pair for concrete pavement and soil foundation interaction with finite sliding formulation are adopted.

3.5. Truck wheel

The impact of the wheel on the pavement is often described as a static load on a circular or rectangular area placed in various positions [13, 19, 20]. In this problem, the wheel load is simulated by a rubber wheel with a circular contact patch diameter of 330 mm, with material properties listed in Table 1, and a pressure applied to the rubber wheel of 0.6 MPa [21]. A pair of rubber wheels will be subjected to a constant speed of 5 m/s from the beginning of the first slab to the end of the third slab within 3 seconds. The problem only considers the case of 1 axle with 2 wheels, with a distance between the wheel centers of 2.1 m.

3.6. Body force

In the problem of concrete pavement structural systems under moving load, the self-weight of the concrete slab plays a significant role in the distribution of loads from the wheels. Based on the material parameters regarding the specific weight of concrete, dowel bars, and the foundation, the step of applying the self-weight is carried out before and is continuously maintained throughout the process of moving loads. The process of the wheel running on the pavement will cause the concrete slab to deform and displace. These phenomena are transmitted through the dowel bars, causing the adjacent slabs to deform and displace as well. Without the self-weight load, this phenomenon cannot be accurately simulated. When there is a self-weight load, the deformations and displacements will be redistributed by the weight of the concrete slab.

3.7. Meshing

The dynamics problem with a complex system consists of 4 parts, especially the moving load of the wheel, which needs to be divided into elements for the problem to converge. Through several trials, the chosen element sizes ensure the accuracy of the mechanical operation process among the components. The model is meshed as shown in Fig. 2.

The soil foundation medium, concrete slabs were represented using C3D8R elements, which are three-dimensional, 8-node linear brick elements featuring reduced integration and hourglass control, as illustrated in Fig. 2 while the dowel bars is modeled as C3D6 elements (6-node linear triangular prism). This reduced integration prevents locking phenomena, although it can result in insufficient stiffness in bending; however, this is not a significant issue when modeling pavement structure. Additionally, because the integration point is positioned at the center of the element, smaller elements are required to accurately capture stress concentrations at the boundaries.

4. Results and discussion

Numerical modeling of the case study provides many results for discussion, including the deflection of the pavement, comparison of the deformations of the dowel bars, and the stress diagrams of the pavement concrete and the dowel bars with the positions of the vehicles.

4.1. Effects of gravity on pavement structure

Initially, the self-weight of the pavement structure begins to cause settlement in the ground, with displacement points evenly distributed along the y-axis. The points on the surface have the largest displacement, and the deeper point, the smaller displacement decreases. Figure 3 shows that, since the pavement structures are the same, points at the same depth experience the same vertical displacement under the influence of gravity.

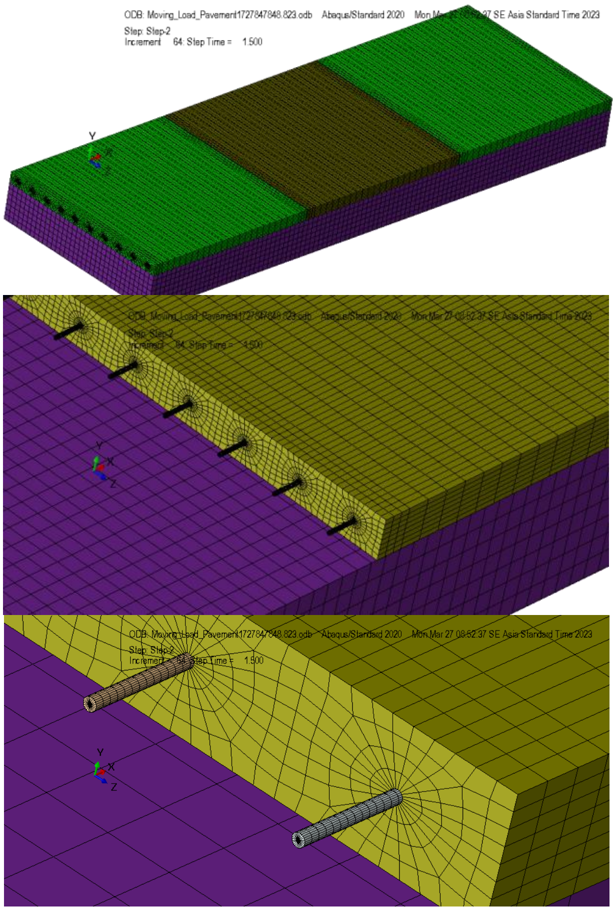

Fig. 2. Numerical meshing for case study.

