DEM simulation of mechanical arcs in granular flow

Paulo Lopes[1] • Milene S Lana[2] •José M Silva[3] •Hernani M Lima[4]

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Abstract Numerical methods are an important tool in engineering as they allow the approximate resolution of problems that do not have exact analytical solution. Recently, several research fields, including geomechanics, engineering, chemistry, physics and applied mathematics, have shown a renewed interest in accurately modeling the granular materials, and examine both the break, flow and deformation. The two main lines of research are continuous mechanical approach and, in contrast, the discrete mechanical approach. This work will focus the discrete approach, from real data flow test in a silo with crushed gneiss, we perform numerical simulation tests, with the discrete elements method, using the PFC2D software. This back analysis elucidated some questions about constitutive properties of the studied material and their behavior during the granular flow, which allowed from a few experimental data, reproduce reasonably the physical phenomenon in question. The simulated granular flow has a difference of less than 5% for the finer size fraction which was tested.

Keywords discrete elements method; numerical modeling; granular flow

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[1] Beyond Mining – Belo Horizonte– Brazil – paulo@beyondmining.tech

[2] Federal University of Ouro Preto (UFOP) – Department of Mining Engineer (DEMIN) – Ouro Preto – Brazil – milene@demin.ufop.br

[3] Federal University of Ouro Preto (UFOP) – Department of Mining Engineer (DEMIN) – Ouro Preto – Brazil – jms@ufop.edu.br

[4] Federal University of Ouro Preto (UFOP) – Department of Mining Engineer (DEMIN) – Ouro Preto – Brazil – hernani.lima@ufop.edu.br

1 Introduction

Granular materials may be defined as a set of discrete or agglomerated solids immersed in a fluid, macroscopic particles characterized by losing energy whenever there is interaction between them. A typical example of these interactions is friction during the collision between grains. The particles that make up such a granular material should be large enough so that they are not subject to fluctuations, convection movements of thermal origin, or Brownian movement. Thus, the minimum size of particle diameter is 1μm of order, and the maximum size varies according to the dimensions of the system being considered. In these cases, it becomes more important that the relative size between the particles and the system than its absolute size.

In the discrete approach, each particle of the granular medium is treated individually as well as their interactions with each other, respecting the basic principles of mechanisms. Despite being easily conceptualized, application of this method requires algorithms and computational routines, in order to process the huge volume of transactions relating thereto.

To this end, we have developed the method of discrete elements, to simulate the movement and interaction of a large number of particles, and is the main tool used in this work number.

Table 1 summarizes step-by-step the basic routine operations, data entry and boundary conditions, generically. The implementation of this algorithm indeed should obey the rules, syntax and constraints inherent in the language or platform used.

Table 1 Generic algorithm illustrating the method of discrete elements (adapted from Göncü, 2012)

INPUT:	Initial positions and velocities Time end of simulation T
BALANCE:	Initialize the time and particle positions, velocities and forces.

```
while t < T do
        for all particles do
            Find contacts or interacting pairs
            Compute and add up forces
        end for
        for all particles do
            Integrate the equations of motion
            Update positions and velocities
        end for
    Update system boundaries
        t = t +Δt
end while
OUTPUT:     Monitoring history
            Vector fields
            Scalar fields
```

Many authors dedicated to the study, including the works of Balevičius (2008 and 2011), Capriz (2008), Cleary & Sawley (2002), Coetzee & Els (2009 and 2010), Göncü (2012), Hill & Selvadurai (2005), Mishra & Thornton (2002), Nedderman (2005), Neves (2009) and Silva (2005 and 2006), which was extracted this case study.

2 Case study

Silva (2005), Silva (2005) used reduced scale physical models to study the influence of several factors on the behavior of the bulk material flow, applicable to underground mining among them were the principal:

- Material column height
- Angle of the passage
- Humidity
- Change of direction (knee) in the passage
- Presence of clay and other fines
- Flow obstruction problems
- Discharge section
- Particle size range of the material
- Material type (gneiss, dolomite, sand)

In Fig. 1 we can observe the actual small-scale model used for the flow tests, as well as an example of the formation of a mechanical arc.

