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VEHICLE AS A KEY FACTOR IN TRANSPORTATION

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PREDGOVOR

Fakultet inženjerskih nauka u Kragujevcu (ranije Mašinski fakultet) tradicionalno u oktobru održava skupove istraživača i naučnih radnika koji proučavaju motorna vozila, motore i drumski saobraćaj. Od 1979. do 2004 godine je održano trinaest Simpozijuma MVM koji su 2006 godine prerasli u internacionalni Kongres. Od tada je održano pet Kongresa MVM a ovog meseca, oktobra 2016. godine, Fakultet inženjerskih nauka Univerziteta u Kragujevcu organizuje šesti Internacionalni Kongres MVM.

Za VI Kongres MVM- 2016 je prijavljen veći broj naučnih radova iz zemlje i inostranstva. Kongres je tradicionalno podržan od Ministarstva za prosvetu, nauku i tehnološki razvoj Republike Srbije, kao i od Agencije za bezbednost saobraćaja i velikog broja prijatelja i saradnika iz delatnosti vezanih za vozila i drumski saobraćaj.

Moto Kongresa „MVM2016“ je „Vozilo kao ključni faktor u transportu“. Radovi istraživača i naučnih radnika iz oblasti motornih vozila, motora i drumskog saobraćaja koji su publikovani na Kongresu „MVM2016“ i ovoga puta su pokazali značaj istraživanja u oblasti vozila, motora i drumskog saobraćaja.

Razvoj, proizvodnja i eksploatacija vozila nalaze se dugi niz godina u žiži interesovanja velikog broja ljudi širom sveta. Unapređenje bilo koje delatnosti koja je u vezi sa unapređenjem proizvodnje i eksploatacije vozila predstavlja doprinos poboljšanju uslova života svih živih bića.

Pred vozilima se danas postavljaju vrlo strogi zahtevi u pogledu tehničkih i ekoloških karakteristika. Vozila koja se danas proizvode, zahvaljujući prvenstveno radu velikog broja istraživača i naučnika, imaju svakim danom sve bolje eksploataciono-tehničke karakteristike.

Vozila, kao multi-disciplinarni objekat razvoja i istraživanja sa jedne strane, i kao potreba sa druge, uvek su aktuelna za razvoj i ulaganja. Vozila su sredstva koja su u službi čoveka pri najrazličitijim delatnostima. Zato je i razumljivo da su teme naučnih i stručnih radova, koje se obrađuju u okviru Kongresa MVM 2016 sve raznovrsnije i da se okviri istraživačkog i naučnog rada u ovoj oblasti sve više šire.

U Kragujevcu,
oktobar, 2016. godine

Naučni i organizacioni odbor
Kongresa MVM2016

FOREWORD

In October, the Faculty of Engineering from Kragujevac (former Faculty of Mechanical Engineering) traditionally holds gatherings of researchers and academics who study motor vehicles, engines and road traffic. From 1979 to 2004, thirteen MVM Symposiums have been held and they grew into an International Congress MVM in 2006. Since then, five MVM Congresses have been held and this month, in October 2016, the Faculty of Engineering of the University of Kragujevac organizes the sixth International Congress MVM.

A large number of scientific papers from the country and abroad were submitted to the sixth Congress “MVM2016”. Congress is traditionally supported by the Ministry of education, science and technological development of the Republic of Serbia, as well as by the Road traffic safety agency and by a large number of friends and associates from activities related to vehicles and road traffic.

The motto of the Congress "MVM2016" is "Vehicle as a key factor in transportation". The papers of the researchers and the academics from the field of motor vehicles, motors and road traffic, published at the Congress "MVM2016", have shown this time the importance of research in the field of vehicles, motors and road traffic.

Development, production and exploitation of vehicles are for many years in the spotlight of a large number of people around the world. Promotion of any activity that is related to improvement of production and exploitation of vehicles represents a contribution to improving the conditions of life of all living beings.

