NEW CONSIDERATIONS in Design and Application of SLUICE SEPARATORS

This article discusses the theoretical background and design of a modern sluice, *the Lamflo,* with brief consideration given to its economics

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A SIMPLE ANALYSIS of the mechanism of operation of a sluice points out two almost separate actions, namely:

1) The downward settling of the particles in the slurry, an action that normally takes place in a limited time and along a limited distance of its axial length (neglecting the very fine particles that are considered to be kept in suspension in the fluid). During this short time, the particles will be subjected to a differential longitudinal displacement (along the axis of the sluice) resulting in a certain degree of separation between the particles of different separation parameters (shape, size and specific gravity). However, due to the relative turbulence in the area, this effect will be assumed negligible and hence the sole role of this phase will be considered as "the deposition of the particles to form a bed of essentially mixed particles on the surface of the sluice."

2) With this bed thus forming, the second and most effective mechanism that takes place is the transportation action along essentially the longitudinal axis of the sluice, through which action the effective separation takes place.

For the present purpose, it is perhaps enough to give the following outline of the theoretical background of each of these two actions.

SETTLING

Settling is a minor effect, but is important to understand, as it reflects on the understanding of the general behavior of particulate movement in a fluid.

The basic laws that govern settling of particles in fluids, or in a broader sense, movement of particles in fluids, are generally considered to be Stokes' and Newton's laws together with Reynolds' number and the second law of motion. These laws describe the resistance to the movement of one single spherical particle in a fluid. However, introducing corrections to allow for the "crowded

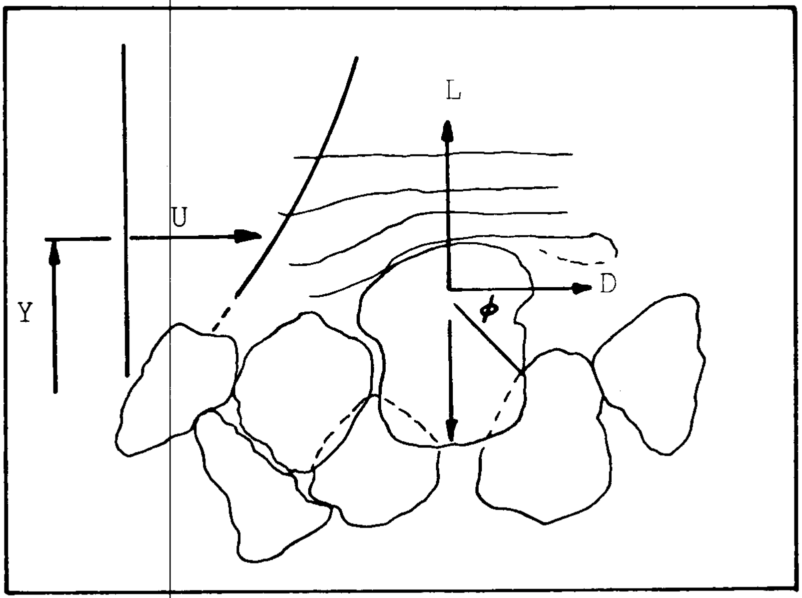

Fig. 1. Forces on typical particle on stream bed (Handbook of Fluid Dynamics, V. L. Streeter, McGraw Hill, 1961)

conditions" of movement and the deviation of shape from the hypothetical sphere; these laws can be given as follows:

1) Stokes' law for small particles of < 50 micron diameter:

$$V = \tfrac{1}{18}\,(1 - \alpha^{2/3})(1 - \alpha)(1 - 2 - \alpha)\,\frac{g(\delta - \delta')}{\mu}\,(d\zeta)^2$$

2) Newton's law for larger particles:

$$V = \frac{\sqrt{4g(\delta - \delta'')}}{3Q\alpha}\,d\zeta$$

3) Reynolds':

$$N = \frac{d\zeta\, V\delta'}{\mu}$$

4) Second Law of Motion:

$$m\,\frac{dV}{dt} = mg - m'g - R'$$

where:

