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RESEARCH NOTE

Experimental Determination of the Optimum Ball Impacts for Solution of Silo Obstruction

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ABSTRACT

A number of considerations should be taken into account in design stage to avoid the foregoing malfunctions of vertical silos containing ore concentrate. One of the silo problems is obstruction at the outlet which blocks the material flow. There are procedures, depending on the material properties and silo dimensions, to solve this problem. A common way is impacting the silo wall by manual hammering or pneumatic impacting. In the present work, the hopper of a laboratory silo containing the magnetite concentrate, for obstruction solution is impacted by single ball. Impacts lead to the bulk fracture and material discharge. Capturing the new arc profile after discharge and registering the required number of impacts which provide the continuous material flow helps us to determine the optimum impacts. Results show that the wall displacement due to the impact is a governing factor in obstruction solution and the best impact position is near the outlet. It is also concluded that at a constant kinetic energy the impacts by higher mass balls are more effective than the impacts by higher velocity balls.

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NOMENCLATURE

D	Silo width	K	Kinetic energy
d	Outlet width	m	Ball mass
h	Hopper height	v	Ball velocity
H	Silo height	s	Distance from the outlet
P	Momentum		

1. INTRODUCTION

The costly flow problems experienced in a silo, bin, or hopper are arching and ratholing. Arching (bridging) occurs when an arch-shaped obstruction forms above the silo outlet and stops flow. It can be an interlocking arch, where large particles mechanically interlock to form an obstruction, or a cohesive arch. A cohesive arch occurs when particles bond together due to effects of moisture, fines concentration, particle shape, temperature, etc.

However there is a strategy for silo design in order to prevent its obstruction [1] but in some cases material sizing and moisture will cause problems in material discharge [2]. A critical value for silo outlet can be evaluated to prevent the obstruction at the specified particle size and moisture. Mathews and Wu [3] investigated the effects of gravity on silo discharge and internal flow patterns by using a novel silo centrifuge model. Their results showed that the width of the flow channel at any given height above the outlet is independent of gravity and the local velocity of discharging material is proportional to the square root of gravitational acceleration. They also stated that the criteria for funnel or mass flow conditions are independent of gravity. In order to predict the rate of silo discharge, Beverloo et al. [4] developed a correlation based on easily measurable silo and material

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properties. Their correlation was modified by others [3] for rectangular outlets by maintaining dimensional consistency and considering that the flow rate increases linearly with silo thickness. Teng et al. [5] studied the effect of geometry deviations in silo body on the buckling modes. They used the Fourier decomposition to model the deviations. Medina et al. [6] experimentally investigated the effect of the orifice dimensions and its geometry on the flow rate of granular material. They showed validation of the relations describing the flow rate versus the grain size and orifice diameter. Leturia et al. [7] studied the flow characteristics of several granular materials by different methods. The effect of vertical vibrations on improving the material flow and silo unjamming was studied experimentally by Mankoc et al. [8]. Vibration was also used for unjamming by Janda et al. [9]. Zuriguel et al. [10] studied the effect of material properties and grain shapes on the silo flow blockage. Experimental data revealed that the arc formation highly depends on the grain shapes. Use of the vibration methods produces waves in silo which may be affected by the waves produced by grain-body interactions. Nateghi and Yakhchalian [11] studied the vibration induced by the interaction of material with the silo body.

A silo in Gol-e-Gohar iron ore complex in Iran encountered blockage which made it out of order. It contains magnetite concentrate. A comprehensive study is currently undertaken to investigate one individual procedure or simultaneously multiple ways to solve the problem. As a part of this research, the impact mechanism which is a candidate solution is studied experimentally. In the present work, the effect of impact parameters (ball size, ball velocity and impact position) on obstruction solution is investigated.

