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Impact of continuous driving and braking on displacements in modular pavements with different laying schemes

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ABSTRACT

Prefabricated concrete elements are widely used for pavement surfaces on urban and local roads. This paper presents an analysis and comparison of pavement structures composed of these elements, focusing on displacements under continuous driving loads and braking forces, to analyze the behavior of prefabricated concrete elements and overall pavement structures under different load actions. The study emphasizes the importance of accounting for braking forces in pavement design, as they significantly influence surface displacements and overall performance. The behavior of the pavement is simulated using five structural configurations, two joint widths, two subbase types, and four subgrade types via the finite element method. Results indicate that elements with 3 mm joints exhibit smaller displacements than those with 5 mm joints and that the geometry of the interlocking significantly influences the deformation under braking-type loading. Furthermore, crushed stone subbases perform better in controlling vertical movements, while natural sand-gravel subbases provide improved horizontal movement behavior.

1 Introduction

Historical evidence shows that pavement of streets and roads began during the Roman Empire. Back then, the pavement surface was typically formed of stone blocks or polygonal sets, while the lower layers (foundation, base, and subbase) had physical and mechanical characteristics analogous to modern granular and binding layers. Throughout history, different elements, such as stone blocks, cobblestones, clay or fired bricks, composite wood, were used for paving roads and streets until the First World War. After that time, the widespread use of such block-type paving for streets diminished, largely due to cost, rising labor requirements, and the growing dominance of bituminous surfaces and concrete pours. The modern practice of constructing pavement structures with prefabricated modular elements in the wearing course has its roots in the Netherlands in the late 1940s. Post-war reconstruction and brick shortages led to experimentation and adoption of prefabricated concrete element paving as an alternative to clay brick [1]. This technology then spread across Europe (notably Germany) and reached North America in the 1970s. Advances in manufacturing in the 1950's made it possible to produce precisely dimensioned prefabricated concrete elements of high strength. Since the early 1980s, industrial production of modern materials (higher strength concrete

mixes, better curing, concrete admixtures, improved shape/geometry, mechanization of laying) has significantly influenced the use of modular pavement structures. These offer a viable, aesthetically appealing alternative. An important practical feature is that installation of block or segmental pavement generally requires less specialized machinery or labor skills compared to cast-in-place rigid or bituminous pavements.

If properly designed and constructed, modular pavement structures can sustain heavy traffic loads, require relatively little maintenance, and provide convenient access to subsurface utilities. They are particularly suitable for applications aimed at traffic calming. Prefabricated concrete elements have demonstrated superior durability under extreme weather conditions and greater versatility compared to conventional asphalt pavements, which has supported their widespread adoption across Europe in recent decades [2]. Moreover, increasing market interest in these pavements is driven by their enhanced technical performance and architectural adaptability [3]. Positive field experience has further promoted their application on local and urban road networks. In addition, such pavement systems have proven capable of supporting the heavy loads imposed by trucks and military vehicles. A notable early example is the installation at the US Army Downs Barracks in Fulda, Germany [4], where approximately 70% of the flexible pavement structure

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was replaced with a modular pavement system after recurring failures at one intersection that required patching every three to four months due to maneuvering M-60 tanks. After nine months inspection revealed no visible damage to the modular pavement structure.

Modular pavement systems generally consist of a wearing course composed of prefabricated concrete elements, a bedding or levelling layer of sand, and one or more base courses [5]. The materials and manufacturing techniques used for prefabricated concrete elements are highly versatile, providing a wide range of design and aesthetic options. The materials employed in the lower layers are comparable to those commonly used in both rigid and flexible pavement structures, and the corresponding design methodologies are, likewise, similar to those adopted for flexible pavements. In the structural analysis of modular pavements, it is commonly assumed that the system exhibits a response analogous to that of a flexible pavement, provided that the prefabricated concrete elements, together with the sand in the joints and levelling layer, act as a single composite layer behaving as a homogeneous, isotropic, and elastic material [6, 7]. Such behavior is achieved only when the pavement is composed of relatively small prefabricated concrete elements (e.g., units with dimensions up to approximately 20 x 10 cm and a thickness of about 6.5 cm, as determined by Cook and Knapton [5]). For larger block dimensions, the structural response increasingly resembles that of rigid pavement systems.

Several studies have modeled modular pavement structures. In these, structural responses such as reactions, stresses, deflections, and displacements have been analyzed, considering varying prefabricated concrete elements shapes, thicknesses, sizes, laying patterns (schemes), and the bearing capacity and stiffness of the base or subbase layers. Outcomes of numerical and experimental investigations have been compared with analytical or semi-empirical models with the aim of model validation. Earlier investigations have reported that the influence of laying scheme (e.g., herringbone versus other patterns) on load distribution due to traffic load of modular pavements may be limited or negligible [8-10]. In somewhat later research, however, there is evidence that implementations using the herringbone laying pattern outperform other block arrangements in reducing deflection and improving overall structural performance [11, 12]. Some studies have also observed that pavement stiffness linearly increases with the number of load repetitions, until a threshold number is reached beyond which additional loading causes minimal further settlement, and elastic behavior (deflection under load with recovery upon unloading) becomes dominant. Such elastic recovery assumptions are used in recent modeling work [13].

