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Large-Scale Direct Shear and Discrete Element Modelling Investigations of Ballast, Sub-Ballast, and Sleeper InterfaceCharacteristics in a Railway Track Structure

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Abstract. A typical railway track structure is composed of different layers of constituent materials. The resulting contact interface between these layers results in displacement discontinuities and largely influences the strength-deformation behavior of the system. In order to assess and quantify the interactions that take place at these interfaces, the present study conducts Discrete Element Analysis (DEM) of large-scale direct shear interface tests using Altair EDEM software. These simulations use the extensive laboratory investigations earlier performed by [1] for validation. The shear stress parameter of the ballast-sub-ballast, ballast-concrete sleeper, ballast-steel sleeper and ballast-geogrid are taken into consideration for this study. The contacts generated at the interfaces of different elements are also realized here. Since the contact interface behavior is largely influenced by the shape of the ballast, the number of contacts and the inherent discontinuities, therefore the calibration of the modelled ballast and sub-ballast particles is also done in terms of static angle of repose value and bulk density before the actual test simulation. The plots of shear stress vs horizontal displacement values are obtained by extracting and relating them using the time parameter. The EDEM simulation results for the test cases are found in agreement with the laboratory test results with the variation lying within the range of ±10%. The variation witnessed here may be because of the assumptions that are made during the simulation in order to reduce the computational time requirement.

Keywords: Interface, Displacement discontinuities, EDEM.

1. Introduction

Railway tracks are composed of different layers of constituent materials. The difference in inherent characteristics and behavior of these materials result in complex interactions which have a large-scale influence on the overall stability of the track structure. The present study aims to quantify these interactions using DEM simulations. The interactions between ballast, sub-ballast, sleepers, and geogrids have been considered for this study. Since ballast and sub-ballast are granular materials, it is not appropriate to treat them as continuous media. The Discrete Element Modelling technique which incorporates the influence of the discontinuities, shape, and size of the discrete granular particles, etc. overcomes this limitation of the conventional finite element analysis technique. On the contrary, for members like sleepers and geogrids, it is more relevant to model them as continuous geometries while analysing the interface interactions occurring in the railway structure. The Discrete Element Modelling (DEM) technique was initially developed for solving problems associated with rock mechanics [2]. A FORTRAN – code (BALL) later implemented this DEM and was used extensively by researchers as an aid to develop a general constitutive model for granular materials based on micromechanical considerations [3]. Later, similar to BALL, TRUBAL was developed for modelling the mechanical behavior using three-dimensional assemblies of spheres [4].

With the advancement of time, particles were modelled as a cluster of several bonded spheres which disintegrated upon load application thus representing particle breakage [5, 6]. Later, another method of simulating particle breakage was developed in which the particles which fulfilled a predefined failure criterion were replaced with an equivalent set of smaller particles. This approach was adopted by various researchers in their subsequent studies [7–9]. Recently, a fully coupled FEM-DEM analysis was carried out by different researchers to study the behavior of ballasted tracks and the reinforcements provided to improve them [10, 11]. These studies, though computationally more accurate require a large simulation time. Since the large-scale direct shear interface tests witness negligible sleeper and geogrid deformation as well as particle breakage owing to the absence of cyclic or impact loading conditions, the present study considers ballast and sub-ballast as rigid cluster of spheres which do not disintegrate during the simulation. In addition, as a practical measure, the sleepers and geogrids in this study are modelled as rigid geometry members neglecting minor deformations occurring in them to further save computation time.

The study is carried out in industry-leading Altair EDEM software version 2021 because of the availability of an extremely wide range of physics models preloaded into the same. The software provides an easy workflow through its GUI (Graphical User Interface), GEMM (Generic EDEM Material Model) database, and easily integrates the prepared CAD geometries.

2. Modelling Procedure

2.1 Creation of Particles and Setting up Models

The simulations were carried out by utilizing the data available from the extensive laboratory investigations carried out by [1]. The ballast particles were generated by fitting a cluster of spheres in the three-dimensional CAD geometry prepared from the available ballast images used during the laboratory tests. The scaled size of the CAD geometry was kept between 40 to 60 mm and clusters were generated by specifying 10x10, 15x15, 20x20, and 30x30 grid sizes. The sub-ballast particles were obtained by scaling down the ballast particle using a ¼ scale. The modeled particle samples are shown in Fig 1. The increase in grid size results in more accurate morphological representation but also causes a significant increase in computation time.

