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# Usage of digital image correlation in assessment of behavior of block element pavement structure

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**Abstract.** In diagnostics of existing road pavement structures deflection measurements have fundamental meaning, because of ability to assess present stiffness (bearing capacity) of whole layered construction. During test loading the reaction of pavement structure to applied load is measured in central point or in a few points located along a straight on a 1.5 ÷ 1.8 m distance (i.e. Falling Weight Deflectometer) in similar spacing equal to 20 ÷ 30 cm. Typical measuring techniques are productive and precise enough for most common pavement structures such as flexible, semi-rigid and rigid. It should be noted that in experimental research as well as in pavements in complex stress state, measurement techniques allowing observation of pavement deformation in 3D would have been very helpful. A great example of that type of pavements is a block element pavement structure consisting of i.e. paving blocks or stone slabs. Due to high stiffness and confined ability of cooperation of surrounding block elements, in that type of pavements fatigue life is strongly connected with displacement distribution. Unfortunately, typical deflection measurement methods forefend displacement observations and rotation of single block elements like paving blocks or slabs. Another difficult problem is to carry out unmistakable analysis of cooperation between neighboring elements. For more precise observations of displacements state of block element pavements under a wheel load a Digital Image Correlation (DIC) was used. Application of this method for assessment of behavior of stone slabs pavement under a traffic load enabled the monitoring of deformations distribution and encouraged to formulate conclusions about the initiation mechanism and development of damages in this type of pavement structures. Results shown in this article were obtained in field tests executed on an exploited pavement structure with a surface course made of granite slabs with dimensions 0.5x1.0x0.14 m.

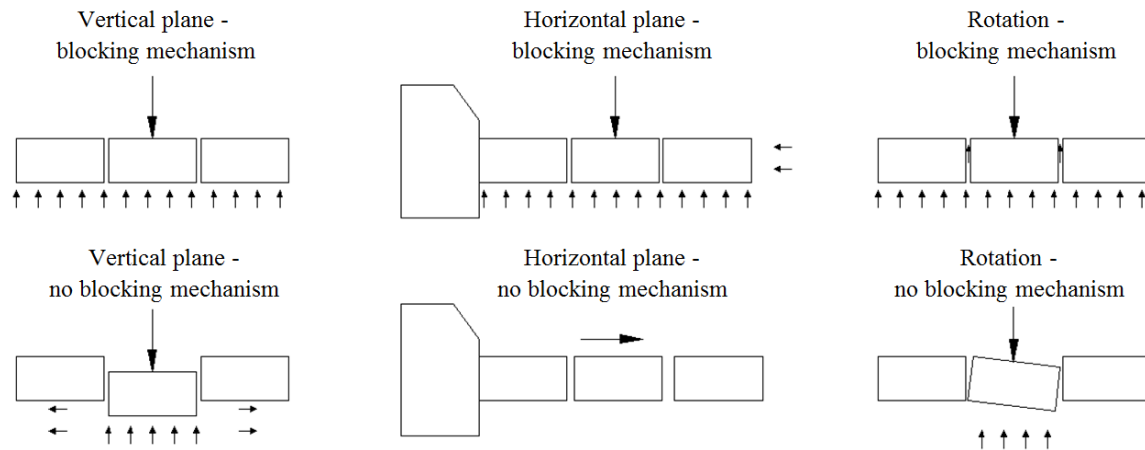
## 1. Introduction

Block element road pavement structures were well known in Roman Empire. Importance of this type of road pavement structures occurred in the time of vibrant development of industry and metropolitan areas. Communication passages with block pavement structures were very popular then, because of high endurance and fatigue life, and respective blocks were easy to assemble. Nowadays block elements are not so popular and not so widely applied, being used only as a surface layers of pedestrian footpaths, cycle paths, squares, in representative city districts or low volume roads [13]. Block element pavement structures have layered construction. The role of sub-base or base is frequently performed by unbound granular layers on which a thin cement-sand laying course and block elements are settled. Joints between block elements are typically filled with fine-graded granular material (i.e. sand) or grout.

