Manganese Nodule Miners on 18,000-ft Deep Seabed: Touchdown, Track-keeping Control and Disturbed Seabed Track History

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This paper reviews and discusses some important design and position-control parameters and issues of the deep seabed nodule collector-miners (mining vehicles) of a few consortia, including the subsystems that the international consortia had independently developed since the 1970s. It includes the Ocean Minerals Co. (OMCO)–Lockheed design and full-scale deployment and touchdown tests of its self-propelled, remotely controlled miner on the 16,000-ft-deep seabed. Furthermore, this paper shows a remarkable change made on the previously disturbed sediment track surface. That track was elevated or disturbed in 1978 by OMCO’s Archimedean-screw miner track blades. Over a 26-year period, the elevated surface became flat and no longer elevated. First, the paper revisits major technological activities from past research and development, design, and tests conducted by the four international ocean mining consortia in the 1970s and proposes baseline design parameters and issue guidance for the development of commercial manganese nodule mining systems from the deep seabed. OMCO already reported the two full-scale, deep-ocean tests and concurrent development of a commercial mining system and technology of automatic ship-pipe-buffer-link-control with a self-propelled, automatic track-keeping miner or mining vehicle.

UNIT CONVERSION:

1 ft = 0.3048 m, 1 m = 3.28 ft, 18,000 ft = 5,487 m, 16,000 ft = 4,878 m

INTRODUCTION AND TECHNICAL ISSUES

In the early 1970s, while 300-ft (91-m) water depth was treated as “deep water,” the goal of the OMCO-Lockheed commercial mining system and technology development in 1974 was to develop an 18,000-ft deep-ocean technology in five years. To achieve this huge challenge, the team and management looked at two choices: (1) an incremental step-by-step technology improvement approach, eventually reaching 18,000 ft (5,487 m); (2) a direct approach, with risks, to develop an 18,000-ft deep-ocean technology.

The OMCO commercial deep-ocean nodule mining system and technology had been developed with advanced system integration, design, and track-keeping control simulation software from 1974–1980 at Lockheed Missiles & Space Co., Inc.–Ocean Mining Program. The automatic track-keeping control of a 300,000-ton ship and seafloor miner control subsystem was developed jointly with TNO, the Netherlands (Brink and Chung, 1981). OMCO executed the full deep-ocean tests with the mining ship Glomar Explorer independent of the commercial mining program (Chung, 2000).

This paper presents the full-scale miner and its seabed touchdown and track-keeping control tests of OMCO’s self-propelling seabed miner from the Glomar Explorer on the 16,000-ft (4,878 m)-deep seafloor under automatic track-keeping control in the North Pacific Ocean in 1978 and 1979. The paper also revisits and supplements some further progress made to the author’s original papers on the commercial mining system (Brink and Chung, 1981; Chung and Felippa, 1981; Chung et al., 1980), as well as the nodule lift flows and an updated 3D nonlinear FEM pipe dynamics developed under the National Science Foundation (NSF) research grant (1992–2000).

The author continued further research and development (1992–2000) with the NSF research grant. It includes more advanced versions of the 3D nonlinear pipe dynamic behavior, including newly discovered issues of long-pipe torsion or twist that were detected during the Glomar Explorer at-sea test in 1979, with more advanced computational methods, including a FEM.

A series of experiments of the hydraulic nodule-sediment mixture lift flows had been published in the proceedings of the ISOPE Ocean Mining Symposium and ISOPE Conferences and Journal (1993–2010). This paper series mainly presents the developments at OMCO. The Ocean Minerals Co. (OMCO) is an international consortium of Billiton B.V. of Royal Dutch/Shell (The Netherlands), Lockheed Missiles and Space Co., Inc. (USA), Amoco Ocean Minerals Co. of Amoco (USA), and Royal Bos Khalis Westminster Group N.V. (The Netherlands). In the early 1970s, OMCO initiated this commercial nodule mining system and technology development program with the task of coming up, within a target time frame, with a more economical, advanced commercial mining system and technology development (Chung, 2021). In parallel, OMCO conducted a full-scale test of the pipe-miner at the 16,000-ft (4,878 m)-deep seafloor with the ship Glomar Explorer in the North Pacific Ocean (Chung, 2020).