Hertz-Mindlin's non-slip contact model was used to define the interaction occurring at the contact points. The model principle is based on the research work of Mindlin. The model provides a reliable analytical explanation for the pressure as well as force acting in the normal direction. The normal force-displacement (N-d) correlation is non-linear in compliance with this law. The standard rolling friction model is used to represent the rolling friction existing between the particles and to account for the interlocking due to the presence of the angular particles.

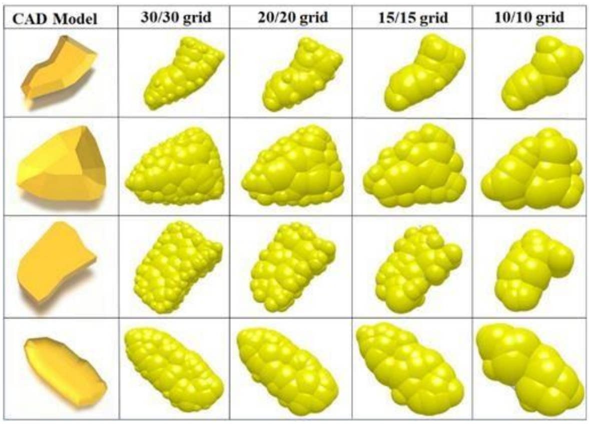


Fig 1. CAD model and generated cluster of spheres for particles

2.2 Calibration of Generated Particles

The morphological characteristics of the ballast and sub-ballast particles and the solid density assigned to them influence the number of particles that can be accommodated in the box, the number of contacts developed, etc. to a large extent. For checking the accuracy of the generated particles, calibration plays a vital role in EDEM. In the present study, to ensure that the simulated cluster of spheres truly represents the actual particles used during laboratory tests, the static angle of repose and the bulk density calibration was carried out. The static angle of repose obtained from lab and EDEM simulation are depicted in Fig 2 (a) and 2 (b) respectively. The particles obtained from the EDEM simulation were colored on the basis of their diameters. The variation is less than 1 % thus confirming the similarity. The bulk density of the ballast and sub-ballast used during laboratory investigations for completely filling the lower box of the large-scale direct shear test was reported to be 1672 and 1632 kg/m^3 respectively. The density sensor in DEM simulations showed a bulk density of 1674 and 1587 kg/m^3 for the modelled ballast and sub-ballast thus showing accurate bulk material behavior. Fig 2 (c) and 2 (d) present the density sensor value obtained from EDEM for ballast and sub-ballast.