Fig. 1 a) Experimental ore pass used for testing. b) Example of granular flow obstruction due to the formation of a mechanical arc

3 Numerical simulation

From this study, we defined practical application factors in the design of bulk material flow situations. Fig. 2 shows the measures of the physical models, extracted and implemented for numerical simulation.

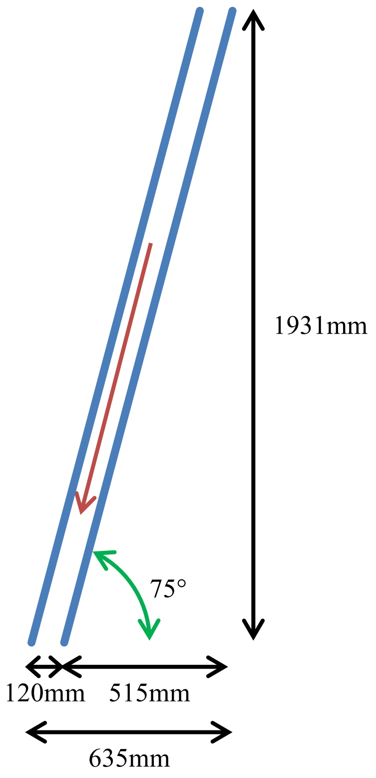


Fig. 2 Conceptual design of the ore pass of case study, to be implemented in the numerical simulation model

The value used on the simulations for the angle of repose was 35° (friction coefficient = 0.7), both the internal friction between the particles and the friction between the particles and the wall of the ore pass. The density value of the gneiss used was 2.63g/cm³.

After construction, the numerical model was filled with particles of sizes from 25 to 19mm (gravel 2), 19 to 9.5mm (gravel 1) and 9.5 to 4.8mm (gravel 0).

Following the generation of particles was started early iteration of the model in order to balance the unbalanced forces of the system, in the condition before the flow.

Finally, after stabilization of the system before the flow, this was released, and there was the formation of a mechanical arc or granular flow, as the particle size range studied.

To measure the mean flow velocity in cases where it occurred were monitored 10 points along the axis of the silo, to create a history of velocities, showing their evolution over the simulation.

4 Results and discussion

The results of the numerical model using the method of discrete elements were divided according to different particle sizes used in the case study reproduction, for comparison of both results. The Fig. 3 shows the formation of a mechanical arc upon releasing the flow into the gravel 2.

