Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Evaluation of Deformations in Two-Layered Pavement Systems under Monotonic Loading using Digital Image Correlation Technique

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Abstract. Accurate and reliable deformation measurements are essential to understand the mechanics of any foundation system. Traditional instruments, including linear variable differential transducers (LVDTs) and potentiometers, are reliable; however, they have limited capability in certain scenarios. They provide mean values of strains and displacements at selected locations and gauge lengths; this renders inadequacy in evaluating a non-homogeneous material behavior. The main objective of this research was to emphasize on the use of Digital Image Correlation (DIC) technique for a layered foundation system to overcome the inadequacy of regular instruments. In the present study, a two-layered reinforced and unreinforced pavement systems consisting of a 300 mm thick aggregate layer (base layer) overlying a 500 mm thick sand layer (subgrade) was prepared in a test chamber of dimensions 0.9m x 0.9m x 1m in length, width and depth. A monotonic load was applied through a strip footing on the pavement layered systems, and the deformations under the loaded area were captured using DIC technique. The results were further validated using conventional measuring devices.

Keywords: Deformations; Digital image processing; Speckling; Reinforced pavement; Monotonic loading.

1 Introduction

Pavements are an integral part of a country's infrastructure; an efficient pavement system is essential for a nation's socio-economic growth. India has the second-largest road network in the world, with 58.98 lakh km. In India, road transport handles more than 60% of the freight and more than 80% of the passenger traffic. Realizing the need for good road infrastructure, the Indian government has embarked on a vigorous road-building effort. In recent times, it has significantly increased the award of projects to construct new roads and highways.

Apart from the planning and construction phases of a project, the maintenance phase plays a vital role to preserve and enhance the benefits of the infrastructure. Hence, maintenance of pavements is a fundamental challenge to be emphasized in order to avoid any kind of pavement failures.

In most of the cases, pavement failures are usually caused by settlements in the pavement layers, degrading the pavement quality. Thus, there is a necessity for innovative road construction techniques in order to focus on combating the settlement problem. The reinforced pavement technique is an evolving technique that is used to reduce the thickness of pavements as well as to curtail the settlements. Many studies have been conducted to investigate the behavior of soil reinforced with different types of geosynthetics through experimental laboratory tests and Finite-Element Analysis (FEA) [1]. By incorporating the reinforcement layer, the lateral restraint and the rigidity of the pavement system can be increased, and the vertical and lateral deformations of the pavement can be minimized.

Recently, geogrids have been widely used for the reinforcement of pavement systems by reducing the base course thickness [2]. Two common types of geogrids used in the pavements are biaxial and triaxial geogrids. Hence, there is a need to quantify the deformation trends for reinforced and unreinforced pavement systems.

Accurate and reliable deformation measurements are essential to understand the mechanics of the pavement system. The life span and the performance of pavement structure are directly related to deformation in the pavement structure. For many years, there have been various conventional methods such as linear variable differential transformers (LVDTs), strain gauges, extensometers, and clip gauges etc., that have been used to measure displacements. However, the measurements from conventional methods provide information only at the point of use.

Due to the contact nature and inability to capture full-field deformations with the conventional methods, it was evident that advancements in displacement measurement systems were necessary to improve the speed and accuracy of pavement systems. Researchers employed the recent developments in digital imaging technology in order to overcome the difficulties faced by experimental mechanics whilst post-processing photography-based measurement data [3].

There are many advantages of the Digital Image Correlation technique, among which main characteristics include absence of contact between instruments and specimen and the ability to measure the full-field displacement and strain [4–6]. These characteristics allow extracting more data from a test at a low experimental cost. DIC technique, for which deployment started in the 1980s, has been significantly improved in the past years achieving less computational cost and improved accuracy [5]. Its concept is based on comparing consecutive images of the same object, which can be displaced and deformed [3]. Researchers became aware of the suitability of DIC for geotechnical engineering applications in the late 1990s. DIC has been the subject of remarkable research efforts and is now reaching maturity due to its wide variety of applications. However, there are still some aspects that need to be explored further.