2. PROBLEM DESCRIPTION

The main problem encountered in mechanisms handling the granular materials may be the wear of components [12]. A silo may be initially well designed but, over a period of operation, variation of the material moisture and particle size causes unstable material discharge. Such a problem occurred in a silo in Gol-e-Gohar iron ore complex in Iran. Unstable discharge and obstruction made it useless. A laboratory silo is used to study the problem. The impact of silo wall is studied as a flow aid mechanism. The experiments are carried out at different impact conditions including the ball size, impact velocity and impact position.

Various terminologies are used for containers of granular materials. Here, the section of the container with vertical walls is referred to as the silo main box and the section of container with sloping walls is referred to as the hopper.

3. LABORATORY SILO

Laboratory apparatus is a square cross-section silo which is made of Plexiglass having visible walls to view the material flow. It has been explained in another work [13]. The laboratory silo is scaled down from the operating full scale silo by the scale factor of about 40:1. Magnetite concentrate with a moisture content of about 5% and bulk density of 2000 kg/m^3 and mean particle size below 3 mm is used for tests. The *D10* for the current material is about 0.8 mm and *D80* is about 2 mm. This means that the size of about 70% of the material ranges between 0.8-2 mm. To have the specified moisture content, the material is firstly dried in a furnace over 100 minutes at the temperature of 100 ^{o}C. After this, the water is added as 5% of the dry material weight. The silo is filled to the specified level. After filling, the grain is allowed to equilibrate for a period of 0.5 h. The wall and the floor of the silo are supported on a steel structure. The hopper is wedge-shaped with a 60 mm slot width. A photograph and schematic image of this silo is illustrated in Figure 1 and its dimensions are given in Table 1.

4. EXPERIMENTAL PROCEDURE

While the outlet is closed by a plate, silo is filled of the magnetite concentrate using a container for period of 1 min to ensure that the same filling conditions are followed for all tests. Foundation is fixed to avoid fluctuations which affect the tests. After the silo is completely filled, the plate is removed to open the silo outlet.

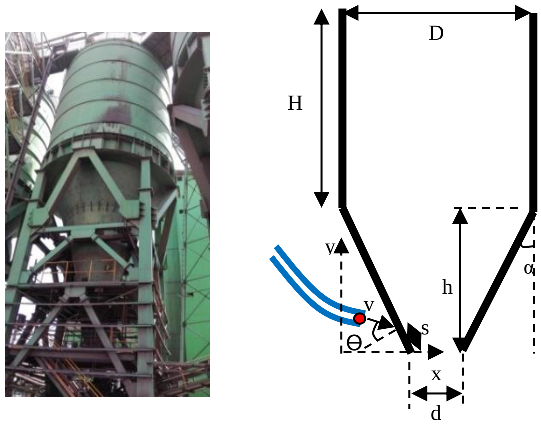


Figure 1. A photograph of the full scale and schematic image of laboratory silo

TABLE 1. Laboratory silo dimensions

H(m)	h(m)	D(m)	d(m)
0.35	0.26	0.25	0.06

If there is no material flow, the impacting process begins. As illustrated in Figure 2, a single ball is released manually from the specified height to move through a curved hose and impact the silo wall. Hose is fixed on foundation to avoid swinging. After individual impacts, the material discharge is allowed to be completed and stationary condition is achieved again. Then, the new material profile at the outlet is captured and the next impact is tried. The impacts are done to have the continuous flow, the stationary condition doesn't occur again and the silo is completely discharged. This will be the end of a test. Because of symmetry, only one hopper wall is impacted and the material profile is captured from the other three sides. In the present work, right, front and left walls with respect to the impacted wall are referred to as wall 1, 2 and 3 respectively.

4. 1. Impact Parameters Impact parameters include the ball size, ball velocity and impact position. Impact position is measured from the hopper outlet to the impact point i.e. distance *s* in Figure 1. Through the text, *sx* means that the impact position is at *x mm* from the hopper outlet and *bx* means that the ball used for impact has a diameter of *x mm* and *vx* means that ball velocity is *x m/s*. The impact positions in the present experiments are *s40*, *s100* and *s170*.

