2D SIMULATION OF ASSISTIVE GROUSER MECHANISM USING DISCRETE ELEMENT METHOD (DEM) FOR TRAVERSING ON UNCONSOLIDATED SOFT SAND

SITI SUHAILA BINTI SABARUDIN

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : DR. AHMAD NAJMUDDIN BIN IBRAHIM

Position : SENIOR LECTURE

Date : 04/04/2022

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : SITI SUHAILA BINTI SABARUDIN

ID Number : MET 17007

Date : 01/04/2022

2D SIMULATION OF ASSISTIVE GROUSER MECHANISM USING DISCRETE ELEMENT METHOD (DEM) FOR TRAVERSING ON UNCONSOLIDATED SOFT SAND

SITI SUHAILA BINTI SABARUDIN

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Manufacturing and Mechatronics Engineering Technology

UNIVERSITI MALAYSIA PAHANG

APRIL 2022

ACKNOWLEDGEMENTS

"In the Name of Allah, The Most Beneficent, The Most Merciful"

First and foremost, I am thankful to the Almighty for grating me such a life time opportunity and give a good health during this time. Secondly, I would like to express my sincere gratitude to my supervisor Dr. Ahmad Najmuddin Bin Ibrahim for his germinal idea, continuous encouragement and constant support in making this research possible. This study would not be possible without their review and correction of my mistake and countless valuable suggestion.

I also would like to acknowledge the staff of Faculty of Manufacturing and Mechatronics Engineering Technology for providing the physical necessities of completing this study as well as generous access to unlimited support, either internal or external resources. And also it is an honor for me to thank the educators for the direct and indirect lesson for me to complete this study.

I own my deepest gratitude to my parents and family for their love, understanding, and motivation throughout competing this study. And lastly, I offer my regards and blessing to all my friend and those who support me along this journey.

