CALIBRATION OF RAILWAY BALLAST DEM MODEL

Ákos Orosz, János P. Rádics, Kornél Tamás
Department of Machine and Product Design
Budapest University of Technology and Economics
Műegyetem rkp. 3., H-1111, Budapest, Hungary
E-mail: orosz.aakos@gmail.com

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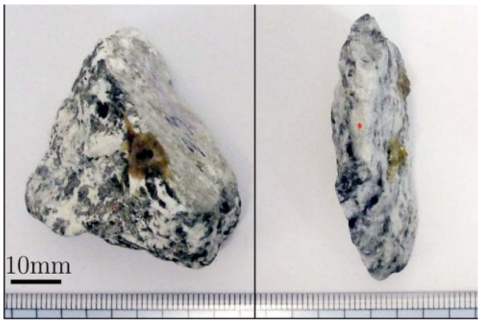
ABSTRACT

The ballast of the railway track is constantly changing due to dynamic forces of train traffic that results in the crushing of the rocks. The feasibility to simulate each particle makes the discrete element method (DEM) suitable for the task.
Different DEM particle models are introduced in our paper and the adequate one was chosen. This new method is based on crushable convex polyhedral elements and random shape generation via Voronoi tessellation and is implemented in the Yade DEM simulation software.
The particle geometry is validated via comparing the simplified shape of natural rough rocks and the randomly generated ones. A 3D scanner was used to digitize the natural rocks. The crushing behaviour is tested as well. The validation of interaction laws and the calibration of the micro parameters is necessary to create a DEM material model with a realistic behaviour. In the calibration process Hummel device is modelled, which provides well measurable parameters for comparing simulation and measurement results.

INTRODUCTION

In a limited number of cases, it is possible to model the railway track ballast as a continuum with the use of finite element method (Shahraki et al. 2015), however this approach does not give information about many aspects. Therefore a new approach should be utilised to simulate the railway track ballast behaviour more realistically.
In our research, the rocks of the ballast are classified into two groups based on their geometry: equant (Figure 1,a) and flat (Figure 1,b). It is well known that both of the shapes mentioned above have to be represented in the railway track ballast to endure the forces effectively. Moreover they have an optimal ratio, which is currently estimated by routine of practice. The determination of its exact value would provide many benefits.



0a) b)

Figure 1: a) Equant and b) Flat Rocks (Asahina and Taylor 2011)

Result of the dynamic forces of the periodical loads is the fragmentation of the rocks, which changes the ratio of the different geometry types. This has a great effect on the loadability of the aggregate. That is one of the reasons to perform the complete maintenance of the railway track. A main objective of our research is to investigate this phenomenon and to determine the period between maintenances more precisely through simulating the long term behaviour of the ballast.
The full maintenance process has different stages completed with different machines. The appropriate model and simulation of the railway track ballast can be used to improve efficiency of finding the optimal machine settings and tool geometries.
Instead of the continuum approach, there is a need to simulate each rock to achieve a realistic simulation, whereby the previous questions can be answered. It is also important to take efforts in the modelling of rock breakage, because crushing of particles is necessary to bring simulation data closer to experimental data (Eliaš 2014). This makes the discrete element method suitable for the task.
This paper represents a brief introduction of the discrete element method, choosing of a discrete element material model based on particle geometry and crushability aspects, the mechanical basics of this model, a solution for random geometry generation and validation of this technique. Also an approach is introduced for calibrating the model with the device used for the Hummel measurement.

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The Discrete Element Method

The discrete element method is a numerical technique, where the simulated material is made of particles (or elements), with independent motional degrees of freedom. Interactions can be created and erased between the elements (Bagi 2007). For this reason the behaviour of the volume modelled with discrete element method depends on the definition of the elements and interaction laws. The sum of these features is called the discrete element material model (or micromechanical properties). The micromechanical properties have direct effect on the element-level behaviour, which results in the measurable, macromechanical behaviour. The aim of the study is to reproduce the measurable characteristics of the aggregate which can be achieved with a proper material model.
The exact relation between micro- and macromechanical behaviour is missing in most cases, and the reasonable parameters can only be reached by the calibration of the material model. This is done by comparing the proper measurement with its simulation, and modifying the properties of the material model until its macromechanical behaviour reproduces the test with acceptable approximation. In our research the Hummel measurement device is used to calibrate the material model.