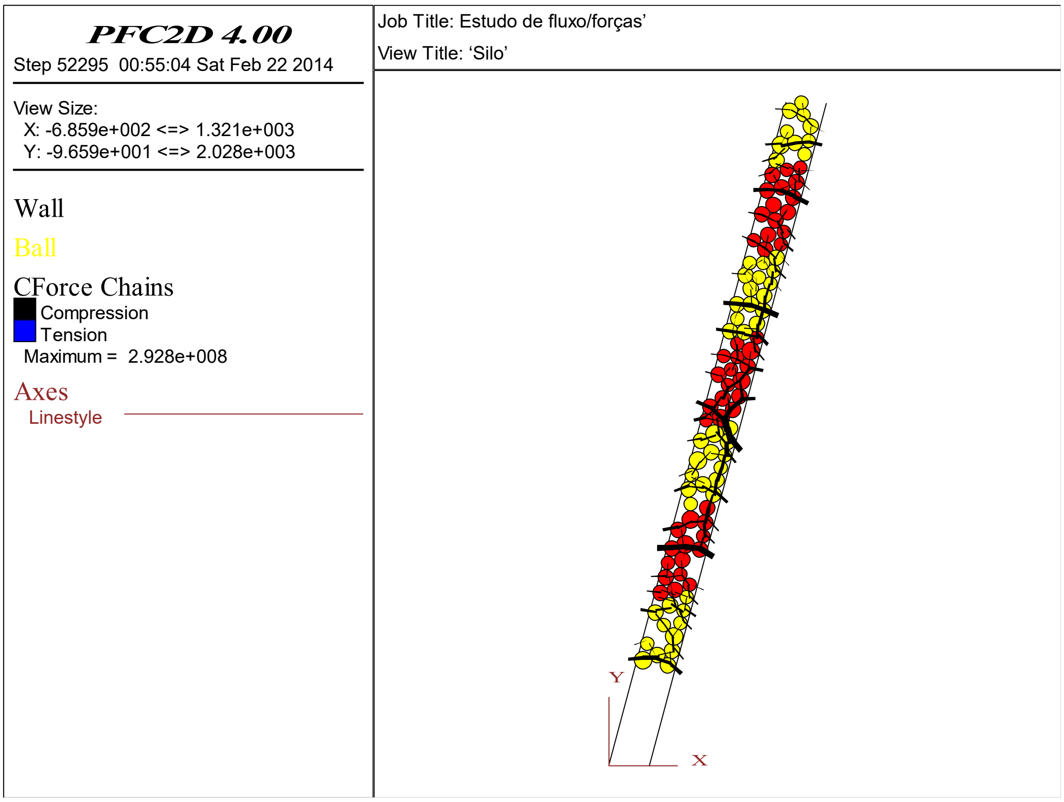


Fig. 3 Mechanical arc after release the flow in the numerical model, for particle size ranging from 25 to 19mm

The numerical model for the particle size ranging from 25 to 19mm was consistent with data from Silva's work (2005), where there was a mechanical arc in all tests.

The Fig. 4 shows the full granular flow after release of the gravel 1.

