Subsea Excavation of Seafloor Massive Sulphides

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Abstract - This paper discusses the excavation phase of seafloor massive sulphide mining. The excavator is part of an overall mining system that will also include a vertical riser to lift the excavated material to the surface, and a shipboard dewatering plant to minimize the loss of fine particles back into the water. External variables affecting the excavator performance include rock properties and terrain. Given a set of rock properties and a desired production rate, we can choose a cutter type and we can estimate the required forces, torques, and power requirements. Typically we can use marinized versions of existing land-based rock cutters for this application. However, we need to pay particular attention to the design of the cutterhead assembly - we need to control the flow field so that we can lift excavated material into the riser and not leave it on the bottom or lose it into plumes. Rock cutters can be deployed in multiple modes, i.e. transverse cutting, sumping, and trenching. The design of the excavator as a system needs to consider the cutting mode and the method of advance of the excavator platform. Examples of excavator advance methods include "lawn mowing", where the cutterheads continuously excavate as the machine advances, "scything", where the cutterhead takes horizontal swaths as the excavator advances, and "open pit mining" where the machine excavates a steep face in front of itself. Each of these modes has advantages and disadvantages in terms of machine size, wear, and time efficiency. Finally, the interface to the riser is important in terms of decoupling vessel and riser motions from the excavator and whether or not the excavator can be mated and unmated to and from the riser while on the bottom.

I. BACKGROUND

Seafloor massive sulphide (SMS) deposits started to attract the interest of scientists in the 1980's, when they noticed similarities with the large volcanogenic mineral deposits on land, concluding that these deposits were likely formed on the ancient seafloor. Some of these land deposits, such as Kidd Creek in Canada and Mt. Isa and Broken Hill in Australia were of enormous economic importance.

Recently a number of subsea mining companies have formed with the intention of mining these deposits. New companies such as Nautilus Minerals Inc. and Neptune Minerals Plc. have been attracting significant investment from major mining companies. Although some technological precedents have been set, e.g. manganese nodule harvesting R&D programs in the 1970s and modern-day shallow-water offshore diamond mining, these new companies must integrate new solutions for the deeper water SMS deposits. They must look to a combination of solutions from the terrestrial mining and the offshore oil & gas industries.

II. OVERALL MINING SYSTEM

SMS mining systems must operate in open ocean conditions. They require surface-based interaction with the seabed in a wide range of waves and currents, while recovering ore from depths of 1200 to 2500 meters [1]. The ore must be liberated from the seafloor and lifted to the surface from the seabed and to a surface vessel, e.g. ship or barge, where it will await transport to shore-based processing.

The ore will be liberated from the seafloor using mechanical excavation techniques. SMS rock has been shown to have strength properties similar to coal - it can be readily cut with pick-type cutters (see Fig. 1 [2]) such as those used in terrestrial coal mining[3]. Such excavator technologies must be marinized and should be optimized for use in the subsea rock-cutting environment.

Fig. 1 Pick-Type Cutter Assembly [2]

More than one Excavator may be required depending on available excavator technologies and target mining production rates.

Ore cuttings will be lifted to the surface via a vertical pipe or “Riser”. Both air-lift pumping and mechanical pumping are candidate technologies for this operation. The Riser will interface to the seabed Excavator and to the surface vessel - it is important that the Riser does not transfer wave, wind, and current effects from the surface vessel to the subsea Excavator.

The Riser will be deployed from a dynamically positioned or moored mining vessel. The vessel will contain handling systems for the Riser, Excavator, and ancillary equipment such as ROVs. It will also contain a dewatering plant, which is required to minimize the loss of fine particles back into the water - the goal is to retain *all* of the retrieved solid particles for processing. Dewatered ore will be offloaded to barges, which will be used to transport the ore to land-based concentrators.