The goal of the analytical approach is to model the behavior of each pavement layer according to the fundamental mechanical and physical properties of the constituent materials. Numerical simulations and computer programs based on the finite element method (FEM) are widely used to predict the stress-strain behavior of prefabricated concrete elements and to develop models, though these often involve considerable computational complexity [13, 14]. A substantial body of recent work has focused on elucidating the complex relationship between deformation and material behavior in modular pavements, particularly varying prefabricated concrete elements shapes, laying patterns, and base layer support conditions [2, 15-21].

Gunatilake and Mampearachchi [2] conducted a 3D FEM study to determine optimal block dimensions, finding that a

block in a herringbone bond pattern minimized deflections and stresses among the configurations considered. Similarly, Siva Rathan et al. [15] performed a parametric study to examine the effects of block shape, thickness, and laying scheme on deflection behavior under static and repeated loading; their results confirmed that herringbone patterns generally outperform non-interlocking or simple rectangular layouts in controlling deformations. Lin et al. [16] developed a FEM-based deflection prediction model using dynamic load tests, demonstrating that construction patterns, particularly herringbone layouts, significantly influence load distribution and deflection behavior. Shubbar et al. [17] investigated 45° and 90° herringbone permeable interlocking concrete pavements, reporting superior structural performance under both traffic and environmental loading for herringbone patterns. Earlier studies by Di Mascio et al. [18], Mampearachchi and Gunarathne [19], and Gunatilake and Mampearachchi [20] analyzed different load positions and prefabricated concrete elements laying schemes, consistently concluding that herringbone layouts provide optimal performance under combined vertical and horizontal loads. Di Mascio et al. [18] specifically applied dynamic traffic loads over single wheel tracks with a cement-stabilized base layer, observing that blocks laid in a herringbone pattern produced more favorable displacement and stress distributions. In addition, some studies have noted that pavement stiffness increases with repeated loading up to a threshold, beyond which further repetitions produce only marginal increases in stiffness, and the pavement response approaches elastic behavior. These findings collectively support the use of herringbone laying patterns and advanced FEM modeling for accurately predicting modular pavement behavior under various loading conditions. Zoccali et al. [21] showed that FEM analysis of pedestrian stone block pavements can verify their stress-strain response and fatigue performance, highlighting that such pavements may be oversized for occasional heavy loads and underscoring the need for rigorous design in shared-use areas.

Horizontal forces during braking actions can be significantly more intense than those during continuous driving, making them crucial considerations in pavement dimensioning. Therefore, it is considered necessary to include braking action in the analysis, because these pavement structures are primarily being used for traffic within urban areas and special purpose areas where braking is frequent and often intense. In this study, horizontal and vertical displacements were analyzed for two types of forces, i.e. brake force and movement force. Additionally, the study examined the influence of two subbase materials (crushed stone aggregate and sand-gravel) on pavement performance, considering varying subgrade bearing capacities (3%, 5%, 7%, and 9% CBR - California Bearing Ratio). The aim was to provide recommendations regarding the optimal subbase material and joint width to enhance the structural integrity and longevity of modular pavements under dynamic loading conditions.

To fill a clear gap in the literature, this paper presents a combined parametric study that, unlike previous works, simultaneously examines continuous driving versus braking actions, joint width, five distinct laying patterns and alternative subgrade/subbase combinations for modular pavements subjected to urban-type wheel loads. Prior studies have explored important but narrower aspects: Siva Rathan et al. [15] examined bearing capacity and herringbone laying with different element sizes using static plate tests; Nejad et al. [13] compared varying joint thicknesses under vertical loading; Shubbar et al. [17]

investigated water infiltration effects on pavement performance for similar laying schemes; and Di Mascio et al. [18] conducted dynamic wheel-load analyses with cement-treated aggregate bases. By contrast, this work directly incorporates braking (horizontal) actions and compares their induced displacements to vertical responses, models an unbound aggregate base typical for the region (rather than cement-treated layers). This integrated approach extends the parametric space and loading conditions considered in the cited literature and therefore supplies practical, design-relevant insight into joint and element behavior under realistic urban traffic patterns.

2 Laying of prefabricated concrete elements

When dimensioning and designing modular pavement structures with surfaces composed of prefabricated concrete elements, particular attention must be paid to the horizontal forces that develop in the wearing course due to traffic loading. These forces are especially significant under braking conditions, particularly for heavy vehicles or emergency maneuvers. To mitigate the effects of such forces, the laying pattern of the prefabricated concrete elements should be carefully selected in a timely manner, i.e. during the design stage. Different laying schemes transfer horizontal forces between elements in distinct ways, and the width of the joints, typically filled with sand, plays a critical role in force distribution and interlock performance.