Hence, the main aim of this research is to use the digital image correlation technique for analyzing the deformations in both unreinforced and reinforced two-layered pavement systems under monotonic loading by validating it with conventional measuring techniques. The deformations of unreinforced and reinforced are quantified and compared using the proposed technique.

2 Experimental program

2.1 Materials

In this study, deformations were obtained for the subbase and subgrade layers of both reinforced and unreinforced pavement system. Three different materials, viz., sand, aggregates and geogrid, were used, in the experimentation.

Sand

Sand used for the present experimental work was Indian Standard (IS) Grade II sand which is commonly known as Ennore sand. Table 1 provides the physical properties of Grade II sand (Hariprasad et.al., 2016). The sand particles of Grade II sand were more uniformly sized with a mean size of 0.49mm. They were classified as poorly-graded sand (SP) as per the Unified Soil Classification System (USCS). The shape of Grade II sand particles was sub-angular to angular.

Aggregates

Locally available quarry-crushed aggregates were used as the subbase layer in a two-layered pavement system. About 500kgs of aggregates were collected and sieved through a standard set of sieves to follow the gradation of the material. The nominal size of the aggregate was found to be 20mm and the maximum dry unit weight obtained was 19.4kN/m^3. Table 1 provides the physical properties of aggregates.

Table 1. Physical properties of sand and aggregates

Properties	Sand	Aggregates
D_{10} (mm)	0.28	8.0
D_{30} (mm)	0.41	12.0
D_{50} (mm)	0.49	14.0
D_{60} (mm)	0.53	15.0
Coefficient of uniformity, C_u	1.89	1.87
Coefficient of curvature, C_c	1.13	1.20
Soil classification	Poorly-graded sand (SP)	Poorly-graded gravel (GP)
Specific gravity, G_S	2.65	-

Geogrid

In the present study, triaxial geogrid was used as the reinforcement material. It has a hexagonal structure with triangular apertures. Figure 1 shows the geogrid used in the present study. Table 2 shows the properties of the geogrid used in the study.

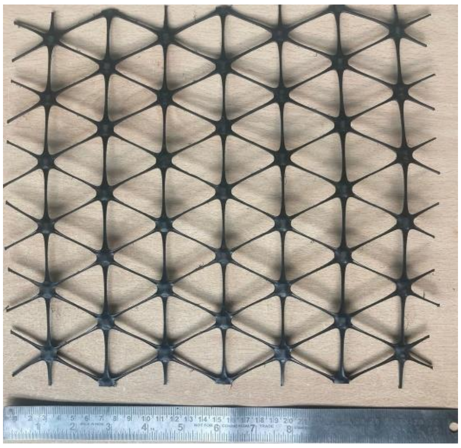


Fig.1. Geogrid used in the present study

Table 2. Properties of the geogrid used in the present study

Product characteristic	Unit	Value
Radial secant stiffness at 0.5% strain	kN/m	390
Radial secant stiffness at 2.0% strain	kN/m	290
Radial secant stiffness ratio	-	0.8
Junction efficiency	%	100
Hexagon pitch	mm	80
Weight of the product	kg/m^2	0.22

3 Experimental program

3.1 Digital Image Correlation Technique

The basic principle of 2D-DIC is to track (or match) the same point (or pixel) between two images recorded before and after the deformation. DIC mainly works on the concept of correlation whereby a series of digital images are acquired successively of a deforming specimen surface throughout the test. The displacement is computed as the difference in the position, i.e., tracking of speckles between the reference image (which is fixed) and the subsequent images (speckled images) captured after deformation. A reference image is an image which is captured at the original (undeformed) state of the specimen (surface) shape. The recorded image is referred to as the calibration image since it is used to calibrate the scale to millimeters.

3.2 DIC Experimental Setup

It is extremely important to prepare the experimental setup properly before the measurement is carried out using the 2D digital image correlation technique. Digital Image Correlation setup mainly consist of a digital camera, illumination lights system, and a test specimen.

Digital Camera- To capture the images for correlation and further to obtain deformations, the lens with 20mm F/ 2.8d specifications were used.

Illumination lights - White source illumination lights were used to improve the speckling contrast of the test sample to obtain good correlation results.

