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Numerical Simulation and Analysis of Pick-ups Drag Force

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ABSTRACT

To solve the problem of drag force calculation between pick-ups mechanics of Beach Cleaner and sand, based on Finite Volume Method (FVM) in FLUENT, a model was built and converted the pick-ups sand shear motion into sand pick-ups erosion motion. By introducing Standard K-ε turbulence model and SIMPLE algorithm with pressure-correction,the force of pick-ups in different sand depth conditions was analyzed. By adopting Least-Squares Method in MATLAB, the simulation and experimental curves of pick-up force were fitted respectively and reached the function expressions, connecting the pick-up forces with sand depth. The results indicate: The relative errors of impact force values of sand from the FLUENT simulation and experimental values from field test decrease to ±4.5% and the fitting lines of simulation and experiment agree closely and prove that the simulation models and methods are feasible to compute the drag force.

Key words: Pick-ups, FLUENT, turbulence model, least-square method

INTRODUCTION

The pick-ups mechanics assembled on SWNZ14 Beach Cleaner is the key component to pick up trash, its performance has a critical effect on the Beach Cleaner's cleaning ability. The pick-ups is a torsion spring made of 65 Mn and its cross section radius is 0.003 m. Studies on the interaction between torsion spring and sand are not common to see but there has been some study about soil and mechanics.

Huang *et al*. (2007) used FLUENT to simulate the thrust and torque coefficient and calculated the pressure and velocity flow behind the propeller. Manuwa (2009) investigated how tillage tools model and operating depth affect the draught force by soil bin test and verified the force increase with the depth of operation but not proportionately. Tanaka *et al*. (2009) used Distinct Element Method (DEM) to analyze the discontinuous property of soil and simulated the soil deformation and resistance. Apsley (2007) used wall functions to handle the no-slip boundary condition at solid surfaces (Rzehak and Krepper, 2013; Zaidi *et al*., 2010), demonstrated the different turbulence model's application in solving CFD problems. Shibly *et al*. (2005) used on-line terrain parameter estimation algorithm approach to simplify formulations and then analyzed the characristics of planetary exploration rovers rigid wheels, the test further showed simplified formulation presented high accuracy in interference experiment. Trautmann *et al*. (1985), Igwe *et al*. (2012) and Barton *et al*. (2001) studied the physical properties and their relations of different sand patterns respectively. By converting the interaction between sand and pick-ups, this study adopted CFD method to simulate the drag force of the pick-ups and compared the results with the field test data.

MATERIALS AND METHODS

Pick-ups configuration: Pick-ups mechanism is mainly composed of liquid motor, pick-ups frame, pick-ups body and pick-ups. Pick-ups are bolted on pick-ups body and rotated by means of liquid motor's driving the pick-ups body. There are four rows of pick-ups evenly distributed in a 2D circle with ten in every row and two adjacent rows of pick-ups offset 0.126 m horizontally with each other. The pick-ups are controlled by hydraulic device to achieve different sand depths (Fig. 1).

Model simplification: By measuring the sand sample's dimensions, sand particles diameter on the test field in Xiamen is averaged nearly 5×10^{-5} m, particle diameter is tiny and porosity is extremely low. Meanwhile loose sand are able to flow, thus it can be approximately seen as fluid body. When pick-ups and sand happened to do relative motion, pick-ups rotate around the rotation axis as well as proceed shear motion with sand, while the pick-ups rotate at the maximum depth in sand, its drag force goes to peak correspondingly.

Seeing the ground as reference system, sand is relatively static while pick-ups motion is translational and rotational simultaneously. Supposed to give an initiative velocity and keep the pick-ups stable when fixing the pick-ups to its maximum sand depth, the sand will impact the pick-ups and then the impact force caused by sand can be calculated.