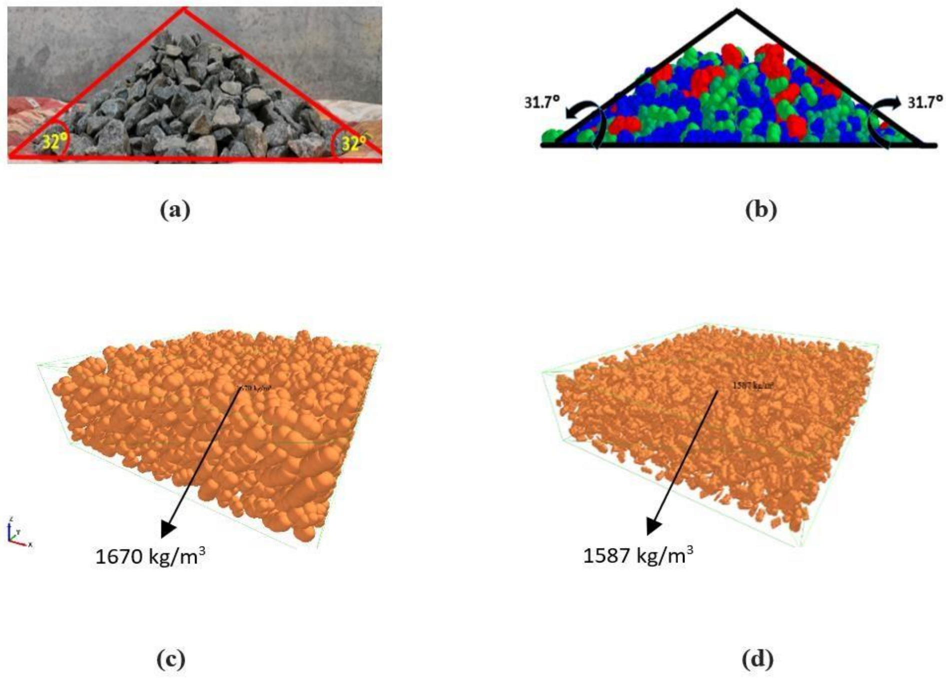


Fig 2. (a) Laboratory static angle of repose test **(b)** Static angle of repose test from EDEM **(c)** EDEM bulk density value for ballast **(d)** EDEM bulk density value for sub-ballast

2.3 Discrete Element Modelling of Interface Tests

For the simulation, two direct shear compartments, with the top faces open were created. Then, a factory was introduced that generated the particles inside the direct shear box which were later compacted by a polygon plate. The Poisson's ratio and shear modulus for both ballast and sub-ballast particles were taken as 0.25 and 10 MPa respectively. The concrete sleeper was assigned the material properties of standard concrete. The direct shear compartments, steel sleeper, and the geogrid were assigned the material properties of standard steel. The material properties are summarized in Table 1. The interaction parameters such as coefficient of restitution, coefficient of static friction and coefficient of rolling friction are summarized in Table 2. In the case of direct shear box, the steel material friction coefficients were set as 0.01 so that its influence on the test was negligible. The coefficient of restitution was kept the same as that of the standard steel.

Table 1 Material Properties

Material Properties	Ballast and Sub-ballast	Concrete	Steel
Poisson's ratio	0.25	0.2	0.28
Shear Modulus (Pa)	1×10^{7}	1×10^{10}	7.5×10^{10}

Table 2 Interaction parameters

Material Properties	Ballast-Ballast and Ballast-Sub-ballast	Ballast-Concrete	Ballast-Steel
Restitution coefficient	0.5	0.5	0.5
Static friction coefficient	0.7	0.5	0.4
Rolling friction coefficient	0.2	0.1	0.1

The geogrid was modelled using AutoCAD and later exported in EDEM as a geometry. The imported geometry and the meshed geogrid are shown in Fig 3 (a) and (b) respectively. After the particles were placed repeated iterations were carried out till the required density was achieved. The upper compartment was finally sheared at a rate of 2 mm/s and the results were obtained. Finally, the response was plotted by graphing the required parameters against time. The model setups are shown in Fig 4 (a) – (d).