Very strict requirements are set in front of vehicles today in terms of technical and environmental characteristics. Vehicles that are produced today have better and better exploitation-technical characteristics, primarily due to the efforts of many researchers and scientists.

Vehicles, as multi-disciplinary objects of research and development on the one hand, and as necessities on the other, are always valid for development and investment. Vehicles are assets that are at the service of man for various activities. Therefore, it is understandable that the topics of scientific and professional papers, presented in the framework of the Congress “MVM2016”, are more and more diversified and that the frameworks of research and scientific work in this area are increasingly wider.

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NUMERICAL SIMULATIONS FOR ADDRESSING FLAWS IN THE FREIGHT WAGON DESIGN, ACHIEVING GOAL OF INCREASED EXPLOITATION FUNCTIONALITY

ABSTRACT: In this paper, the problem of deposition of granular material during unloading of freight wagon is addressed. The problem occurs as a result of design flaws, in particular insufficient angles of slopes. On these tilted surfaces certain amount of granular materials remains after the wagon is emptied which increases unloading time and operation costs. In order to analyze unloading process, numerical simulations which utilize linking of Finite Element Method (FEM) and Smoothed Particle Hydrodynamics (SPH) are used. Granular material is modelled with meshless SPH method, while wagon geometry is modelled with FEM. This allows engineers insight into significance of material properties and contact parameters which governs interaction between wagon and granular material. Numerical simulations result show that slight decrease of friction coefficient removes deposition. To achieve this on existing wagons, coating of contact surfaces is proposed. This is the most practical solution considering number of wagons that are already constructed. The same methodology can be implemented while designing new wagons. Smooth interaction of granular materials with wagon surfaces can be ensured during design phase, thus removing a need for subsequent surface treatment.

KEYWORDS: Freight Wagon, Granular Materials, Finite Element Method, Smoothed Particle Hydrodynamics

INTRODUCTION

Since the invention of the locomotive in the late 18th century by James Watt, railroads have been used for fast and cheap transportation of materials and goods [3]. Granular materials are one of the most manipulated matters in engineering and are transported by special freight wagons. Speed of freight trains is limited by the great weight of wagons and cargo as well as a high centre of gravity, which increases chance of derailing in short radius curves [13]. Because of this, engineers are focused on designing wagon boxes which can hold most material, while keeping centre of gravity as low as possible. This practice results in wagons which have great characteristics on paper, but in exploitation they cause problems originating from their flawed design: deposition of granular material on box slopes during unloading. If the deposited material remained in wagon, effective capacity of wagon would be

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reduced, while the energy consumption for transportation of the same amount of material would be increased, so station workers need to manually remove deposited material. This is tiresome and potentially dangerous process, which increases unloading time and operation costs. Numerical methods have been used to analyse hazardous working conditions [11,12], but it would be better if the wagon unloading does not require additional manual labour. Therefore, engineers need to think about functionality of unloading mechanism and wagon shape as well. Numerical simulations have become essential step in designing new wagons [1]. Finite Element Method (FEM) is used to simulate the wagon response to different loading condition, thus reducing design time and improving overall wagon characteristics [9]. On the other hand, FEM is not adequate for modelling of granular materials due to large deformations that occur within granular materials, so mesh-free method is better suited. In this paper coupling of Smoothed Particle Hydrodynamics (SPH) and FEM is presented [2]. This coupling gives unique perspective on granular material behaviour during unloading process and represents state of the art in numerical methods implementation for wagon design. With this methodology, engineers can test wagon functionality with realistic load modelling, which was previously impossible with standard FEM analysis.

SPH IN SOLID MECHAINCS

Smoothed Particle Hydrodynamics (SPH) is mesh-free numerical method based on continuum mechanics [7]. Originally created for solving astrophysical problems [4,8] it's applications were later extended into computational fluid dynamics [10] and solid mechanics [6]. In this paper, SPH with material strength is used to simulate large deformations in granular materials. SPH is convenient for granular material simulation because it uses discretization of continua into pseudo-particles [7]. Each SPH particle is similar to an element in FEM method, but there are no common nodes between them. These particles can have different neighbours throughout analysis which enables better handling of large deformations. Downside is that mesh-free methods require frequent searches for neighbouring particles [6]. To solve conservation laws of continuum mechanics in SPH method two principles are used: kernel approximation and particle approximation [7].