Theoretical analysis: If pick-ups stay stationary at the maximum depth, the sand will flow over the pick-ups to form circumfluence motion. According to hydrodynamics rules, the pick-ups will get two different forces that is circumfluence force and lift force. The lift force vector direction is perpendicular to the sand's flowing vector direction, the drag force exposed on pick-up's rotation is so small that it can be neglected, so only circumfluence force is left. Circumfluence force can be divided into two parts: Frictional resistance D_f and pressure resistance; D_p frictional resistance is the component force of resultant force of shear stress that the fluid effected on pick-up's surface on flowing direction, pressure force is the component force of resultant force of pressure force that the sand effected on pick-up's surface. Supposed to extract a micro area d_A from the circumfluence surface (Fig. 2), the fluid impact on the pick-ups surface d_A and formed shear stress τ_w and pressure stress p_w, the included angle between the exterior normal of pick-ups surface and flowing direction is named as α thus, the frictional resistance and pressure resistance that the sand exerted on pick-ups respectively are:

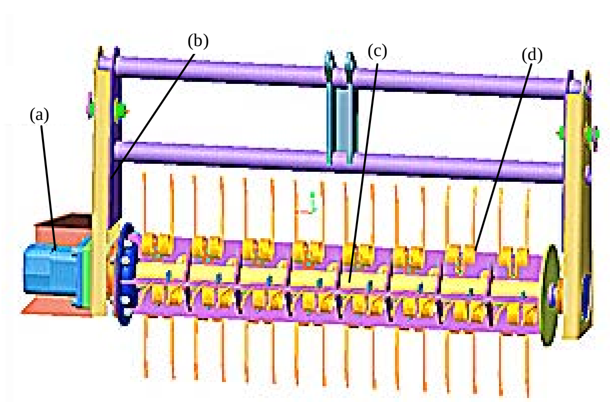

Fig. 1(a-d): Pick-ups mechanism, (a) Liquid Motor, (b) Pick-ups Frame, (c) Pick-ups Body and (d) Pick-ups

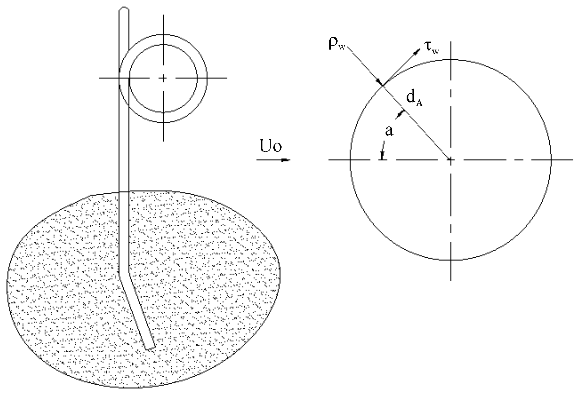

Fig. 2: Pick-ups sand interaction model

$$D_f = -\iint_A \tau_W \sin\alpha d_A \tag{1}$$

$$D_p = -\iint_A p_w \cos\alpha d_A \tag{2}$$

In the formulation, minus sign represents the drag vector direction is opposite with the flowing direction. Here introduced the concept of circumfluence resistance coefficient, C_d circumfluence resistance is equivalent to the formulation below:

$$D = D_f + D_p = C_d A \frac{\rho v_0^2}{2} \tag{3}$$

In the formulation, ρ stands for the density of fluid, v_o for flowing velocity, A for the area that the fluid projected on the direction, vertical with flowing direction, C_d coefficient can be received from test, in turn the drag force that the sand impacted on pick-ups can be calculated.

Geometry model: Created the pick-ups sand motion model, adopted Creo 2.0 to create pick-ups model, then imported the model file into FLUENT analyzing module in ANSYS. To cut down the calculating time, supposing the beach terrain is flat so that every pick-up's sand depth is identical and every pick-up drag force is equal as well, so studying one pick-ups drag force in different sand depths is agreeable. Extract the pick-up's surface as solid wall, make the sand impact the wall and export the pressure contour of the walls. Finally list all node's force and sum them up to figure out the drag force of pick-ups. As shown in Fig. 3, a 0.1 m long, 0.08 m wide box was created with its height dimension similar to the sand depth.