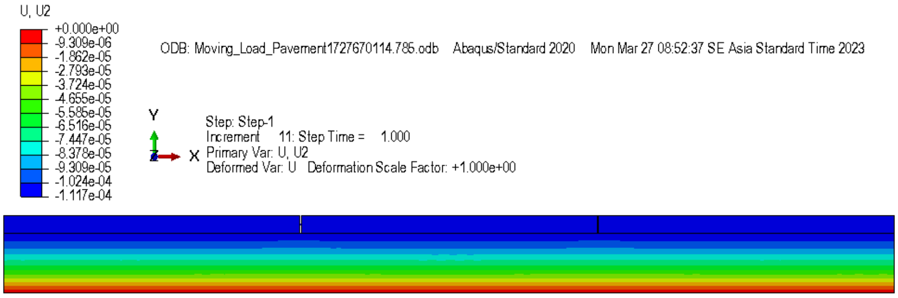

Fig. 3. Effects of gravity on pavement structure.

As can be seen clearly in Fig. 3, Fig. 5, and Fig. 6, the study takes into account the self-weight of the entire system, including the pavement and the foundation. Under the initial action of gravity, before the vehicle moves, the top surface of the concrete slabs experiences a vertical displacement of approximately 0.1 mm.

When the construction process of the pavement structure is completed, the settlement due to its own weight will no longer develop, but the weight of the concrete slab will still contribute to the deformation and displacement of the slabs and the dowel bars throughout the operation process.

4.2. Dynamic performance of pavement structure

Figure 4 shows the vertical displacement of points along the vehicle's path as the wheels reach different positions. At a vehicle speed of 5 m/s, each wheel axle will take 1 second to travel pass through a 5 meter long concrete slab. Fig. 4(a), 4(b), 4(c), and 4(d) correspond to the positions when the distance traveled by the wheel axle is S = 2.5 m, 3.97 m, 5 m, and 7.5 m, respectively. Due to the symmetry, positions where the vehicle travels a distance S > 7.5 m are symmetrical to those where S < 7.5 m.

When the wheel reaches the middle of each concrete slab along the tire track, the vertical displacement at that position is the largest and relatively equal ($U_y = 0.227$ mm), while the vertical displacements at other positions are smaller, but at the joint with the adjacent concrete slab, the displacement is in the opposite direction. In other words, when the load is in the middle of the concrete slab, the slab bends downward, and the edge of the slab can be lifted higher when the vehicle load is applied.

Figure 4 also shows that the vertical displacement of the road pavement is the greatest when the wheel is positioned at the joint between two concrete slabs (Fig. 4(c)). The reason for this phenomenon can be explained by the fact that at the joint between the two concrete slabs, the entire slab does not work together; instead, only the load transfer bars redistribute the load between the two slabs. However, the number of load transfer bars is often insufficient to make the joint behave like a part far from the joint.

Figure 5 and 6 compare the vertical displacements of points on the pavement along the wheel track and points on the pavement at the center of the concrete slab when the travel distances of S = 2.5 m, 3.97 m, 5 m, and 7.5 m. In general, the vertical displacements at the points under the wheel track are approximately 30% greater than those at the center of the concrete slab for the same wheel position.

Figure 5 shows that the positions of the wheels cause the largest vertical displacement of the pavement structure at the point directly beneath the wheel. When the wheel is at the joint between two concrete slabs, it causes a displacement that is 36%

greater compared to when the wheel is on a concrete slab. As the wheel approaches the joint (before it contacts the adjacent concrete slab), there is a jump between the two slabs as shown in Fig. 4(b) or Fig. 5, with the wheel moving a distance of 3.97 m.