A general outline of OMCO’s 18,000-ft (5,487 m) commercial ocean mining system and technology was first revealed at the Offshore Technology Conference, 1981. The present paper discusses the miner/collector and their position control in the automatic 300,000-ton ship-miner control loop and supplements the miner/collector in Brink and Chung (1981).
The present “commercial mining system” development (Figs. 1 and 2) has been updated with further progress made since 1980. The further update includes OMCO’s self-propelling Archimedean-screw miner full-scale test performance with Glomar Explorer (Fig. 3), conducted in the North Pacific Ocean in 1978 and 1979 with

- the miner deployment-touchdown-retrieval operations,
- traction power performance,
- track-keeping maneuvering control, and
- miner weight, immersion, and stability supplemented with some key results from the Glomar Explorer at sea test.


The commercial mining system, now more economical, further incorporates recent computer-controlled automatic track-keeping control operation simulations, as well as the miner speed control accounting for varying seabed geotechnical properties and nodule abundance distribution for the given nodule production goal. The integrated system of ship—pipe—miner subsystems and design and control operation will follow in a series of papers.

Buffer-Miner Flexible Links

Upon the success of the OMCO mining system full-scale test with the buffer-to-miner flexible links, most other organizations’ mining systems since the 1980s have adopted the use of OMCO’s basic “flexible” link concept—essentially, the links of the 18,000-ft (5,487 m) mining system with “flexible” links connect the miner and buffer at the bottom end of the pipe (Brink and Chung, 1981, Fig. 1). Since the flexible buffer-to-miner link was first revealed in 1981 to the public, most newcomers have

Other International Consortia Ocean Mining Tests

Three other international consortia conducted their deep ocean mining systems independently of one another:

- Kennecott Exploration (Heine and Suh, 1978) had conducted at 15,000 ft (≈ 4,500 m) various deep seafloor tests with a small-scale tow-system miner/collector. The seafloor tests during a two-year test period were equipped with various instruments.
- OMA Deepsea Ventures, Inc. (Kaufman et al., 1985) conducted its miner tow test in 1977–78 at the 15,000-ft (≈ 4,600 m) seafloor in the Pacific Ocean. The floating platform towed their
miner attached at the pipe end. Kaufman et al. (1985) claimed that there was no need for a self-propelling miner.

- Ocean Management Inc. (OMI) of Inco, Preussag, Metallgesellschaft AG, SEDCO. OMI in 1978 conducted in-line pump and airlift with drillship SEDCO 445, according to Kaufman et al. (1985).

Organizations in France tested a few screw-propelling miner/dredge and nodule lift concepts and a submersible shuttle miner system. Japan in the 1980s initiated a national program of the nodule mining system and technology development. Its collector was a tow sled system. The development includes mostly miner subsystems of ship-tow-sled miner and a pump for hydraulic nodule lift, which conducted small-scale experiments. However, the program ended following a scaled-down miner tow test in the 1990s.

Glomar Explorer Full-scale Test on the 16,000-ft (4,878 m) Seafloor of the North Pacific Ocean

In 1978, the Glomar Explorer had a large-sized “moon pool” with its bottom hull plates capable of sliding open and closed while in the ocean. Some particulars of the Glomar Explorer and the moon pool (Figs. 3 and 4) are noted as follows:

- Automatic track-keeping thruster system
- Moon pool size: 270 ft (82 m) long, 70 ft (21 m) wide
- Ship bottom can be opened and closed while operating in the ocean
- Heavy-lift system and heave compensator with pipe top gimbaled
- Pipe: 16,000 ft (≈ 4,860 m) long, OD = 15 in (38 cm); ID = 7.5 in (19 cm)
- Derrick height on the ship is approximately 300 ft.