Computer System - Computer system was connected to the digital camera throughout the experiment. The recorded data from camera was transferred to the system and further used for analysis. This system was mainly used for the digital image collection and correlation to obtain the results. VIC 2D Version 2009, a commercially available algorithm, was used to correlate the DIC images, and special effort was taken to ensure that the system was calibrated correctly.

Test specimen - One of the crucial factors that might directly impact the accuracy and precision of the correlation results was the creation of random speckle patterns on the specimen surface. The pattern size must be small to achieve a high and precise correlation. During the experiment the speckled surface images are captured to get the deformation results. Figure 2 shows the complete experimental setup of DIC.

Fig. 2. Digital Image Correlation setup (a) Digital camera with lens, (b) Two illumination lights, (c) Computer system used in the study, and (d) Test specimen

3.3 Conventional technique

In this study, LVDT and potentiometers were used as conventional contact-based techniques, to obtain displacements at the point of contact. The vertical deformations obtained from the DIC technique at the mid-span of the specimen are validated with the deformations measured from the LVDT and potentiometer. The DIC technique's reliability and accuracy was confirmed by obtaining satisfactory correlating results between DIC and LVDT measurements.

3.4 Experimental procedure

All the experiments were carried out in a test chamber of dimensions 900 mm x 900 mm x1000 mm (in length, width, and depth). A perspex sheet in the front side of test chamber facilitates the visibility of the pavement layers filled in the test chamber. The pavement system mainly consisted of two layers, i.e., sand and aggregates. In order to prepare the sand and aggregate layers as two-layered pavement system mainly two methods were used:

- Pluviation method
- Vibration method

Pluviation method

According to the calibration studies carried out previously (Hariprasad et.al., 2016) the pluviation method produces sand beds with a uniform and repeatable density. In order to create sand beds in the test chamber, a full-scale pluviator with plan dimensions equal to 890 mm x 890 mm was employed. The relative density of the sand bed achieved using pluviator was 85%.

Vibration method

In the present study, a pneumatic vibratory method was used for the preparation of aggregate layers. The aggregates bed was prepared in three layers and each layer was compacted to achieve the density of 19.4 kN/m3. Figure 3 shows the cross section of two-layered pavement system.

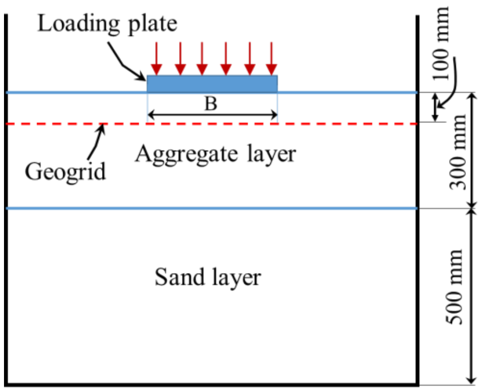


Fig. 3. Schematic showing the cross section of geogrid reinforced two – layered pavement system

The top-most layer was aggregates of thickness 300mm and the bottom layer was IS Grade II sand (Ennore Sand) of thickness 500mm. A plate of 300mm x 900 mm (width x length) was placed on the top of prepared bed of pavement layers right at the center, on which monotonic loading was applied using the hydraulic loading system. The overall thickness of the pavement system was equal to 800mm for both reinforced and unreinforced cases. In reinforced pavement system the geogrid was placed at a depth of 100mm from the top within the aggregate layer.

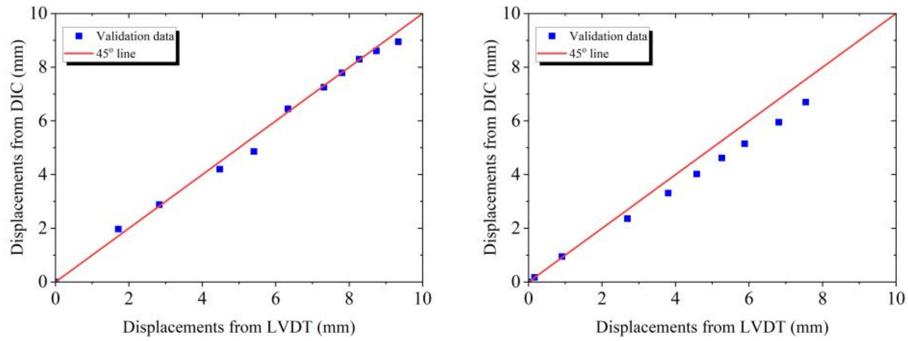
The monotonic load was gradually applied at varying intervals, allowed to remain steady for a while, until no deformations were visible, at that point the deformations were captured using Vic SNAP. Following this loading pattern, the deformations were obtained.