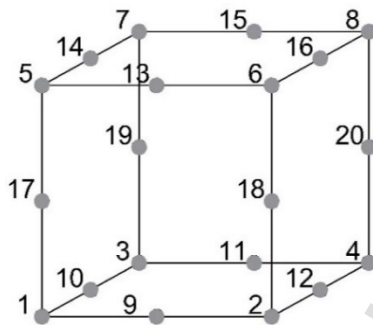
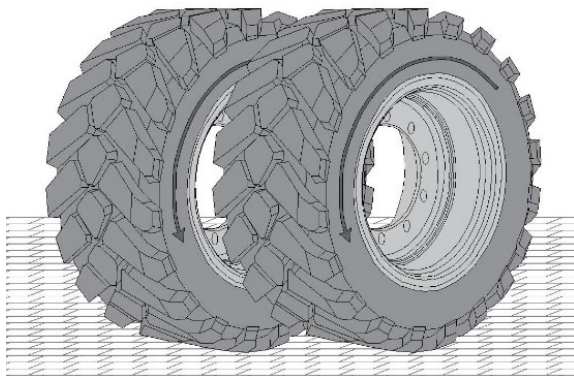


Figure 1. Arrangement of edge nodes on one prefabricated concrete element

To analyze and minimize the effect of horizontal forces, it is useful to consider a single prefabricated concrete element in three-dimensional space. Depending on the element configuration, each unit may have up to 20 edge nodes (Figure 1). Increasing the number of nodes generally improves the stability and durability of the wearing course and, consequently, the entire pavement structure. When



arranging prefabricated concrete elements, designers should avoid direct “joint-to-joint” alignments, which can reduce structural interlock and increase local stress concentrations. Figure 2 illustrates two examples of prefabricated concrete element arrangements, showing that herringbone patterns provide a greater number of edge nodes compared to double (parquet) layouts, thereby enhancing the distribution of horizontal forces and overall structural performance.

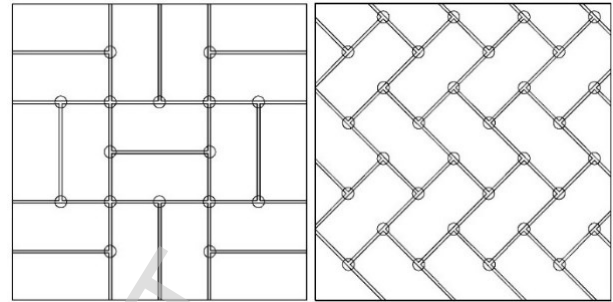


Figure 2. Illustration of the number of edge nodes for two alternative prefabricated concrete element laying patterns

3 Modelling procedure

For the simulation of pavements composed of prefabricated concrete elements, the ABAQUS software package [22, 23] was employed. ABAQUS v. 6.13 is a comprehensive FEM software suite, developed by Hibbit, Karlsson & Sorensen Inc., consisting of a series of integrated engineering programs. It is widely used to solve a broad range of problems in mechanics and other scientific and engineering applications. In the context of prefabricated concrete element analysis, static, quasi-static, and dynamic approaches can be applied. This study adopts the static approach, incorporating simulations of both wheel movement and braking actions to evaluate horizontal and vertical displacements in the pavement structure.

The finite element model of the modular pavement structure represents prefabricated concrete elements placed atop the pavement base (bearing) layers. For conventional flexible and rigid pavements, wheel loads are typically modeled as uniformly distributed pressures applied over rectangular or circular contact areas [24]. In modular pavements, however, the wheel load is distributed across multiple elements, reflecting the load-sharing behavior of the interlocking units. The input parameters for pavement design include traffic volume, material properties of the base and

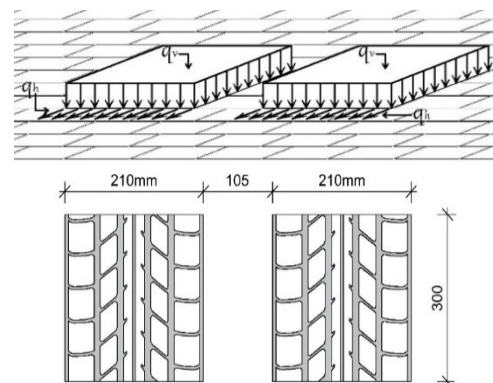


Figure 3. Traffic load

subbase layers, and characteristics of the subgrade soil. The bearing capacity of the subgrade is expressed using the CBR, which provides a standard measure for evaluating foundation soil performance.

