Design of a Combined Gravity Concentration and Leaching Plant for the Small-scale Gold Mining Industry in Ghana

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Abstract

The issue of gold losses and low recovery is critical in the small-scale mining industry. Despite the mechanization of the industry, most small-scale miners use simple and less efficient traditional sluices to concentrate gold from the gangue minerals. Research shows that recovery in these traditional sluices yields much losses of the gold (mostly fine gold) to tailings, resulting in low/poor recovery. Therefore, this project seeks to design a combined gravity concentration and leaching plant to improve gold recovery in the small-scale mines. The system design was modelled using CAD software (solidworks). The design incorporated a multiple stage sluice-box and a mechanically agitated cyanide-based leaching drum. Based on the design analysis and calculation, maximum mass of gold ore material needed to be processed at a time on the sluice-box was 415 kg. The transmission power required to adequately agitate or mix the pulp of mass 900 kg in the leaching drum of capacity 0.64 m^3 was 25.2 kW, at a drum mixing speed of 100 rpm. The power was transmitted to the drum through belt pulley and bevel gear systems, reducing the engine speed from 2400 rpm to the required mixing speed of the drum. This combined technique would demonstrate an improvement in gold recovery in a cost-effective and environmentally benign manner. Therefore, adopting this design in their operations to reduce gold losses, improve local production of gold, and to boost their profit.

Keywords: Gravity concentration, leaching, small-scale mining, Sluice box.

1 Introduction

Small scale gold mines are the mines that use relatively small and low-quality devices to extract ore containing gold from the earth's crust. This mine is currently operated by both licensed (trained people) and unlicensed people who are locally referred to as "Galamsey" operators (Aryee *et al.*, 2003). As part of the mining sector, small-scale gold mines contribute significantly to the total value of gold mined in the country with promising economic benefits (Hilson, 2002). The mine serves as a source of employment for many. On the other hand, gold recovery in the small-scale mine has been poor due to the less efficient mining methods and tools employed. Therefore, an increase in productivity (gold recovery) in these small mines will, in turn, improve the livelihood of its employees.

The issue of gold losses and low recovery is critical in the small-scale mining industry despite the mechanisation of the industry. Majority of the artisanal and small-scale miners rely solely on traditional mining methods where they employ and feature simple equipment, rudimentary tools, and techniques like shovels, pans, sluices, pick-axes, chisels and hammers for recovery. For instance, in Tarkwa, where the ore deposit is mostly alluvial, the sluicing technique is commonly employed by to concentrate the gold which is further processed using mercury amalgamation.

Studies has shown that the traditional sluicing technique yields many losses of gold particles to tailings as it is ineffective in capturing fine gold. Thus, resulting in poor/low recoveries of gold. Also, the gold amalgamation technique generates significant mercury emissions, resulting in environmental and health-related problems. Fig. 1

shows a traditional sluicing method (poor gold recovery method) at a small-scale mine site. This picture was taken at a mine site in Tarkwa.

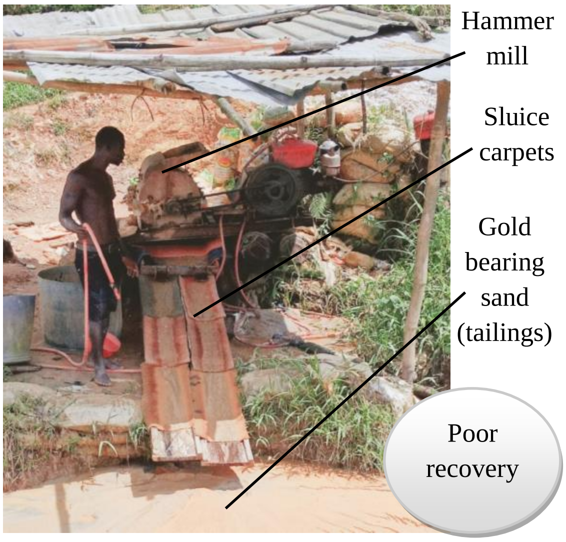

Fig. 1 Setup of a Hammer Mill and a Traditional Sluice System

This work seeks to minimise fine gold losses and improve gold recovery by combined gravity concentration and leaching plant.