4. 2. Velocity Determination Because of the energy waste through the ball path in the present impacting mechanism the energy conservation principle may give incorrect evaluations for the ball velocity. The velocity measurement tests are performed at first. The ball is released from a specified height (h_1 in Figure 2), moves through a curved hose, exits it and undergoes a free falling path to the ground surface. Distances q and h_2 (Figure 2) are measured and the ball velocity at the hose exit is evaluated using the free falling relation as follows:

$$h_2 = \frac{1}{2} g \left(\frac{q}{v\cos\beta}\right)^2 + q\tan\beta \qquad (1)$$

where g is the gravity acceleration and other parameters are given in Figure 2.

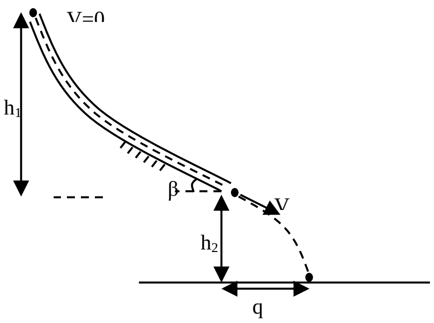


Figure 1. Schematic representation of the procedure of ball velocity measurement

The hose end is possibly placed perpendicular to the hopper wall but it is not completely achieved. So, the angle of the hose end and hopper wall is measured in order to evaluate the normal part of the ball velocity, i.e. $v_n = v\cos\Theta$ (Θ in Figure 1). The velocity which is referred to in the foregoing results is the normal velocity. Sufficient space is considered between the hose end and hopper wall to allow the ball to fall down after impact and the double impact be avoided.

5. BULK BEHAVIOR DUE TO IMPACT

Arching often occurs in the form of cohesive arching and mechanical blockage. Cohesive arching occurs with cohesive materials whereby an arch of material is formed above the silo outlet, able to support both its own weight and the weight of the above material [14]. The material elements are in equilibrium under the body force and surface forces. The gravity produces the dominant body force which governs the material flow in silo [3]. Surface forces include normal and shear stresses due to the internal pressure and material cohesive effects. A schematic representation of typical material element is illustrated in Figure 3.

According to the Jenike Yield Locus (JYL) which is illustrated in Figure 4, initiation of the material flow depends on the normal pressure and shear loads. The JYL represents a line that divides between operating conditions.

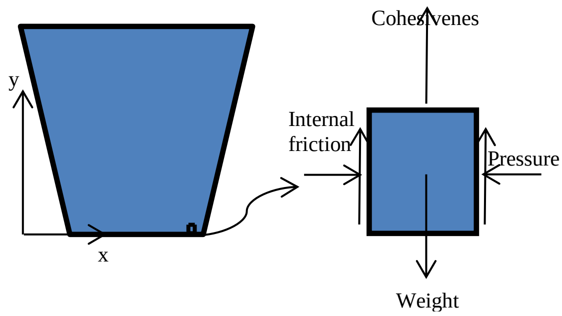


Figure 3. Scheme of a material element at silo outlet

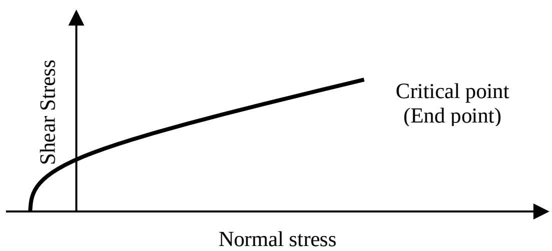


Figure 4. Chase, G. G.[15] describing the relation of normal and shear stress which causes the granular material departure

Above the JYL, the shear stress is sufficient to lead to the material flow. Below the JYL, the normal stress is too large to let the material to flow at the given shear stress.