In the dimensioning process, as well as during the analysis of stresses and strains, the total equivalent traffic volume over the design period is considered for the lane being analyzed, expressed in terms of a standard 80 kN axle load. It was also assumed that the largest number of trucks in the region has four wheels per axle, so the load was applied over two wheels, representing half of the axle (Figure 3). The wheel load in the model is applied as a surface pressure over the tire-pavement contact area. Continuous movement is represented in a quasi-static manner by sequentially shifting this loaded surface along the wheel travel direction by 0.30 m (one contact length), achieved through a prescribed horizontal displacement of the surface supports. The load path is defined by the imposed displacement history rather than by dynamic rolling. Braking is modeled exclusively as a static horizontal action via an increased friction coefficient at the tire-pavement interface, without considering inertial or dynamic effects. Vertical and horizontal loads are applied simultaneously within the same step, allowing direct comparison of their respective displacement effects. A friction link with a coefficient of 0.44 was introduced between the wheels and the pavement structure, corresponding to a typical urban speed of 40 km/h [21]. The braking action was modeled using the same friction link with an increased coefficient of 0.8 [22, 23], following the approach adopted by Di Mascio et al. [18] for simulating braking-induced horizontal forces.

The distributed vertical load on the tire-pavement contact area and the total transverse force were calculated using the following equations (1) to (3):

$$q_v = \frac{Q}{2 \cdot A} = \frac{40 \text{ kN}}{2 \cdot (0,21 \text{ m} \cdot 0,3 \text{ m})} = 317,46 \text{ kN/m}^2 \quad (1)$$

$$\text{continuous driving } T = f_t \cdot \frac{Q}{2} = 0,44 \cdot \frac{40 \text{ kN}}{2} = 8,8 \text{ kN} \quad (2)$$

$$\text{braking action } T = f_t \cdot \frac{Q}{2} = 0,8 \cdot \frac{40 \text{ kN}}{2} = 12,8 \text{ kN} \quad (3)$$

where:

q_v - is distributed vertical load [kN/m²];

Q - is wheel load equal to half the standard axle of 80 kN;

A - is wheel contact surface [m²];

T - is horizontal force [kN];

f_t - is tangential friction coefficient.

The pavement structure model (Figure 4) was constructed using 3D solid deformable elements. All components of the structure were modeled as solid elements, for which the C3D8R hexahedral element was employed. This element is a cube-shaped solid element with a characteristic edge length of 20 mm and reduced integration, with the integration point located at the element's centroid [22]. A mesh-sensitivity analysis was performed with characteristic element sizes of 30 mm, 22 mm, 20 mm (reference), and 18 mm, showing that the resulting maximum displacements vary by less than 2%, which indicates a weak dependence on mesh density and confirms the adequacy of the adopted reference mesh.

The interaction between prefabricated concrete elements and the sand in the joints and beneath the elements was modeled as a frictional contact, characterized by a coefficient of 0.7. This value was assumed based on laboratory tests conducted by Uesugi et al. [28] and Canakci et al. [29], which demonstrated that the frictional resistance between concrete and sand depends on the sand type, moisture content, and surface roughness of the concrete. The contacts between pavement layers were modeled as rigidly tied, which provides a convenient approximation for the bonded interface. On the lateral boundaries, both horizontal and vertical displacements are restrained, while at the bottom boundary vertical and horizontal displacements as well as rotations are constrained, representing an idealized support condition. Examination of the numerical results indicates that both displacements and stresses decrease rapidly with distance from the loaded area and decay well before reaching the model boundaries, suggesting that boundary effects on the responses of interest are limited. Nevertheless, this boundary treatment introduces a modeling limitation, as the imposed constraints idealize the actual soil-structure interaction and may influence the response under horizontal braking actions; this aspect should therefore be considered when interpreting the results.

A pavement structure with a surface area of 1.0 x 1.0 m was modeled, with layer thicknesses corresponding to those shown in the typical cross section (Table 1, Figure 5). In this study, the modular pavement structures with unbound aggregate base and subbase layers were analyzed. The prefabricated concrete elements have dimensions of 20 x 10 cm with a thickness of 8 cm. Two joint widths were considered: 3 mm and 5 mm, reflecting the most common

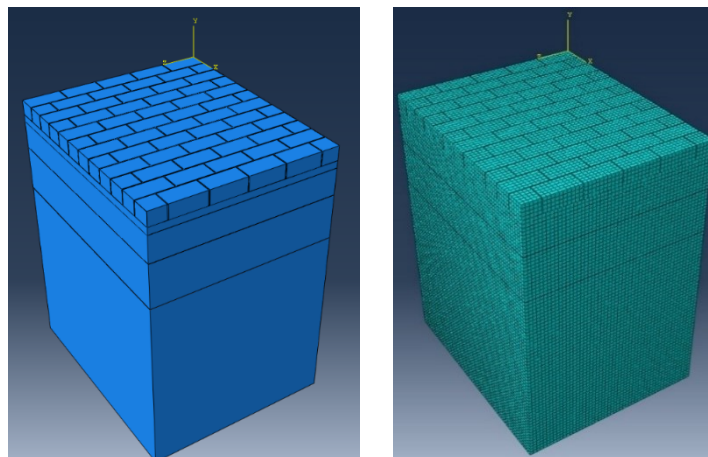


Figure 4. Pavement structure model (left) and FEM mesh layout (right)

practices locally. All materials were modeled as linear elastic, homogeneous, and isotropic. The subgrade bearing capacity was expressed using the CBR, with values of 3%, 5%, 7%, and 9% used in the simulations. The subgrade modulus of elasticity was estimated from CBR values using the commonly adopted empirical correlation according to which the subgrade modulus [MPa] is approximately ten times the CBR [%] value, as widely reported in pavement engineering literature (e.g., [30] and [31]).