The need to increase the recovery of gold has resulted in several different techniques for extracting or recovering the gold in both small-scale and large-scale mines. The use of long leaching time and a Carbon-in-Leach (CIL)/Carbon-in-Pulp (CIP) recovery system may eliminate the need for gravity concentration, but gravity concentration method has recently gained attention and seen as an inexpensive way of improving the recovery on existing plants (Lovedayt, 1982). Hence, combining the effects of both gravity concentration and leaching methods for extraction is essential to an increased rate of gold recovery.

Sluice or sluice-box is an inclined, flat-bottomed trough with the bottom lined with trapping mechanism known as the sluice carpet or mat. A sluice uses water to wash gold ore down an angled platform. The working principle of a sluice-box is that denser particles sink to the bottom of a stream of flowing water while the lighter particles tend to be carried downstream and discharged off the end of the sluice (Veiga *et al.*, 2006). The sluice carpets and rifles capture the heavy gold particles as the slurry flows down the sluice-box. Sluices are usually inclined at a 5 to 15-degree angle and are efficient to separate gold particles from the gangue when well used. The kinetic energy of water increases as the water flows down the sluice. A higher gold is recovered if the force of the water moving down the sluice is decreased. The use of riffles helps break the flow to improve recovery. Zigzag sluice or multiple stage sluice-box where a top sluice drops material (slurry) onto a second sluice can also be used to break flow velocity and therefore increase gold recovery (Veiga *et al.*, 2006).

Duncan and Rudolph (1973) showed that gravity concentration of gold prior to cyanidation made a significant improvement in the recovery of very fine gold.

Stewart and Ramsay (1993) conducted experimental studies that described how the design of a sluice-box could be modified to improve its effectiveness so that both grade and recovery of fine heavy mineral (fine gold) can be improved. They carried out the study in a Perspex sluice-box (3.5×0.1 m), fitted with various riffle designs and a flow measurement device, which could be tilted to vary the slope of the sluice-box. The experiment included changes in flow (patterns), riffle spacing, riffle geometry, and development quiescent (dead) zones. In presenting their experimental results, they concluded that once the flow rate in the sluice-box is great enough to maintain most of the solids in suspension, then solid is retained in the box in quiescent (dead) zones. The size of these zones is dependent on flow patterns within the box, which in turn are mainly dependent on box geometry. Settled gangue particles in a sluice-box provide quiescent zones where fine gold can be trapped. Increasing the sluice-box slope increases the flow rate but causes a reduction in the dead space, which can cause a decrease in recovery. They also concluded that sluice-boxes could be improved to increase both grade and recovery the riffles design in a manner that the dead zone is established and the movement in the dead zone optimised.

Subasinghe (1993) reviewed a mechanistic approach to the modelling of sluice-box operations. He formulated a tentative model based on a modified version of the Shields criterion of sediment transport theory to predict the performance, covering a wide variety of feed and operating conditions. He established the application of non-linear optimisation procedures to evaluate the optimal sluice configuration and optimal operating flowrate for processing of alluvial deposits with given gold and gangue size distributions.

Mundhra (2016) invented or designed a sluice-box having a sluice bed which contains riffles of different or varying patterns and profiles to increase the chances of retaining gold particles, and other precious ore, while more effectively removing the unwanted material. The sluice-box comprised a diverter to help transfer water through the sluice bed.

Lehmann (2020) highlighted the importance of the factor “frequency of cleanups” of batch-operated sluices. He performed the investigations and tests in a German gravel plant, which led to the conclusion that the cycle time, respectively, the frequency of cleanups is also an important factor for the assessment of the recovery of a sluice-system. He obtained a set of data pairs by feeding a test mat-sluice under industrial conditions and determining the mass and content of trapped gold after different feeding times. He characterised the heavy mineral (gold) enrichment in a sluice as a process, and his experiments led to the approach of modelling this process (the enrichment of sluice with gold) by a saturation curve of the form $y = ax/(x+b)$. He concluded that the more often the sluice is cleaned per time interval, the higher is the recovery of gold.