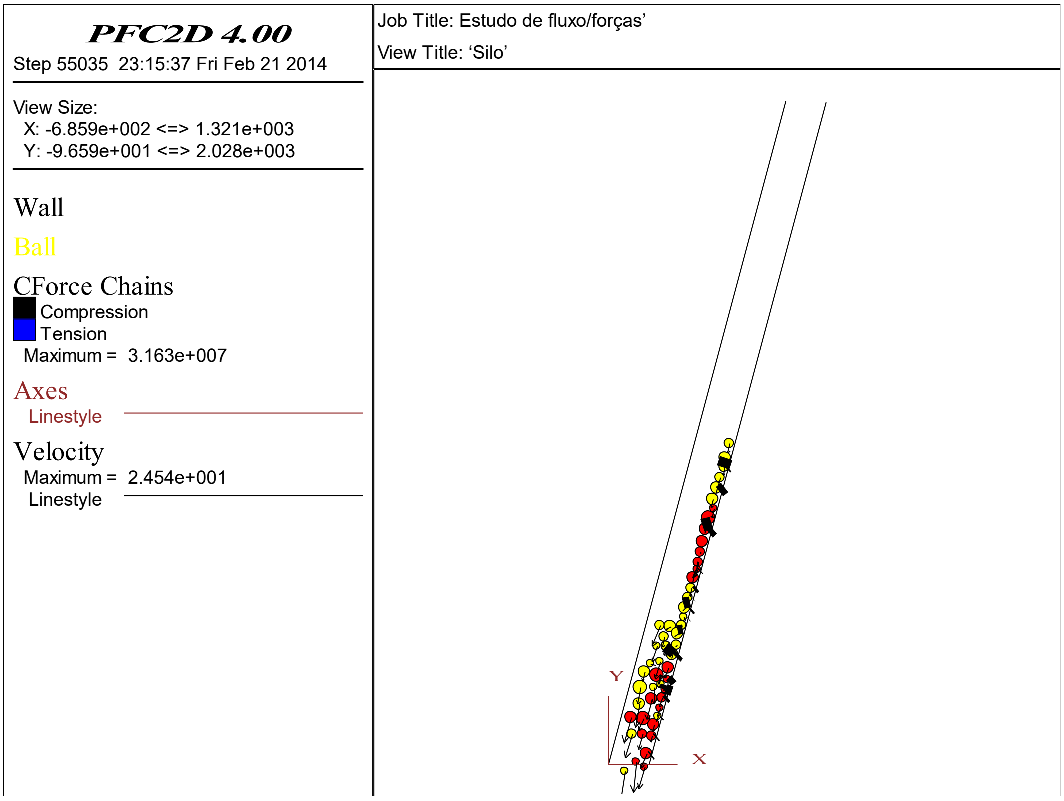


Fig. 4 Full flow occurrence in the numerical model, the particle size range from 19 to 9.5mm

The numerical model for the particle size range from 19 to 9.5mm was consistent with experimental data, where there full granular flow in all tests. It was measured the evolution of the mean flow velocity as the velocity history shown in Fig. 5.