**Link to Seafloor Miner/Collector**

Every part of the pipe-buffer-link-miner preassembled inside the moon pool (Fig. 4) must be secured against any possible damage prior to its launch through the huge moon pool opening. The buffer docking ring in Fig. 4 was designed, manufactured, and installed in a few days before the Glomar Explorer departed for the North Pacific test journey. This buffer ring is a strength member to protect against potential damage to the buffer, miner, and the ship hull in case of the ship’s excessive roll and pitch motion as well as the associated moon pool sloshing, when the ship with its bottom hull plate open encounters the heavy sea. The flexible hose links for the nodule-sediment mixture transport are not strength members, and the support link cables or ropes are designed as structural strength links to hold the miner on the seafloor and buffer in position within the slant range or support cable length, protecting the flexible nodule-transport link hoses. Link configuration is subject to the nodule mixture density, flow speed, friction, and its material stiffness.

**Recent Self-Propelling Traction Belt-Type Miner-Collectors**

Pipe behavior along its length is one of the key parameters for miner track-keeping control design and operation, as they are subject to time lag:

- Slant range (approximately buffer-miner link length)
- Pipe motion along the pipe
- Pipe oscillation along its length, vertical and lateral
- Ship and pipe bottom end (buffer) stop
- Ship and buffer turn
- Ship and buffer stop
Further details and integration of the self-propelled miner on the seafloor to the ship-pipe-buffer-miner system are updated with some further developments since 1980, including the continued research conducted under the U.S. National Science Foundation (NSF) research from 1993–2000 by the present author.

For deep-ocean mining, the ship’s maneuvering/positioning thruster control system interacts with the individual subsystems of the pipe-buffer-link-miner moving on the deep seafloor. This results in the need for interactive control among the entire subsystems. That can be achieved with automatic positioning or track-keeping control of the ship and miner. One of the critical issues is the static, as well as dynamic, response behavior of the long pipe, in view of static and dynamic motion displacements of the long-pipe bottom end (5,500 m long in this paper). Additional thruster control of the buffer position is also simulated to test the necessity of buffer thruster(s) (Chung, 2022).

The author, under the NSF Research program (1992–2000), conducted further research supplementing OMCO’s pipe-buffer-link behavior with the development of new program 3D nonlinear coupled pipe axial-bending-torsion with more advanced FEM and MEM. Refer to Chung and Cheng (1999), as well as a series of experiments on hydraulic solid-sediment mixture lift flows in Newtonian as well as non-Newtonian liquids (Chung, Yarim, and Yavasci, 1998, 1999).

The introduction of torsion/twist of a very long pipe and the associated biaxial bending-torsion coupling and the elastic pipe joints is to account for the change in dynamic behavior of the long pipe and more during the design study. Associated issues with pipe twist/torsion were raised during the 1979 at-sea test. This was a key reason behind the new 3D pipe dynamics software and associated experiments sponsored by the NSF. A series of papers on these and associated issues were referred to in Chung and Cheng (1999).

Seafloor Nodule Collection and Preparation for Transport to the Ship

Manganese nodules are distributed on and close to the seabed surface. The seafloor nodules, as collected and thoroughly washed on site, are still mixed with sediment and other materials. For the pump transport through the links to the buffer, the nodule-sediment mixture needs to be prepared at the seabed level—cleaned, sized, and sorted before transferring through the links to the buffer and then to the ship.

Preparation of the Collected Nodules from the Seafloor

The preparation steps are: (1) sort and size the nodules and crush larger nodules; (2) wash the sediment or mud from the surface of the nodules and prepare for pump transport through the links to the buffer located at the bottom end of a long pipe; and (3) lift or transport the nodule mixtures to the ship.