Material element remains in equilibrium until the state of stress is below the JYL. Impact of hopper wall is a way to disturb this equilibrium. It leads to the rapid displacement of the wall which affects the material internal pressure. Hopper wall undergoes a reciprocating motion which instantly lowers the material internal pressure. The suddenly weaken pressure leads to the bulk fracture. A partial discharge occurs and the remained material constitutes a new blockage profile. Here, the new blockage profile after impact is called fracture boundary. Depending on the impact parameters and material properties, there is different response to impact. Schematic representation of the silo hopper is illustrated in Figure to describe the fracture boundary due to the impact. In this figure, region A separates from the total bulk during a single impact. The material in region B is still in equilibrium and more impacts are required. The impacts are repeated until the total material flow occurs and silo is completely discharged.

6. RESULTS AND DISCUSSION

Discharge of material after a single impact leaves a new profile for the arc bridge at the silo outlet. Captured image of this profile helps us to represent it quantitatively. A typical photograph of arc profile and the corresponding graph is illustrated in Figure 6. The arc profile height is measured from the silo outlet. In labels of the graphs in Figures 6 and 7, the ordinate is *y/h* and abscissa is *x/D* which *y* and *x* are illustrated in Figure 3 and *h* and *D* are the hopper height and main box width, respectively. Profiles are measured with Calipers with an accuracy of 0.01 mm. However the profile boundary includes the granular material, but the maximum care have been paid to have lower than 5% error. In the following figures, as said before, *bx* means the ball by diameter of *x* mm and *sx* means that the impact position is *x* mm from the silo bottom.