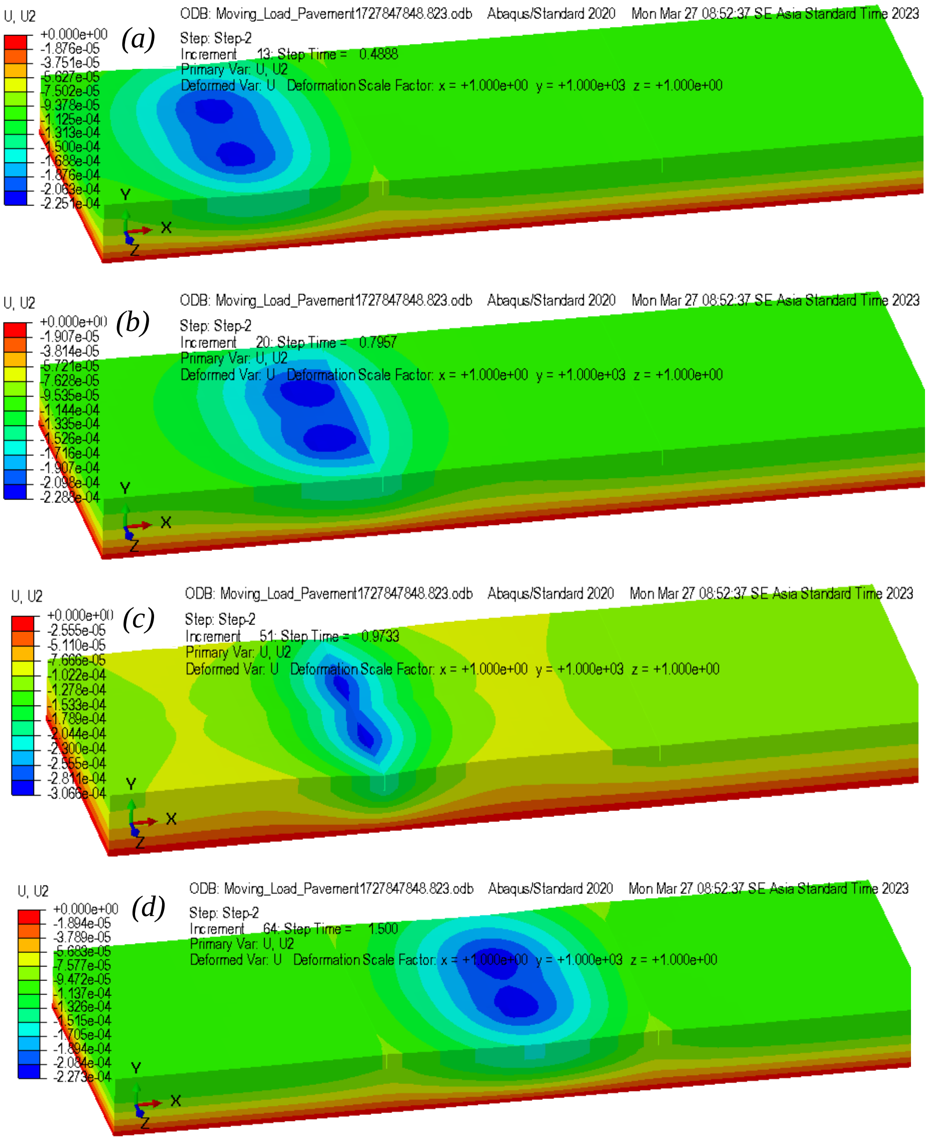

Fig. 4. Concrete pavement displacements at different wheel axle positions.

The vertical displacements of the pavement along the center of the concrete slabs (not under the wheel track) have a smoother elastic profile. The reason for this phenomenon is that the concrete slab itself redistributes the loads from the wheels onto the pavement structure. It can be confirmed that the concrete slab is often damaged right under the wheel track (Fig. 6).

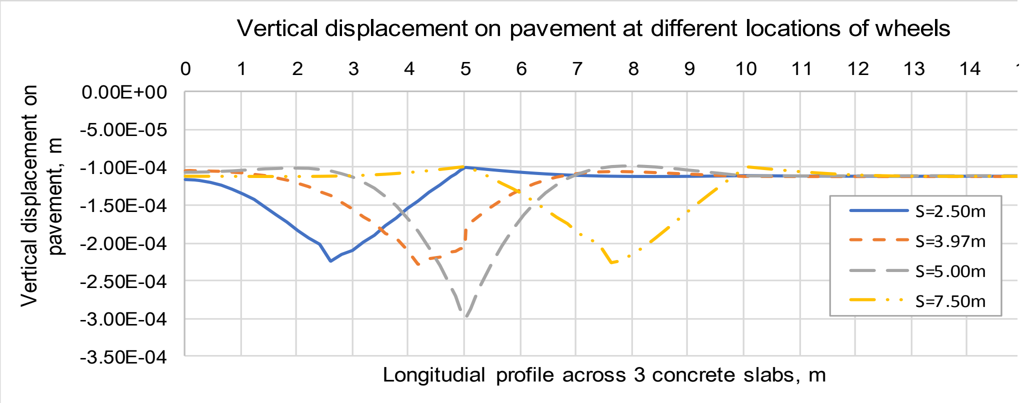

Fig. 5. Vertical displacement on the pavement at different locations of wheels along the wheel traces.