Adopt CFD physic model to mesh and generate mesh on all parts. For controlling the mesh element on the pick-ups surface as refined as possible, set the element size at 2×10^{-3} m, created named selections as inlet face, outlet face and wall faces, use FLUENT as the solver.

Turbulence model and correction: According to formulation (Kostyukov, 1967).

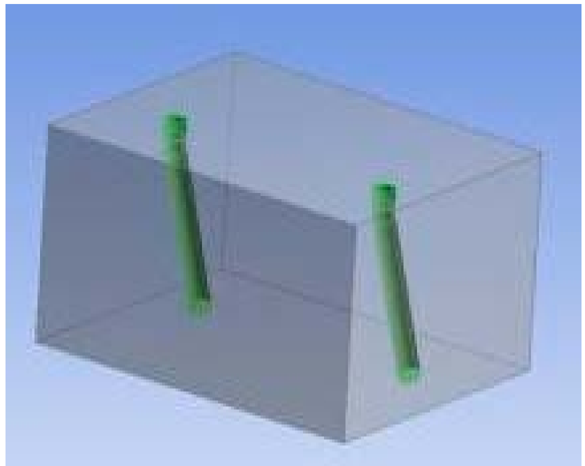

Fig. 3: Simulation geometry model of pick-ups

$$R_{ek} = \frac{\rho \cdot v_K \cdot d}{\mu} \tag{4}$$

Where:

R_{ek} = Critical Reynolds number
ρ = Density of fluid
v_k = Critical velocity of fluid
d = Tube diameter
μ = Dynamic viscosity coefficient. Because of the sand's dynamic viscosity coefficient is nearly zero. That is, its critical Reynolds number is close to infinite, so choose standard turbulence model under as its physical model:

- Set material mode as sand, the average diameter is 5×10^{-4} m density is 1500 kg m^{-3}
- Set the inlet boundary conditions, define inlet boundary as pressure inlet, inlet pressure values is standard atmosphere, value is 0.101 Mpa, then set the inlet velocity, turbulence intensity and hydraulic diameter. According to turbulence intensity formula (Wesseling, 2001):

$$I = 0.16\times(\mathrm{Re})^{\frac{-1}{8}} \tag{5}$$

Considering the sand's Reynolds number is extremely high, so its turbulence intensity can be set at 1%. Also, calculate the hydraulic diameter according to hydraulic diameter equation (Potter and Wiggert, 2003):

$$d_H = 4\times\frac{A}{S} \tag{6}$$

In detail, A stands for the area of cross section of passage, S for the circumference that the fluid contact with the solid body on the cross section of passage.

- Define the outlet boundary conditions. As a result of minor investment of the wall boundary, the back flow agrees to be neglected, so set the outlet boundary as pressure outlet, pressure value is 0.101 MPa; (5) Adopted no slip, stationary wall boundary, friction coefficient is 0.48, as defined above, the inlet boundary is pressure and initiative velocity, so the solver is SIMPLE algorithm of semi-implicit formula based on pressure-coupling, in this way the solving speed will be accelerated
- Control the convergent residual curve: Control the energy convergent residual within the order of 10^{-6} velocity convergent residual within 10^{-5}, solving step size at 1000, then press the solving button

RESULTS

Test design: Pick-ups beach test measured the drag force of pick-ups by means of recording the inlet and outlet pressures differences of liquid motor when it performs in different sand depth, (Fig. 4). When carried on the test, connect the pressure gauges at the inlet and outlet points respectively, then adjusted the sand depth of pick-ups by the hydraulic device, write down the indications on the gauges in different sand depths, in turn calculated the drag force correspondingly (Fig. 4).