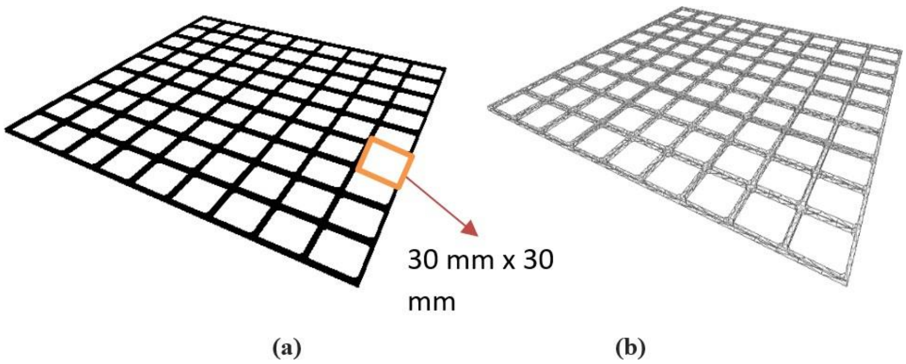


Fig 3. (a) AutoCAD geogrid model (**b)** Meshed geogrid in EDEM

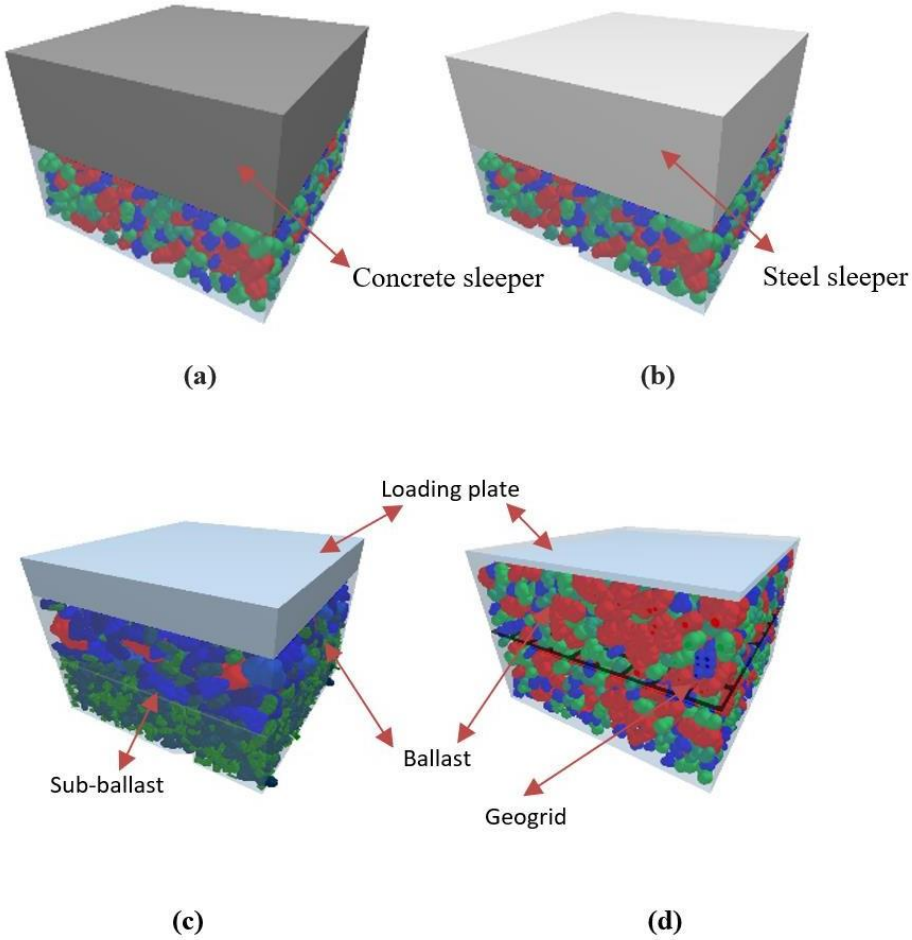


Fig 4. (a) Concrete sleeper-Ballast EDEM setup **(b)** Steel sleeper-Ballast EDEM setup **(c)** Ballast-Sub ballast EDEM setup **(d)** Ballast-Geogrid EDEM setup

The calculation of normal and tangential forces in EDEM is done on the basis of the contacts established between the different elements taken into consideration. These contacts are updated after each time step and are used as the basis for the calculation of contact forces to be used in the next time step. The contacts established for the concrete sleeper-ballast simulation at the initial and final stages of shearing are shown in Fig 5 (a) and (b) respectively. Similarly, the contacts for steel sleeper-ballast, ballast-sub ballast, and ballast-geogrid are shown in Fig 6 (a) and (b), Fig 7 (a) and (b) and Fig 8 (a) and (b) respectively.

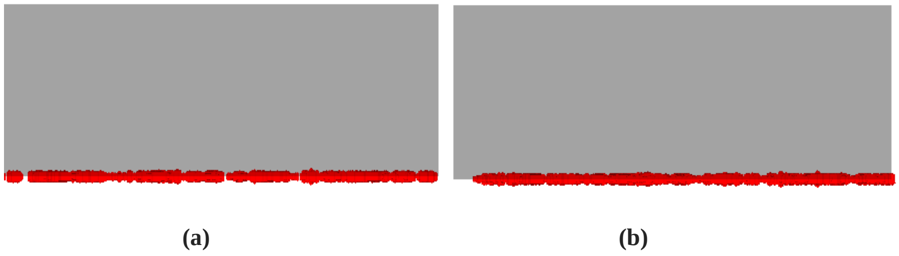


Fig 5. (a) Contacts between concrete sleeper-ballast before shearing **(b)** Contacts between concrete sleeper-ballast after shearing