ABSTRAK

Robot beroda adalah salah satu jenis robot bergerak yang digunakan diatas permukaan kasar kerana mempunyai daya tarikan yang baik di atas permukaan yang rata. Salah satu cabaran robot beroda dalam situasi sebenarnya adalah kecenderungan roda tenggelam ke dalam permukaan pasir ketika melalui permukaan pasir yang tidak sekata. Banyak kajian daripada beberapa penyelidik telah dilakukan untuk memperbaiki prestasi robot beroda. Salah satunya ialah kajian yang mengusulkan "*assistive grouser*" yang dipasang pada sisi roda untuk mengurangkan masalah roda tenggelam ketika melalui cerun curam yang mempunyai pasir lembut. Tetapi semasa ujikaji dijalankan, interaksi antara *grouser*-pasir tidak dapat dilihat dengan jelas. Oleh itu, dalam kajian ini, satu model simulasi dijalankan untuk memerhati penggunaan *assistive grouser* terhadap interaksi antara pasir-*grouser*. Simulasi ini dibahagikan kepada tiga fasa, Fasa 1 mensimulasikan beberapa *fixed grouser* dan *assistive grouser* yang dipasang pada roda (*Conventional Wheel* - CW 80 mm dan *Assistive Wheel*- AW 90 mm), Fasa 2 mensimulasikan *fixed grouser* tunggal dan *assistive grouser* tunggal yang dipasang pada roda (CW 20 dan 80 mm, AW 50 dan 90 mm), dan Fasa 3 mensimulasikan satu *assistive grouser* tunggal dengan panjang *grouser* yang tenggelam berbeza (10, 20, 30 dan 40 mm) dan penggunaan *grouser angle* yang berbeza (0 dan 30-darjah). Pemerhatian memfokuskan pergerakan pasir apabila *grouser* bergerak sama ada ia menghasilkan tenaga untuk menggerakan roda ke hadapan atau tenaga itu dibazirkan dengan menggali permukaan pasir. Daripada Fasa 1, ia disimpulkan bahawa CW 80 mm dan AW 90 mm akan mempunyai tenaga yang cukup untuk menghasilkan daya untuk roda bergerak ke hadapan hasil daripada purata anjakan pasir yang tinggi (CW 80 mm tinggi sebanyak -6 mm), purata had laju pasir yang tinggi (CW 80 tinggi sebanyak -0.414m/s), dan jumlah anjakan pasir yang tinggi (AW 90 mm tinggi sebanyak 9790 pasir). Walau bagaimanapun, penggunaan CW 80 mm menunjukan roda berpotensi untuk mengalami masalah tersekat/tenggelam di dalam permukaan pasir disebabkan *fixed grouser* mengangkat butiran pasir ke atas permukaan semasa ia bergerak tetapi ini tidak berlaku apabila menggunakan AW 90 mm. Daripada Fasa 2, di permukaan cerun 0 dan 30-darjah, *grouser* yang panjang (CW 80 mm dan AW 90 mm) mempunyai prestasi yang lebih baik dari segi mengerakkan roda kehadapan berbanding *grouser* yang pendek (CW 20 mm dan AW 50 mm). Tetapi, dengan menggunakan CW 80 mm, nilai daya tolakan pasir (kearah atas) adalah tinggi (-100 N di cerun 0-darjah dan -190 N di cerun 30-darjah). Situasi ini menunjukan *fixed grouser* mengalami rintangan apabila berputar. Tetapi apabila menggunakan AW 90 mm, situasi ini tidak berlaku kerana pergerakan *assistive grouser* adalah dalam bentuk traslasi justeru mengurangkan potensi untuk *assistive grouser* menggali permukaan pasir. Daripada Fasa 3, ia dapat disimpulkan bahawa *grouser* yang lebih panjang (40 mm) memberi prestasi yang lebih baik berbanding *grouser* yang pendek berdasarkan nilai purata anjakan pasir yang tinggi (-55 mm untuk paksi X, 54 mm untuk paksi Y), daya penolakan *grouser* yang tinggi (688N) dan kawasan yang terjejas akibat pergerakan *grouser* yang besar (1803.53 mm^2). Prestasi penggunaan *assistive grouser* menurun apabila mendaki cerun 30-darjah dengan anjakan purata pasir dan daya penolakan lebih rendah. Tetapi ia telah diselesaikan dengan menetapkan *grouser angle* sama seperti kecenderungan cerun. Pada cerun 30-darjah, *grouser angle* 30-darjah adalah lebih sesuai digunakan kerana ia boleh menghasilkan daya penolakan serta purata anjakan pasir yang tinggi. Kesimpuannya, simulasi ini berjaya mengesahkan andaian berkaitan pergerakan pasir dan prestasi *grouser* yang digunakan di dalam kajian lepas untuk menerangkan

kelebihan prestasi *assistive grouser* pada permukaan cerun yang mempunyai pasir lembut.