Further, the images captured were analysed in VIC 2D software by using correlation method to obtain the desired results. To observe the deformation trends, settlements were obtained for both unreinforced and reinforced pavement system using DIC.

4 Results and discussions

4.1 Validation studies

Prior to the exact problem of interest, the accuracy of the DIC results was validated in two different loose samples prepared with sand and aggregate. Two-layered system made of 300 mm of sand and 300 mm of aggregate with and without geogrid reinforcement layer was tested at different loads and the deformations were recorded from conventional and DIC setups. The samples were loosely compacted with minimum vibration. DIC facilitates to get the clear picture of the deformations for whole surface, whereas the conventional method which gives the deformations at the point of contact as mentioned earlier. Figures 4(a) and 4(b) show the validation of the DIC results with the conventional measurement. The DIC and conventional measurements were found to have well matched.



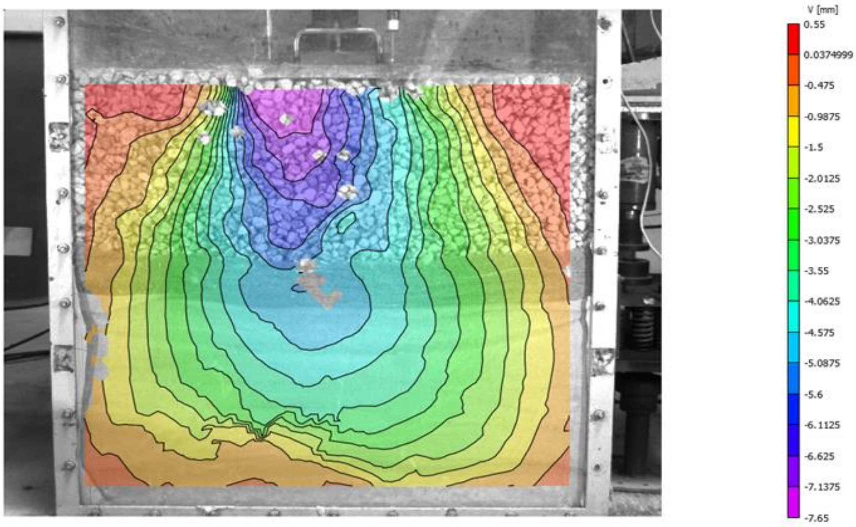
(a) Sand and aggregate layer (b) Sand and aggregate layer with geogrid

Fig. 4. Validation experiment for (a) sand and aggregate layer, and (b) sand and aggregate layer with geogrid setup

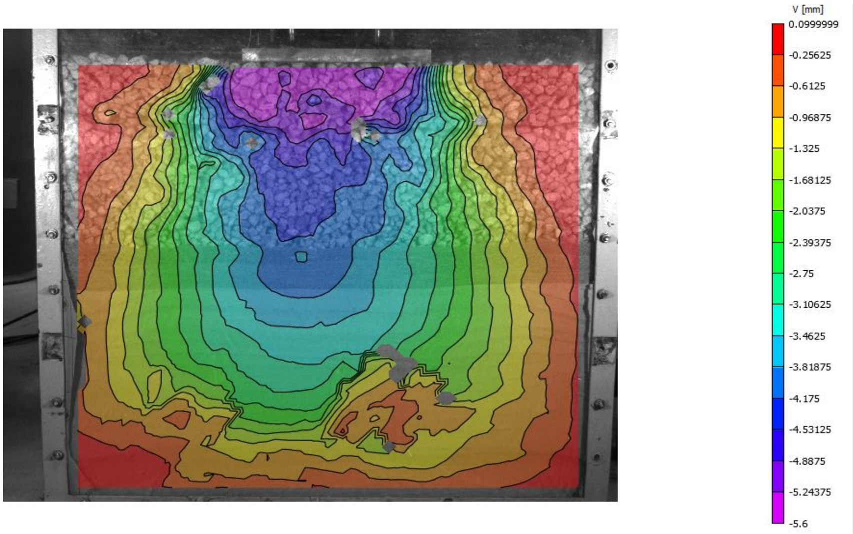
4.2 DIC results on two-layered pavement system