Research on behavior of block element pavements were carried out in many works [3][4][10][11][12]. The most important aspect of proper work of block element pavement is cooperation between respective elements. Mampearchchi and Senadeera [8] described so called

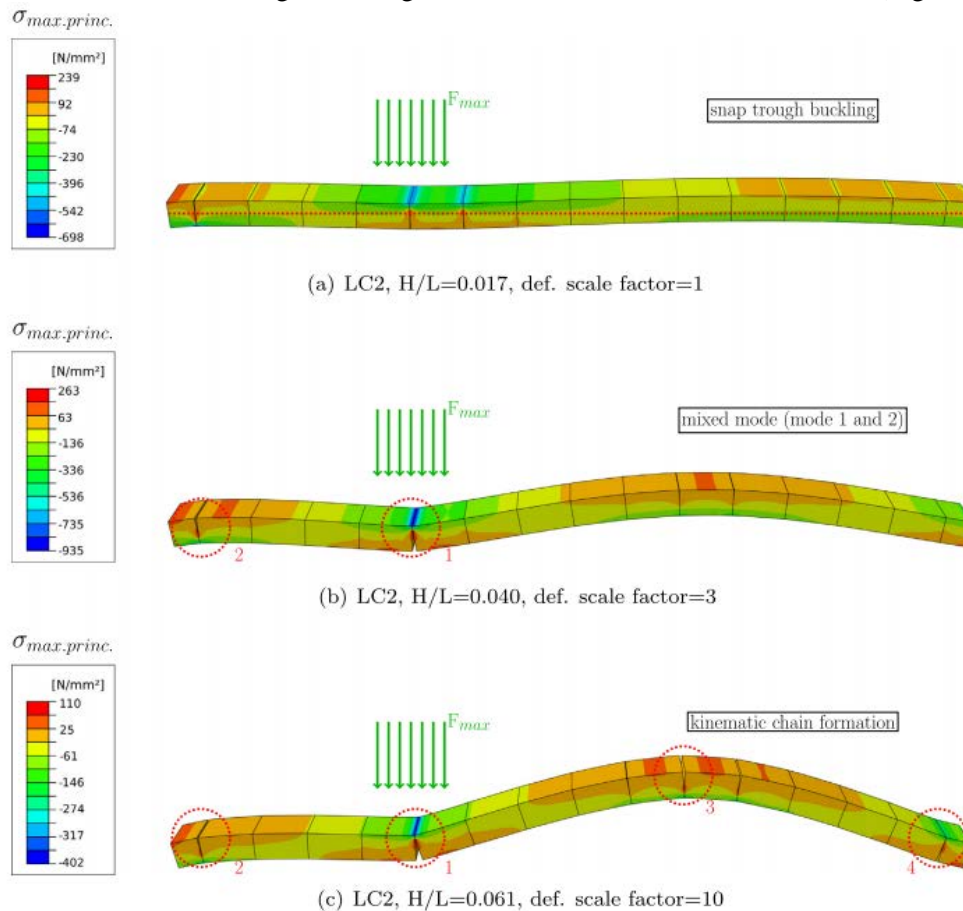


blocking mechanism in which block elements block each other and make impossible a respective element to rotate or translate (Figure 1).



**Figure 1.** Blocking mechanism in vertical and horizontal plane and rotation.

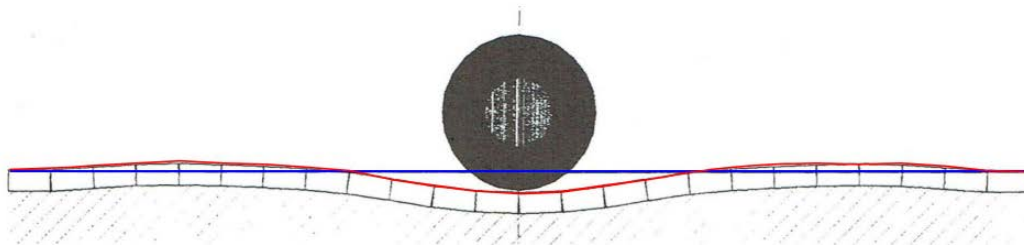
Behavior of block element pavements was also carried out in numerical analyses [6][7][9]. Hengl and Füssl [7] point out variable mechanisms of block pavement destruction. On the basis of numerical model composed of 14 block elements limited on both edges by curbs authors gained three different mechanisms of destruction - through buckling, kinematic chain formation and mixed (Figure 2).



**Figure 2.** Deterioration mechanism of block element pavement - through buckling, mixed, kinematic chain formation [7].