V = terminal velocity of particles
d = diameter of particles
R' = resistance to motion
μ = viscosity of fluid
m = mass
g = gravitational constant
Q = Newton's correction factor
δ, δ', δ'' = specific gravities of the fluid, solid and suspension respectively.
α = volumetric fraction of suspended solids and suspension respectively.
ζ = shape correction factor

From which we can deduce that "smaller particles have their terminal velocity as a function of the square of their radius, while larger particles have theirs as a function of the square root of their radius. Therefore, smaller particles reach their terminal velocities very rapidly compared to the larger ones and thus take appreciably longer time to settle or to travel." Also, from the same set of relations, the ratio of equal settling or moving particles can be derived as approximately:

$$\frac{r_2}{r_1} = \frac{(d_1 - d')^m}{(d_2 - d')}$$

where: $m = \tfrac{1}{2}$ for small particles and $= 1$ for larger particles.

TRANSPORTATION

Similarly, the second action that takes place on a sluice, transport, is also governed by a set of basic laws, essentially being the two laws of conservation of energy and matter. The former is usually applied in terms of Bernoulli's equation and the latter in the form of equation of continuity. These, together with Reynolds' number and Manning's and Duboys' equations in its initial or Einstein's modified forms; explain and describe, to a degree, whatever mechanism is occurring in bed transportation.

Fig. 1 illustrates diagrammatically a general case of a bed of particles and shows some of the forces in action together with a characteristic velocity profile. It is to be noted here that D actually represents both the skin friction drag and the form drag, and that L (lift) = $\sum$ [illegible] (pressure) on particle. In addition to these forces, the turbulent velocity fluctuations are superimposed on the mean velocity field and thus renders both L and D variable and fluctuating both in magnitude and direction. Finally, there is also the friction and forces resisting movement due to contacts between the particle and other particles which add to the complications in the force system on these particles.

These forces result in one or all of the three actions: rolling, saltation, or suspension. Suspension affects the other two movements indirectly through its effect on the density of fluid and hence the resultant drag D. Suspension and the interaction between particles that may result in the formation of dunes or antidunes, as both of these phenomena will be assumed to take place mainly in par

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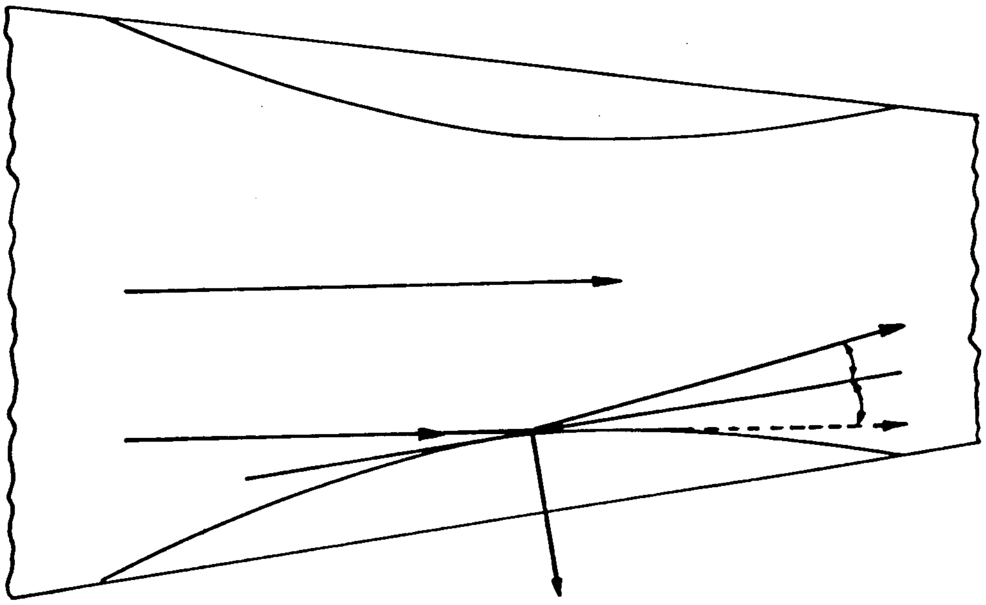

Fig. 2. Effect of converging curvature in Lamflo on particles

ticle sizes or velocities outside the ranges being considered here.