ABSTRACT

Wheeled rovers are one type of mobile robot used to drive over rough terrain, with an advantage for being energy efficient on a flat surface with reasonable traction force. One of the challenges of wheeled rovers in actual operation is the tendency for the wheel to sink into the sand surface when traversing on an unconsolidated sand surface incline. Many previous studies have been done to improve rover mobility performance. One of the studies proposed an “assistive grouser” attached to the side of the wheel to minimize the sinkage problem when traversing on a steep slope of soft sand. However, during the experimental test alone, the interaction between the grouser-sand cannot be seen clearly. Therefore, in this study, a simulation modelling was carried out to observe the effect of assistive grousers on sand-grouser interaction. This simulation was divided into three phases, Phase 1 simulates multiple fixed and assistive grousers attached to a wheel (Conventional Wheel - CW 80 mm and Assistive Wheel - AW 90 mm), Phase 2 simulates a single fixed and assistive grouser attached to a wheel (CW 20 and 80 mm, AW 50 and 90 mm), and Phase 3 simulates a single assistive grouser with different sinkage length (10, 20, 30 and 40 mm) and grouser angle of attack (0 and 30-degree). The observation focuses on the flow of sand particles during grouser movement, whether the grouser transfers its energy to push the wheel forward or waste energy excavating sand from below the surface (digging). From Phase 1, it can be concluded that CW 80 mm and AW 90 mm will generate a significant amount of traction force for the wheel to move forward from high values of average particle displacement value (CW 80 mm has higher -6 mm), high values of average particle velocity magnitude (CW 80 mm has higher -0.414 m/s) and high values of total displaced particle (AW 90 mm has higher 9790 particles). However, usage of CW 80 mm has also shown an increased tendency for the wheel to enter the stuck stage as the grouser lifts more sand from under the surface upward but not when using AW 90 mm. From Phase 2, the results show that for both 0 and 30-degree inclination slope, longer grouser (CW 80 and AW 90 mm) has better performance in generating forward traction force than shorter grouser (CW 20 mm and AW 50 mm). However, when using CW 80 mm, the value of negative pushing force (upward push) is higher (-100 N on 0-degree slope and -190 N on 30-degree slope). This condition indicates that the grouser experiences resistance when moving from under the wheel toward the surface. However, by using AW 90 mm, there is minimal negative force value because of the translational movement of the assistive grouser. So, there is less tendency for the grouser to dig the sand surface. From Phase 3, it was concluded that longer grouser sinkage length (40 mm) gives better performance compared to shorter sinkage length because of high average particle displacement (-55 mm for X-axis, 54 mm for Y-axis), high grouser pushing force (688 N) and larger destructive area (1803.53 mm^2). The performance of the assistive grouser was reduced when climbing the inclination slope. When climbing the 30-degree slope, the average particle displacement and the grouser pushing force is smaller. But this has been solved by setting the grouser angle of attack to be the same as the slope inclination angle. On a 30-degree slope, the grouser angle of attack 30-degree is more suitable to be used because it can generate higher grouser pushing force and a higher average particle displacement. In conclusion, the simulation carried out by this study has successfully verified the assumptions and justifications related to the flow of sand particles and grouser performance that was applied during previous work to explain the better performance of assistive grousers on a steep slope of soft sand inclines.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Φ_d	Absolute angle
l_s	Grouser length under the sand surface
θ_{slope}	Inclination slope angle
θ_g	Grouser angle of attack
A	Destructive area
l_d	Total distance of the traveled area
h_s	Sand height in the box
E	Equation
S	Simulation

LIST OF ABBREVIATIONS

NASA	National Aeronautics and Space Administration
CWR	Conventional Wheel Rover
MWR	Modified Wheel Rover
3D	3-Dimensional
2D	2-Dimensional
DEM	Discrete Element Method
FEM	Finite Element Method
CFD	Computational Fluid Dynamic
CW	Conventional Wheel
AW	Assistive Wheel

LIST OF APPENDICES

REFERENCES

Akiyama, K., Nagatani, K., & Yoshida, K. (2012). 1A2-I10 Development and Evaluation of a Wheel with Verticality-penetration-lug Mechanism(Wheeled Robot/Tracked Vehicle(2)). *The Proceedings of JSME annual Conference on Robotics and Mechatronics (Robomec), 2012*, _1A2-I10_11. doi:10.1299/jsmermd.2012._1A2-I10_1

Arvidson, R., Bell, J., Bellutta, P., Cabrol, N., Catalano, J., Cohen, J., . . . Yen, A. (2010). Spirit Mars Rover Mission: Overview and selected results from the northern Home Plate Winter Haven to the side of Scamander crater. *Journal of Geophysical Research, 115*. doi:10.1029/2010JE003633

Asaf, Z., Shmulevich, I., & Rubinstein, D. (2006). Predicting soil-rigid wheel performance using distinct element methods. *Transactions of the ASABE, 49*, 607-616. doi:10.13031/2013.20477

Azmi, H. N., Hajjaj, S. S. H., Gsangaya, K. R., Sultan, M. T. H., Mail, M. F., & Hua, L. S. (2021). Design and fabrication of an agricultural robot for crop seeding. *Materials Today: Proceedings*. doi:https://doi.org/10.1016/j.matpr.2021.03.191

Brilliantov, N. V., Spahn, F., Hertzsch, J.-M., & Pöschel, T. (1996). Model for collisions in granular gases. *Physical Review E, 53*(5), 5382-5392.