For small values of superelevation and high values of applied loads pavement structure was destructed through buckling, because in block elements high values of compression forces were locally obtained. For high values of superelevation the destruction of pavement was caused by kinematic chain formation due to ability of single element to rotate or translate under a low value of applied load. In this destruction scheme block elements were also peeled away causing improper behavior of pavement structure.

This issue was also noticed as an important problem by Polish researchers. Koba [5] in his work showed that paving made of concrete blocks transfers loads on lower layers by two mechanisms: effect of distribution and effect of plate. Especially important is effect of plate (Figure 3) which can cause various pavement damages such as characteristic upheaval of whole pavement structure in the loading area. This situation is connected with block pavements laid on weak subgrade and is expressed in modulus of elasticity. On the sections with observed upheaval tensile stresses were obtained which can cause damages to joints located between the edges of lifted elements. Mechanisms of destruction of block element pavements mentioned in the literature are difficult to observe in situ. The main problem is to measure displacements of respective elements with satisfactory accuracy and in all characteristic points at one time.



**Figure 3.** „Effect of plate” in pavement with block elements in surface course [5].

The Digital Image Correlation method mentioned in this article and used in field tests on pavement with surface course made of granite slabs with dimensions 0.5 x 1.0 x 0.14 m allowed to attain adequate area of measured displacements. Due to DIC method it was possible to explain causes of existing damages of pavement, which were strongly connected with mechanisms described in other research.

## **2. General characteristic of Digital Image Correlation**

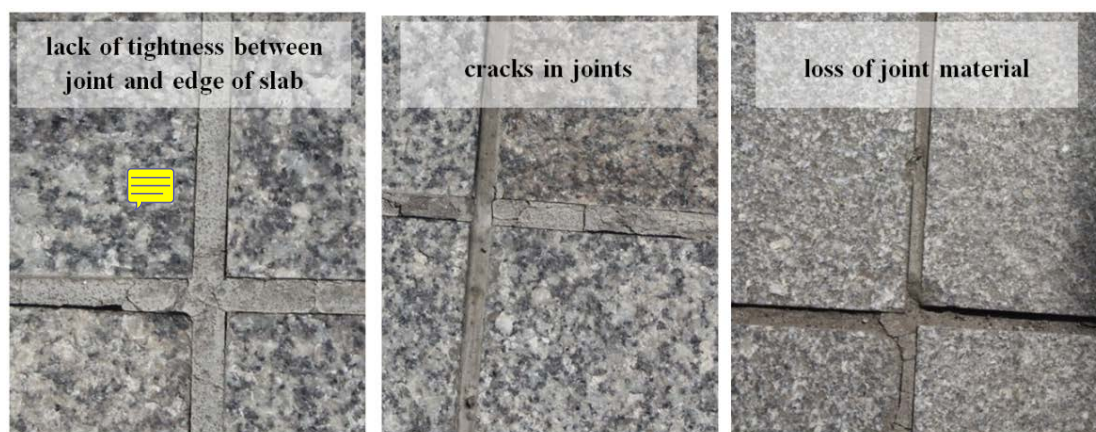
The Digital Image Correlation system used to measure pavement's displacements in 3D is a measuring technique widely used in aviation, space and automotive industry, nuclear and wind energy and in laboratories to investigate mechanical parameters of high-tech and advanced materials (i.e. composites, CFRP, GLARE etc.). Nowadays DIC systems are increasingly used in civil engineering [1][2], especially in laboratories. DIC 3D measurement technique is based on stereoscope vision systems in which at least two cameras record image of tested object from two different perspectives. Due to prior calibration of system, dedicated software analyses the image and obtain information about the distance between cameras and tested object, the angle between both cameras and distance between them. Additionally the calibration process allows to correct errors resulting from imperfection of optical devices such as spherical aberration. Tested object has to be marked with special markers to gain proper results. Markers are also reference points in the test. The algorithm of software finds the markers and assigns them three dimensional coordinates x, y, z. Systems makes measurements of displacements of marked points and due to comparison of gathered data in every step of loading it is possible to show the relationship between load and deformation or displacement. Stereoscope cameras system and 3D space calibration enables the measurement of 3D displacements. Results are shown in a graphic manner similarly as it is in Finite Element Method, therefore system can be used to validate FEM models.