In the balance of forces outlined, it can be seen that both D and L are essentially functions of the mean velocity of stream which was described by Manning. For a bed of a mixture of various sizes of particles, where the effective particle size is taken as that size at which 65 percent by weight is finer, the Manning equation is:

$$\frac{V}{\sqrt{T/\rho}} = 7.66\,\frac{(R)^{1/6}}{d}$$

where:

$T =$ bed shear due to particles
$\rho =$ density of fluid
$R =$ hydraulic radius of bed
$d =$ diameter of sediment particles

from which the mean boundary shear can be deduced as follows:

$T = \gamma RS$

where:

$\gamma =$ specific gravity of slurry

This equation has been the subject of various studies. However, a simple way of analyzing it, as applied here, would be to assume that transport takes place as a series of superposed layers that approximate the particle diameter in thickness and that the speed of the successive layers decrease linearly by increments from a maximum at the surface layer to almost zero for the nth layer with increments of Δv. Therefore, the surface layer speed is $(n-1)\,\Delta v$. Thus, the weight rate of transport per unit width, which is an essential factor deciding the capacity of a sluice, is equal to the product of the specific gravity of the slurry, the total thickness of the layers and the mean velocity of the layers, or:

$$G = \gamma nd\,\frac{(n-1)\,\Delta v}{2} \qquad \text{(DuBoys' equation)}$$

where:

$G =$ bed load transport rate in dry weight per second per unit width

So far, the uniform stream has been considered with channels and beds of uniform linear parallel walls.

CONVERGING WALLS

If we consider the case of a gradually varied width of channel, the variation in depth Y of bed with width of channel X can be derived from Manning's approximately as:

$$Y_2/Y_1 = (X_1/X_2)^{0.642}$$

CURVED CONVERGING WALLS

If we introduce curved walls, instead of straight ones, such that we still maintain the continuous gradual decrease in width, the balance of forces acting on any section of the stream and bed is further changed by the addition of a velocity vector which is a function of θ and the initial velocity and its direction is angular to the original resultant by an angle $= \cos^{-1}\theta$ (fig. 2).

Analyzing the effect of this angular vector we can deduce the following:

1) The final resultant drag will be in a direction towards the axis of the channel rather than parallel to it.

2) The velocity of the stream at the wall sides is reduced by the curved sides more than in the case of straight walls.

3) The velocity of stream in the central section of the sluice being higher than along the sides results in a higher transport rate of lifted light particles, or in other words the resultant effect of the curved walls would be to assist the fast removals of the lifted