The reviewed studies on sluice-boxes captured in this work seek to improve the sluice-box effectiveness in recovering gold. The issue of fine gold losses in sluice-box operations is critical in the artisanal and small-scale gold mines. Using low flow rate increases fine gold recovery in sluices, but at the expense of keeping more gangue minerals in the concentrates. However, high flow rates, which transport gangue minerals along and off the sluice, also carry some fine gold into tailings. In the quest to minimize these losses, this work seeks to combine the operations of a sluice-box and a leaching plant to improve gold recovery.

2 Design Optimization and Operation

The optimized design combines a cyanide-based leaching system to the operation of a multiple stage sluice-box. The leaching system uses continuous rotation of a drum with baffles and blade to agitate or mix the pulp for leaching to be achieved. The optimized design together with its exploded view is as shown in Fig. 2 and Fig. 3 respectively.

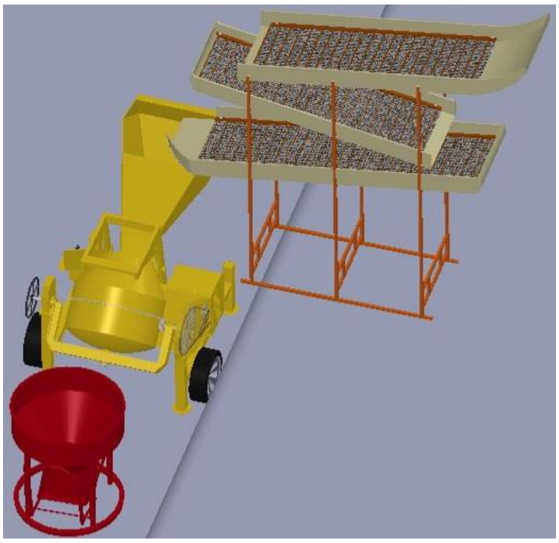

Fig. 2 Isometric View of Optimized Design

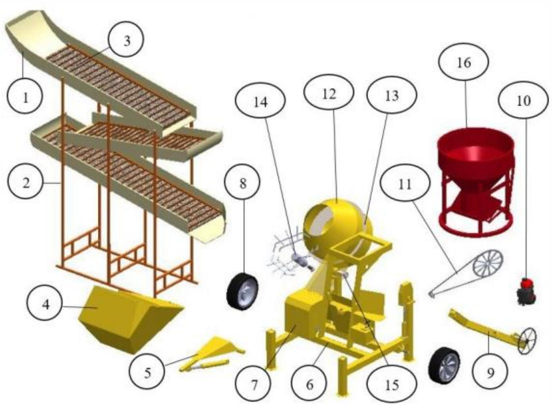

Fig. 3 Exploded View of the Optimized Design

The part list with the various names, quantity and material used for each component is as shown in Table 1.

Table 1 Part list

No.	Item Name	Material Description	Qty
1	Sluice channel	Aluminium	3-sets
2	Sluice support	Grey cast iron	6

	frames		
3	Carpets and Riffles	Miners moss and Aluminium riffles	3
4	Hopper/Receiver	Mild steel	1
5	Hydraulic cylinder support	Carbon steel	1
6	Chassis	Grey cast iron	1
7	Engine housing	Grey cast iron	1
8	Wheels	Rubber	2
9	Angle bar and Handle	Medium carbon steel	1
10	Engine	-	1
11	V-belt and pulley system	Cast iron pulleys and leather belts	1
12	Drum	Stainless steel	1
13	Gear rim	Cast steel	1
14	Baffles/Blades	Stainless steel	1
15	Output shaft	Alloy steel (40Ni2Cr1Mo28)	1
16	Collector/Container	Stainless steel	1

2.1 Mode of Operation of Optimized Design

The riffles and the carpets (3) capture the heavy gold particles as the slurry flows down the sluice channels (1). The hydraulically operated hopper (4) directs the slurry which is discharged off the end of the sluice into the drum (12). Cyanide is added to the pulp after it has been thickened to about 46% solids. The drum is then rotated continuously by gear (13) moving to start the leaching process. An engine (10) drives the drum through a V-belt and pulley systems (11). Baffles or blades (14) inside the drum aid the mixing or agitation of the pulp to keep the solids in suspension, and to keep air/oxygen in the process to achieve leaching. Zinc cementation technique, where gold adsorbs or cements onto zinc shavings, is then used to further recover the leached gold from the solution after the process. Also, the concentrates on the sluice board are treated using the direct smelting of gold technique to get ‘pure gold’.