The modulus of elasticity and unit weight of all materials were adopted based on statistical data obtained from the laboratory database of the Department of Civil Engineering and Geodesy at the Faculty of Technical Sciences from Novi Sad. Given the large volume of data, only representative values are presented in Table 1. Five different prefabricated concrete element positions, corresponding to alternative laying patterns, were analyzed (Figure 6), considering joint widths of 3 mm and 5 mm:

- basket weave or parquet bond;
- stretcher or running bond;
- 90° herringbone bond;
- 45° herringbone bond, movement direction 1;
- 45° herringbone bond, movement direction 2.

4 Results and discussion

Figures 7 and 8 present the results of the FEM analysis for five different laying configurations of prefabricated concrete elements, each assessed with joint widths of 3 mm and 5 mm. Two types of subbase materials (crushed stone aggregate and natural sand-gravel) were modelled over subgrades with bearing capacities defined by CBR values of 3%, 5%, 7%, and 9%. Both vertical and horizontal displacements of the surface elements were evaluated under two loading conditions: continuous movement (D) and braking (B).

Table 1. Mechanical characteristics of the pavement structure

Material		Thickness [cm]	γ [kg/m ³]	E [MPa]	ν
Prefabricated concrete elements (10 x 20 cm)		8	2,410	31,000	0.20
Sand (levelling layer)		4	1,800	35	0.35
type 1	Base, crushed stone aggregate 0/31,5 mm	12	2,130	300	0.35
	Subbase, crushed stone aggregate 0/63 mm	25	2,130	120	0.35
type 2	Base, sand-gravel aggregate 0/31,5 mm	12	2,050	240	0.35
	Subbase, sand-gravel aggregate 0/63 mm	25	2,050	100	0.35
Subgrade		N/A	1,600	10 x CBR	0.4