Bui, H. H., Kobayashi, T., Fukagawa, R., & Wells, J. C. (2009). Numerical and experimental studies of gravity effect on the mechanism of lunar excavations. *Journal of Terramechanics, 46*(3), 115-124. doi:10.1016/j.jterra.2009.02.006

Chen, P. Y. P., & Hahn, E. J. (2000). Side clearance effects on squeeze film damper performance. *Tribology International, 33*, 161-165. doi:10.1016/S0301-679X(00)00022-0

Chen, Y., Mei, Y., & Wang, W. (2017). Kinetic theory of binary particles with unequal mean velocities and non-equipartition energies. *Physica A: Statistical Mechanics and its Applications, 469*, 293-304. doi:https://doi.org/10.1016/j.physa.2016.11.104

Cundall, P. A., & Strack, O. D. L. (1979). A discrete numerical model for granular assemblies. *Géotechnique, 29*(1), 47-65. doi:10.1680/geot.1979.29.1.47

Dellinger, G., Simmons, S., Lubitz, W. D., Garambois, P.-A., & Dellinger, N. (2019). Effect of slope and number of blades on Archimedes screw generator power output. *Renewable Energy, 136*, 896-908. doi:https://doi.org/10.1016/j.renene.2019.01.060

Feng, Y., & Owen, D. R. J. (2002). An Energy Based Corner to Contact Algorithm.

Gertzos, K. P., Nikolakopoulos, P. G., & Papadopoulos, C. A. (2008). CFD analysis of journal bearing hydrodynamic lubrication by Bingham lubricant. *Tribology International, 41*(12), 1190-1204. doi:10.1016/j.triboint.2008.03.002

Gu, S. (2017). Application of finite element method in mechanical design of automotive parts. *IOP Conference Series: Materials Science and Engineering, 231*, 012180. doi:10.1088/1757-899X/231/1/012180

Guo, Y., & Yu, X. (2017). Comparison of the implementation of three common types of coupled CFD-DEM model for simulating soil surface erosion. *International Journal of Multiphase Flow, 91*, 89-100. doi:10.1016/j.ijmultiphaseflow.2017.01.006

Halvorsen., H.-P. (2016). *Introduction to MATLAB.* University College of Southeast Norway

Hirosawa, F., Iwasaki, T., & Iwata, M. (2019). Kinetic analysis of mechanochemical reaction between zinc oxide and gamma ferric oxide based on the impact energy and collision frequency of particles. *Powder Technology, 352*, 360-368. doi:https://doi.org/10.1016/j.powtec.2019.04.050

Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics, 39*(1), 201-225. doi:https://doi.org/10.1016/0021-9991(81)90145-5

Ibrahim, A. N., Aoshima, S., Shiroma, N., & Fukuoka, Y. (2016). The Effect of Assistive Anchor-Like Grousers on Wheeled Rover Performance over Unconsolidated Sandy Dune Inclines. *Sensors (Basel), 16*(9). doi:10.3390/s16091507

Ignell, N. B., Rasmusson, N., & Matsson, J. (2012). *An overview of legged and wheeled robotic locomotion*. Paper presented at the Mini-Conference on Interesting Results in Computer Science and Engineering.