III. CUTTERHEAD DESIGN

A. Cutterhead Power and Size

Given a target ore production rate and the rock properties or the ore (especially the UCS - unconfined compressive strength), an approximate cutterhead size can be determined using the following relations [4]:

(Cutting power) = (specific energy) * (volumetric production rate) (1)

(Cutting power) = (cutting torque) * (cutter angular velocity) (2)

(Cutting power) = (cutter tangential drag force) * (pick speed) (3)

(Specific energy) ≈ (rock UCS) (4)

(Cutter tangential drag force) ≈ (rock UCS) * (cutter length) * (average pick penetration) (5)

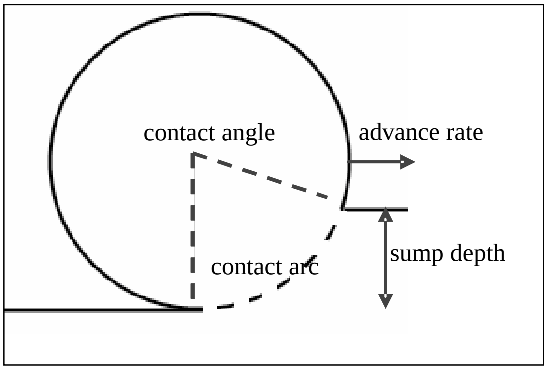
(Cutter torque) = (cutter tangential drag force) * (cutter radius) (6)

(Average Pick penetration)
= (cutter advance rate) / ((pick-sets/rev) * (rev/sec)) * ((sump depth) / (contact arc length)) (7)

See Fig. 2.

These relations tell us the following:

1. The rock strength and the target production rate determine the required Excavator power (from (1) and (4)).
2. For a given power level, we can trade off cutter torque and rpm (from (2) or (3)).
3. The specific energy of cutting (energy /unit volume) is determined by the amount of stress we need to generate across the width and depth of the cut (4).
4. We can vary our torque by changing the depth of cut (penetration) and the size of the cutterhead (from (5) and (6)).
5. We can vary the depth of cut by changing the rate of advance of the cutter, the rpm of the cutter, and the number of pick-sets, i.e. the number of picks on the cutter that will cut the same groove (from (7)).



Also note that pick spacing (i.e. spacing between grooves) is important - recommended ratios of pick spacing to penetration depth range from 1 to 5 [5]. This ratio affects the relation (4) above. Optimized spacings can reduce the specific energy (i.e. energy required per unit volume of rock cut, which can be expressed in units of pressure) well below the UCS; poor spacings will raise it well above the UCS.

B. Cutter Arrangement and Slurry Flow

A counter-rotating cutter arrangement is a natural design choice for a subsea cutterhead - it spreads the cutting load between cutters, and it throws the cuttings toward a central collection location (see Fig. 2). Some type of capture arrangement is required to prevent these particles from being lost as plumes.

Note that a major difference between subsea and terrestrial rock-cutting is that: “as a chip of rock is broken out, a cavity is created, and hence a pore suction. This needs to be balanced by water flow either via the crack or through the rock itself. The viscosity of the water reduces the speed at which the chip can leave the host rock matrix compared to the same situation in air.”[3] This slow release of chips from the rock matrix increases the likelihood of chips being broken multiple times (“re-ground”) by cutter picks, which is very wasteful of energy. It also increases the likelihood of a heavy slurry remaining in the trench. We need to pay close attention to water flow - both to help liberate chips from the matrix and to lift chips and slurry up from the bottom of the trench into the Riser.

We have three power sources for water flow - suction from the Riser pumping system, the pumping effect of the cutters themselves, and any additional water jets that we may add.

Fig. 2 shows a shroud around the cutters to help contain the water flow to the vicinity of the cutters in addition to capturing cuttings thrown by the counter-rotating cutters.

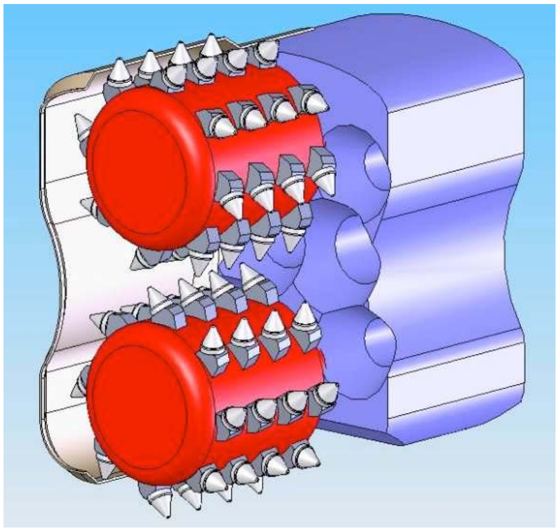


Fig. 2 Counter-rotating Cutterhead Assembly

We can analyze the spinning action of the cutters to see if it is adequate to lift the cuttings off of the seafloor [6]. The cutters pull water around their perimeter, acting as pumps. The pumps are loaded by the drag of the fluid and by the acceleration and lifting of the cuttings/slurry from the seafloor.