Due to multiple options offered by hardware and software the whole system can be used to investigate variable objects and specimens. DIC system can analyze complete 3D surface in real time

with frequency up to 5 Hz (depends on maximum data acquisition frequency of camera and on maximum data transfer link between PC or laptop) and in frequency up to one million frames in post processing [14]. This innovative technique gives also new possibilities in road engineering.

### 3. Road pavement characteristic

Tested pavement structure was a pathwalk with permission of traffic of heavy trucks and lorries servicing local public facilities and stores. Surface course was made of granite slabs with dimensions 0.5 x 1.0 x 0.14 m. The pavement structure also consisted of cement-sand laying course (4 cm), unbound granular base 0/31,5 mm (25 cm), unbound granular sub-base 0/31,5 (30 cm) and geotextile layed on subgrade.



**Figure 4.** Stages of joint's deterioration.

Characteristic feature of granite slabs pavement were damages of joints between slabs. Several types of this damages could be distinguished such as lack of tightness between joint and edge of slab, cracks in joints and loss of joint material (Figure 4). Dilatation joints were exceptional, because of the elastic material used to fill joint which was not damaged (Figure 5).

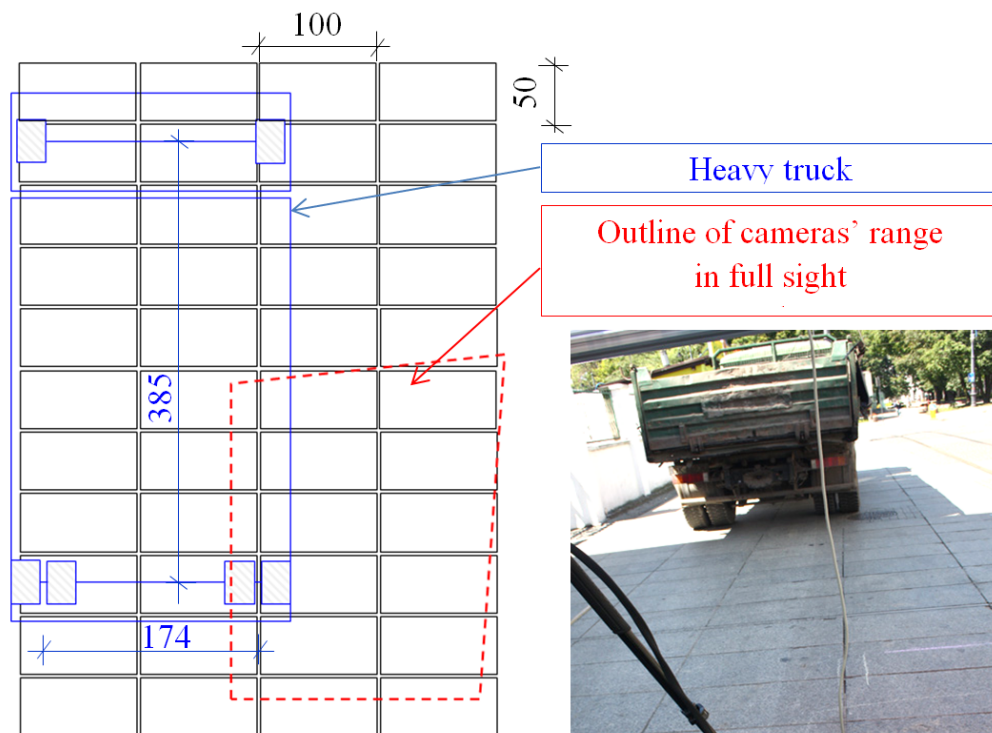


**Figure 5.** Example of dilatation joint in good condition (vertical), grout joint with some damages (horizontal).

### 4. Test stand

Tests were performed on a selected area with dimensions 2.3 x 1.4 m (Figure 6). During the tests a heavy truck with single axes and twin wheels on rear axis was used. Heavy truck meets the requirements for vehicles used to beam deflectometer measurements. The pressure on the rear axis was equal to 99.8 kN.