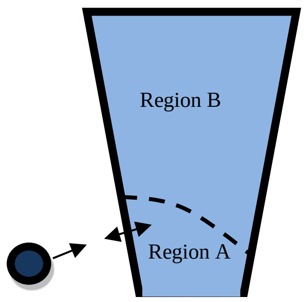


Figure 5. Fracture boundary in the silo hopper due to the single impact

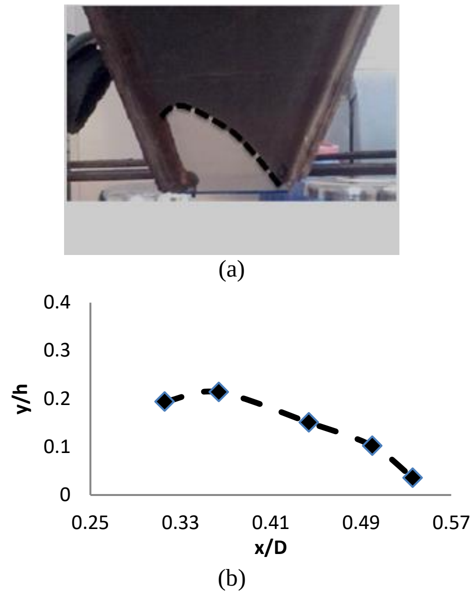


Figure 6. Arc bridge profile a) by image and b) by graph

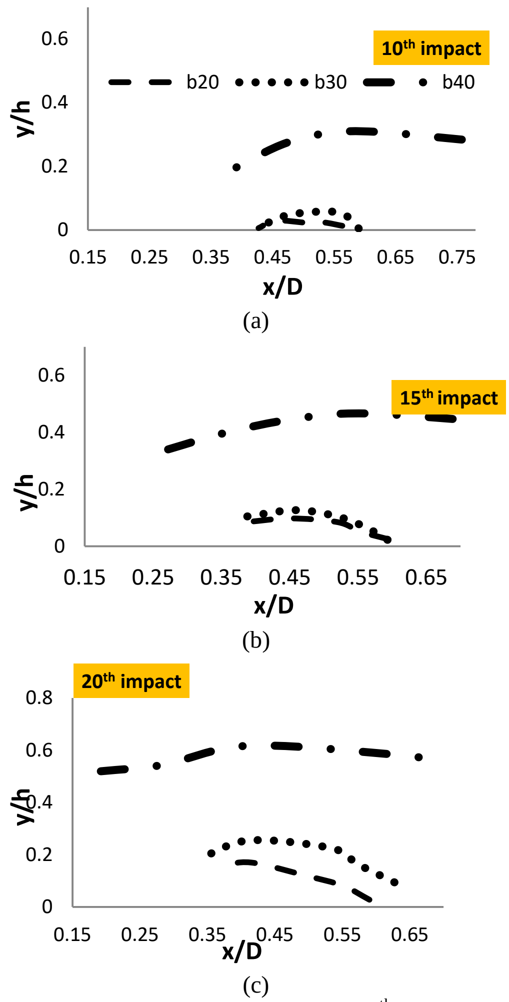


Figure 7. Arc bridge profile after a) 10^{th} impact, b) 15^{th} impact and c) 20^{th} impact, impact position: s40, impact velocity: v= 2.5 m/s

As depicted in Figure , the fracture boundary progresses as the number of impacts increases. According to this figure, more discharge occurs near the impacted side (left side) which displays the higher progress of arc profile compared to other sides. The maximum height of the arc profile near the hopper walls 1, 2 and 3 after the specified number of impacts is illustrated in Figure 2. Arc bridge profile height near wall 2 which is at the opposite side of the impacted wall (far from the impact point) is less than the profile height near the other sides. Arc bridge profile near the walls 1 and 3 is approximately identical.

By increasing the impact number, the arc bridge profile progresses toward the silo interior. The rate of progress at different impact conditions is illustrated in Figure 9. The rate of profile variation can be determined by appropriating an approximate linear relation to the data of Figure 9. These rates are given in Table 2. The maximum rate is obtained by ball 40 mm at the impact position of *s40*. It means that the impacts at a little distance of the silo outlet are the most effective impacts for the obstruction solution.

Impact process ends when the continuous flow occurs and the silo is completely discharged without material blockage. Results show that the required number of impacts for initiation of the continuous flow, *Nr*, depends on the ball size, ball velocity and impact position. Figure 10 shows the required number of impacts (*Nr*) at different impact conditions.

The data of Figure 9, Table 2 and Figure 10 reveal that the ball size is a dominant factor in silo obstruction solution by impact. It has slight positive influence on the rate of arc profile progress. From the impact position point of view, *s40* gives the better results. As the impacts situate more far from the silo outlet, more impacts are required for silo discharge. Another important impact parameter is the ball velocity whose effect is discussed from the kinetic energy and momentum points of view.

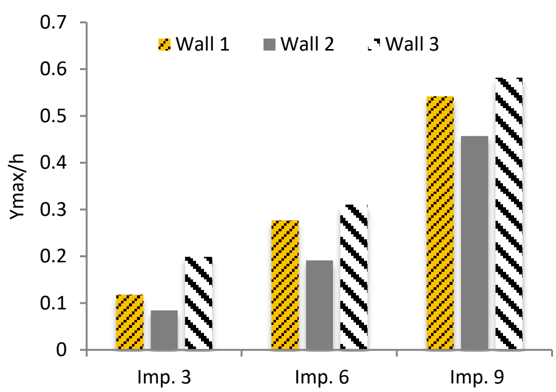


Figure 2. Maximum height of the arc profile near the hopper walls, b40, s40, v2.5