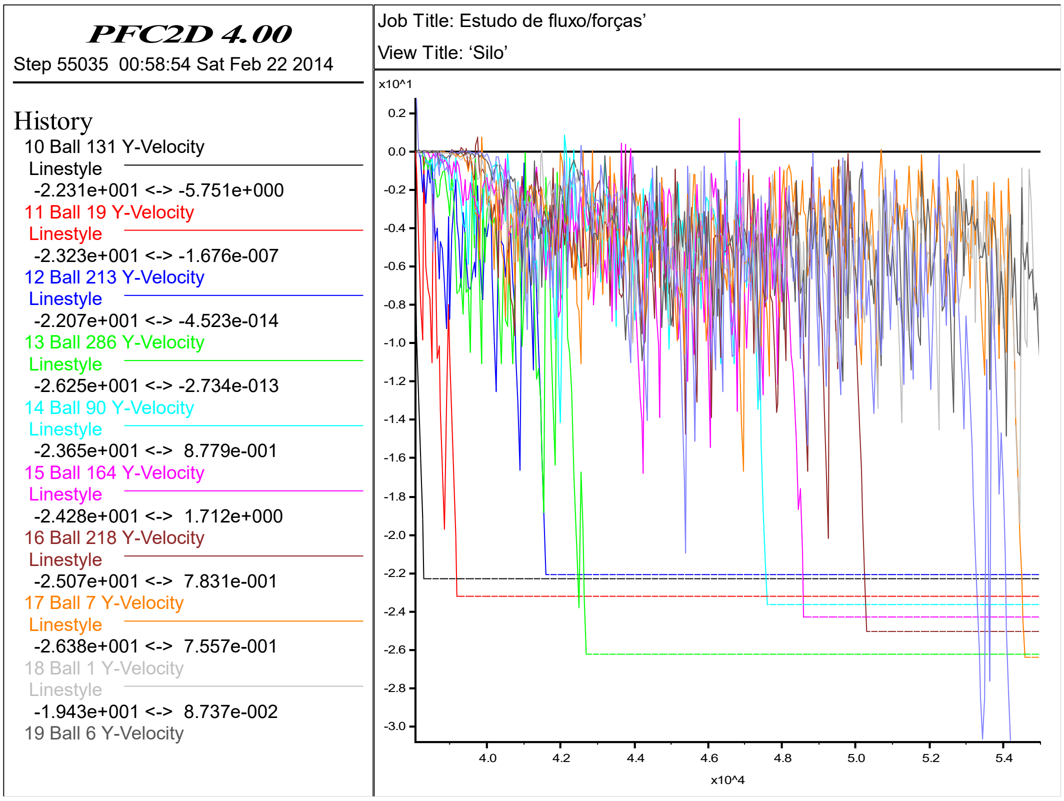
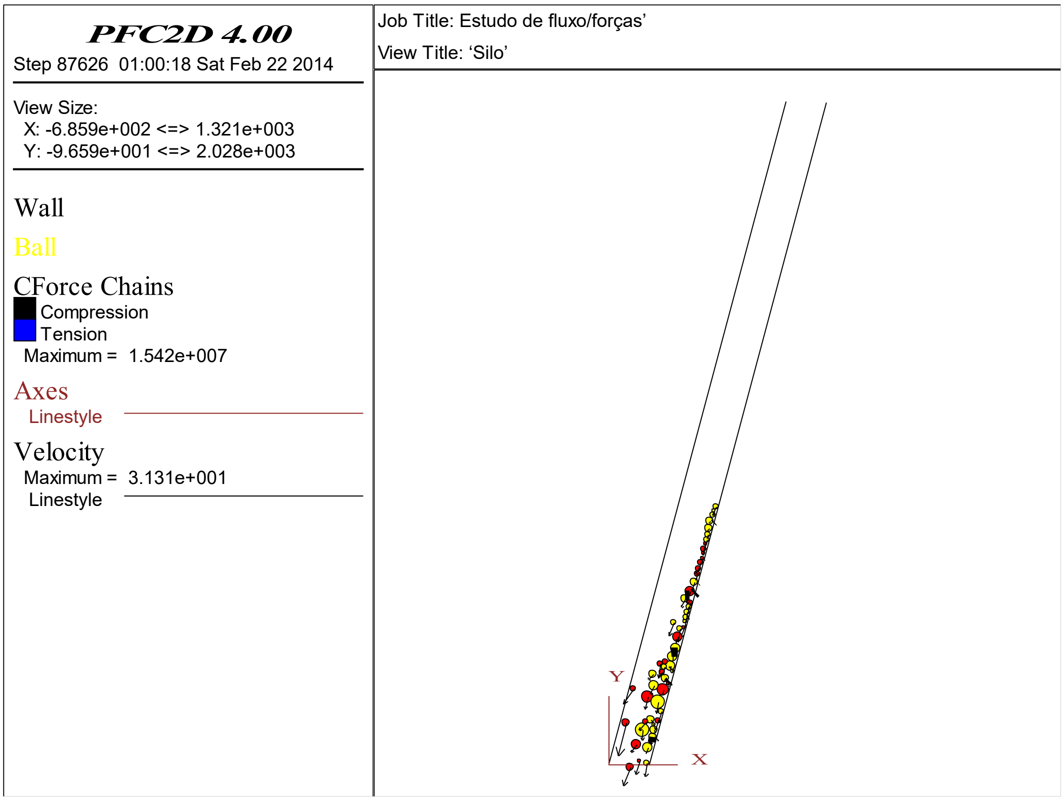