MATERIAL MODEL

The first difficulty of creating the model was the decision about the shape of the particles. The simplest solution is to create a volume made of spheres. This also gives an advantage in computational speed. However it is known that many type of aggregates such as sand – or in our case the railway track ballast –cannot be modelled properly with spheres because of the rolling contact surfaces versus the actual friction sliding of real particle surfaces (Lane et al. 2010).
To keep the advantages of spheres but to also be able to use model elements with more complex shape, the so called clumps are used. The clumps are made of spheres with rigid connections between them. Example is shown on Figure 2,a. (Coetzee and Nel 2014).
The clump particle is still smooth and is missing the sharp corners and edges. Particle approximation can be improved by reducing the element size of the clump particle, but the highly increasing computation time have to be accepted. Therefore an extensive effort was made to simulate the aggregate with polyhedral elements. An example of the shape of these particles is shown in Figure 2,b .
There are different programs e.g. Grains3D (Wachs et al. 2012), BLOKS3D (Huang and Tutumler 2011) for handling polyhedral particles, but these are hardly accessible softwares and there is no opportunity to make modifications. Jan Eliaš also created a polyhedral particle model (Eliaš 2014), which features the possibility of crushing particles with low computation need and is implemented in the Yade open source DEM software. The available source code creates the chance to make modifications and improvements in the embedded material models, which is a significant benefit. The built-in crushing effect and the possibility of improvements are the main reasons that the crushable polyhedral material model (Eliaš 2014) was selected for further studies.

a) b)

Figure 2: Examples for Modelling Rocks with Clumps (Coetzee and Nel 2014), and Polyhedra (Huang and Tutumler 2011)

Creating polyhedral shaped elements

There are several ways to create the shape of the polyhedra. The simplest way is to create them manually, estimating the geometry of rocks with the desired precision. Advanced way is using a 3D scanner and simplifications (such method is described later in the validation section), or even automatized image processing technology has promising results (Huang and Tutumler 2011). However, what is common in these methods is that only a limited number of rocks can be processed and then reproduced. There is a need to extend the productivity of the creation process and to raise the variability of the particles. There is no pattern in the shape of the natural particles. Therefore it is feasible to generate the shapes randomly without remarkable deviation from the mined rocks. Such a solution is implemented in the chosen material model, which was inspired by Asahina and Bolander (2011) and relies on the Voronoi method (Figure 3). In 2D it is based on random points created in an area with a defined minimal distance. Then polygons are created by finding the union of apothems of the lines between the closest nuclei pairs.

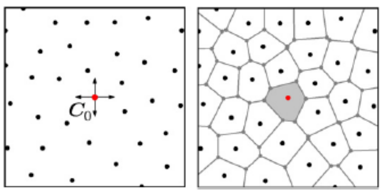

Figure 3: Voronoi Method (Eliaš 2014)

Interactions between the elements

The material of the elements is ideally rigid. The effect of plasticity is modelled within the definition of interactions (repulsive force). The model is non-cohesive. Normal and shear force is included, which arise when the polyhedrons come into contact.
The forces act in the centroid of mass of the overlapping volume. The magnitude of normal force between two particles is obtained from the magnitude of their overlapping volume by multiplying it with the factor named normal volumetric stiffness.

The direction of the normal force is perpendicular to the plane fitted by the least square method on the intersecting lines of the particle shells.
The shear force (friction) is proportional to the mutual movements and rotations of the elements. Its maximum value is regulated by the Coulomb friction model (Equation 1, where $|\mathbf{F_s}|$ is the magnitude of shear force, $|\mathbf{F_n}|$ stands for the magnitude of normal force, and φ is the internal friction angle).

$$|\boldsymbol{F_s}| \leq |\boldsymbol{F_n}| tan\varphi \qquad (1)$$

Many material models do not include velocity based damping such as the mentioned polyhedral material model (Eliaš 2014) or the model by D'Addetta et al. (2001) to dissipate kinetic energy, so it is worth considering to use an artificial damping. This numeric damping decreases the forces which increase the particle velocities and vice versa by a factor λ_d: 0-1 (Šmilauer et al. 2015).