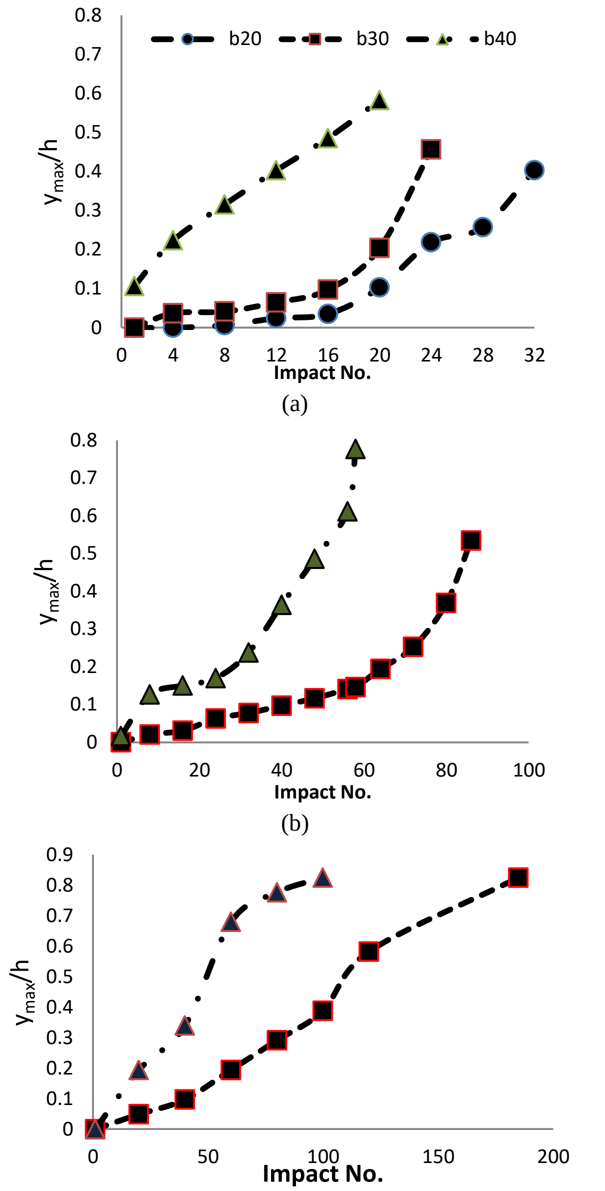


Figure 9. Dimensionless maximum height of the arc profile, v2.5, a) s40, b) s100 and c) s170

TABLE 2. Rate of increase of maximum height of breaking boundary

Ball size (mm)	Impact position	rate
20	s40	0.012
30	s40	0.016
40	s40	0.024
30	s100	0.004
40	s100	0.011
30	s170	0.003
40	s170	0.008

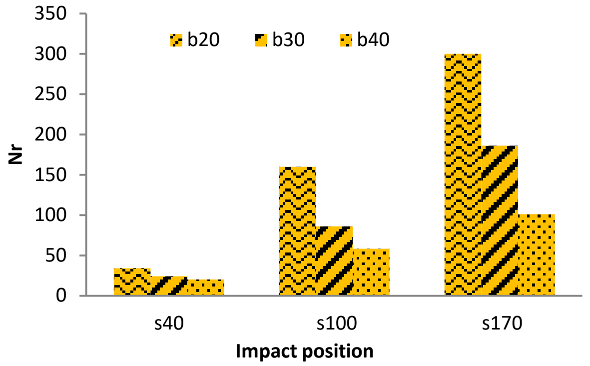


Figure 10. Required number of impacts for initiating the continuous flow

Ball kinetic energy and momentum are as follow:

$$K = \frac{1}{2}mv^2 \tag{2}$$

$$P = mv \tag{3}$$

In which *K* is the kinetic energy, *P* is the momentum, *m* is the ball mass and *v* is the ball velocity. Effect of impact velocity, in the form of kinetic energy and momentum variation, on the required number of impacts for producing the continuous flow (*Nr*) has been illustrated in Figure .

To have an incremental manner of data by increasing the ball impact energy and its momentum, we use *1/Nr* in graph processing.