3 Detailed Design

3.1 Drum Specifications and Capacity

The shape of the leaching drum is that of a cylinder and a frustum of a cone welded together as a single piece to form the drum shape. The bottom or base of the drum is designed to have a small elliptical head. But in the design calculations of the drum, the shape of the drum base is assumed to be flat-bottomed. Fig. 4 shows the dimension of the drum.

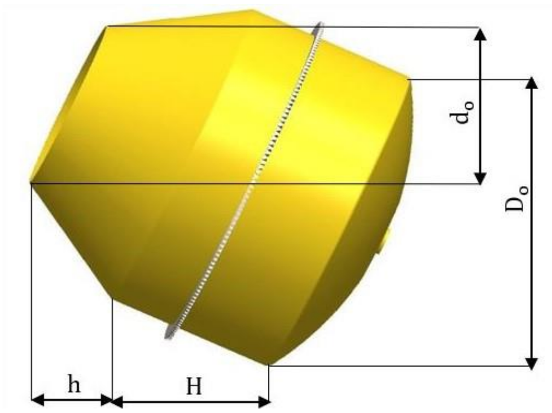

Fig. 4 Dimensions of the Drum

The drum dimensions were taken per design consideration, material and space requirements. It has a wall thickness, $t = 0.004\,\mathrm{m}$ and a total height, $H_T = 1.2\,\mathrm{m}$;

D_o = Cylinder outer diameter = $1.0\,\mathrm{m}$

d_o = Cone outer diameter = $0.5\,\mathrm{m}$

h = Cone height = $0.4\,\mathrm{m}$

H = Cylinder height = $0.8\,\mathrm{m}$

The capacity of the drum is given by equation (1).

$$D_{capacity} = (\pi R_i^2 H) + \frac{\pi}{3}(R_i^2 + r_i^2 + R_i r_i)h \quad (1)$$

where, R_i = Cylinder inner radius

r_i = Cone inner radius

Substituting the various values into (1) yields drum capacity to be $0.8\,\mathrm{m}^3$.

To prevent pulp overflow, volume of pulp (V_{pulp}) to be leached is calculated to be 20% less than the drum capacity. Therefore,

$$V_{pulp} = 0.64 \text{ m}^3$$

3.2 Mass of Pulp to be Leached

Mass of pulp to be leached is given by equation (2).

$$M_{pulp} = V_{pulp} \times \rho_{pulp} \qquad (2)$$

where, ρ_{pulp} = Pulp density

Assuming the slurry is thickened to a pulp of 46% solids, $\rho_{pulp} = 1400 \text{ kg/m}^3$ (Kotze *et al.*, 2005).

By substitution,

$$M_{pulp} = 900 \text{ kg}$$

3.3 Volume of Material Required for Drum

Volume of material (V_{dm}) required for the drum is given by equation (3) below.

$$V_{dm} = \pi H({R_o}^2 - {R_i}^2) + \frac{\pi}{3}h[({R_o}^2 + {r_o}^2 + R_o r_o) - ({R_i}^2 + {r_i}^2 + R_i r_i)] + (\pi t {R_o}^2) \qquad (3)$$

where, R_o = Cylinder outer radius

r_o = Cone outer radius

Substituting the various values into (3) yields

$$V_{dm} = 0.0169 \text{ m}^3$$

3.4 Mass of the Empty Drum

Mass of the empty drum material (M_{dm}) is given by equation (4).

$$M_{dm} = V_{dm} \times \rho_{dm} \qquad (4)$$

where, ρ_{dm} = drum material density = 8000 kg/m^3 (for stainless-steel material).