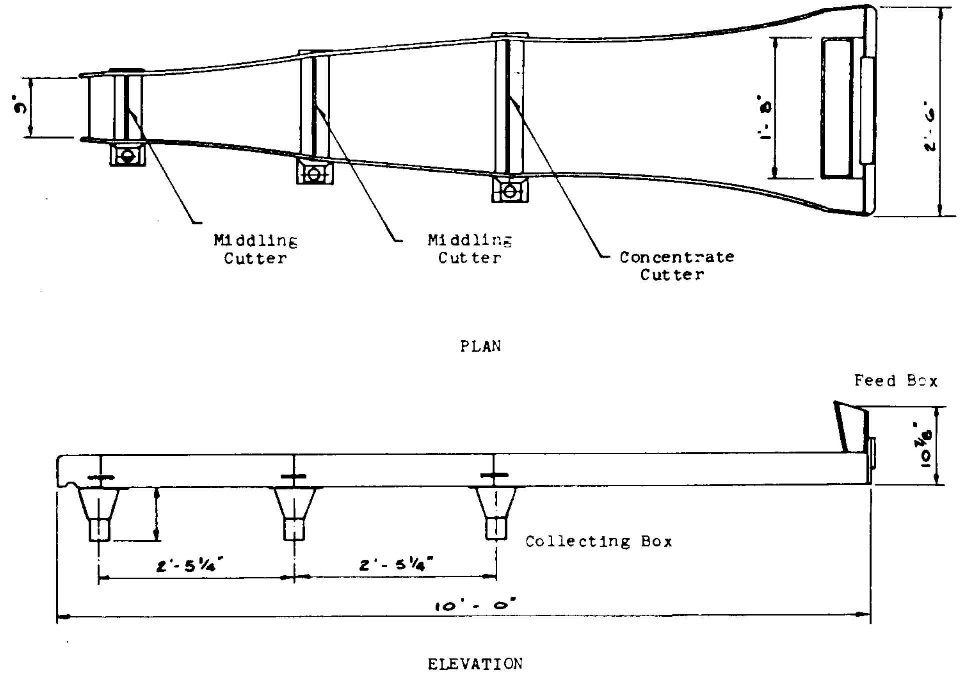

Fig. 5. Lamflo sluice. Curved side walls in first and third sluices and straight converging sides in middle sluice permit efficient separation over a wide range of particle combinations

APPLICATION CONSIDERATIONS

As a versatile basic separation tool, the Lamflo can be visualized to have wide use and application in mineral beneficiation. However, three cases of rather large industries—coal, iron ore, and beach and mineral sands—and the role Lamflo can play in them illustrate the potential field of application of this sluice.

COAL:

Essentially there are two objectives in coal beneficiation: removal of shales and desulfurization in coal fines (approximately minus 28 mesh).

Shale particles with specific gravity of 2.6 will be assumed to have a sphericity correction factor = 0.7; pyrites are normally conchoidal or uneven and specific gravity 4.8–5.1 while coal, though similarly conchoidal or uneven is of specific gravity 1.2–1.6 and will be assumed here to have shape correction factor = 0.8.

The size distribution will be assumed such that the mean hydraulic size can be taken as 50 mesh (200 microns).

Thus the effective size of the shales would be = 300 × 0.76 = 228 micron while coal = 300 × 0.8 = 240 microns and hence both are of the same order of magnitude of size.

But, the resistance of the layers of particles depends upon the submerged weight of the moving layers and a friction coefficient between them, and is equal to the tractive force acting on the surface layer or: $To = \xi\ (\gamma s - \gamma) nd$

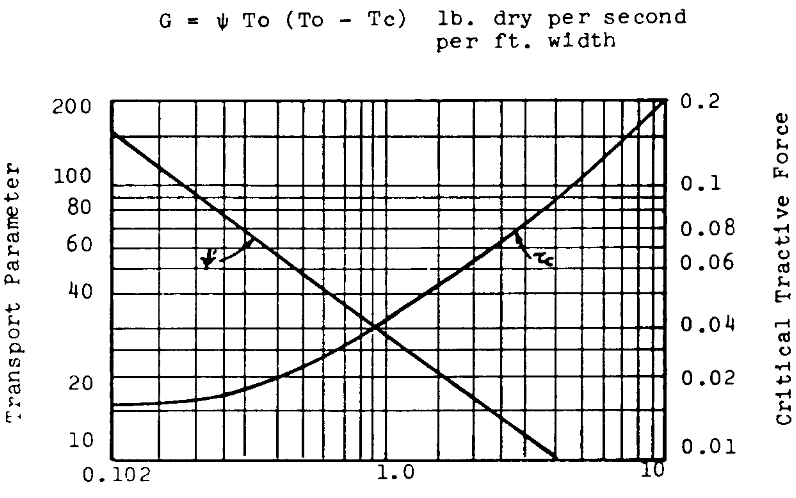

Fig. 6. Transportation parameter and critical tractive force for DuBoys bed load equation (L. G. Straub, The Missouri River)

To = bed shear
ξ = friction coefficient
γs & γ = specific gravities of sediments and fluids
n = number of layers
d = thickness of layers (or particle diameter)

from which it is clear that with everything else being equal, the resistance is a direct function of the specific weight of the particles, hence the relative relations between coal, shale, and pyrites would thus be:

$$To\ \text{coal}/To\ \text{shale} = \frac{0.4}{1.6} = 0.25$$

$$To\ \text{coal}/To\ \text{pyrite} = \frac{0.4}{4} = 0.10$$

Considering the limits of such separation and applying DuBoys' equation and the curves in fig. 6 we can deduce:

A) That the limiting size of shales that can be transported at the critical shear is 1/4 the size of the coal particle and in case of pyrite it is 1/10 size of coal, or in our case, 60 microns ($\simeq$ 250 mesh) of shale and 24 microns (minus 400 mesh) in case of pyrite.