Crushing behaviour

A further aim of the research is to simulate the fragmentation process of the rocks in the railway ballast, which leads to a great decrease in loadability. This can be obtained with a proper crushing model. (Eliaš 2014) also has the conclusion that the modelling of crushing is necessary to get a realistic behaviour of the simulated aggregate.
In the simulation crushing occurs, when the von Mises stress in the polyhedral element exceeds the so-called size-dependent strength (f_t). Using the von Mises stress is a simplification, as it is best applies to isotropic and ductile metals. However, this simplicity is an advance in discrete element modelling, as the aim is always to find the simplest material model which reproduces the aggregate (macro) behaviour with the proper micromechanical parameters.
According to Lobo-Guerrero and Vallejo (2005) the strength of the rock is dependent on its size. This phenomena is implemented in the model and is represented by Equation 2. Where f_0 is a material parameter and r_{eq} is the radius of the sphere with same volume as the polyhedra.

$$f_t = \frac{f_0}{r_{eq}} \qquad (2)$$

When crushing occurs, rocks are intentionally split into 4 pieces (Figure 4). The two mutually perpendicular cutting planes are perpendicular to the plane defined by σ_I and σ_{III} principal axes and form angles of π/4 with the planes defined by σ_I-σ_{II} and σ_{III}-σ_{II} axes.

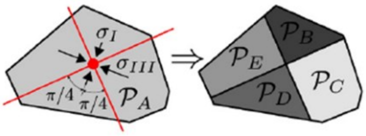

Figure 4: Crushing of Rocks (Eliaš 2014)

VALIDATION

The investigation of the properties of the polyhedral material model (Eliaš 2014) lead to a decision to use it to simulate the behaviour of railway ballast.
The first step of the process is the validation of the material model to determine if it is appropriate for the task. Two uncommon features of the selected material model are the particle geometry generation with Voronoi method and the crushing effect. The validation of these is performed by examining the particles individually. If the validation is successful, the next step is the calibration of the material parameters with the use of particle aggregate.

Particle Shape validation

To validate the randomly created polyhedral particle shapes, the generated ones were compared with the natural ones. A 3D laser scanner (NextEngine) was used to digitize the natural rock shapes. This resulted in a very complex surface geometry, which was simplified in a 3D CAD software. Simple planes were fitted on the rough surfaces using the least-square method (Figure 5). The planes were trimmed by the penetration lines. Between the manually created shapes and the randomly generated ones a high level of similarity was well observable. The average number of sides, vertices, as well as the areas of the sides and magnitudes of angles was equal with a good approximation.
A substantial simplification of the random generation is that it always creates convex polyhedra. It is easy to find concave areas on the surface of crushed rocks, which are possible stress concentration spots. The magnitude of the stress concentration effect depends on the size and shape of these concave areas and has a significant influence on the strength of the rocks.
Despite the existence of stress concentration effect at concave polyhedra, convex ones are accepted. The reason is that their strength is adjusted with the size-dependent strength material parameter and their efficient generation is also possible with Voronoi tessellation. The geometry of the crushed rocks can be estimated by the randomly generated ones relying on the Voronoi method.

Figure 5: Steps of Rock Shape Digitalizing with 3D Scanner

Crushing test of a simple rock particle

An individual polyhedron has to crush into 4 pieces, when the von Mises stress exceeds its size-dependent strength. It occurs when the load on an element reaches a critical magnitude. The crush can occur multiple times, however, the fragmentation has to stop beside the same load, as the created new elements have greater strength because of their smaller size.

The following stages can be observed in the process (Figure 6):

1. Beginning of the load: the loading plate has not reached the rock yet.
2. The plate reaches the rock, the force starts rising.
3. Crush of the rock: when the von Mises stress exceeds the strength of the rock, it breaks into 4 pieces. After the crush, the normal force drops down to zero as the contact between the rocks and the plate interrupts.
4. Moving, sliding of the rocks. When they reach their final place, the force starts rising steeply again.
5. A second break occurs. In this case the force does not reach zero, as the contact persists.
6. Reaching the maximum force and beginning of unloading.