Inotsume, H., Moreland, S., Skonieczny, K., & Wettergreen, D. (2019). Parametric study and design guidelines for rigid wheels for planetary rovers. *Journal of Terramechanics, 85*, 39-57. doi:10.1016/j.jterra.2019.06.002

Irani, R. A., Bauer, R. J., & Warkentin, A. (2011). A dynamic terramechanic model for small lightweight vehicles with rigid wheels and grousers operating in sandy soil. *Journal of Terramechanics, 48*(4), 307-318. doi:10.1016/j.jterra.2011.05.001

Johnson, J. B., Duvoy, P. X., Kulchitsky, A. V., Creager, C., & Moore, J. (2017). Analysis of Mars Exploration Rover wheel mobility processes and the limitations of classical terramechanics models using discrete element method simulations. *Journal of Terramechanics, 73*, 61-71. doi:https://doi.org/10.1016/j.jterra.2017.09.002

Johnson, J. B., Kulchitsky, A. V., Duvoy, P., Iagnemma, K., Senatore, C., Arvidson, R. E., & Moore, J. (2015). Discrete element method simulations of Mars Exploration Rover wheel performance. *Journal of Terramechanics, 62*, 31-40. doi:10.1016/j.jterra.2015.02.004

Johnson, K. L., Kendall, K., & Roberts, A. D. (Sept 1971). *Surface Energy and the Contact of Elastic Solids.* Paper presented at the Proceedings of The Royal Society A: Mathematical, Physics and Engineering Science.

Karpman, E., Kövecses, J., Holz, D., & Skonieczny, K. (2020). Discrete element modelling for wheel-soil interaction and the analysis of the effect of gravity. *Journal of Terramechanics, 91*, 139-153. doi:https://doi.org/10.1016/j.jterra.2020.06.002

Khot, L. R., Salokhe, V. M., Jayasuriya, H. P. W., & Nakashima, H. (2007). Experimental validation of distinct element simulation for dynamic wheel–soil interaction. *Journal of Terramechanics, 44*(6), 429-437. doi:10.1016/j.jterra.2007.12.002

Kumar, P. G., & Jayalekshmi, S. (2018). A Study on Wheel Sinkage and Rolling Resistance with variations in wheel geometry for Plain and Lugged wheels on TRI -1 Soil

Simulant. *IOP Conference Series: Materials Science and Engineering, 330*, 012127. doi:10.1088/1757-899x/330/1/012127

Liu, D., Bu, C., & Chen, X. (2013). Development and test of CFD–DEM model for complex geometry: A coupling algorithm for Fluent and DEM. *Computers & Chemical Engineering, 58*, 260-268. doi:10.1016/j.compchemeng.2013.07.006

Mahmud, M. S. A., Abidin, M. S. Z., Mohamed, Z., Rahman, M. K. I. A., & Iida, M. (2019). Multi-objective path planner for an agricultural mobile robot in a virtual greenhouse environment. *Computers and Electronics in Agriculture, 157*, 488-499. doi:https://doi.org/10.1016/j.compag.2019.01.016

Md-Tahir, H., Zhang, J., Xia, J., Zhang, C., Zhou, H., & Zhu, Y. (2019). Rigid lugged wheel for conventional agricultural wheeled tractors – Optimising traction performance and wheel–soil interaction in field operations. *Biosystems Engineering, 188*, 14-23. doi:10.1016/j.biosystemseng.2019.10.001

Nagatani, K., Kiribayashi, S., Okada, Y., Otake, K., Yoshida, K., Tadokoro, S., . . . Kawatsuma, S. (2013). Emergency response to the nuclear accident at the Fukushima Daiichi Nuclear Power Plants using mobile rescue robots. *Journal of Field Robotics, 30*(1), 44-63. doi:10.1002/rob.21439

Nakashima, H., Fujii, H., Oida, A., Momozu, M., Kanamori, H., Aoki, S., . . . Ohdoi, K. (2010). Discrete element method analysis of single wheel performance for a small lunar rover on sloped terrain. *Journal of Terramechanics, 47*(5), 307-321. doi:10.1016/j.jterra.2010.04.001