We can consider the combination of water and solids in the cutter trench as a settling slurry. Flows of settling slurries are known (from pipeline research) to exhibit different behaviors at different velocities. Four settling regimes are recognized in slurry flows [7]:

1. Stationary bed, in which most of the solids have settled out along the bottom of the duct.
2. Moving bed, in which the larger solids form a moving bed along the bottom of the duct.
3. Heterogeneous mixture with all solids in suspension - the solids concentration decreases with height above the base of the duct.
4. Homogeneous or pseudo-homogeneous mixture with all solids in suspension.

Transitions between these flows occur sequentially as a function of flow velocity. Our goal is to achieve at least a heterogeneous mixture. An analysis of the flow field, combined with the loading effects of the slurry, should be used to help choose a minimum operating rpm for the cutters to help ensure that the slurry remains in heterogeneous suspension.

IV. EXCAVATOR DESIGN

A. Cutting Modes

Rotating drum cutters are typically designed to work in three different cutting modes (see Fig. 3), i.e:

1. Sumping or collaring - where the cutter is pushed directly into the rock.
2. Trenching - where the cutter works from inside a trench, extending the trench in a direction orthogonal to its own rotational axis.
3. Transverse cutting - where it works from inside a trench, extending the trench in a direction parallel to its own rotational axis.

Illustrative terrestrial equipment examples (see [2]) include “continuous mining machines” which are designed to work in trenching mode, and “transverse roadheaders” (see Fig. 1) which are designed to work in transverse mode.

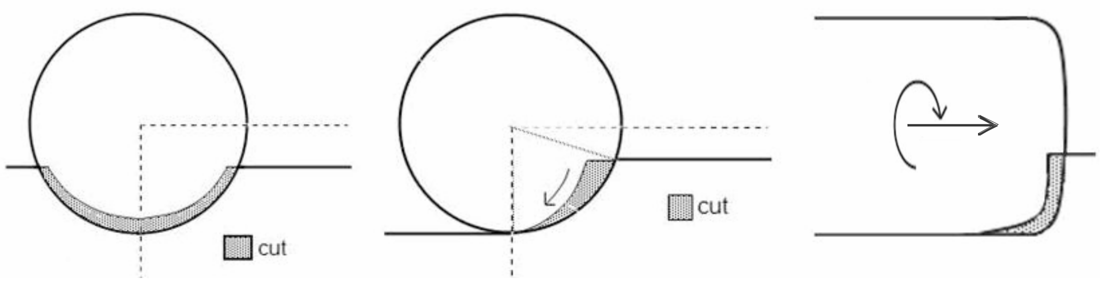


Fig. 3 Cutting Modes - Sumping (left), Trenching (center), Transverse (right)

Each cutting mode requires a unique analysis to determine cutterhead forces, torques, and production rates. Forces to consider include the pick forces (normal, drag, lateral) which determine the size of the picks, cutter tangential force which determines the cutter torque, and the overall cutterhead normal, drag (parallel to pick motion) and transverse forces which largely determine the overall Excavator size.

The pick normal forces can be calculated from pick drag forces (see Cutterhead Design section above) by multiplying by an assumed normal: drag force ratio. Typical ratios for terrestrial rock-cutting with pick-cutters range from 1:1 to 5:1, depending on the rock type [4]. Note, however, that these ratios have not been well established for subsea rock-cutting at this time. The cutterhead normal, drag, and transverse forces are calculated as orthogonal components of the vector sums of the normal, drag and lateral pick force contributions over the contact area.

B. Excavator Configurations

The purpose of the Excavator is to deploy the cutterhead, keep it engaged with the rock, and to interface to the Riser. These requirements determine the Excavator configuration.

We can envision a number of different cutterhead deployment scenarios, e.g:

- "lawn mowing" - where the cutterhead is fixed to the front or bottom of the Excavator, which moves continuously over the seafloor in trenching mode, e.g. on tracks, and the cutterhead continuously excavates as the machine advances;
- "scything", where the Excavator moves the cutterhead back and forth in front in of itself, in trenching or transverse mode, in horizontal swaths, as the Excavator advances (see Fig. 4); and
- "open-pit mining" where the cutterhead is mounted on the end of a boom, e.g. an open-pit mining shovel, operating in trenching or transverse mode, and the Excavator mines a steep face in front of itself.