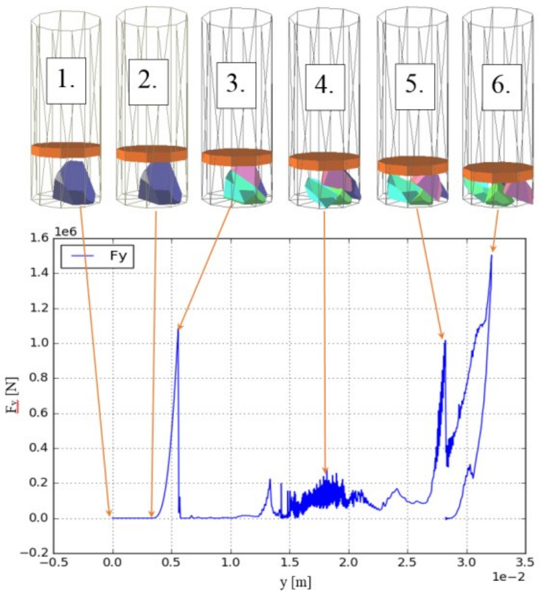

Figure 6: Loading Process of a Rock (F_y: Normal Force [N], y: Horizontal Displacement of the Plate Downwards [m])

The polyhedron breaks into 4 fragments at every crush as expected. This is certainly not a natural behaviour, however it is not an issue, because the research is more intended to create the proper model of the whole aggregate. Only the number of crushes and the further behaviour of the aggregate is important.

Despite the fact that splitting intentionally into 4 pieces is certainly not a natural behaviour, the model can be used in further applications to analyse the behaviour of an aggregate.

CALIBRATION OF THE MATERIAL MODEL

To create the model of the railway ballast with approximately the same macromechanical parameters as the natural aggregate, the proper setting of micromechanical parameters is needed. It can be obtained by calibration. During the calibration process, the simulation of a properly chosen measurement is compared to the corresponding experimental data. The adequate measurement process applies similar loads as the forces acting in natural aggregate, so the appropriate material parameters can be set. In our case, the measurement device used in the Hummel procedure is applied for the calibration process, where crushing occurs as the effect of quasi-static loads.

Hummel Device

The Hummel procedure (Hungarian Standards Institution 1983) gives information about the static loadability of construction aggregates. The standard describes the properties of the tested material, the geometry of the tool (Figure 7) and the process of loading progress. Particles of the aggregate are crushing during the test. The Hummel process enables the determination of force-displacement and particle size distribution curves under different peak loads for the tested aggregate. Tested material parameters have to be changed in order to be able to perform the test, as the 31.5/50 mm railway ballast rocks are too big for the Hummel device. Therefore, the laboratory tests and the DEM simulation is performed with 22/32 mm rocks. In the further research, grain size sensitivity simulations and measurements will be performed with smaller rocks in order to get information about the particle size dependency of the aggregate behaviour. The parameters of the 31.5/50 mm railway ballast rocks can be set by extrapolation.

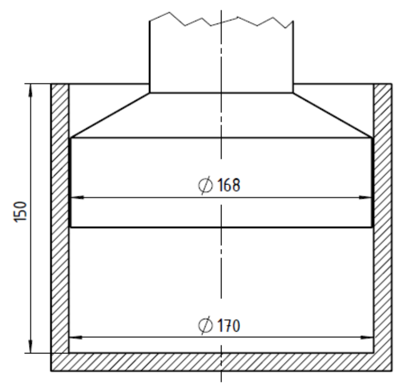

Figure 7: Hummel Device (Hungarian Standards Institution 1983)

Creating the Geometry

To obtain the optimal processing speed besides the proper geometry, the tube was approximated with a regular decagonal prism, created from triangular facets. The polyhedral particles were generated in this volume with the desired geometry (equant or flat). In the first stage of the research, equant elements were modelled. The randomly generated polyhedra are created in a cuboid volume (Figure 7/a.) inside the prism. To create a dense pack of polyhedra on the bottom of the tube model, gravitational deposition was used (Figure 8.). Gravity load is applied in the simulation and the elements fall down freely to the bottom of the prism. The height of the produced dense pack is bigger than the Hummel device has, so the elements with centroid higher than 150 mm were removed (Figure 9).