Miner Velocity

Ocean mining operation with the miner maneuvering on the deep seabed surface takes place at a velocity in the range of 0.5–2 knots. This velocity range is one order of magnitude slower than the ocean-going ship’s speed range. The miner velocity along the seafloor mining (nodule-collecting) path track depends on:

- miner traction efficiency
- miner path track-keeping efficiency
- seabed sediment properties for the miner traction force
- nodule pickup efficiency
- the seabed surface nodules distribution or abundance (rich or poor)
- miner-sediment interaction
- seabed terrain, e.g., slope, and more

OMCO in 1978 and 1979 also operated the full-scale self-propelled miner in the North Pacific Ocean on the 16,000-ft-deep seafloor (Fig. 4), and some of the miner touchdown and its miner track-keeping control along its path are presented below.

Pipe Stretch: Static as well as Dynamic

As an 18,000-ft-long pipe (Whitney and Chung, 1981), the static stretch pipe with the buffer and miner held below at the pipe’s bottom end is in the range of 25–28 ft. In addition, the amplitudes of dynamic axial oscillatory displacement at the resonance are in the same order of magnitude as the static stretching displacements (Fig. 6; Whitney and Chung, 1981).

Axial pipe oscillation amplification at resonance with a ship’s heave and pitch motion as a function of pipe length occurs in the operating Sea State, as shown in Fig. 6, and the effects of pipe diameter and mass are in Whitney and Chung (1981).

Axial Pipe Stretch, Static as Well as Dynamic Axial Oscillation

The static stretch of the pipe with the buffer and miner held below at the pipe’s bottom end is in the range of 25–28 ft, which is to be accounted for during the miner touchdown and recovery
operations. In addition, the amplitudes of dynamic axial oscillatory displacement at resonance are in the same order of magnitude as the static stretching displacements (Fig. 6, Whitney and Chung, 1981).

Lateral Oscillation and Time Lag

When a ship with an 18,000-ft-long pipe deployed undergoes a horizontal oscillatory motion, there is a time lag between the pipe top and the bottom end of the buffer.

Examples of horizontal motions:

1. **Horizontal or lateral oscillatory motion** (Fig. 7): When the pipe top end on the ship starts to undergo a coupled surge-sway-yaw horizontal oscillatory motion, it takes some 58 s before the pipe bottom end realizes the initiation of top oscillation of the 18,000-ft-long (5,486 m) pipe. Before the miner touchdown operation, the buffer and miner are held at the pipe bottom end (Chung et al., 1980).

2. **Horizontal or lateral translatory motion**: Traditional ship turning simulation (Fig. 8): When the ship with the pipe top starts its maneuver, making a 180° turn in 4,800 s, the pipe bottom end starts to move following the ship maneuver, some 58 s later. When the mining ship and 18,000-ft-long pipe undergo motion in the ocean, the pipe’s vertical motion and lateral motion are actually coupled. A 90° turn simulation video clip is referred to in Chung (2021).

**Miner Deployment-Touchdown–Retrieval and Weather Window: Glomar Explorer in the North Pacific Ocean**

**Pipe-Buffer-Miner Touchdown at 18,000-ft Seabed.** The true length of a long pipe near the miner touchdown on seabed is actually elongated/stretched and greater than the total length counted while deploying from the ship. The pipe statically stretches or elongates in the range of 25 ft for the present 18,000-ft-long pipe system and, in addition, dynamically oscillates axially some 25 ft in amplitude at the resonance. The axial resonant period increases with the excitation period, as do amplification (Fig. 6) and buffer mass. It decreases with pipe thickness (Chung and Whitney, 1981; Chung, 2022). Sea waves in these axial pipe resonance periods are common in the ocean.

The primary parameters for oscillatory axial pipe stretching are pipe length and pipe-buffer-miner mass. Further parametric analyses can lead to a way to alleviate such potential problems.