Therefore,

$$M_{dm} = 135.2 \text{ kg}$$

Total mass of loaded drum is given by:

$$M_T = M_{dm} + M_{pulp} = 1035.2 \text{ kg}$$

3.5 Ore Mass on Sluice-Box

With negligence to the mass of gold concentrates trapped by the carpets and riffles after sluicing, mass of solid ore (M_{solids}) to be processed at a time on the sluice-box is estimated as:

$$M_{solids} = \text{Percentage solids} \times M_{pulp} \qquad (5)$$

By substitution,

$$M_{solids} = 415 \text{ kg}$$

3.6 Power Requirement of the Leaching Drum

The force (F) required for proper mixing of the pulp is given as:

$$F = M_T \times g \times L_f \qquad (6)$$

where, M_T = mass of loaded drum

g = acceleration due to gravity

L_f = mixing factor due to paddle diameter

Assuming that the mixing factor due to blade or paddle diameter equals half drum mean diameter, therefore;

$$L_f = \frac{R_i + r_i}{2} = 0.371$$

Substituting the various values into (6) yields

$$F = 3768 \text{ N}$$

The torque (T) required is given as;

$$T = F \times R_o \qquad (7)$$

Substituting the various values into (7) yields a required torque of 1884 Nm.

The mixing power or output power required is given by equation (8).

$$P = F \times V \qquad (8)$$

where, P = Power required (kW)

F = Mixing force

V = Drum peripheral velocity = $\frac{\pi \times N_{drum} \times D_o}{60}$

N_{drum} = Drum speed/agitation speed

According to Shah (2012), a standard agitation speed or drum speed of $100\,\text{rpm}$ is selected to adequately mix the pulp for effective leaching.

Substituting the various values into (8) yields drum peripheral velocity, $V = 5.236\ \text{m/s}$ and a mixing power, $P = 19.73\,\text{kW}$.

Therefore, considering safety factor of 1.27, the designed power becomes:

$$P = 25.1\,\text{kW}$$

Based on the power and speed requirement, a C1.5 generator engine with a brake power of $25.2\,\text{kW}$ and a speed of $2400\,\text{rpm}$ is selected from a standard engine ratings guide (U.S. EPA Tier 4 Final Ratings) to drive the system.

3.7 Belt and Pulley Specifications

According to Khurmi and Gupta (2005), for power ranging from $7.5\,\text{kW}$ to $75\,\text{kW}$, the suitable V-belt type selected is C;

σ = allowable stress of belt = 2 MPa

μ = coefficient of friction = 0.35

ρ = belt density = $1150\,\text{kg/m}^3$

2β = groove angle = $34°$ (i.e. $\beta = 17°$)

b = top width of belt = 22 mm

t = belt thickness = 14 mm

Let a and b represent the input and output pulleys respectively;

N_a = Engine shaft/pulley speed = 2400 rpm

D_a = Input/engine pulley diameter = 200 mm

D_b = Output pulley diameter = 500 mm

The output pulley/shaft speed (N_b) is given by the speed relation below:

$$\frac{N_b}{N_a} = \frac{D_a}{D_b} \qquad (9)$$

Substituting the various values into (9) yields

$$N_b = 960\,\text{rpm}$$

Torque (T_o) transmitted by the output shaft is given as:

$$T_o = \frac{60P}{2\pi N_b} = 250.669\,\text{Nm}$$

According to Khurmi and Gupta (2005), the centre to centre distance (C) between driving and driven pulley is given as:

$$C = 2D_a + D_b = 900\,\text{mm}$$

Also, the pitch length of the open belt drive is given as:

$$L = \frac{\pi}{2}(D_a + D_b) + 2C + \frac{(D_b - D_a)^2}{4C} \qquad (10)$$

Substituting the various values into (10) yields

$$L = 2925\,\text{mm}$$

The angle of contact (θ) for open belt drive is obtained as:

$$\theta = 180 \pm 2\alpha\left(\frac{\pi}{180}\right) \qquad (11)$$

where

$$\alpha = \text{angle of wrap} = \sin^{-1}\left(\frac{D_b - D_a}{2C}\right) = 9.594°$$

Substituting the various values into (11);

For input (smaller) pulley, $\theta_1 = 2.807\ \text{rad}$

For output (bigger) pulley, $\theta_2 = 3.476\ \text{rad}$

According to Khurmi and Gupta (2005), maximum tension (T) in the belt is given by equation (12).