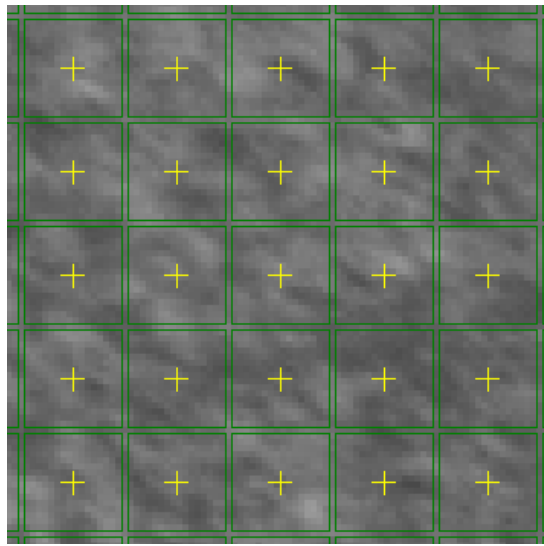




**Figure 6.** Scheme of tested pavement and heavy vehicle.



**Figure 7.** Test stand during DIC deflection measurements of block element pavement structure.



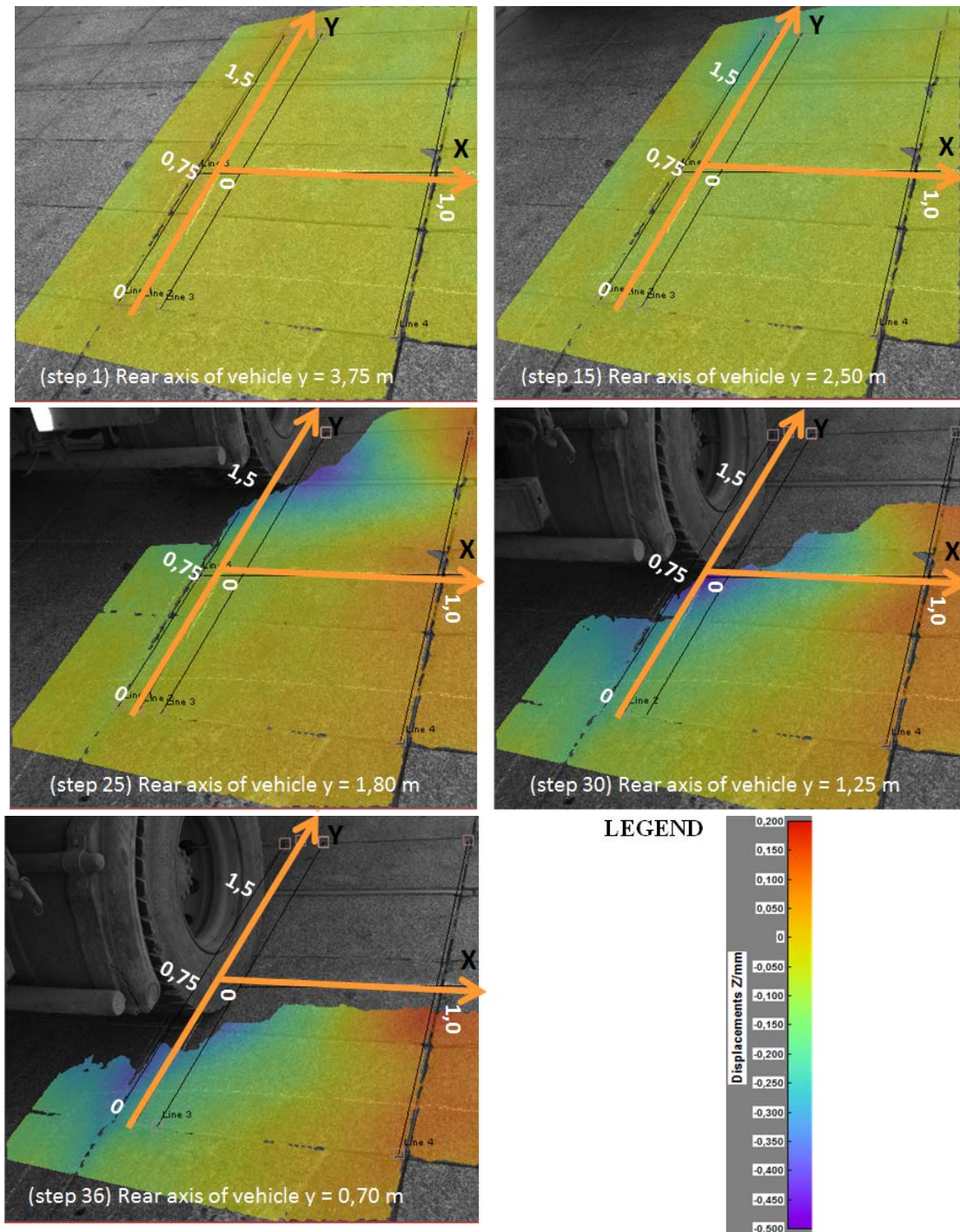
**Figure 8.** Magnified structure of pavement surface. Natural markers (grains) in gray-scale are visible.