**Long Pipe Design Stress: Bending or Axial?**

There were a few important findings during the 16,000-ft pipe retrieval on the Glomar Explorer in 1978—pipe thread at some pipe joints were loosened, possibly caused by the pipe’s torsion. This was a very important finding for the pipe joint design and for pipe deployment and retrieval operation, including possible loss of the pipe below the joint. When the 300-ft-long pipes are joined as deployed from the ship, there are many cables tied around and along the pipe. This could have induced torsion of the long pipe by ship velocity and current in the water column (Chung and Whitney, 1993).

The Glomar Explorer operation team in 1979 reported this problem at the pipe joint while they retrieved the pipe. At the time, the commercial mining system development team was developing a new FEM software of 3D nonlinear pipe behavior and also confirmed that, for a very long vertical pipe, the axial pipe stress or tension were an order of magnitude larger than bending stress. This changed the designer perception of bending as design stress. The axial stresses were found to be a critical design parameter for designers of such a long, deep-ocean pipe (for example, 18,000-ft-long here). This was further confirmed with another software developed under the National Science Foundation research (1993–2000, Chung).

Ship or pipe top motion in the 3–10-s-period waves are in the axial pipe resonance period range that is commonly encountered in the ocean, and the ship’s heave motion, subject to the 3–10-s-period waves, can easily excite the axial pipe resonance (Fig. 6).

**Weather Window and Ship Heave Resonance**

While deploying and operating ship and pipe in an 18,000-ft-deep ocean, it is important to determine the pipe deployment timing to avoid a high Sea State that could excite the ship’s excessive heave motion and the associated pipe bottom end displacement—also to avoid potential timing of the pipe axial resonance period (Fig. 6; Chung and Whitney, 1980) when it is close to the ship heave resonance.

The simulation capability of the pipe’s axial static stretch or elongation and dynamic oscillating stretch motion amplitude with the aid of a 3D nonlinear pipe behavior software onboard the ship can be of great help in determining the touchdown timing. Video cameras on the miner and buffer level will aid the final miner touchdown operation.

The availability of the marine weather window and the estimate of time lag between the pipe top held at the ship and the pipe bottom end with the buffer and the miner (Figs. 6–8) are very important parameters in decision-making on the timing for deployment and retrieval operations. Marine weather forecast provides the weather window to prepare and deploy the integrated pipe-buffer-miner, and so does the retrieval.
As to the potential axial flow-induced vibration, there was no incidence of axial-flow-induced vibration due to the nodule-sediment mixture lift flows during the full-scale deep-ocean test.

FULL-SCALE MINER TOUCHDOWN AND TRACK-KEEPING CONTROL TEST: SET-POINT MANAGEMENT AND LEARNING

OMCO conducted the full-scale pipe-buffer-miner touchdown and track-keeping tests remotely controlled from the Glomar Explorer in the North Pacific Ocean in 1978 and 1979. The tests included:

- miner touchdown and recovery
- miner attitude on the seafloor
- miner submergence below the seafloor surface
- miner traction force
- self-propulsion and speed control of the miner
- track-keeping control along the preplanned set-point track path, stop, turn, and return path next to the previous track path
- track-keeping control along the preplanned set-point track path, turn, and return path by “learning.” Then continue along the next track path.

Weather Forecast

The weather forecast (wind and waves), including duration, is a very important parameter in the miner launch/retrieval operation, as the waves induce the ship’s 6-degrees-of-freedom motion, both vertical and lateral: surge, sway, heave, roll, pitch, and yaw, which again induce lateral and vertical motion displacements as well as vertical stretch oscillation of the buffer at the pipe bottom end and the miner. Video cameras installed on the buffer, as well as the miner monitoring of the miner and the seafloor, were very helpful in determining the final touchdown decision.