Results comparison: Change the sand depth while keep other parameters unchanged, by controlling the convergence into a low level, the calculation results are displayed (Fig. 5). Export all the nodes' force on the flowing direction into excel document and sum them up, finally compare with the simulation values correspondingly, the drag force of pick-ups mechanics in different sand depths are listed in Table 1.

From the pressure contours, we concluded the drag force of pick-ups force increase with the sand depth, the maximum stress is mainly located at the center of pick-ups and decrease gradually to either side. From Table 1, by summing up all nodes' force, the drag force for single pick-ups can be calculated and then multiplies the number of pick-ups to get the final result. The simulation values are close to the test values, and thorough relative errors, we clearly see the highest value is 4.5% which is within the permission values, that is, the simulation values are effective and so are the adopted calculating models.

Fig. 4: Field test of beach cleaner on xiamen beach

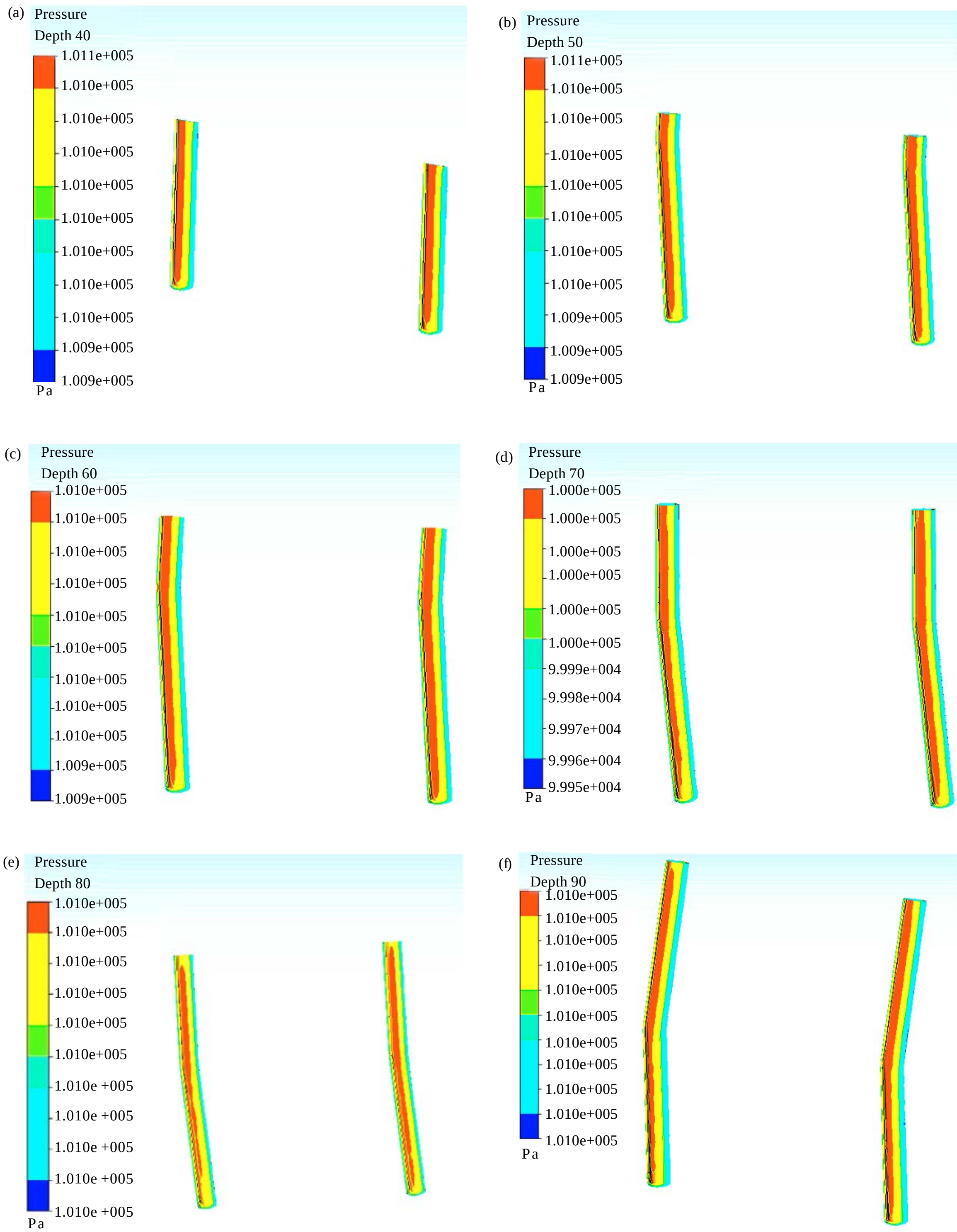

Fig. 5(a-g): Continue

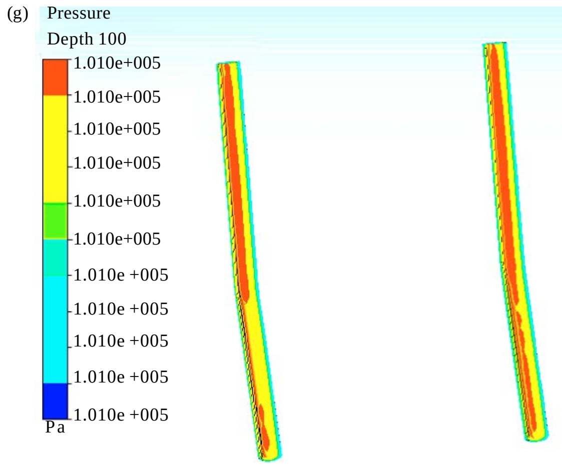