Fig. 5 History of the descending flow velocities in numerical model along its axis in the particle size ranging from 19 to 9.5mm

The mean flow reached an stable velocity, at each monitored point, of 23.63 cm/s. This value is consistent with the results obtained in the physical modeling experiments which was 20.73 cm/s.

The Fig. 6 shows the full granular flow after releasing the gravel 0.



PFC2D 4.00
Step 87626 01:00:18 Sat Feb 22 2014

View Size:
X: -6.859e+002 <=> 1.321e+003
Y: -9.659e+001 <=> 2.028e+003

Wall
Ball
CForce Chains
■ Compression
🟦 Tension
Maximum = 1.542e+007
Axes
Linestyle
Velocity
Maximum = 3.131e+001
Linestyle

Job Title: Estudo de fluxo/forças'
View Title: 'Silo'

Fig. 6 Full flow occurrence in the numerical model, the particle size ranging from 9.5 to 4.8mm

The numerical model for the particle size ranging from 9.5mm to 4.8mm was consistent with experiments data, where there full granular flow in all tests The mean flow velocity evolution was measured and recorded as show in Fig. 7.

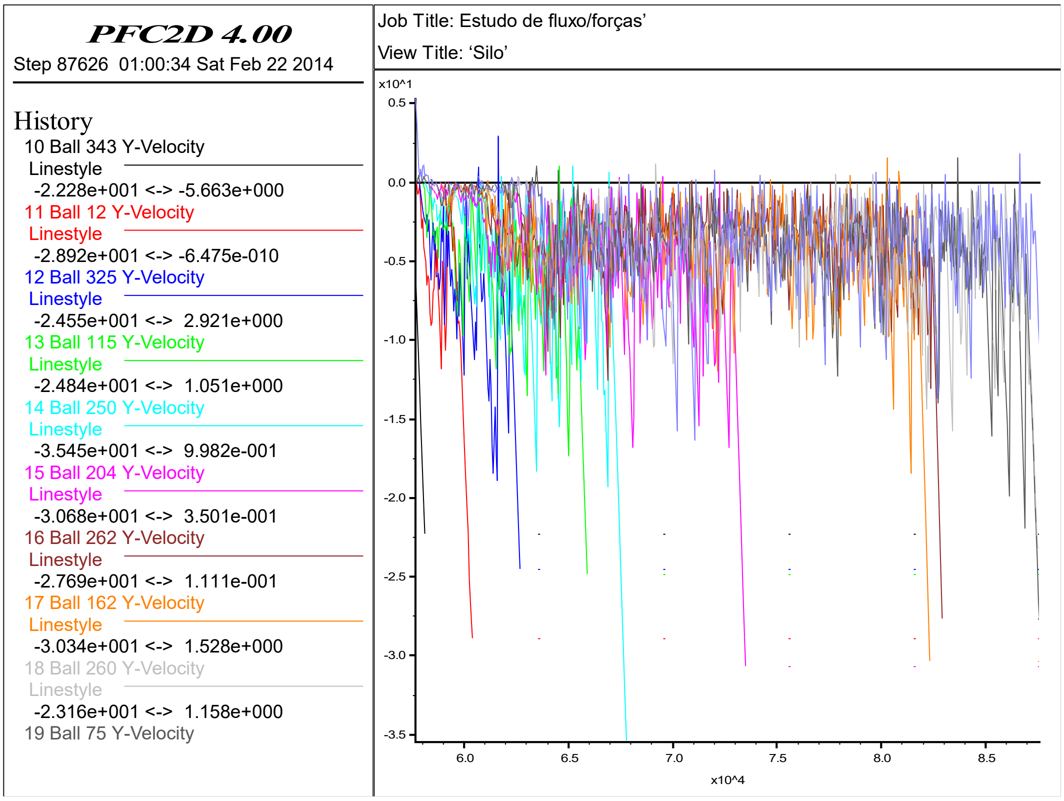


Fig. 7 History of the descending flow velocities according to the numerical model along its axis in the particle size ranging from 9.5 to 4.8mm

The mean flow reached an stable velocity, at each monitored point, of 27.55cm/s. This value is consistent with the results obtained in the physical modeling experiments which was 28.55cm/s

The difference of the velocities for the particle size range from 19mm to 9.5mm are the result of the spherical shape of real particles, which in conditions arising from the case study of scale, allow greater packaging and exert more pressure on the walls of the ore pass, hindering the flow.

Note that the difference of velocities for the particle size range from 9.5mm to 4.8mm in results was smaller, due to the better response to the flow of gravel 0 (D/d=16.78) in the actual situation, allowing a closer numerical simulation.

5 Conclusions

Table 2 shows the results obtained in different simulations compared to the physical model reproduced. Note that you as the D/d decreases, the adherence of the numerical model increases.

Table 2 Comparison and results between models

Type	Gravel 2	Gravel 1	Gravel 0
Size range (mm)	25 to 19	19 to 9.5	9.5 to 4.8
D/d	4.8	6.3	12.6
Mean flow velocity (physical model)	-	20.73	28.55
Mean flow velocity (DEM model)	-	23.63	27.55
Relative difference (%)	-	12.3%	-3.6%

The numerical reproduction of the experimental model was satisfactory because it allowed evaluate the sensitivity of granular flow friction both between particles and between particles and wall. The sphericity was also a point of discussion as it is an obstacle to be overcome for conducting a close simulation of the real phenomenon, once the sphericity of the crushed gneiss was not measured. Finally, the numerical model makes room for further analysis of the sensitivity of other variables such as the state of stress and deformability in granular media.