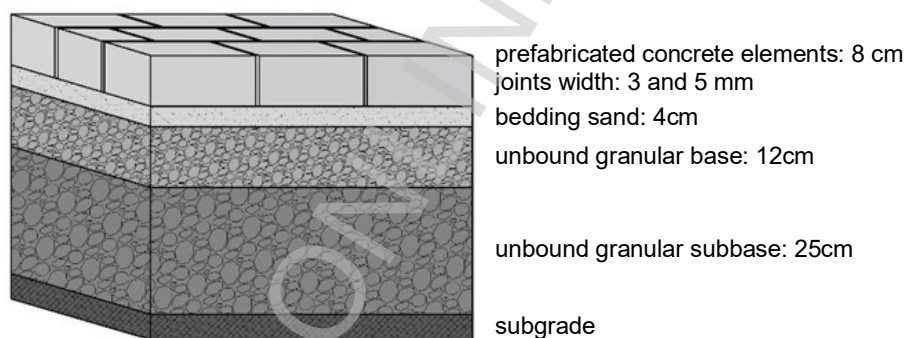


Figure 5. Pavement structure layers

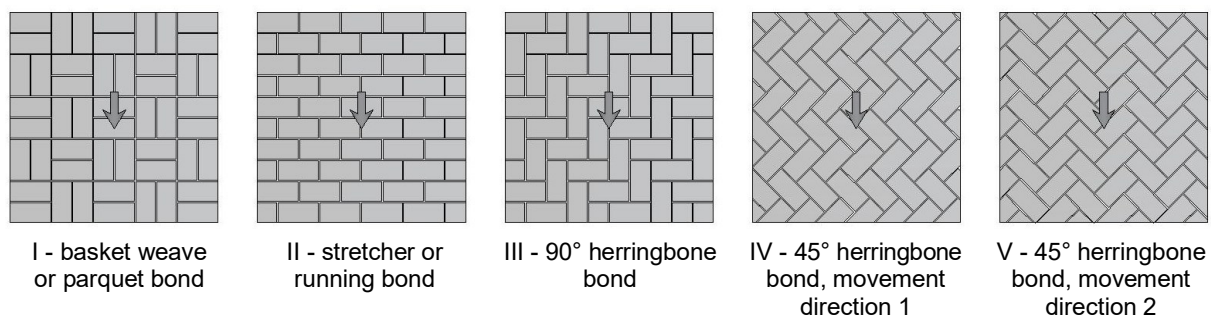
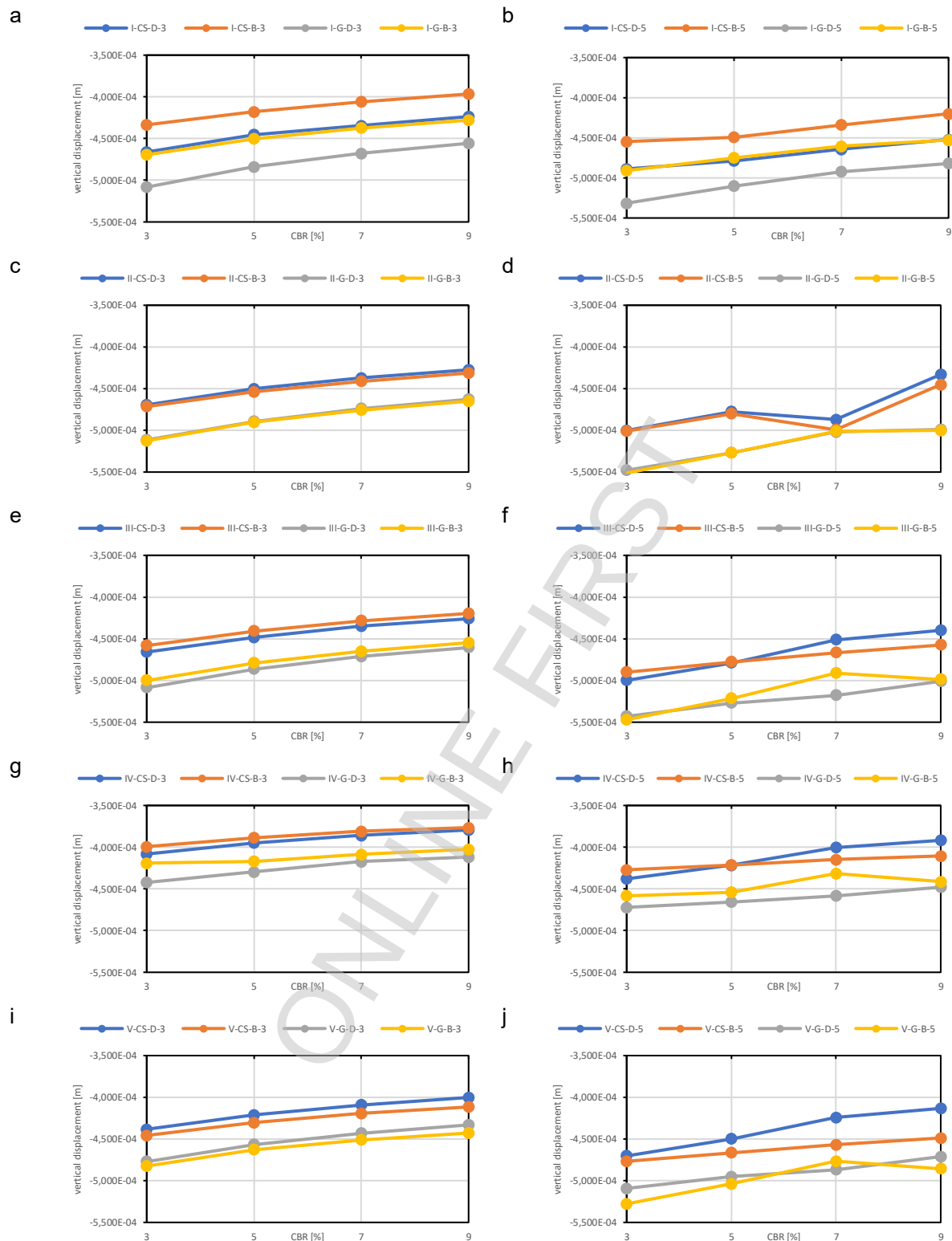


Figure 6. Schemes of prefabricated concrete element arrangement evaluated in the study

Impact of continuous driving and braking on displacements in modular pavements with different laying schemes



I, II, III, IV, V - laying method of concrete elements, CS - crushed stone, G - gravel, D - driving force, B - braking force, 3 - joints of 3 mm width, 5 - joints of 5 mm width