$$T = \sigma \times bt \qquad (12)$$

Substituting the various values into (12) yields

$$T = 616\ \text{N}$$

Centrifugal tension (T_c) in belt is given by (13):

$$T_c = mv^2 \qquad (13)$$

where,

m = mass of belt per unit length

$= \rho \times bt = 0.3542\ \text{kg/m}$

v = linear velocity of the belt

$= \frac{\pi \times N_a \times D_a}{60} = 25.133\ \text{m/s}$

Substituting the various values into (13) yields

$$T_c = 223.74\ \text{N}$$

Tight side tension (T_1) is obtained from equation (14) below:

$$T = T_1 + T_c \tag{14}$$

Substituting the various values into (14) yields

$$T_1 = 392.26 \text{ N}$$

Tension in slack side of the belt (T_2) is obtained from the equation as follows;

$$\frac{T_1}{T_2} = e^{(\mu \times \theta \times \csc \beta)} \tag{15}$$

Substituting the various values into (15) yields

$$T_2 = 13.62 \text{ N}$$

According to Khurmi and Gupta (2005), power transmitted per belt is given as:

$$P = (T_1 - T_2)v \tag{16}$$

Substituting the various values into (16) yields

$$P = 9.5 \text{ kW}$$

Number of V-belts (n) required is given by:

$$n = \frac{\text{Total power transmitted}}{\text{Power transmitted per belt}} = \frac{25.2}{9.5}$$

$$= 3 \text{ belts}$$

3.8 Design of the Output Shaft

The shaft is supported in two bearings. It has a pulley at one end and a pinion (bevel gear) at the other end. It holds one side of the angle bar, which also supports the weight of the drum. To completely design the output shaft, the angle bar load, gear forces, and the loads due to pulley weight and belt tensions are all determined in order to calculate its maximum bending moment. Fig. 5 shows the output shaft geometry and the loads it carries.

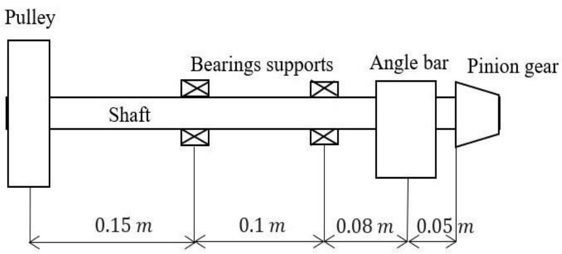

Fig. 5 Shaft Geometry and Loads

After determining the various forces components (vertical and horizontal) acting on the shaft, the space diagram, shear force diagram and bending moment diagram of the shaft are shown below.

Figs. 6, 7 and 8 show the space diagram, shear force diagram and bending moment diagram of the shaft due to the vertical loads respectively.

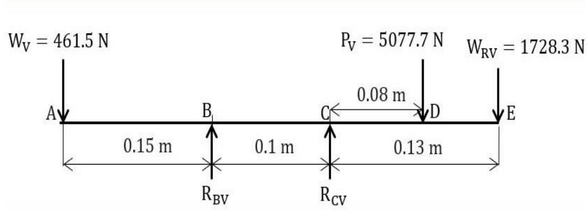

Fig. 6 Space Diagram for Vertical Loading

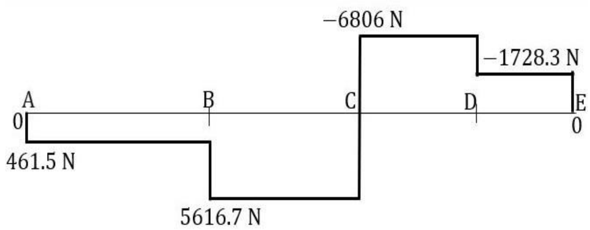

Fig. 7 Shear Force Diagram for Vertical Loading

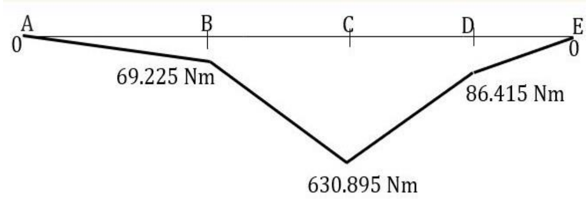

Fig. 8 Bending Moment Diagram for Vertical Loading

Figs. 9, 10 and 11 show the space diagram, shear force diagram and bending moment diagram of the shaft due to the horizontal loads respectively.