Fig. 5(a-g): Countinue pick-ups force in different depth, (a) Depth 0.04 m, (b) Depth 0.05 m, (c) Depth 0.06 m, (d) Depth 0.07 m, (e) Depth 0.08 m, (f) Depth 0.09 m and (g) Depth 0.1 m

Table 1: Pick-ups force in different depth

Sand Depth: h(m)	Single	Whole row	Test values	Relative errors (%)
0.04	46.1	368.8	352.9	4.5
0.05	58.6	468.8	470.5	-0.4
0.06	67.9	543.2	529.4	2.6
0.07	73.3	586.4	588.2	-0.3
0.08	79.5	636.0	617.6	3.0
0.09	87.6	700.8	676.4	3.6
0.1	103.0	824.0	794.0	3.8

DISCUSSION

Analysis of test values' fitting curves: In order to further verify the accuracy of the simulation results in FLUENT and field test results, as well as to study the force curve of pick-ups in different sand depth, here introduced MATLAB method to do the curve fitting. Based on Least Square Method, control the convergences' square at the minimum. Use linear, quadratic, cubic, quartic fitting polynomial to fit the values respectively, establish sand depth h as the independent variable, the pick-ups drag force in a row as dependent variable, its relations meet to the expressions:

$$F = F(h) = a_0\, h^4 + a_1\, h^3 + a_2\, h^2 + a_3\, h + a_4$$

where, a_0, a_1, a_2, a_3, a_4 are undetermined coefficients.

At first, fit out the curves of test values with linear to quartic fitting polynomial, the fitting lines are demonstrated (Fig. 6).