Figure 7. Maximum vertical displacement of prefabricated concrete elements

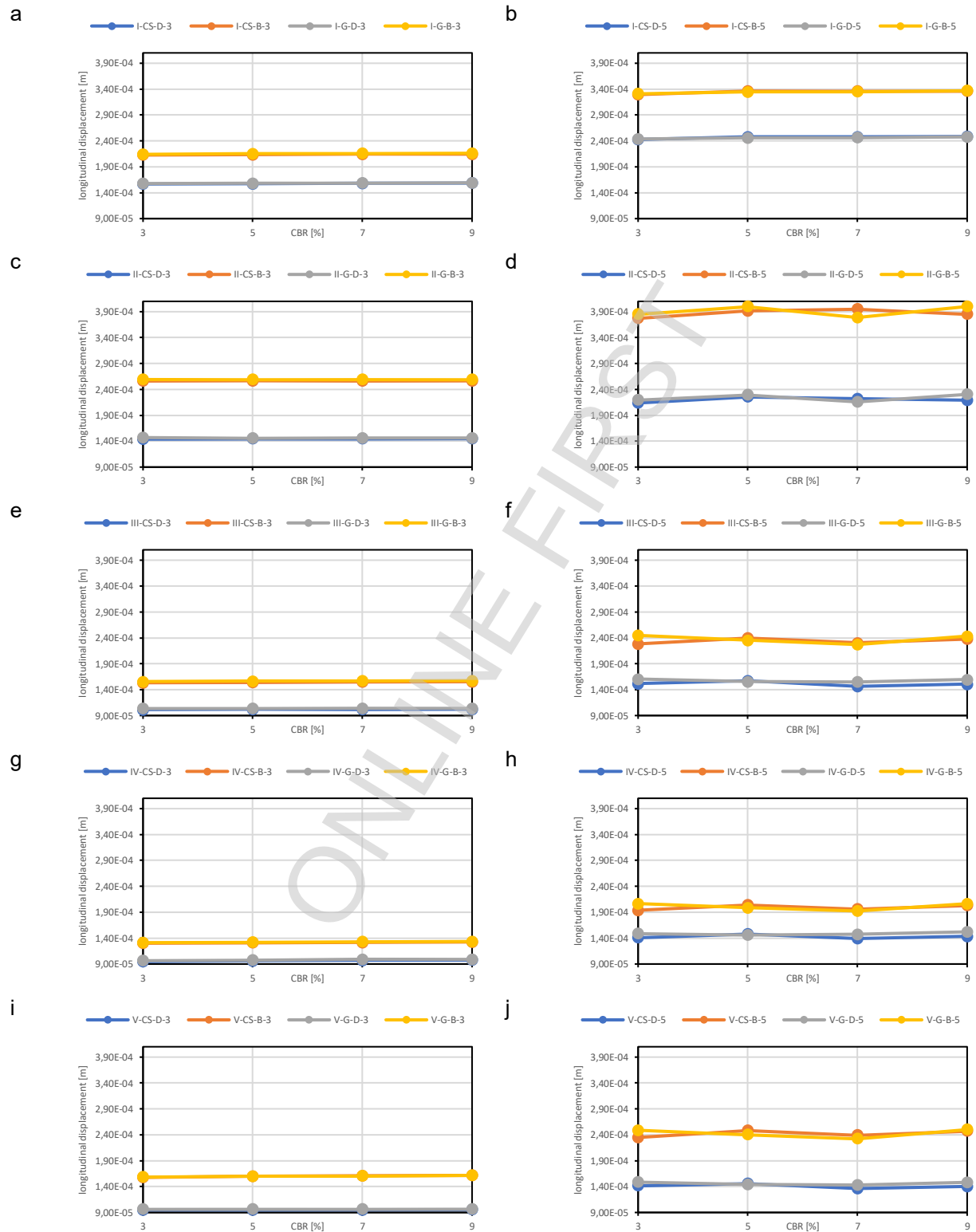
As presented in Figure 7, vertical displacements systematically decrease with increasing subgrade bearing capacity, confirming that subgrade stiffness is the dominant parameter controlling vertical deformation. The only significant deviation occurred in scheme II (elements

oriented perpendicular to the traffic direction) particularly for joints of 5 mm width, where displacement increased unexpectedly between 7% and 9% CBR. This anomaly may be attributed to local stress concentration effects along the transverse joints, reducing interlock efficiency. In all other

configurations, a nearly monotonic decrease in displacement is observed with the increase in the bearing capacity of the subgrade.

Overall, pavements with sand-gravel subbases exhibited higher vertical displacements than those with crushed stone, consistent with the lower angularity and reduced interparticle

friction of rounded grains. This finding aligns with the FEM-based observations by Di Mascio et al. [18], who reported that base stiffness and interlayer bonding strongly affect surface deflection, and by Siva Rathan et al. [15], who demonstrated similar sensitivity when varying subbase stiffness in modular pavement simulations. The comparative



I, II, III, IV, V - laying method of concrete elements, CS - crushed stone, G - gravel, D - driving force, B - braking force, 3 - joints of 3 mm width, 5 - joints of 5 mm width

Figure 8. Maximum longitudinal displacement of prefabricated concrete elements

results also support the findings of Shubbar et al. [17], who noted that herringbone patterns tend to minimize vertical deformation under combined loads, and Zoccali et al. [21], who emphasized the need for adequate base stiffness in block pavements subjected to exceptional loads in shared-use urban areas.

Collectively, these results confirm that joint width, subbase type, and subgrade stiffness jointly govern the vertical response of modular pavements. Crushed stone subbases and narrower joints consistently enhance load transfer, reduce deflection, and thus contribute to improved serviceability.

Figure 8 shows the maximum longitudinal displacements obtained under both movement and braking forces. The results clearly indicate that horizontal displacements are significantly more sensitive to braking forces than to continuous driving, highlighting the pronounced influence of tangential loads on the performance of modular pavements. For elements with 3 mm joints, a gradual reduction in displacement is observed with increasing subgrade stiffness, confirming enhanced interlock and reduced lateral mobility. In contrast, pavements with 5 mm joints exhibit more variable behavior, where displacement trends depend strongly on the combination of subbase type and subgrade capacity.