Using DIC, the deformation values and deformation contours were obtained for unreinforced and reinforced two-layered pavement systems. To understand the deformation trends precisely, deformations at depths of 0.25%, 0.5% and 1% of the width of footing were observed.

Deformation values and deformation contours were obtained by applying monotonic load on two-layered pavement system from 5kN to 40kN with the interval of 5kN. Figures 5(a) and 5(b) show the deformation contours of two-layered pavement system under 40kN for unreinforced and reinforced conditions i.e., at maximum settlement. From these deformations, we can observe that with the increase in load there is a reduction in percentage increase in settlement. For unreinforced case, there was a reduction in increase in settlement from 100% initially to 15.7%, and in reinforced case, the reduction in the increase in settlement varied from 100% to 13.4% for loads at 5kN and at 40 kN (refer to Table 3.).



(a) Deformation contours of unreinforced pavement system



(b) Deformation contours of reinforced pavement system

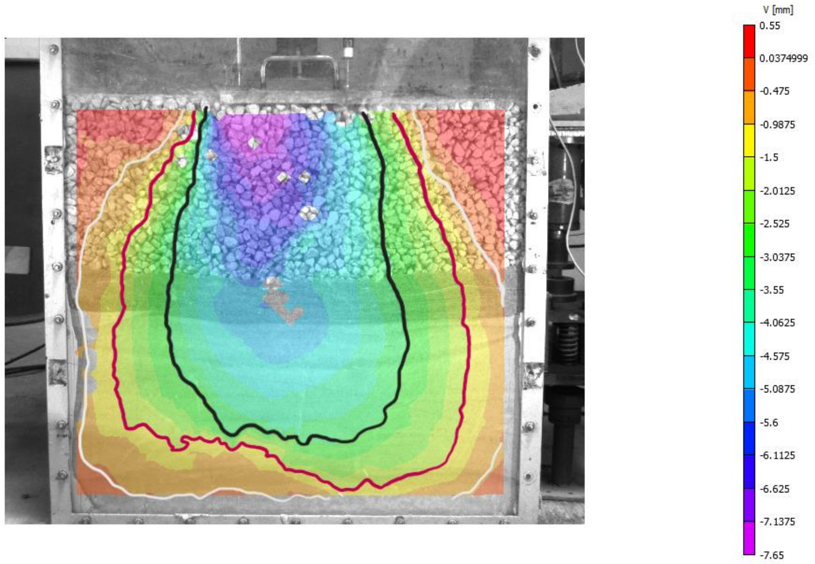
Fig. 5. Deformation contours of (a) Unreinforced pavement system, and (b) Reinforced pavement system