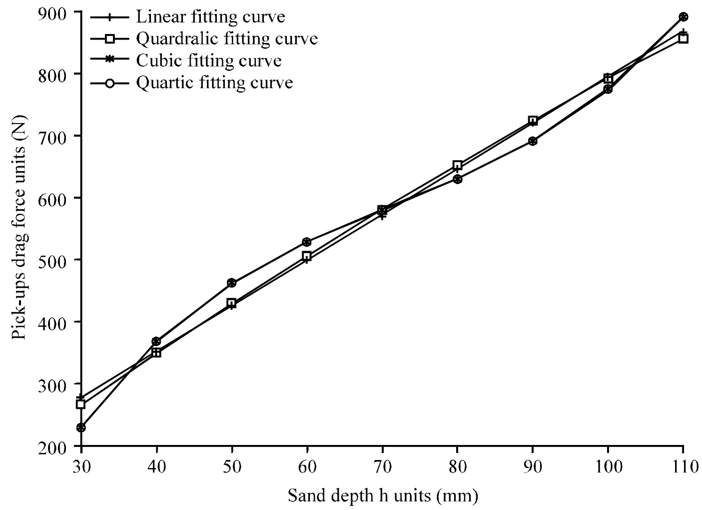

Fig. 6: Fitted curves of pick-ups force in different depth

Table 2: Variance values of fitted linear to quartic curves

Parameters	Value
Linear	7540
Quadratic	5270
Cubic	792.2629
Quartic	171.9210

In order to evaluate, the precision of those fitting curves and confirm which fitting curve is the most ideal line for the simulation, the following table compares the variances of pick-ups force in these seven different points. By comparison, it clearly shows which fitting curve's variance value is minimum (Table 2).

As demonstrated in Table 2, the variances of fitted curve from linear to quartic are calculated, it is clear that selecting quartic polynomial have reached a fine fitting precision. Contrary, selecting a higher power not only will worsen the precision distinctly but also will make the curve's smoothness fall and reflect more quantization error of test data (Chen *et al*., 2010). Figure out the undetermined coefficients of quartic polynomial and put the values into the expressions, so its exact equation is:

$$F = F(h) = 6\times10^{6}\ h^{4}-1.2\times10^{7}\ h^{3}+8.37\times10^{4}\ h^{2}-1.04\times10^{7}\ h+81.259$$

Polynomial comparison: Fit two quartic curves of pick-ups force got from simulation and test, (Fig. 7). Through observation, these two line meet at the sand depth of 0.06 m but the simulation curve is overally on the head of the experimental curve, this is mainly due to the fact the porosity of sand was neglected so as to look the sand as fluid. Furthermore, both lines appear very close gradient after the point of 0.08 m which represents a constant difference value between simulation and field test. When the beach cleaner works, its real working sand depth is within the 0.03-0.1 m, so these lines are satisfied with the real working conditions of pick-ups and the simulation fitted curve can be used to estimate the drag force of pick-ups.

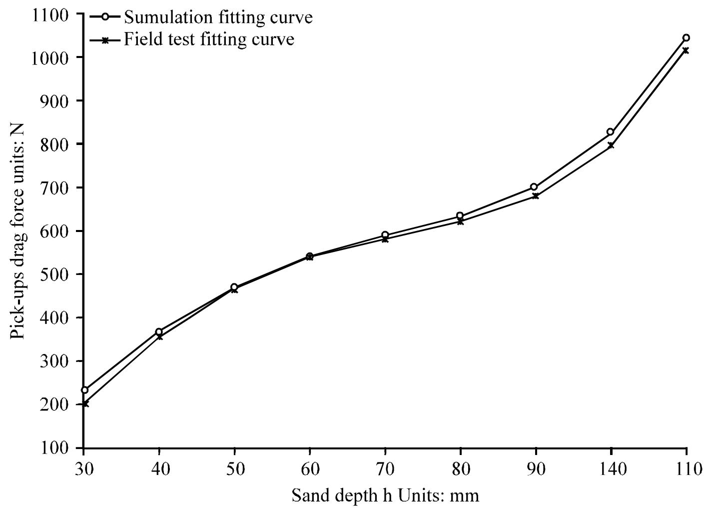

Fig. 7: Comparison between fitted simulation curve and fitted experimental curve of pick-ups force

In previous studies, the way to analyze the interaction between soil or sand and mechanics is mostly depended on EDEM which is used to study physical particles. But EDEM simulation requires a super processor and full-equipped material properties data bank. In this study, CFD constituted for EDEM method to do the simulation work, CFD has such advantages as: First, CFD calculation don't need an excellent computer and calculation time can be greatly cut down; second, the sand particle on Xiamen beach is enough tiny to be seen as fluid, adopting CFD method is valid; finally CFD, instead of EDEM, is a new method to study the pick-ups drag force with appropriate model parameters setting.