In these scenarios, we trade off machine complexity vs. amount of Excavator locomotion required. The lawn mowing configuration is the simplest, but it requires the Excavator to cover the largest amount of ground. The open-pit mining configuration requires that the Excavator move the cutterhead assembly in two or more degrees of freedom, but it allows the Excavator to sit in one spot until it has excavated its reachable volume. The scything configuration is intermediate between these two - it moves the cutterhead in a single degree of freedom.

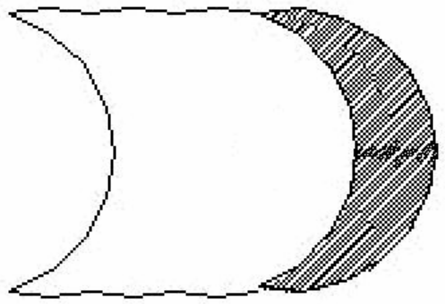


Fig. 4 Scything Mode (plan view)

The advantage of the simple lawn-mowing type of machine is that it can be lighter (and therefore smaller) than the more complex machines. It can sit nearly overtop of the cutterhead and use its weight to provide the required normal cutterhead forces (see "Cutting Modes" above). Such machines should also be less expensive than the more complex ones. The major problem with them is the large amounts of ground that they must cover. Firstly, wear on their tracks is an issue. Secondly, the overall mining system (including surface vessel and Riser) needs to be designed to allow the Excavator to be in constant motion - the surface vessel may need to move constantly to stay aligned with the Excavator. In addition, it is not clear how these machines can handle the rugged terrain typical of known SMS deposits [1].

The more complex machines not only require less track maintenance, but they can also handle rugged terrain. Especially the open-pit mining configuration - like a mining shovel, these machines can build their own roads.

C. Time Efficiency

The production rate of the Excavator is directly proportional to its “time efficiency”. Any time used in repositioning the machine and/or cutterhead is wasted and reduces the overall production rate. Also, scenarios that require the cutterhead to move in and out of the rock are less time-efficient than those which keep the cutterhead fully engaged with the rock.

In Fig. 4 (scything mode), the shaded area is the part that is cut during each swing of the cutterhead. Note that the only place in the swath where the entire depth of the cutterhead is engaged is the widest part, i.e. in the middle of the swath. Otherwise the depth of the swath is less than the full cutterhead length. Although there are many benefits to machine configurations where the cutters move in arcs, engineers must consider their time-efficiencies related to this effect.

In any Excavator configuration, we need to ensure that we keep the individual cutter picks in contact with the rock, and that we do not try to bury the picks deeper than their design depth. These issues are of concern when we reposition the Excavator between cuts, thereby losing our previous alignment. Excavator designs should be avoided where cutter alignment is critical after repositioning the machine. Far too much time will be wasted in repositioning and realigning the machine between cuts. In the scything mode the cutters are moved completely out of the rock between cuts, and their orientation is at right angles to the path of the Excavator. These factors combine to make this configuration relatively insensitive to misalignments of the Excavator.

Part of the task of keeping the cutterhead engaged in the rock is ensuring that it doesn’t bounce. With any type of machine configuration, care must be taken in the mechanical and control system design to ensure that the primary vibrational modes are highly damped.

D. Cutting Forces and Machine Size

The overall machine size will be driven by the cutting forces that we need. The brief analysis shown in Table 1 shows that the normal force for the example case is 25 Tonnes, assuming a normal/drag force ratio of 5:1. It is generally easier to generate this normal force by cutting downward rather than side-to-side. For example, a machine could stand in one spot and cut a set of downward passes in front of itself and to each side.

Backhoe Excavators are an interesting machine configuration - they can excavate a large volume of rock without needing to reposition. Because the machines do not need to move often, either legs or tracks can be considered for locomotion. However, they are large in proportion to the cutterhead size, and they are heavy in relation to the required normal cutting forces due to their reactive torque requirements.