Table.3 Percentage reduction in settlement increment with the load increase

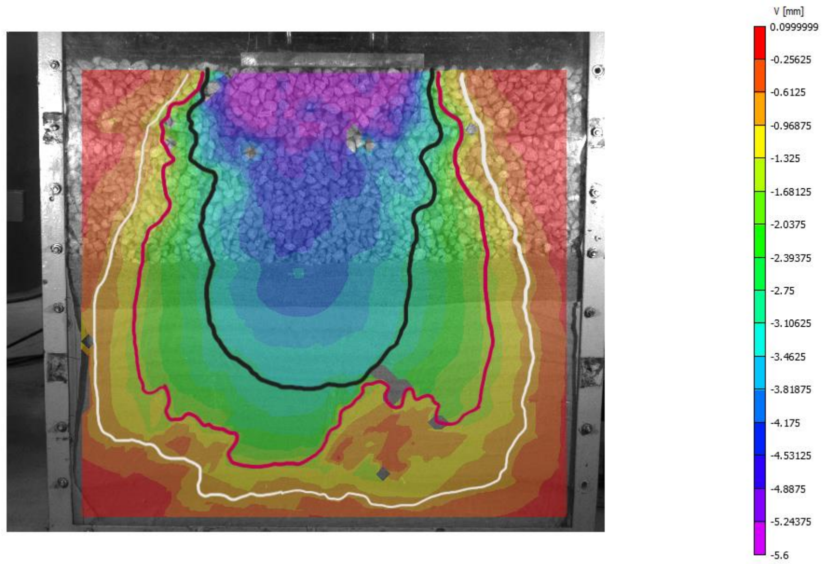
Monotonic load (kN)	Unreinforced (mm)	Percentage increase in settlement (%)	Reinforced (mm)	Percentage increase in settlement (%)
5	0.16	100	0.19	100
10	0.45	64.4	0.24	20.8
15	1.88	76.0	1.21	80.2
20	3.16	40.5	2.20	45.0
25	4.12	23.3	3.08	28.6
30	4.85	15.0	3.96	22.2
35	6.45	24.8	4.85	18.3
40	7.65	15.7	5.60	13.4

To understand the deformation trends for unreinforced pavement system at various depths deformation contours are marked at 0.25%, 0.5% and 1% width of footing, i.e., at 0.75mm, 1.5mm and 3mm as width of footing is 300mm. The influence of the deformations could be observed from 15kN to 40kN. The influence zone of the deformation contours increased with the increase in load. The white line represents settlement to width ratios of 0.25%, red line represents 0.5%, and black line represents the 1% width of footing. Quantitatively, the influence zone extended from 0.42 m to 0.55 m under the load of 15 kN to 40 kN with respect to settlement equal to 0.25% of the width of the footing in reinforced case, and the same was equal to 0.68 m to 0.8 m in unreinforced case. Similar trends were observed for the influence zones corresponding to settlements equal to 0.5% and 1% of the width of the footing.

Figures 6(a) and 6(b) show the deformation contours at depth of 0.25%, 0.5% and 1% of width of footing influence for unreinforced and reinforced cases under 40kN.



(a)



(b)

Fig. 6. Deformation contours at depth of 0.25%, 0.5% and 1% of width of footing influence under the load of 40 kN for (a) Unreinforced pavement system and (b) Reinforced pavement system

4.3 Comparisons inferred between unreinforced and reinforced pavement systems

From Table 4, it can be observed that as monotonic load increases, the estimated percentage reduction in settlement from an unreinforced to a reinforced pavement system gradually decreases. Additionally, we can see a significant decrease in settlement from unreinforced to reinforced, which is an expected result.

Table. 4 Percentage reduction in maximum settlement

Monotonic Load (kN)	Unreinforced (mm)	Reinforced (mm)	Percentage reduction in settlement (%)
5	0.16	0.19	-18.8
10	0.45	0.24	46.6
15	1.88	1.21	35.6
20	3.16	2.20	30.3
25	4.12	3.08	25.2
30	4.85	3.96	18.3
35	6.45	4.85	24.8
40	7.65	5.60	26.8

5 Conclusions

Following are the conclusions that are drawn from the experimental study carried out:

i. DIC technique helped in obtaining the quantitative results throughout the experimental study for the full front surface without having any contact with the test specimen. Clearly, this method was found to be advantageous in comparison to the conventional methods like Linear Variable Differential Transducer, (LVDT) which gives displacements only at the point of contact.

ii. Under a monotonic loading of 40 kN applied on the two-layered system, a percentage reduction of 26.8 in the maximum settlement was observed for reinforced layer system compared to unreinforced system. The percent increase in settlement for unreinforced and reinforced cases varied between 15.7-100% and 13.4-100% for incremental loading under applied loads up to 40 kN.

iii. The influence zone of settlements equal to 0.25% of width of the footing varied between 0.42 m to 0.55 m in reinforced case, and 0.68 m to 0.8m for unreinforced case, for the applied loads ranging between 5 kN and 40 kN.

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