When analyzing images 8b, 8d, 8f, 8h and 8j, for braking force significantly smaller displacements appear for a 3% subgrade of sand-gravel material compared to crushed stone aggregate. For the sand-gravel subbase, the lowest horizontal displacements were recorded for the weakest (CBR=3%) and strongest (CBR=9%) subgrades, while crushed stone subbases achieved smaller displacements for intermediate subgrade strengths (CBR=5-7%). This alternating trend suggests that deformation compatibility between the modular layer and the underlying support governs the horizontal response more than stiffness alone. By analyzing the displacement forces for continuous driving with 5 mm joints, it is observed that the sand-gravel material has a significantly lower displacement in the subgrade with a bearing capacity of 3, 7 and 9%, while a slightly lower value is observed in crushed stone aggregate in the subgrade of 5%.

The influence of braking force is particularly evident, showing significantly larger horizontal displacements than continuous driving conditions, especially for the 5 mm joint configurations. The pronounced influence of braking forces aligns with observations by Shubbar et al. [17], who demonstrated that dynamic and braking-type loading substantially increase joint deformation, particularly in pavements with wider joints or less interlocked configurations. Similarly, Siva Rathan et al. [15] confirmed through FEM parametric analysis that joint width and laying scheme significantly influence lateral stress propagation and displacement amplitudes. The results also resonate with Di Mascio et al. [18], who noted that interfacial stiffness between layers plays a crucial role in limiting horizontal strain transfer. Although Zoccali et al. [21] focused primarily on vertical deformation, their conclusions regarding the need to design for unexpected loads in shared-use pavements extend directly to the effects of horizontal braking forces observed here.

Overall, these findings reinforce that braking forces can induce increased horizontal displacements, especially when wider joints and weaker interparticle bonding in the subbase are combined. The 3 mm joint configuration consistently provides better interlock and reduced movement, supporting its recommendation for urban and local pavements subject to frequent braking events.

The finite element results are consistent with the observations of Di Mascio et al. [18] and Siva Rathan et al. [15] regarding the sensitivity of modular pavements to base stiffness and interfacial bonding and align with Shubbar et al. [17] in showing that interlocking geometry strongly affects deformation under braking-type loading. The results also support Zoccali et al. [21] in underlining the need to consider exceptional horizontal loads in design to avoid premature surface distress. The numerical results are qualitatively consistent with trends reported in previous experimental and numerical studies, which supports the plausibility of the adopted modelling approach; however, a dedicated quantitative validation against field or laboratory measurements was beyond the scope of this study and remains a subject for future work. Finally, braking and friction coefficients may vary in practice; however, the influence of such variations on pavement response was not explored in this study and is suggested as a topic for future sensitivity analyses.

5 Conclusions

Modular pavement structures, traditionally applied at pedestrian crossings and low-speed traffic areas, are increasingly used on urban and local roads carrying heavy goods vehicles at speeds below 40 km/h. Finite element modeling provides a robust framework for evaluating their mechanical response by incorporating realistic boundary conditions, contact behavior, and material properties.

This study examined prefabricated concrete elements arranged in five laying patterns with joint widths of 3 mm and 5 mm under continuous driving and braking loads using a frictional contact formulation. Evaluation of horizontal and vertical displacements led to the following design-relevant conclusions:

- A joint width of 3 mm is preferable in areas with frequent braking and acceleration due to improved interlock and reduced surface displacements;
- Crushed stone subbases offer superior vertical load-bearing performance, while well-graded sand-gravel layers may be acceptable where deformation compatibility or higher subgrade stiffness limits horizontal sliding;
- Herringbone and staggered patterns enhance multidirectional load transfer and reduce stress concentrations;
- Braking-induced horizontal forces should be explicitly considered in the structural design of modular pavements subjected to significant tangential loading.

All layers and joints were modeled as linear elastic, homogeneous, and isotropic materials; therefore, the analysis is limited to elastic displacements under quasi-static loading. Long-term effects such as permanent deformation, rutting, fatigue, and damage accumulation were not considered, and the results should be interpreted comparatively, emphasizing relative trends among joint widths, laying patterns, subbase types, and subgrade CBR values.

This study provides one of the few detailed FEM-based analyses of braking effects on modular pavements, demonstrating that horizontal load actions can be as critical as vertical stresses for the performance of interlocking block pavements. The findings contribute to the foundation for more comprehensive mechanistic-empirical design approaches for modular pavements in urban environments and on local roads.

CRedit authorship contribution statement:

According to the Contributor Role Taxonomy (CRedit) guidelines, the authors contributed to this work as follows:

Igor Jokanović: Conceptualization; Methodology; Validation; Resources; Writing - review and editing; Supervision.

Mila Svilar: Conceptualization; Methodology; Software; Investigation; Writing - original draft preparation; Visualization.

Nebojša Radović: Formal analysis.

Miloš Šešlija: Validation; Formal analysis; Investigation; Data curation; Writing - review and editing.

Vlado Radanović: Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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