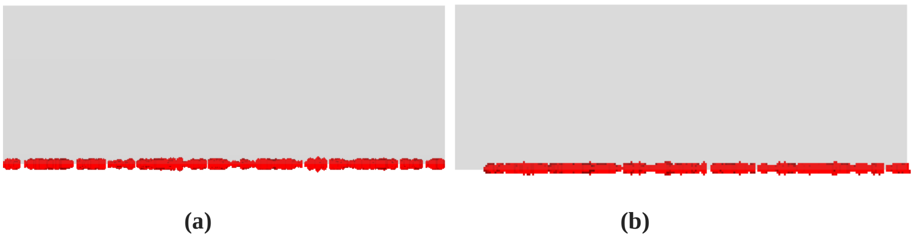


Fig 6. (a) Contacts between steel sleeper-ballast before shearing **(b)** Contacts between steel sleeper-ballast after shearing

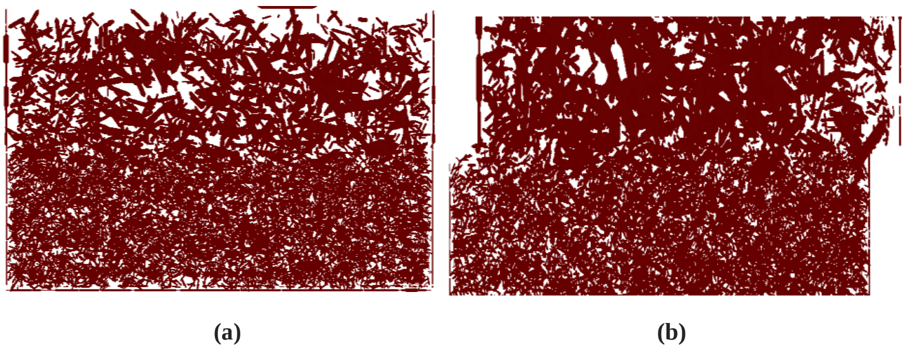
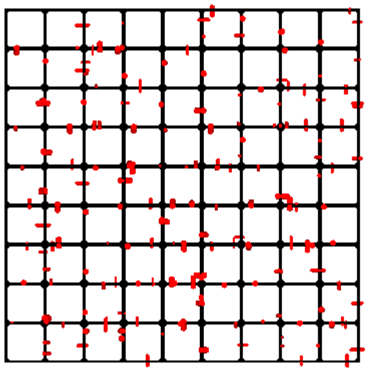
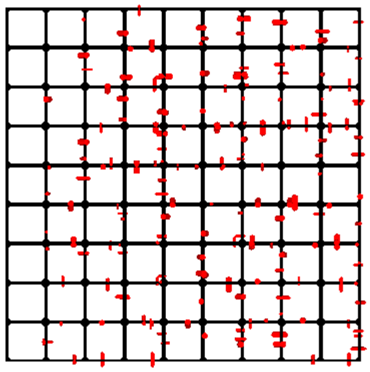


Fig 7. (a) Contacts between ballast-sub ballast before shearing **(b)** Contacts between ballast-sub ballast after shearing



(a)



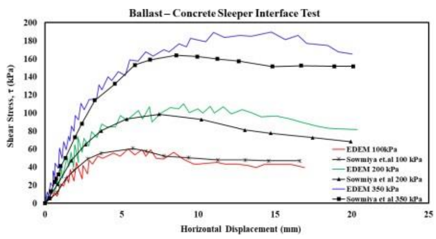
(b)

Fig 8. (a) Contacts between ballast-geogrid before shearing **(b)** Contacts between ballast-geogrid after shearing

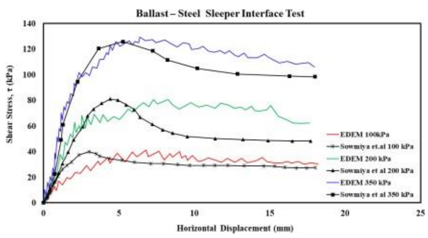
The established contacts of particles with the geometry elements reduced in number in the shearing direction with time because they lost contact with particles after moving out of the shear box. This can be observed in the above images. Thus, the observed behavior in EDEM is in agreement with the practical behavior of the interface tests.

3. Results and Discussions

The shear stress variation with respect to the horizontal displacement was obtained for all the cases by using the rate of displacement and the total time of the simulation. The graph results are shown in Fig 9 (a) to (d). The peak stress values corresponding to different normal stresses are then plotted in Fig 10 (a) to (d). The variation of EDEM peak stress from the lab peak stress values was finally found out and is summarized in Table 3.