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Appendix A: Source code of simulation (gravel 2)

```
new
set random
title 'Estudo de fluxo/forças’
DEF create_hopper
        command
                wall id=1 kn=1e8 ks=1e8 friction=0.7 nodes (0,0) (120,0)
                wall id=2 kn=1e8 ks=1e8 friction=0.7 nodes (120,0) (635.615,1931.8587)
                wall id=3 kn=1e8 ks=1e8 friction=0.7 nodes (515.615,1931.8587) (0,0)
                plot wall black
        end_command
END
DEF create_balls
        command
                gen id 1 120 rad 19 25 x 525.615 625.615 y 1931.8587 7000
        end_command
END
DEF acomodate_balls
        command
                wall id=4 kn=1e8 ks=1e8 nodes (635.615,1931.8587) (635.615,7000)
                wall id=5 kn=1e8 ks=1e8 nodes (515.615,7000) (515.615,1931.8587)
                prop kn 1e8 ks 1e8 friction=0.7 dens 1000
                hist id 1 diagnostic muf
                solve
                cycle 30000
                del ball range y 1930 10000
                Delete wall 4
                Delete wall 5
        end_command
END
DEF diferenciate_balls
        Command
                prop color 1
                prop color 0 range y 250 500
                prop color 0 range y 750 1000
                prop color 0 range y 1250 1500
                prop color 0 range y 1750 2000
        end_command
END
DEF create¬_hist_vel
```

```
    command
        his nstep 50
        his id 10 ball yvelocity 60,0
        his id 11 ball yvelocity 111.561,193.239
        his id 12 ball yvelocity 163.123,386.479
        his id 13 ball yvelocity 214.684,579.718
        his id 14 ball yvelocity 266.246,772.957
        his id 15 ball yvelocity 317.807,966.196
        his id 16 ball yvelocity 369.369,1159.436
        his id 17 ball yvelocity 420.930,1352.675
        his id 18 ball yvelocity 472.492,1545.914
        his id 19 ball yvelocity 524.053,1739.153
        his id 20 ball yvelocity 575.615,1925.000
    end_command
END
DEF hist_vel
    command
        plot hist 10 11 12 13 14 15 16 17 18 19 20
    end_command
END
DEF monitor
    whilestepping
    skip = skip + 1
    if skip < 100
        exit
    endif
    skip = 0
    bp_ = ball_head
    loop while bp_ # null; escaneia todas as bolas
        bnext = b_next(bp_)
        if b_y(bp_) < -50.0; deleta as bolas
            ii=b_delete(bp_)
        endif
        bp_ = bnext
    endloop
    bnext = null
    bp_ = null
END
; create plot
create_hopper
plot set back White
SET grav 0.0 -9.81
create_balls
plot add ball yellow
SET disk on ;
acomodate_balls
diferenciate_balls
plot add cforce black blue
plot add axes brown
plot set title text ‘Silo’
plot add vel
delete wall 1
create¬_hist_vel
cycle 10000
solve
```

Appendix B: Source code of simulation (gravel 1)

```
new
set random
title 'Estudo de fluxo/forças’
DEF create_hopper
```

```
        command
                wall id=1 kn=1e8 ks=1e8 friction=0.7 nodes (0,0) (120,0)
                wall id=2 kn=1e8 ks=1e8 friction=0.7 nodes (120,0) (635.615,1931.8587)
                wall id=3 kn=1e8 ks=1e8 friction=0.7 nodes (515.615,1931.8587) (0,0)
                plot wall black
        end_command
END
DEF create_balls
        command
                gen id 1 300 rad 9.5 19 x 515.615 635.615 y 1931.8587 7000
        end_command
END
DEF acomodate_balls
        command
                wall id=4 kn=1e8 ks=1e8 nodes (635.615,1931.8587) (635.615,7000)
                wall id=5 kn=1e8 ks=1e8 nodes (515.615,7000) (515.615,1931.8587)
                hist id 1 diagnostic muf
                prop kn 1e8 ks 1e8 friction=0.7 dens 1000
                solve
                cycle 10000
                del ball range y 1930 10000
                Delete wall 4
                Delete wall 5
        end_command
END
DEF diferenciate_balls
        Command
                prop color 1
                prop color 0 range y 250 500
                prop color 0 range y 750 1000
                prop color 0 range y 1250 1500
                prop color 0 range y 1750 2000
        end_command
END
DEF create¬_hist_vel
        command
                his nstep 50
                his id 10 ball yvelocity 60,0
                his id 11 ball yvelocity 111.561,193.239
                his id 12 ball yvelocity 163.123,386.479
                his id 13 ball yvelocity 214.684,579.718
                his id 14 ball yvelocity 266.246,772.957
                his id 15 ball yvelocity 317.807,966.196
                his id 16 ball yvelocity 369.369,1159.436
                his id 17 ball yvelocity 420.930,1352.675
                his id 18 ball yvelocity 472.492,1545.914
                his id 19 ball yvelocity 524.053,1739.153
                his id 20 ball yvelocity 575.615,1925.000
        end_command
END
DEF hist_vel
        command
                plot hist 10 11 12 13 14 15 16 17 18 19 20; o principal e lembrar o id alocado
        end_command
END
DEF hist_fdes
        command
                plot hist 1
        end_command
END
DEF monitor
        whilestepping
        skip = skip + 1
        if skip < 100
```

```
		exit
	endif
	skip = 0
	bp_ = ball_head
	loop while bp_ # null
		bnext = b_next(bp_)
		if b_y(bp_) < -50.0
			ii=b_delete(bp_)
		endif
		bp_ = bnext
	endloop
	bnext = null
	bp_ = null
END

; create plot
create_hopper
plot set back White
SET grav 0.0 -9.81
create_balls
plot add ball yellow
SET disk on
acomodate_balls
diferenciate_balls
plot add cforce black blue
plot add axes brown
plot set title text ‘Silo’
plot add vel
delete wall 1
create¬_hist_vel
monitor

cycle 17000
```