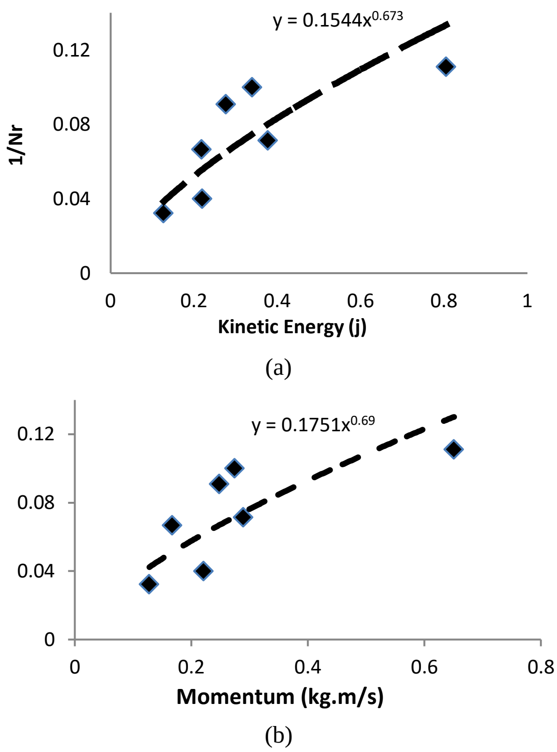


Figure 11. Variation of *1/Nr* with respect to the a) ball kinetic energy and b) ball momentum

To compare the effect of impact energy and impact momentum on improvement of the ability of impact in obstruction solution, a power equation in the form of ax^n is fitted to experimental data of Figure . According to these relations, either coefficient *a* and power *n* are greater in case of momentum consideration than the energy consideration. It reveals that the momentum increment is more effective in obstruction solution than the energy increment. Since the energy depends on velocity by power of 2 while the momentum depends on it by power of 1, and they depend on ball mass by power of 1 it can be inferred that the effect of ball velocity is less than the effect of ball mass. It means that we should use possibly massive balls instead of high velocity ones to have the efficient arc breakage. The silo wall stress analysis should be done to prevent the wall failure.

As mentioned, the wall displacement due to the ball impact leads to disturbing the stress state of material and results in the fracture of layers in the bulk material. A procedure is devised to measure the approximate wall displacement in order to see whether the appropriate impacts correlate with the wall displacement or not. This is done by using the light and slender rods which their tips are put in contact with the impacted wall. End of these rods comes out from the opposite side. The rods are in contact with the impacted wall but they don't adhere to it. Bulk material helps the rods to remain in contact with the hopper wall and they don't encounter extra movement. As the wall is impacted, the wall and rod tip move forward in direction of the impact. The wall returns but the rods don't do. After impact, the rod displacement is visible from the opposite side of impact and we can measure it by Caliper. The estimated error will be less than 0.1 mm. Scheme of rods within the hopper is illustrated in Figure . The results of wall displacement are illustrated in Figure . It is seen that the wall displacement due to impact at *s40* is more than the impacts at *s100*. Moreover, it increases as the ball size increases. These confirm that the wall displacement is the governing factor in silo obstruction solution.

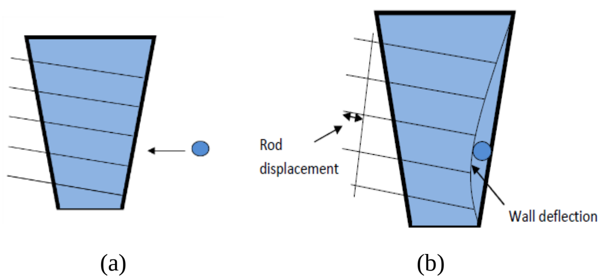
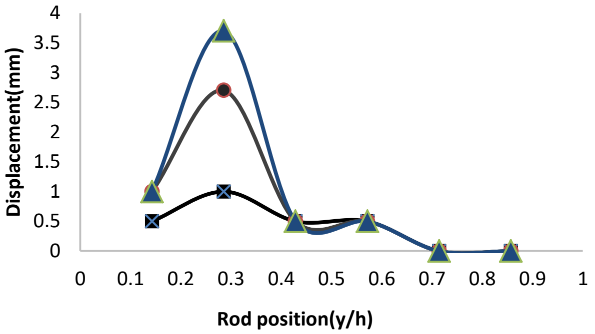
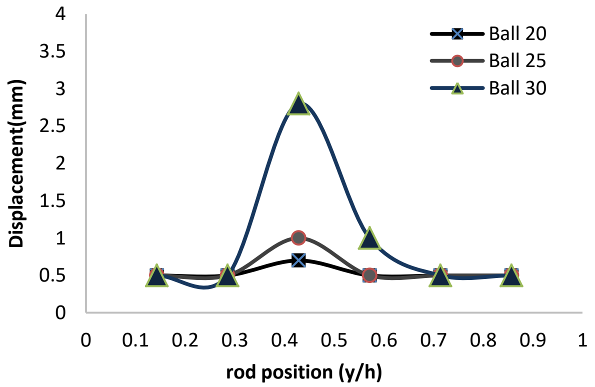