Kernel approximation

The conservation laws of continuum mechanics are in form of partial differential equations which can be transformed into integral equations using interpolation function that gives "kernel estimate" of the field variables at point. Exact value of function $f(\mathbf{x})$ in integral form is given with (1)

$$f(\mathbf{x}) = \int_{\Omega} f(\mathbf{x}')\delta(\mathbf{x}-\mathbf{x}')d\mathbf{x}', \tag{1}$$

where $f(\mathbf{x})$ is a function of position vector **x** defined in the domain Ω and Dirac delta measure is given with (2)

$$\delta(\mathbf{x}-\mathbf{x}') = \begin{cases} 1 & \mathbf{x}=\mathbf{x}' \\ 0 & \mathbf{x}\neq\mathbf{x}' \end{cases}. \tag{2}$$

Replacing with $\delta(\mathbf{x}-\mathbf{x}')$ with kernel function $W(|\mathbf{x}-\mathbf{x}'|,h)$, where *h* is the smoothing length, gives us kernel approximation of function $f(\mathbf{x})$ given with (3)

$$\langle f(\mathbf{x})\rangle = \int_{\Omega} f(\mathbf{x}')W(|\mathbf{x}-\mathbf{x}'|,h)d\mathbf{x}'. \tag{3}$$

Particle approximation

Another important aspect of SPH is particle approximation. Integral form given in equation (3) is not practical for numerical implementation because analyzed continuum is divided into finite number of particles which carry individual mass and occupy individual space. Continuous integral representations given with (3) can be converted to discrete forms of summation over all particles within support domain defined by smoothing length *h*. If the infinitesimal volume $d\mathbf{x}'$ from equation (3) is replaced by finite volume of the particle ΔV_j (where particle mass m_j and particle density ρ_j can be used to define finite volume as $\Delta V_j = m_j/\rho_j$) and if the summation of all particles within support domain is implemented in equation (3) we get discredited particle approximation of function $f(\mathbf{x})$ for particle *i* given with (4)

$$\left\langle f(\mathbf{x}_i)\right\rangle \cong \sum_{j=1}^{NNP} f(\mathbf{x}_j) W\left(\left|\mathbf{x}_i-\mathbf{x}_j\right|,h\right) dV_j = \sum_{j=1}^{NNP} \frac{m_j}{\rho_j} f(\mathbf{x}_j) W\left(\left|\mathbf{x}_i-\mathbf{x}_j\right|,h\right). \tag{4}$$

Conservation laws

Conservation of mass in continuum mechanics is defined by equation (5)

$$\frac{d\rho}{dt} = -\rho\nabla\mathbf{v} = -\rho\frac{\partial v^{\beta}}{\partial x^{\beta}}, \tag{5}$$

where $\mathbf{v}$ is velocity vector. Kernel approximation of equation (4) gives (6)

$$\left\langle \frac{d\rho}{dt}\right\rangle = -\int_{\Omega} W\left(\left|\mathbf{x}-\mathbf{x}'\right|,h\right)\frac{d\rho'}{dt} d\mathbf{x}'. \tag{6}$$

Particle approximation of conservation of mass for particle *i* with some rearranging gives (7)

$$\left\langle \frac{d\rho_i}{dt}\right\rangle = \rho_i \sum_{j=1}^{NNP} \frac{m_j}{\rho_j}\left(v_i^{\beta} - v_j^{\beta}\right)\frac{\partial W\left(\left|x_i - x_j\right|,h\right)}{\partial x_i^{\beta}}. \tag{7}$$

Conservation of momentum in continuum mechanics is defined by equation (8)

$$\frac{dv^{\alpha}}{dt} = \frac{1}{\rho}\frac{\partial \sigma^{\alpha\beta}}{\partial x^{\beta}}. \tag{8}$$