Displacements of pavement structure under a load generated by heavy truck were measured using Digital Image Correlation system. Test stand was shown in the Figure 7. The test stand consisted of three cameras located linearly on a stiff aluminum profile with length of 2.0 m. Monochromatic cameras with 5 Mpx resolution and lenses with focal length equal to 12 mm were used. The central camera was located around  $3678.32 \pm 0.10$  cm from the central point in the field of view (FOV). For granite slabs there were no necessity to mark the surface with stochastic markers, because granite has a natural grained structure with different gray scale tones (Figure 8). Analysis of deformation was executed using a mesh with more than 13 000 elements with size of single facet equal to 17 px. In the principal point (central point of the FOV) resolution is equal to 1Px/1mm, but resolution of DIC measurement is different in different areas of the FOV. In the areas covered by three cameras resolution is better than in areas covered just by two cameras. Optical axis of cameras was inclined at 45 degrees to the measured surface, what means that in the area closer to the cameras resolution was better than for area further away from the cameras. Resolution in horizontal and vertical direction in Px/mm is the same. Calibration was executed using square calibration board with a 750 mm long edge. The X and Y axes in coordinate system were set in plane of tested surface.

## 5. Test and analysis of results

During the tests pavement surface was loaded by heavy truck which was moving with low velocity along the shorter edge of slab (Figure 6) which is along the OY axis (Figure 8). Vehicle started passing in point  $y = 5.0$  m (rear axis location) and moved slowly to point  $y = 0.75$  m. During the passing joints between the slabs were located between twin wheels. Measurements were registered only for the rear axis, because of vanishing field of view during the movement of heavy truck. Map of vertical displacements of observed area of pavement in several positions of rear axis is shown in Figure 8. Maximum measured and calculated with DIC deflections of pavement structure are equal to 0.500 mm. It is worth to say that this value is not the maximum vertical displacement value, because it was unable to measure displacements of pavement between twin wheels. The analysis of vertical displacement maps (Figure 8 - step 25 and step 30) shows that along the loaded edge (along OY axis) negative values of displacements were noticed (“top down”) and along the non-loaded edge positive values of displacements were noticed (“bottom up”). In order to further analysis of vertical displacements the distribution of vertical displacements along OY (Figure 8) and perpendicular OX (Figure 9) axis was made. The distribution of vertical displacements along the loaded edge (Figure 8)

shows only the negative value of displacement. It is worth emphasizing the strong influence of rear axis on the 1.0 m distance.