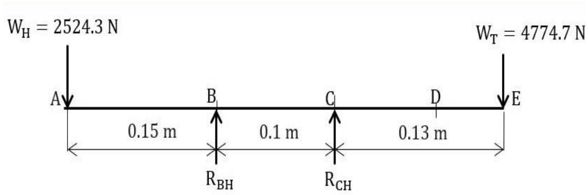

Fig. 9 Space Diagram for Horizontal Loading

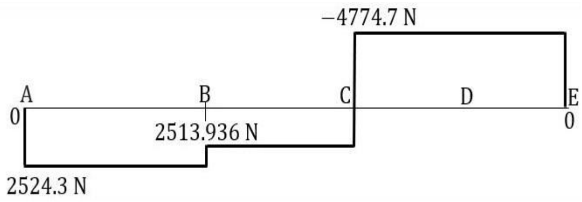

Fig. 10 Shear Force Diagram for Horizontal Loading

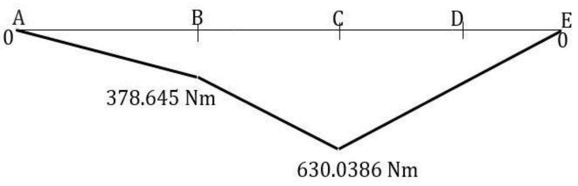

Fig. 11: Bending Moment Diagram for Horizontal Loading

Therefore, maximum bending moment for the vertical loading, $M_V = 630.895$ Nm, and it occurs at bearing C.

Also, maximum bending moment for the horizontal loading, $M_H = 630.0386$ Nm, and it also occurs at the bearing C.

The resultant bending moment (M) on the output shaft is given by:

$$M = \sqrt{(M_V)^2 + (M_H)^2} \quad (17)$$

Substituting the various values into (17) yields

$$M = 891.615 \text{ Nm}$$

By maximum shear stress theory, shaft diameter (d) is obtained from the equation as follow:

$$d = \sqrt[3]{\frac{16 \times T_e}{\pi \times \tau_{max}}} \quad (18)$$

where,

τ_{max} = Maximum allowable shear stress of shaft = 45 MPa for alloy steel-40Ni2Cr1Mo28 (Khurmi and Gupta, 2005)

T_e = Equivalent twisting moment $= \sqrt{(K_m \times M)^2 + (K_t \times T_d)^2}$

K_m = Combined shock and fatigue factor for bending

K_t = Combined shock and fatigue factor for torsion

T_d = Design torque = $T_o \times K_L$

T_o = Torque transmitted by the output shaft

K_L = Load factor

From Khurmi and Gupta (2005), $K_L = 1.75$ for line shaft. For suddenly applied load with heavy shocks, the selected values for K_m and K_t are 2.5 and 2.0 respectively.

Therefore, by substitution;

$$T_e = 2395.482 \text{ Nm}$$

Again, substituting the various values into (18) yields,

$$d = 64.72 \text{ mm}$$

Therefore, the diameter of the output shaft which will be driving the leaching drum is 65 mm.

4 Result and Discussion

Based on the design analysis and calculation, mass of gold ore material needed to be processed on the sluice-box was 415 kg. The transmission power required to adequately agitate or mix the pulp of mass 900 kg in the leaching drum of pulp holding capacity 0.64 m^3 was 25.2 kW, at a drum mixing speed of 100 rpm.

The power was transmitted to the drum through a belt pulley and bevel gear systems, reducing the engine speed from 2400 rpm to the required mixing speed of the drum. The diameter of the output shaft driving the drum is 65 mm.

Input and output pulleys of diameters 200 mm and 500 mm respectively, and shafts centre to centre distance of 900 mm were used to transmit the power (25.2 kW) from the engine via three (3) v-belts of lengths 2925 mm.

5 Conclusion

The design of the combined gravity concentration (sluice-box system) and leaching plant has been achieved. This combined technique would demonstrate an improvement in gold recovery in a cost-effective and environmentally benign manner. Small-scale gold miners will reduce gold losses, improve local production of gold, and boost their profit margins. Its recommended that an optimized design be considered.

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