Nakashima, H., & Kobayashi, T. (2014). Effects of gravity on rigid rover wheel sinkage and motion resistance assessed using two-dimensional discrete element method. *Journal of Terramechanics, 53*, 37-45. doi:10.1016/j.jterra.2014.03.004

Niksirat, P., Daca, A., & Skonieczny, K. (2020). The effects of reduced-gravity on planetary rover mobility. *The International Journal of Robotics Research, 39*, 027836492091394. doi:10.1177/0278364920913945

Nishiyama, K., Nakashima, H., Yoshida, T., Ono, T., Shimizu, H., Miyasaka, J., & Ohdoi, K. (2016). 2D FE–DEM analysis of tractive performance of an elastic wheel for planetary rovers. *Journal of Terramechanics, 64*, 23-35. doi:10.1016/j.jterra.2015.12.004

Okada, T., Botelho, W. T., & Shimizu, T. (2009). Motion Analysis with Experimental Verification of the Hybrid Robot PEOPLER-II for Reversible Switch between Walk and Roll on Demand. *The International Journal of Robotics Research, 29*(9), 1199-1221. doi:10.1177/0278364909348762

Osumi, H. (2014). Application of robot technologies to the disaster sites. *Report of JSME Research Committee on the Great East Japan Earthquake Disaster*, 58-74.

Plassiard, J.-P., Belheine, N., & Donze, F.-V. (2009). A spherical discrete element model calibration procedure and incremental response. *Granular Matter, 11*(5), 293-306.

Radford, A. N. A., Strawser, P., Hambuchen, K., Mehling, J. S., Verdeyen, W. K., Donnan, A. S., . . . et al. (2015). *Valkyrie: NASA's First Bipedal Humanoid Robot* (Vol. 32): John Wiley and Sons Ltd.

Ranjan, V., Pai, R., & Hargreaves, D. (2006). Stiffness and Damping Coefficients of 3-axial Groove Water Lubricated Bearing Using Perturbation Technique. In M. Fillon (Ed.), *Proceedings of Futuroscope: 5th Workshop Bearing Behaviour under Unusual Operating Conditions:* (pp. 1-6). France, Futuroscope Chasseneuil: Universite de Poitiers.

Sakaguchi, E., Kawakami, S., Tamura, S., & Tobita, F. (1996). Simulation on Discharging Phenomena of Crains by Distinct Element Method

Influence of Shapes of Element on Flowing States. *Journal of the Japanese Society of Agricultural Machinery, 58*(4), 9-17. doi:10.11357/jsam1937.58.4_9

Silbert, L. E., Ertaş, D., Grest, G. S., Halsey, T. C., Levine, D., & Plimpton, S. J. (2001). Granular flow down an inclined plane: Bagnold scaling and rheology. *Physical Review E, 64*(5), 051302.

Silva, E. P. d., Silva, F. M. d., & Magalhães, R. R. (2014). Application of Finite Elements Method for Structural Analysis in a Coffee Harvester. *Engineering, 06*(03), 138-147. doi:10.4236/eng.2014.63017

Smith, W. (2014). Modeling of Wheel-Soil Interaction for Small Ground Vehicles Operating on Granular Soil.

Smith, W., Melanz, D., Senatore, C., Iagnemma, K., & Peng, H. (2014). Comparison of discrete element method and traditional modeling methods for steady-state wheel-terrain interaction of small vehicles. *Journal of Terramechanics, 56*, 61-75. doi:https://doi.org/10.1016/j.jterra.2014.08.004

Smith, W., & Peng, H. (2013). Modeling of wheel–soil interaction over rough terrain using the discrete element method. *Journal of Terramechanics, 50*(5), 277-287. doi:https://doi.org/10.1016/j.jterra.2013.09.002

Smith, W. C. (2014). Modeling of Wheel-Soil Interaction for Small Ground Vehicles Operating on Granular Soil (Doctor of Philosophy), The University of Michigan