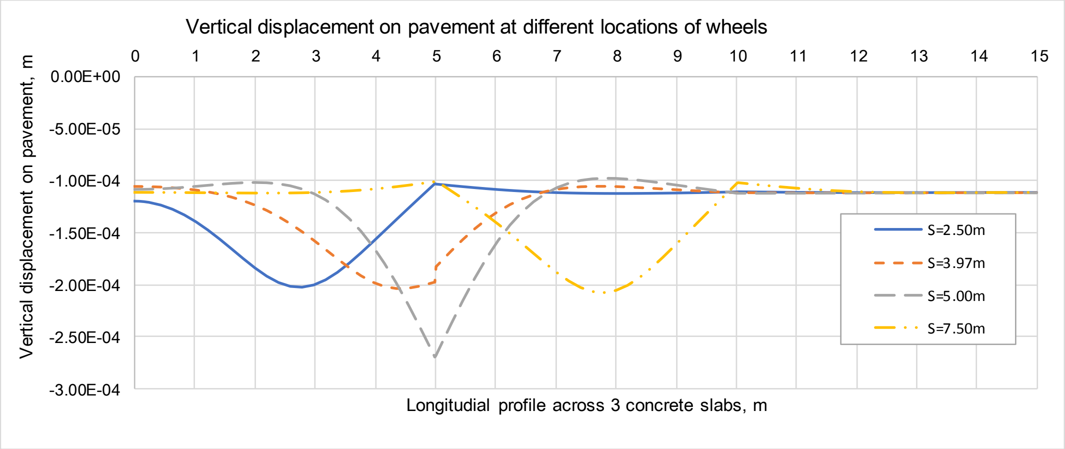

Fig. 6. Vertical displacement on the pavement at different locations of wheels along the centre of concrete slabs.

Figure 7 compares the vertical displacements and deformations of the load transfer bars at the gap between the two slabs when the load is applied at that gap. Essentially, the beams have the largest vertical displacement at the center of the beam, with the beams closer to the wheel exhibiting greater vertical displacement. The beams located between the two wheels have greater vertical displacement than those outside the two wheels (on a wheel axis). Because the wheel is placed in the section between bar 3 and bar 4, the order of vertical displacement of the load transfer bars in decreasing order is bar 4, 3, 5, 2, and 1 (0.292, 0.287, 0.275, 0.250, and 0.215, respectively).