Appendix C: Source code of simulation (gravel 0)

```
new
set random
title 'Estudo de fluxo/forças’
DEF create_hopper
	command
		wall id=1 kn=1e8 ks=1e8 friction=0.7 nodes (0,0) (120,0)
		wall id=2 kn=1e8 ks=1e8 friction=0.7 nodes (120,0) (635.615,1931.8587)
		wall id=3 kn=1e8 ks=1e8 friction=0.7 nodes (515.615,1931.8587) (0,0)
		plot wall black
	end_command
END
DEF create_balls
	command
		gen id 1 400 rad 4.8 19 x 515.615 635.615 y 1931.8587 7000
	end_command
END
DEF acomodate_balls
	command
		wall id=4 kn=1e8 ks=1e8 nodes (635.615,1931.8587) (635.615,7000)
		wall id=5 kn=1e8 ks=1e8 nodes (515.615,7000) (515.615,1931.8587)
		hist id 1 diagnostic muf
		prop kn 1e8 ks 1e8 friction=0.7 dens 1000
		solve
		cycle 10000
		del ball range y 1930 10000
		Delete wall 4
```

```
        Delete wall 5
    end_command
END
DEF diferenciate_balls
    Command
        prop color 1
        prop color 0 range y 250 500
        prop color 0 range y 750 1000
        prop color 0 range y 1250 1500
        prop color 0 range y 1750 2000
    end_command
END
DEF create¬_hist_vel
    command
        his nstep 50
        his id 10 ball yvelocity 60,0
        his id 11 ball yvelocity 111.561,193.239
        his id 12 ball yvelocity 163.123,386.479
        his id 13 ball yvelocity 214.684,579.718
        his id 14 ball yvelocity 266.246,772.957
        his id 15 ball yvelocity 317.807,966.196
        his id 16 ball yvelocity 369.369,1159.436
        his id 17 ball yvelocity 420.930,1352.675
        his id 18 ball yvelocity 472.492,1545.914
        his id 19 ball yvelocity 524.053,1739.153
        his id 20 ball yvelocity 575.615,1925.000
    end_command
END
DEF hist_vel
    command
        plot hist 10 11 12 13 14 15 16 17 18 19 20; o principal e lembrar o id alocado
    end_command
END
DEF hist_fdes
    command
        plot hist 1
    end_command
END
DEF monitor
    whilestepping
    skip = skip + 1
    if skip < 100
        exit
    endif
    skip = 0
    bp_ = ball_head
    loop while bp_ # null
        bnext = b_next(bp_)
        if b_y(bp_) < -50.0
            ii=b_delete(bp_)
        endif
        bp_ = bnext
    endloop
    bnext = null
    bp_ = null
END

; create plot
create_hopper
plot set back White
SET grav 0.0 -9.81
create_balls
plot add ball yellow
SET disk on
```

```
acomodate_balls
diferenciate_balls
plot add cforce black blue
plot add axes brown
plot set title text ‘Silo’
plot add vel
delete wall 1
create¬_hist_vel
monitor
cycle 30000
```