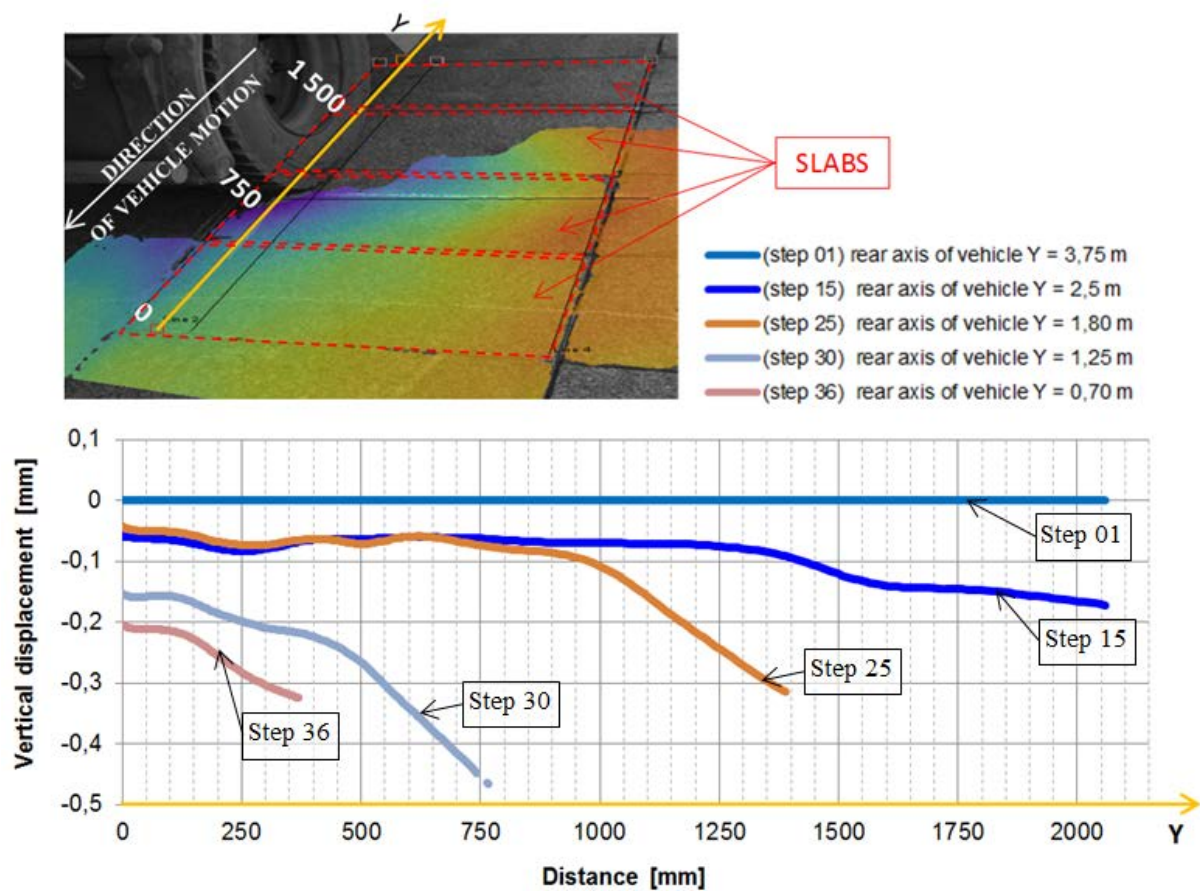


**Figure 9.** Maps of vertical displacement of pavement surface due to different location of load (rear axis of vehicle).

On the following 1.5 m the reaction of pavement structure is also observed, however displacements registered on this section are definitely lower (around  $0.04 \div 0.06$  mm) and they are slightly higher than error (around 0.03 mm) of their calculation (Figure 10). The distribution of vertical displacements