Figure 12. Configuration of rods to measure the impacted wall displacement, a) before impact, b) magnification of the maximum deflection



(a)



(b)

Figure 13. Displacement of impacted wall by balls b20, b25 and b30 at impact positions a) s40 and b) s100

7. CONCLUSIONS

The silo has been scaled down from the operating full scale silo in Gol-e-Gohar iron ore complex by the scale factor of about 40:1. The small-scale silo satisfies the dimension scaling but the shape scaling is limited because of the limitations in fabricating process. The silo body is made up of Plexiglass; it could hardly be made in conic shape. This may not be the problem. The main point of the present study is whether the ball impact is applicable to excite the compacted material and provide the material discharge. The governing parameters include the material internal pressure and friction. On the other hand, the mechanical properties of the hopper body are important. The present results reveal that the magnetite concentrate positively responds to the ball impacts if the ball position and impact energy are set appropriately. The results show that the best impact position for optimum discharge is about 15% of the hopper height from the silo outlet. Before this, the operators of the full scale silo carried out the body impacting by means of the manual pendulum close to the silo outlet and didn't achieve the acceptable discharge. According to the present results, they changed the impact position to the 15% of the hopper height, 1.68 m above the silo outlet, and the better discharge was obtained. It is, by itself, a worthy result of the present work which was used for full scale silo. Moreover, the results of the present work slightly reveal that the main factor in obstruction solution by impact is impact position which influences the wall displacement. However, the test by the full scale silo is hardly possible; we can model the full scale silo in the analytical software to determine the impacts which give the maximum wall displacement.

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RESEARCH NOTE

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چکیده

برای پیشگیری از کارکردهای نامناسب سیلوهای حاوی کنسانتره معدنی باید ملاحظاتی در مرحله طراحی در نظر گرفته شود. یکی از مشکلات عملکردی این سیلوها انسداد دهانه است که جریان مواد را متقف می کند. با توجه به خواص مواد و ابعاد سیلو راهکارهایی برای رفع این مشکل بکار گرفته می‌شود. یک راه رایج، ضربه زدن به بدنه سیلو با چکش دستی و یا پنوماتیکی است. در کار حاضر بدنه یک سیلوی آزمایشگاهی حاوی کنسانتره مگنتیت، جهت رفع انسداد، مورد اصابت گلوله قرار می‌گیرد. ضربات موجب شکست توده مواد و تخلیه آنها می‌شود. ثبت پروفیل انسداد بعد از هر برخورد و تعیین تعداد برخورد لازم جهت برقراری جریان پیوسته مواد، بعنوان معیارهایی در تعیین شرایط بهینه ضربه جهت رفع انسداد مورد استفاده قرار می‌گیرد. نتایج نشان می‌دهد که جابجایی بدنه در اثر ضربه فاکتور مهمی در تاثیرگذاری ضربات بر رفع انسداد بوده و ضربات نزدیک دهانه خروجی مناسب تر از دیگر محل های برخورد است. همچنین مشخص شد در انرژی جنبشی ثابت، گلوله‌های با جرم بیشتر بهینه‌تر از گلوله‌های با سرعت بالاتر در رفع انسداد عمل می‌کنند.

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