Sutoh, M., Yusa, J., Ito, T., Nagatani, K., & Yoshida, K. (2012). Traveling performance evaluation of planetary rovers on loose soil. *Journal of Field Robotics, 29*(4), 648-662. doi:10.1002/rob.21405

Taheri, S., Sandu, C., Taheri, S., Pinto, E., & Gorsich, D. (2015). A technical survey on Terramechanics models for tire–terrain interaction used in modeling and simulation of wheeled vehicles. *Journal of Terramechanics, 57*, 1-22. doi:10.1016/j.jterra.2014.08.003

Tsuji, Y., Kawaguchi, T., & Tanaka, T. (1993). Discrete particle simulation of two-dimensional fluidized bed. *Powder Technology, 77*(1), 79-87. doi:10.1016/0032-5910(93)85010-7

Wong, J. Y. (2010). Terramechanics and off-road vehicle engineering : terrain behaviour, off-road vehicle performance and design: Second edition. Amsterdam : Elsevier, 2010.

Wong, J. Y., & Kobayashi, T. (2012). Further study of the method of approach to testing the performance of extraterrestrial rovers/rover wheels on earth. *Journal of Terramechanics, 49*(6), 349-362. doi:10.1016/j.jterra.2012.10.004

Yamamoto, R., Yang, Y., Sun, Y., & Ma, S. (2014, 18-22 Aug. 2014). *Influences of lug motion on lug-soil reaction forces in sandy soil.* Paper presented at the 2014 IEEE International Conference on Automation Science and Engineering (CASE).

Yamamoto, R., Yang, Y., Sun, Y., & Ma, S. (2015). Characteristics of lug-soil interaction forces acting on a rotating lug in sandy soil. *2014 IEEE International Conference on Robotics and Biomimetics, IEEE ROBIO 2014*, 451-456. doi:10.1109/ROBIO.2014.7090372

Yang, Y., Sun, Y., & Ma, S. (2014). Drawbar pull of a wheel with an actively actuated lug on sandy terrain. *Journal of Terramechanics, 56*, 17-24. doi:10.1016/j.jterra.2014.07.002

Yang, Y., Sun, Y., & Ma, S. (2014, 31 May-7 June 2014). *Effect of lug sinkage length to drawbar pull of a wheel with an actively actuated lug on sandy terrain.* Paper presented at the 2014 IEEE International Conference on Robotics and Automation (ICRA).

Yang, Y., Sun, Y., Ma, S., & Yamamoto, R. (2014). Characteristics of normal and tangential forces acting on a single lug during translational motion in sandy soil. *Journal of Terramechanics, 55*, 47-59. doi:10.1016/j.jterra.2014.05.006

Zhang, H. P., & Makse, H. A. (2005). Jamming transition in emulsions and granular materials. *Physical Review E, 72*(1), 011301.

Zhang, M., Yang, Y., Luo, J., Xie, S., Pu, H., Sun, Y., & Liu, N. (2017, 29 Oct.-1 Nov. 2017). *Modeling of lug-soil interaction forces acting on a single lug during rotational motion in sandy soil.* Paper presented at the IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society.

Zhang, R., Pang, H., Dong, W., Li, T., Liu, F., Zhang, H., . . . Li, J. (2020). Three-dimensional Discrete Element Method simulation system of the interaction between irregular structure wheel and lunar soil simulant. *Advances in Engineering Software, 148*, 102873. doi:https://doi.org/10.1016/j.advengsoft.2020.102873

Zhao, C.-L., & Zang, M.-Y. (2017). Application of the FEM/DEM and alternately moving road method to the simulation of tire-sand interactions. *Journal of Terramechanics, 72*, 27-38. doi:10.1016/j.jterra.2017.04.001

Zhao, T. (2017). Introduction to Discrete Element Method *Coupled DEM-CFD Analyses of Landslide-Induced Debris Flows* (pp. 25-45).