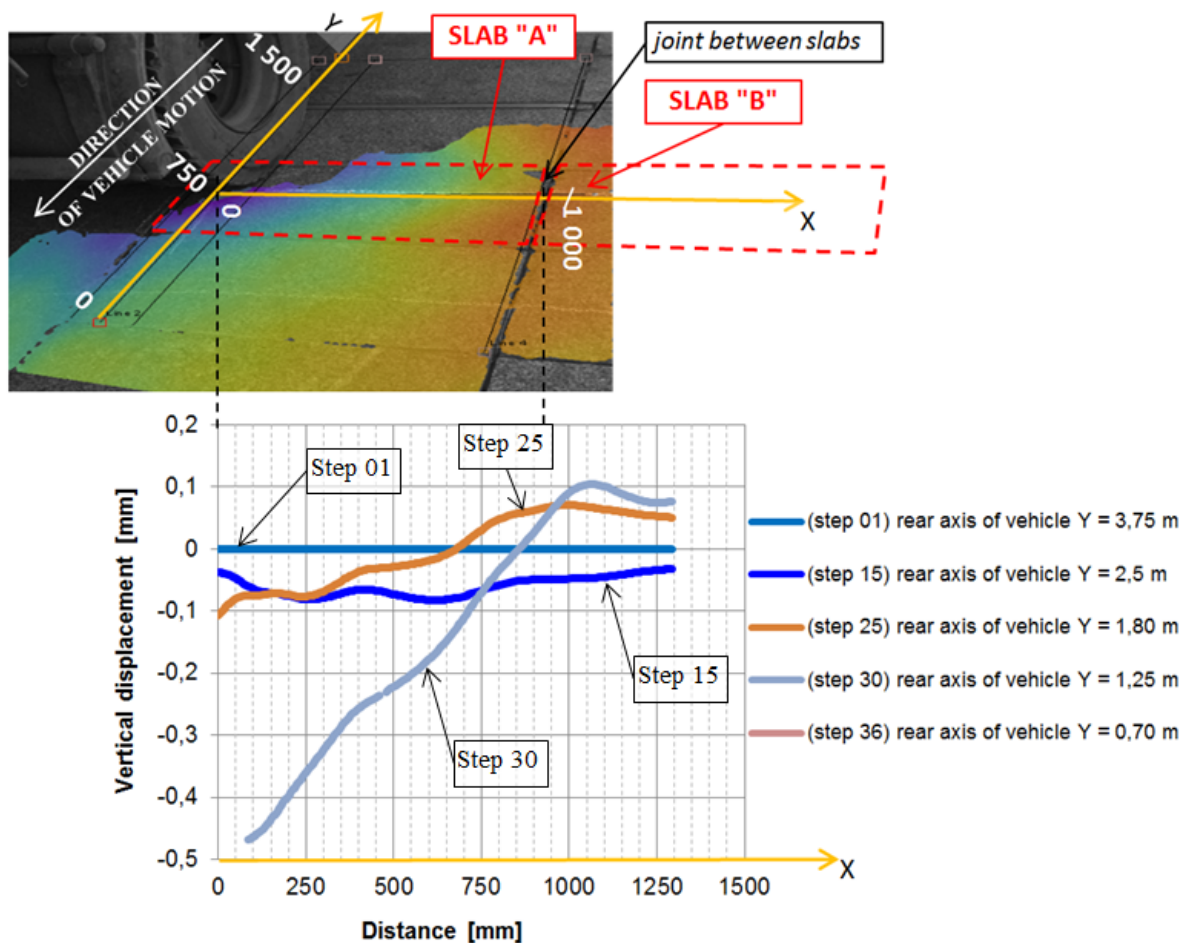


along the perpendicular OX axis shows characteristic upheaval of outer edge of slab (slab A) near the joint (Figure 10). Also the slab B's outer edge is uplifted. Vertical displacement in the „upper direction” reach values even equal to 0.200 mm (Figure 9) and it is higher value than the error of calculation of DIC equipment. It can be said that during the loading of pavement non-loaded edge is uplifting. Near the edge of uplifting slabs tensile stresses appear between edge of slab A - material of joint - edge of slab B. Having considered that tensile strength of edge - joint - edge configuration, appearance of tensile stresses causes deterioration of pavement structure - rupture the connection between elements and deterioration of material in joints. This model of destruction is similar to mechanism showed by Hengl and Füssl [7] and called kinematic chain formation (Figure 2).



**Figure 10.** Distribution of vertical displacements of pavement surface along Y axis due to different location of rear axis of moving vehicle.

It is worth noticing that upheaval of elements only appears on the shorter edge of slab - opposite to the loaded edge. When load was applied along the longer edge of slab, the counter edge was not being uplifted (Figure 11). The results allow to formulate thesis - vertical displacement “bottom - up” will appear when one of the edges will be loaded and the subgrade beneath the block element pavement structure is too flexible and weak. The value of vertical displacement (uplifting) will depend on the value of loading, weakness of subgrade and distance between the loaded edge of slab and opposite edge.



**Figure 11.** Distribution of vertical displacements of pavement surface along X axis due to different location of rear axis of moving vehicle.

## 6. Conclusions

Executed tests and analysis allow formulation such conclusions:

Pavement structure with surface course made of natural stone slabs was tested. On the surface of pavement there were noticed damages such as damages and lack of tightness between slabs.

Digital Image Correlation system enabled showing the distribution of displacements of pavements with block natural stone elements (dimensions around 2.0 x 1.3 m) in surface course. Due to generated vertical displacement map the distribution of displacements in random profile set in the area of measurement. DIC system allows to analyze complex displacement state of pavement i.e. with surface course made of block elements with load applied by traffic.

It was stated that loading shorter edge of slab causes rotation of the slab and upheaval of opposite edge. This type of deformation of pavement made of block elements causes tensile stresses in area of edge of slab A - joint - edge of slab B to result in break off the connection between side edge of slabs and joint. Vertical displacement in the “bottom - up” direction has to be negative, because it leads to destruction of joint and further leads to reduction of fatigue life and aesthetic values of pavement structure

Further research will be focused on analysis of loading position on distribution of displacements. Furthermore, gathered DIC data enable validation of physical model describing behavior of pavement from block elements.

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