B) For the capacity of the sluice to operate on such a mixture, the maximum transport capacity = 11.24 tons/hour assuming practical conditions.

IRON ORE:

Application of the sluice to iron ores can be similarly treated whereby the following can be deduced:

A) The relative relation between shales or silica sands and iron would be = 0.4, thus the size of shale particles transported with 150-mesh iron particles would be 40 microns.

B) The maximum capacity assuming practical conditions and limitations = 6.5 tph (assuming V in this case = 22.2 cms/sec instead of 71.1 as in case of coal).

BEACH AND MINERAL SANDS:

For the more difficult case of beach and mineral sands, where the sluice has already been introduced with success, the results of pilot tests for a major plant actually being installed at present and which will have a capacity of approximately 1000 tph (more difficult mineral deposits are currently being pilot tested on Lamflos) can be summarized as follows:

A) Feed in this particular case is as follows:
2.1 percent minerals sp gr = 4.5
0.7 percent minerals sp gr = 4.0
97.2 percent minerals sp gr = 2.65

B) Size of particles ranged from minus 2 to minus 325 mesh with a mean hydraulic equivalent of 125 mesh.

C) The cutter openings used varied between 6/32 to 8/32 in.

D) The slurry density varied from 58 to 62 percent weight solids.

E) In one single pass, rougher, the recovery is 95.3 percent at an upgrading ratio of 1.77 and downgrading ratio of 5.0.

F) The overall recovery of three stage was 85 percent.

G) With progression of stages, the upgrading ratios were raised to 1.96 and 2.07 in the second and third stages respectively (cleaner and recleaner).

To visualize a prospective coal application, and for the sake of simplification it can be assumed:

1) Same established separation results hold for coal, with same type flow sheet.

2) Objective is to reduce pyrite content of coal from 5 percent to 1 percent.

Reflecting the available results, the following can be expected:

a) Pyrite can be reduced to 1 percent (removal of 80 percent).

b) Pyrite concentrate will contain 20 percent coal, corresponding to approximately 1 percent of original feed. Thus coal recovery would be in the order of 99 percent (without taking into consideration loss in slimes).

c) If we consider the comparative ease in separating coal from pyrites (considering particle sizes and difference in specific gravities); it can be foreseen that one whole stage (recleaner) may be eliminated from the above mentioned flow sheet while still maintaining the required desulfurization and recoveries.
(The same type analysis holds in case of iron—shales or sands separation.)

ECONOMICS

It is rather difficult to assess the exact economics of the application of Lamflos in coal and iron, neither has been sufficiently tested to allow for exact figures to be established. However, bearing in mind that the flow sheets should be simpler, the established economics of Lamflos in heavy mineral industry can be given here as probably the upper limits of the expected economics in case of coal or iron.

In the case of the previously mentioned heavy minerals mill, the following economic parameters are established:

A) Capacity of Lamflo plant = 1000 tph

B) Rougher Lamflos = 486
Cleaner Lamflos = 210
Recleaner Lamflos = 70
Scavengers = 210
TOTAL = 976

C) Fresh feed/Lamflo (rougher) 4.12 tons

D) Capital cost of Lamflos (total) $976,000

E) Capital cost of Lamflos (total) installed $1,220,000

F) Capital cost/ton capacity/hour $1109

G) Capital cost/ton treated 1.4¢

H) Direct operating cost/ton treated
Power @ 3 hp/ton = 2.3¢
Labor = 2.4¢
Maintenance = 1.6¢
TOTAL = 6.3¢