(a)



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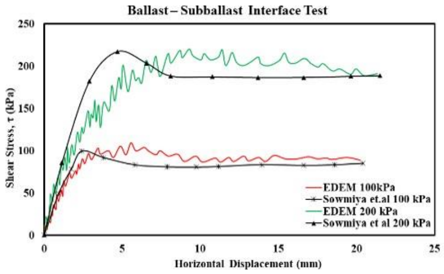

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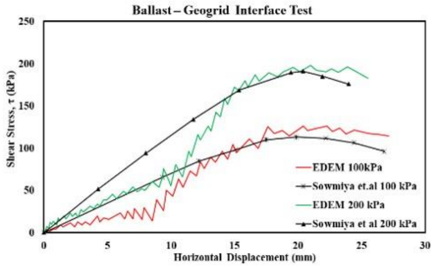
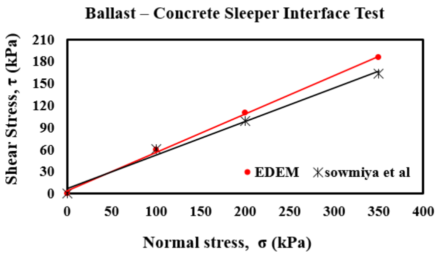
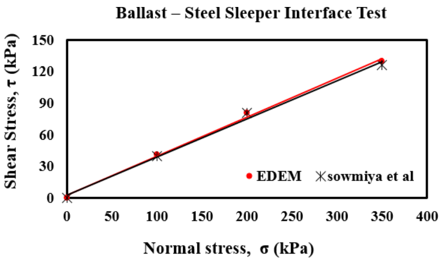


(d)

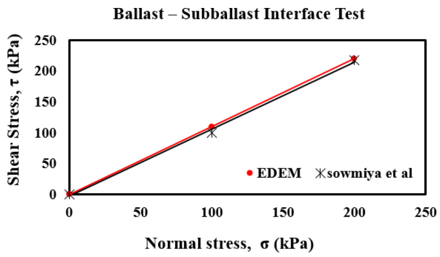
Fig 9. Horizontal displacement vs Shear stress plot for **(a)** Ballast-Concrete sleeper Interface **(b)** Ballast-Steel sleeper Interface **(c)** Ballast-Sub ballast Interface **(d)** Ballast-Geogrid Interface Test



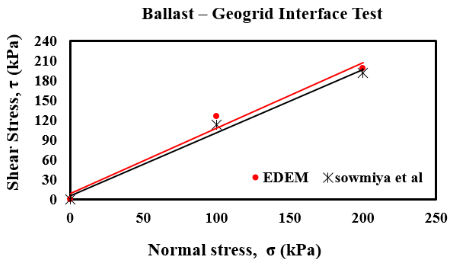
(a)



(b)



(c)



(d)

Fig 10. Normal Stress vs Shear stress plot for **(a)** Ballast-Concrete sleeper Interface **(b)** Ballast-Steel sleeper Interface **(c)** Ballast-Sub ballast Interface **(d)** Ballast-Geogrid Interface Test

Table 3 EDEM Peak stress variation from laboratory results (%)

Peak stress (kPa)	Ballast-Concrete Sleeper (%)	Ballast-Steel Sleeper (%)	Ballast- Sub ballast (%)	Ballast- Geogrid (%)
100	-0.971	3.315	9.598	9.280
200	9.485	-0.507	1.347	3.671
350	10.01826	2.834316	-	-

4. Conclusion

The EDEM peak stress values showed a maximum variation of about 10 % from the available lab data. Thus, the results were in agreement with the laboratory tests. The occurring variation might be because of the unavailability of actual material parameters such as solid density, shear modulus, Poisson's ratio, etc. In addition, slight variation could also be because of the rigid behavior consideration of sleepers and geogrid. The use of DEM analysis here helps in understanding the internal phenomena and interactions such as element forces and contact point variations that occur in granular media which is not possible in either laboratory investigations or FEM analysis. The only significant problem associated with this analysis technique is the computation time. Higher accuracy requirement results in an exponential rise in computational cost and thus adequate practical assumptions are needed before modelling and simulation.

5. Acknowledgement

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