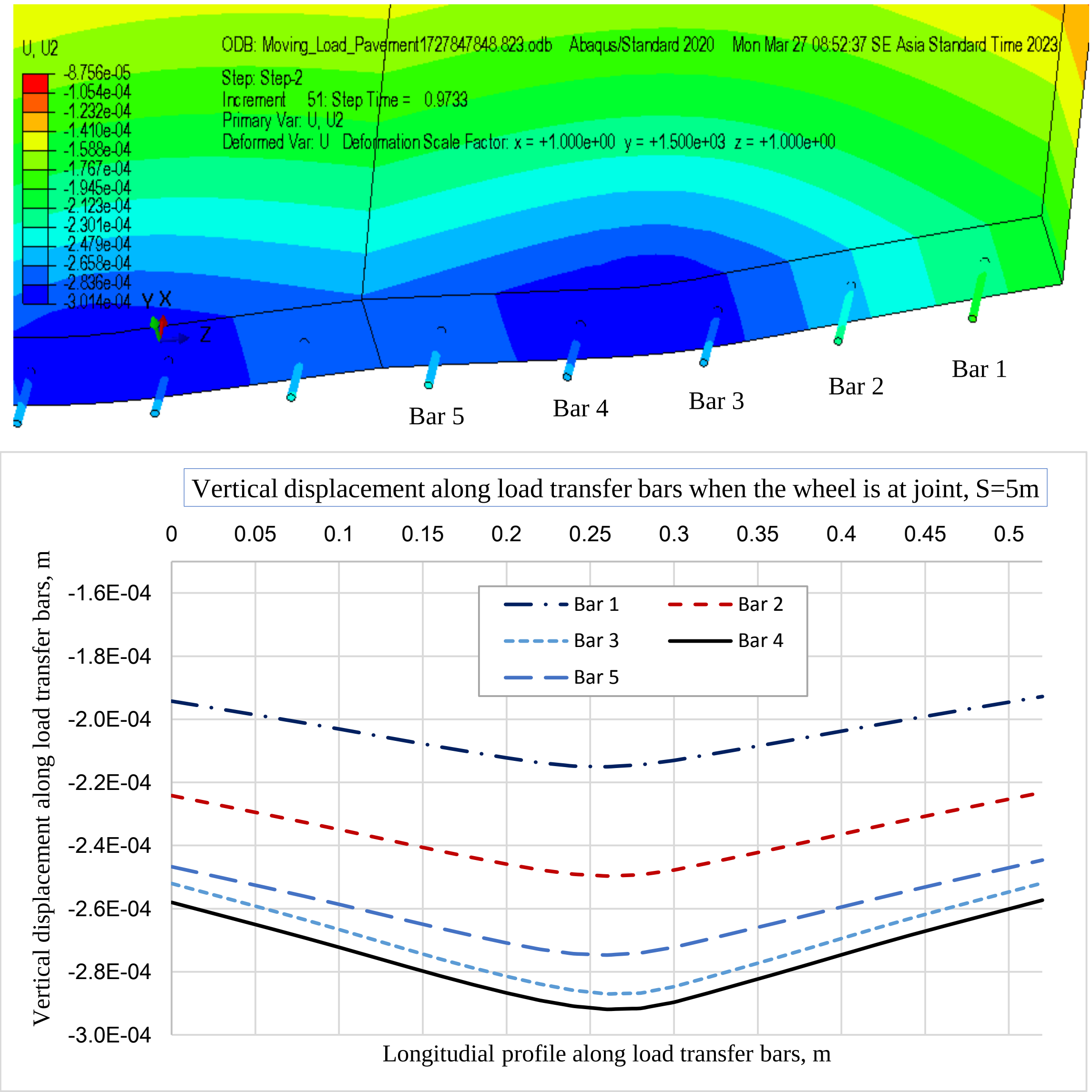

Fig. 7. Vertical displacement along load transfer bars when the wheel is at joint, S = 5 m.

Figure 8 shows the vertical displacement of points along the load transfer bars as the wheel approaches the side slab. The load transfer bars exhibit significant deformation when the vehicle load is applied, which is even less in the beam as the load approaches the concrete slab. From the different deformation states of the load transfer bars, the choice of size and density of the beams can assist engineers in easily calculating the details of the rigid pavement structure under moving loads.