E. Riser Interface

As mentioned above, the Excavator provides the interface between the cutterhead and the Riser. Although the surface vessel should be capable of accurately positioning the top end of the Riser, waves and mid-water currents will try to induce motions and vibrations at the bottom of the Riser. Options for dealing with this effect include anchoring the bottom of the Riser or providing a soft hose between the Riser and the Excavator. In any case, care must be taken to ensure that the Excavator is capable of reacting the forces induced on it by the Riser interface and decoupling them from the cutterhead.

The primary wear items on Excavators will be the cutters, especially the picks themselves. Ideally we would like to recover only the cutterhead from the seabed and leave the Excavator on the bottom. ROV-assisted subsea mating and un-mating scenarios should be considered. Furthermore, we would like to be able to recover the Excavator for maintenance without recovering the entire Riser. Again, subsea mating and un-mating of the Excavator to and from the Riser is highly desirable.

V. EXAMPLE EXCAVATION PERFORMANCE ANALYSIS

An example performance analysis for a hypothetical counter-rotating cutterhead (e.g. as shown in Fig. 2) is shown in Table 1. Note that “Time Efficiency” is defined as the percentage of time that the machine is cutting (not repositioning the cutterhead or the Excavator itself) multiplied by the average percentage of the cutterhead that is engaged in the rock. Utilization means the time that the machine is actually up and running - i.e. on location, powered up, and fully operational, e.g. not undergoing maintenance or being launched or recovered.

Table 1 Excavator Performance Estimate

Rock Parameters			**Cutting Requirements :**		
UCS	20	MPa	Production Rate	1.0	m^3/min
Normal:Drag Ratio	5	:1			
Cutter Parameters					
Length	1.0	m			
Diameter	0.9	m	**Results:**		
Sump Depth	0.4	m	Force	49	kNt
Rotation Rate	1.8	rev/sec	Torque	5.1	kNt-m
Pick-sets/rev	2	ps/rev	Normal Force	244	kNt
Advance Rate	0.004	m/ps		25	Tonnes
Time Efficiency	75%		Pick speed	5.1	m/s
Utilization	85%		Power	518	KWatts

The hypothetical Excavator has a production rate goal of 1.0 m^3/minute and must excavate 20 MPa rock. A normal/drag force ratio of 5:1 is assumed. This is achieved with a counter-rotating cutterhead assembly 1.0 m long by 0.9 m diameter, rotating at 1.8 rev/second, and working from a trench depth of 0.4 m. The cutterhead assembly requires a normal force of 25 Tonnes and needs to deliver around 520KWatts to the rock. (Note that the actual power requirement must include drive train inefficiencies plus slurry drag effects.)

VI. Summary and Conclusions

The Excavator is part of an overall mining system which includes the surface vessel and Riser. The Excavator design is closely related to the overall system design, e.g. through the Excavator to Riser interface and the alignment motions required of the surface vessel to keep up with subsea Excavator locomotion.

A method has been outlined that will allow us to predict the performance of subsea rock cutters including the cutting (drag) force and power requirements. The cutting power required is determined by the rock strength, production rate, and the suitability of the pick spacing design.

Cutterhead flow field design is important for efficient excavation and to ensure that chips and fine particles are not lost to plumes or left on the ocean floor. The flow field can be powered by three sources: suction from the Riser, the pumping action of the cutters, and any additional water jets that we may add.

Excavator configuration options trade off Excavator complexity vs. locomotion requirements. More complex machines, i.e. those that move their cutterhead(s) in multiple degrees of freedom, can sit in one spot for longer periods of time, reducing surface vessel motions and traction wear. Also, they can generally manage more difficult terrain. However, these machines are larger, heavier, and more expensive than simpler machines.

For a given rock type, production rate, and cutterhead design, minimum machine sizes are dictated by the normal cutting forces, i.e. the forces required to keep the cutters moving into the rock. These forces can be estimated by multiplying the cutting drag forces by "rule of thumb" Normal:Drag force ratios. However, good estimates of these ratios do not exist for deep water massive sulphide excavation at this time.

The production rate of an Excavator is dependent upon its "time efficiency", which is inherent in the machine design. Time efficiency estimates must consider repositioning/realignment time and the percentage of engagement of the cutterhead with the rock. Any bouncing of the cutterhead against the rock will significantly reduce this efficiency.

Finally, to reduce down-time, the Excavator design should consider the possibility of in situ mating and un-mating between the Excavator and the Riser, and between the cutterhead and the Excavator.

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