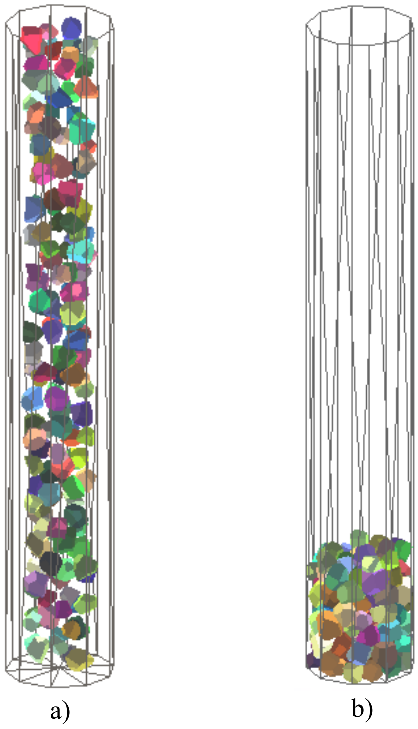

Figure 8: a) Created Polyhedra; b) the Result of Gravitational Deposition

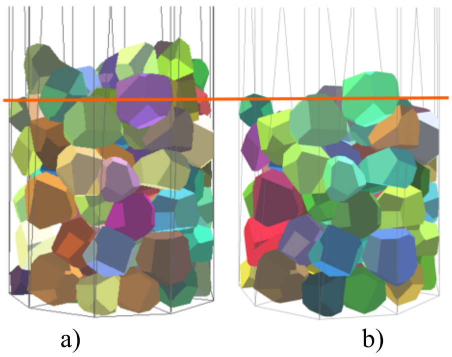

Figure 9: a) The Polyhedra Pack Before; b) and After the Removal Process

Applying the Load

The initial and the maximum load state of the simulation can be observed on Figure 10. The load is applied through the top plate which is also a polyhedron type element with disabled crushing and has a special shape to fit in the tube. The plate moves down with constant velocity, thus the magnitude of the force on the plate is displacement driven, which is constantly measured. When the pre-defined maximum force is reached, the direction of the plate movement changes and the unloading process begins. The simulation ends at the moment, when the normal force reaches zero. Data are saved in text format.

The force-displacement curve of a typical simulation is represented on Figure 11. It corresponds to the theoretical assumptions stated in the followings. In the first part of the loading process the normal force raises slowly. In this session the elements can move easily because of the high porosity of the aggregate. As the porosity decreases, the elements have less space to move, the curve becomes steeper, and also the rate of crushing events increases. In the unloading phase, the normal force drops down to zero. Crushing can cause peak forces, which eliminate in a few timesteps and have no significant influence on the loading characteristics. Therefore it is now assumed that they can be ignored, but further investigations will be done.

Considering that the simulation used preliminary material parameters, the results are acceptable and the material model and calibration method can be utilized in the further research.

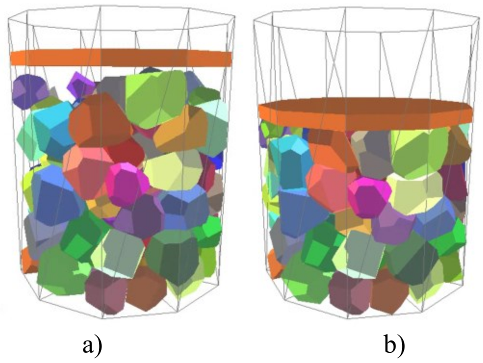

Figure 10: a) The Device Before Beginning of Load; b) at Maximum Load

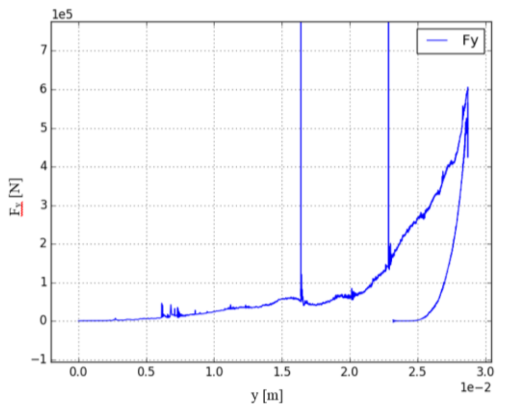

Figure 11: Normal Force (Fy [N])-Displacement (y [m]) Graph of the Hummel Device

CONCLUSIONS

In this paper an ongoing research for modelling the railway ballast is introduced. Different DEM material models were investigated, and the one featuring randomly generated convex crushable polyhedral elements was chosen. The mechanical basics of the model, random element generation via Voronoi tesselation and a crushing behaviour was investigated and validated. A calibration method was created that uses the Hummel device.

In the studied discrete element material model the geometry of the polyhedral elements approximates the shape of the rocks sufficiently, the mechanical model reproduces the behaviour of the rock aggregate, and the crushing works. The discrete element method is capable to simulate the railway ballast.