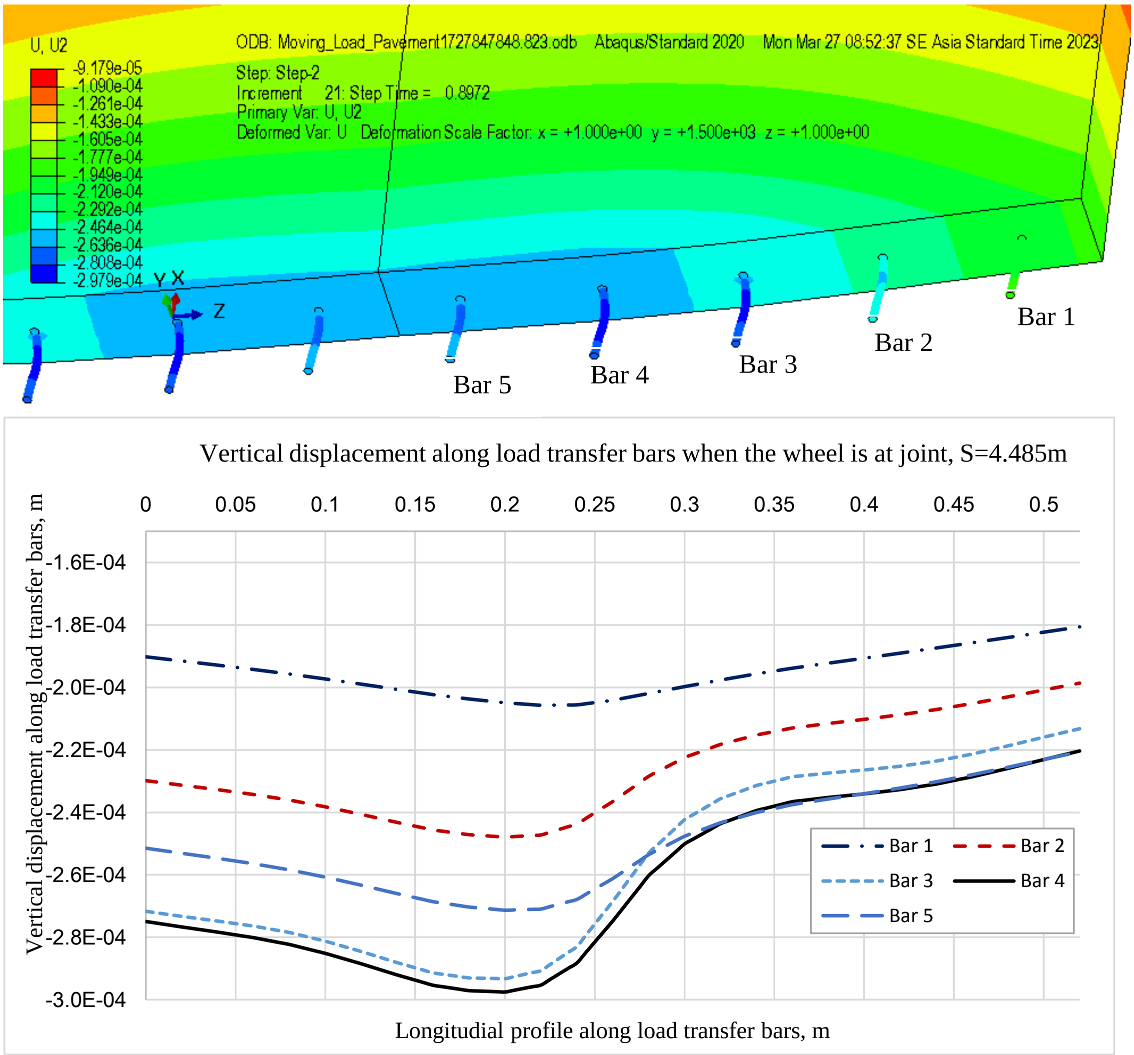

Fig. 8. Vertical displacement along load transfer bars when the wheel is at joint, S = 4.485 m.

5. Conclusion

The article studied the model of a cement concrete pavement structure with load transfer bars, subjected to its own weight and the load of moving vehicles at a constant speed. The research delved into the development of vertical displacements at points on the pavement along the wheel path and at the midpoint of the wheel axle (where the wheel does not pass). The problem takes into account the soil-structure interaction using a dynamic model that considers the damping of the structure. The study also compares the deformation of the load transfer bars when vehicles are in motion, serving as a basis for investigating the size and density of the load transfer bars when designing cement concrete pavements.

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Tóm tắt: Ứng xử động lực học của hệ tấm mặt đường bê tông xi măng có thanh truyền lực dưới tác dụng của tải trọng di động là nội dung được nhiều học giả quan tâm. Tuy nhiên, để hiểu bản chất trạng thái ứng suất biến dạng của tấm bê tông xi măng, thanh truyền lực và móng đường trong hệ kết cấu áo đường cần có thêm nhiều nghiên cứu. Bằng phương pháp số sử dụng phần mềm thương mại ABAQUS 2020, bài báo nghiên cứu đầy đủ các ứng xử động lực học của hệ kết cấu áo đường cứng khi tải trọng di động với vận tốc đều. Kết quả của nghiên cứu này minh họa ứng xử động lực học của kết cấu mặt đường cụ thể về chuyển vị theo phương thẳng đứng của mặt đường và chuyển vị theo phương thẳng đứng dọc theo các thanh chuyển tải lực tại các vị trí khác nhau của bánh xe. Kết quả nghiên cứu sẽ khuyến cáo các kỹ sư đường, sân bay một tầm nhìn sâu sắc về thực tế làm việc của hệ kết cấu áo đường cứng.

Từ khóa: *Mặt đường; tải trọng di động; thanh truyền lực; móng đường; độ võng; ứng suất; tương tác đất công trình.*

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