Using kernel and particle approximation on equation (8) we get (9)

$$\left\langle \frac{dv_i^{\alpha}}{dt}\right\rangle = \sum_{j=1}^{NNP} m_j \left(\frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{\sigma_i^{\alpha\beta}}{\rho_j^2}\right)\frac{\partial W\left(\left|x_i - x_j\right|,h\right)}{\partial x_i^{\beta}}. \tag{9}$$

Conservation of energy in continuum mechanics is defined by equation (10)

$$\frac{dE}{dt} = \frac{\sigma^{\alpha\beta}}{\rho}\frac{\partial v^{\alpha}}{\partial x^{\beta}}. \tag{10}$$

Using kernel and particle approximation on equation (10) we get (11)

$$\left\langle \frac{dE_i}{dt}\right\rangle = \frac{\sigma_i^{\alpha\beta}}{\rho_i^2}\sum_{j=1}^{NNP} \frac{m_j}{\rho_j}\left(v_i^{\alpha} - v_j^{\alpha}\right)\frac{\partial W\left(\left|x_i - x_j\right|,h\right)}{\partial x_i^{\beta}}. \tag{11}$$

GENERALIZED CAP MATERIAL MODEL FOR GRANULAR MATERIALS

Generalized cap model represents modification of Drucker-Prager model, which is one of the most used elasto-plastic material models in soil mechanics [5]. Failure surface, which divides elastic and plastic regions in principal stress space for Drucker-Prager model is streight cone, while for generalized cap model it's curved cone which is more realistic. In $J_{2D} - I_1$ space this curve is defined as:

$$f = \sqrt{J_{2D}} - k - \theta I_1 + \gamma e^{-B_1 I_1}, \tag{12}$$

where I_1 represent first invariant of stress, J_{2D} is the second invariant of deviatoric stress and k,θ,γ,B_1 are material constants [4]. Granular materials also yield under pressure and therefore have another elliptical plastic surface (called cap surface) which is defined by equation:

$$f_c = \left(I_1 - L\right)^2 + R^2\left(J_{2D} - B^2\right) = 0\,, \tag{13}$$

where *L*, *R*, *B* are material constants. Intersection of cap surface with failure surface is denoted with V, while intersection of cap surface with I_1 axis is given with $X = RB + L$ (Fig 1).

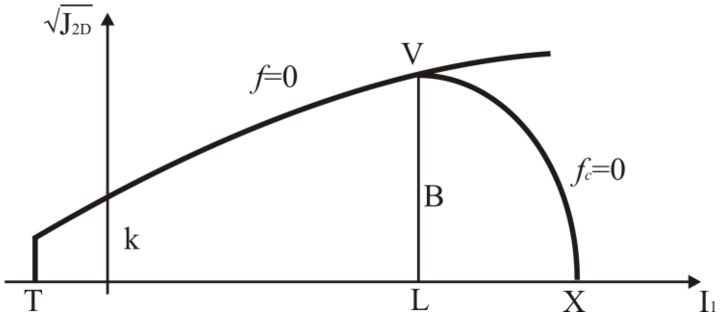

Figure 1 *Generalized cap model in* $J_{2D} - I_1$ *space*

Granular materials have very limited or no tensile strength at all [4], which is represented on Figure 1 with tension cut-off *T*. With this material model, behavior of sand and gravel can be accuretly modeled using numerical metods such is SPH.

ANALYSIS OF FREIGHT WAGON MATERIALS

Analyzed wagon satisfy safety criteria for all cases of vertical and horizontal loads, as well as for load combinations. This was concluded after numerous FEA simulations, but numerical verification of safety requirements is not topic of this paper. Instead, we focus on the exploitation problem which occurs during unloading process, as the granular material deposits on box slopes. Wagon is designed to transport sand (density 1700 kg/m^3) or gravel (density 1400 kg/m^3) and its schematically illustrated on Figure 2.