The gravitational deposition executes with the assigned micro parameters in the created geometry. The characteristics of the load-displacement curve is the same as theoretically expected. In some cases, peak forces occur during breakage, but they have no significant effect on the nature of the curve. In further studies they will be investigated in detail.

The model of the measurement based on the Hummel device is proper, so the calibration of the discrete element material model can be performed in the further stages of the research.

FURTHER RESEARCH

The next step is the static calibration of the material model. It is performed by processing the measurement data, and running a series of simulations of the Hummel device measurement with different material parameters to find the parameter combination that reproduces the experimental data with the best approximation.

A calibrated and validated material model can be used to simulate the behaviour of railway ballast and answer the technical questions discussed in the introduction.

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REFERENCES

Asahina, D. and J.E. Bolander. 2011. "Voronoi-based discretizations for fracture analysis of particulate materials". *Powder Technology* 213, 92–99.

Asahina D. and M.A. Taylor. 2011. "Geometry of irregular particles: Direct surface measurements by 3-D laser scanner". *Powder Technology* 213, 70-78.

Bagi, K. 2007. *A diszkrét elemek módszere*. BME Department of Structural Mechanics, Budapest, 5-12.

Coetzee, C.J. and R.G. Nel. 2014. "Calibration of discrete element properties and the modelling of packed rock beds". *Powder Technology* 264, 332–342.

D'Addetta, G.A.; F. Kun; E. Ramm and H.J. Herrmann. 2001. "From solids to granulates - Discrete element simulations of fracture and fragmentation processes in geomaterials". In *Continuous and Discontinuous Modelling of Cohesive-Frictional Materials. 2001*, Vermeer, P.A.; S. Diebels; W. Ehlers; H.J. Herrmann; S. Luding and E. Ramm. Berlin Heidelberg 231-258.

Eliáš, J. 2014. "Simulation of railway ballast using crushable polyhedral particles". *Powder Technology* 264, 458–465.

Huang, H. and E. Tutumluer. 2011, "Discrete Element Modeling for fouled railroad ballast". *Construction and Building Materials* 25, 3306–3312.

Lane, J.E.; P.T. Metzger and R.A. Wilkinson. 2010 "A Review of Discrete Element Method (DEM) Particle Shapes and Size Distributions for Lunar Soil" *NASA/TM* 216-257.

Lobo-Guerrero, S. and L.E. Vallejo. 2005. "Crushing a weak granular material: experimental numerical analyses". *Geotechnique* 55, No.3 245-249.

Hungarian Standards Institution. 1983. *Building rock materials. Strength testing of aggregates. Hummel test (MSZ 18287-3:1983).*

Shahraki, M; C. Warnakulasooriya and K.J. Witt. 2015. "Numerical study of transition zone between ballasted and ballastless railway track". *Transportation Geotechnics* 3, 58-67.

Šmilauer, V. et al. 2015. "Yade Documentation 2nd ed." In *The Yade Project* (http://yade-dem.org/doc/)

Wachs, A.; L. Girolami; G. Vinay and G. Ferrer. 2012. "Grains3D, a flexible DEM approach for particles of arbitrary convex shape — Part I: Numerical model and validations" *Powder Technology* 224 374–389.

AUTHOR BIOGRAPHIES

ÁKOS OROSZ was born in Hódmezővásárhely, Hungary. He is doing his mechanical engineering MSc studies at the Budapest University of Technology and Economics, where he received his BSc degree in 2016. He is also a member of a research group in the field of discrete element modelling. His e-mail address is: orosz.aakos@gmail.com and his web-page can be found at http://gt3.bme.hu/oroszakos.

JÁNOS P. RÁDICS is an assistant professor at Budapest University of Technology and Economics where he received his MSc degree. He completed his PhD degree at Szent István University, Gödöllő. His main research is simulation of soil respiration after different tillage methods, and he also takes part in the DEM simulation research group of the department. His e-mail address is: radics.janos@gt3.bme.hu and his web-page can be found at http://gt3.bme.hu/radics.

KORNÉL TAMÁS is an assistant professor at Budapest University of Technology and Economics where he received his MSc degree and then completed his PhD degree. His professional field is the modelling of granular materials with the use of discrete element method (DEM). His e-mail address is: tamas.kornel@gt3.bme.hu and his web-page can be found at http://gt3.bme.hu/tamaskornel.