CONCLUSION

Considered the Xiamen beach sand as fluid approximately, fixed the position when the pick-ups rotate at the maximum sand depth, created the pick-ups and sand interaction model, controlled the turbulence model parameters and convergent residual error, then computed the pick-ups drag force.

Compared the simulation values with field test values of pick-ups, the relative error is within ±4.5%, it demonstrated that by converting the relative motion between pick-ups and sand, the calculating model is feasible to compute the drag force.

The fitting curves of pick-ups drag force got from MATLAB, especially the quartic polynomial can be used to suitably explain the functional expressions between pick-ups drag force and sand depth, this method overcame the deficiency that calculates the force in virtue of empirical formula.

Computational Fluid Dynamics (CFD) is a new method to study discrete objective if the studied object can be proved to be look as fluid or has fluid properties. In comparison to EDEM, CFD can save much calculation time while keep a high precision of the results.

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REFERENCES

Apsley, D., 2007. CFD calculation of turbulent flow with arbitrary wall roughness. Flow Turbul. Combust., 78: 153-175.

Barton, M.E., A. Cresswell and R. Brown, 2001. Measuring the effect of mixed grading on the maximum dry density of sands. ASTM Geotech. Test. J., 24: 121-127.

Chen, L., K. Zhou and Z. Li, 2010. Dynamic characteristics fitting of air springs and numerical analysis of air suspensions with variant stiffness. J. Mech. Eng., 46: 93-98.

Huang, S., X.Y. Zhu, C.Y. Guo and X. Chang, 2007. CFD simulation of propeller and rudder performance when using additional thrust fins. J. Mar. Sci. Appl., 6: 27-31.

Igwe, O., H. Fukuoka and K. Sassa, 2012. The effect of relative density and confining stress on shear properties of sands with varying grading. Geotech. Geol. Eng., 30: 1207-1229.

Kostyukov, V.D., 1967. Distribution of the density of sand in the sliding wedge in front of anchor plates. Soil Mech. Found. Eng., 4: 12-13.

Manuwa, S.I., 2009. Performance evaluation of tillage tines operating under different depths in a sandy clay loam soil. Soil Tillage Res., 103: 399-405.

Potter, M.C. and D.C. Wiggert, 2003. Mechanics of Fluid. 3rd Edn., China Machine Press, Beijing, China.

Rzehak, R. and E. Krepper, 2013. Bubble-induced turbulence: Comparison of CFD models. Nucl. Eng. Des., 258: 57-65.

Shibly, H., K. Iagnemma and S. Dubowsky, 2005. An equivalent soil mechanics formulation for rigid wheels in deformable terrain, with application to planetary exploration rovers. J. Terramech., 42: 1-13.

Tanaka, H., M. Momozu, A. Oida and M. Yamazaki, 2000. Simulation of soil deformation and resistance at bar penetration by the distinct element method. J. Terramech., 37: 41-56.

Trautmann, C.H., F.H. Kulhawy and T.D. O'Rourke, 1985. Sand density measurements for laboratory studies. Geotech. Test. J., 8: 159-165.

Wesseling, P., 2001. Principles of Computational Fluid Dynamics. Springer, Berlin, Germany, ISBN-13: 9783540678533, Pages: 644.

Zaidi, H., S. Fohanno and R. Taiar and G. Polidori, 2010. Turbulence model choice for the calculation of drag forces when using the CFD method. J. Biomech., 43: 405-411.