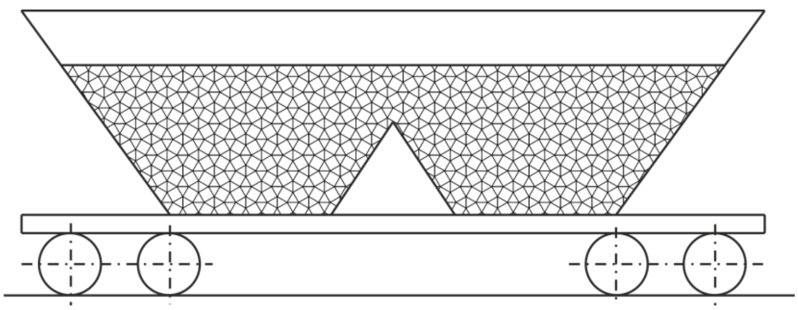

Figure 2 *Scheme of freight wagon*

The friction coefficient between steel sheet plates and granular material is 0.55. The critical regions for material deposition are intersections between side and front/back box plates. This happens because intersection egde has much lower angle to the horizontal in comparison to the angle of the plates (Fig. 3).

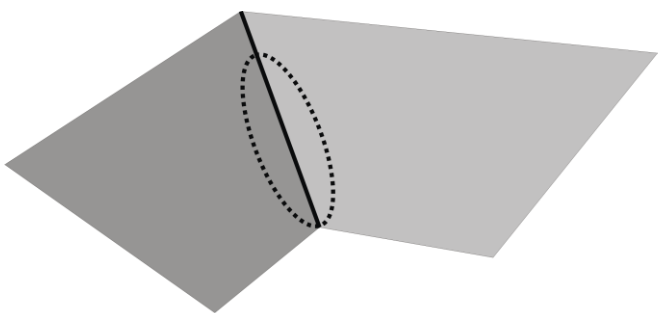

Figure 3 *Deposition of granular material in box corners*

Coupling between FEM and SPH methods enables realistic modeling of unloading process. This coupling is state of the art in numerical analysis and it's implemented only in LS-DYNA and ABAQUS commercial programs. There is a number of non-mommercial solutions that are currently developed at universities and scinentific institutes, and the authors are involved in development of such program. However, for this analysis, commercial software LS-DYNA is used. Granular material (gravel or sand) is modeled by SPH pseudo-particles using generalized cap model which is designated as material 25 in LS-DYNA. Contact between steel plates modeled with FEM shell elements and sand/gravel modeled with SPH pseudo-particles is characterized with friction coefficient of 0.55. Analysis confirms observation of railroad station workers, small amount of gravel remain deposited on the box edges (Fig. 4).

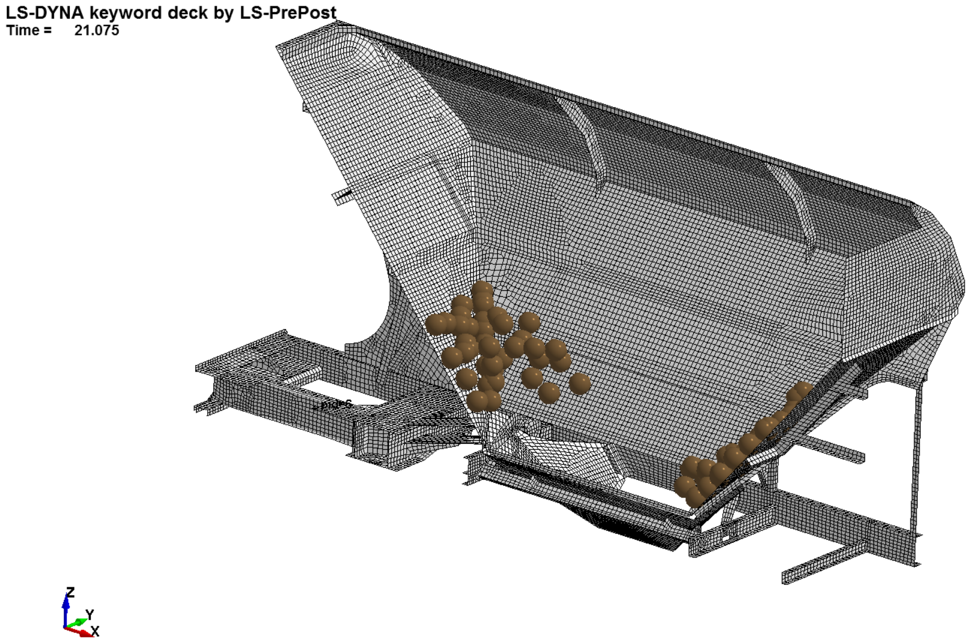

Figure 4 *Numerical recreation of deposition problem*

If the friction coefficient is reduced to 0.45 deposition is removeded (Fig. 5).

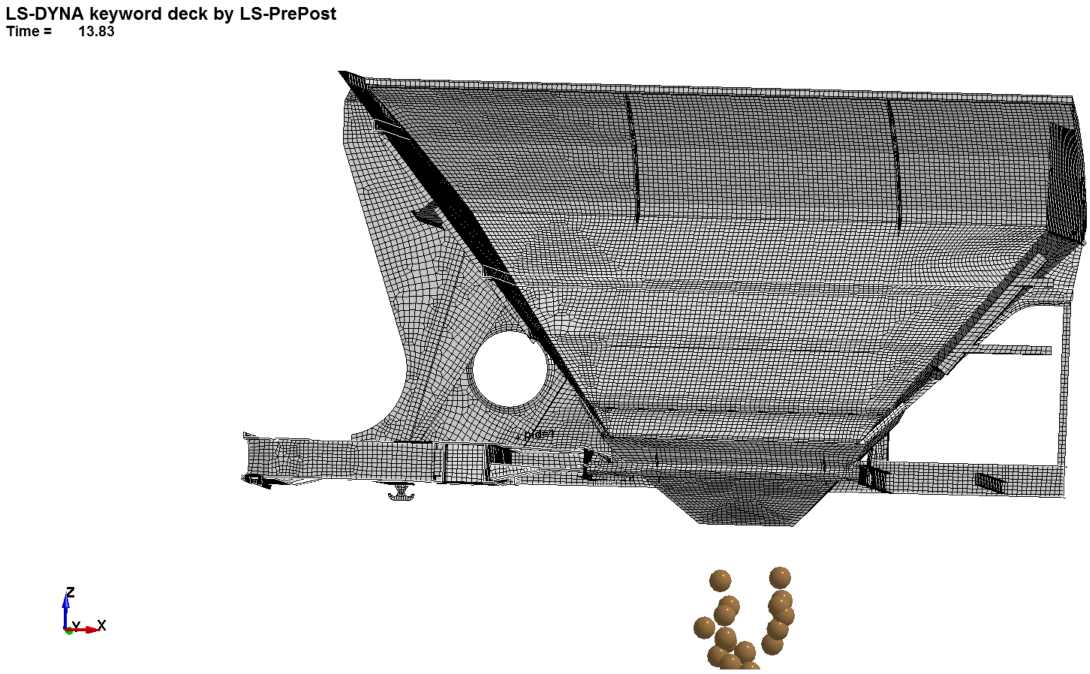

Figure 5 *Complete unloading of wagon with reduced friction*

Reduction of friction coefficient can be achieved by coating contact surfaces.

CONCLUSIONS

Reduction of friction coefficient is the most practical solution to the deposition problem on existing wagons. Other more expensive solution might be instalment of vibration devices which would excite granular particles into sliding down box slopes. Results shown in this paper demonstrate methodology which could be used during designing of the new wagons which would prevent deposition. Coupling of FEM with SPH is the state of the art in multiphysics analysis. This coupling enables discretization of wagon into shell finite elements and discretization of granular material into SPH particles. SPH method enables realistic calculations of loads that are transferred to FEM nodes.

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