In addition to the computer simulation of the pipe’s static stretch and dynamic axial oscillation amplitudes, the instruments measured and monitored the miner, link, and buffer behavior, including:

- screw-propulsion system performance
- operation of the screw miner and the buffer along the track-keeping path
- seafloor current velocity: The Glomar Explorer test-recorded non-zero current speed at the seafloor level with the current meter deployed on the 16,000-ft seafloor.
- collector and nodule crusher
- and more

MINER LAUNCH, DEPLOYMENT, AND TOUCHDOWN AND RETRIEVAL SEQUENCE

The snapshots in Fig. 9 were part of the video recordings taken from the cameras on the buffer level and on the miner. The following presentation shows the OMCO screw-propelling Archimedean screw touchdown and track-keeping controlled from the Glomar Explorer.

This miner launch-deployment test took several steps on site to determine the right timing for the safe miner touchdown while undergoing the miner’s axial oscillatory motion coupled with a lateral oscillatory motion. The miner motion follows the pipe-bottom end’s coupled axial and lateral swinging motion.

Upon successful touchdown, the video camera monitored the miner attitude, including its predesigned propulsion screw submergence level below the seabed surface.

The buffer camera recorded the video of the launch of the miner-buffer-pipe from the Glomar Explorer with the large hull bottom door or moon pool in the North Pacific Ocean. Computer software was used to estimate the static pipe stretch as well as the axial and lateral oscillation amplitudes of the pipe bottom end induced by the ship motion in the operational sea state. This information was useful in determining the buffer and miner camera locations (Fig. 4) and in determining the on-site miner touchdown timing.

Some missing or unavailable input data for computer simulation of pipe behavior, in addition to surface waves and wind forces, are onsite data input in the water column along the pipe length, including:

- current speed and direction that vary along pipe length
- temperature
- density
- viscosity

Water-column current velocity varies locally in direction, as well as speed, along the pipe length, and it can change additional local pipe motion or displacement. At the moment, there appear
to be very little data on such environmental properties in the water column in deep ocean and pipe-buffer deployment.

The video snapshot in Fig. 9a shows the moment the swinging miner coupled with the oscillatory motion of the pipe bottom end or the buffer just before touchdown. The snapshot in Fig. 9b shows the initial touchdown period, splash-spraying the surface sediment-soil. The stripes on the outer screw cylinder display the miner submergence level, which was part of the miner weigh/buoyancy test. The photo also shows manganese nodules at the test area.

The miner at touchdown with black and white marking stripes shows a neutral buoyancy of the miner propulsion-screw on the seabed sediment surface as designed. Video cameras were installed on the buffer level as well as on the miner (Fig. 9b).

**Miner Traction Force, Propulsion, and Track-keeping Maneuver**

Upon touchdown, a series of dry-run tests of screw traction power, track-keeping control on the set-point track path, direction control, etc., are conducted. Figure 10 is a snapshot from the buffer-level video of the screw miner in action tested in 1978 for neutral buoyancy, screw traction power, and track-keeping maneuver.

**Self-Propelling, Remote-Controlled Miner’s Track-keeping Control Along Preset Seabed Track Path**

The self-propelling miner’s track-keeping control test along the preset seabed track path from the Glomar Explorer was conducted successfully via passive control of the buffer (at the bottom of the pipe) and active control of the seabed miner. The miner track-keeping control was preset to move along the track path on the seabed. The miner was connected via flexible link(s) to the buffer. The pipe length was 16,000 ft long. While track-keeping, the miner and the buffer stayed within the target slant range or the link envelope.

The track path with the seabed surface disturbed behind the rotating Archimedean screw miner path or set-point path is discussed with an example in detail later in the paper.

**Similar Track Path in Use in the Industry.** Zig-zag mining track path on the seabed has been in use in mining sands and mineral particles in shallow offshore waters in Southeast Asia. The miner and mining track path is shown with a video snapshot on the continuous line bucket (CLB) miner (Chung, 1991).

**OMCO’s 1978 Disturbed Track Surface and the Changed Surface 26 Years Later**

This paper further updates Chung (2021) and shows a remarkable change made in the sediment track surface that was disturbed in 1978 by the OMCO’s Archimedean-screw miner tracks during a 26-year period (Miljutin et al., 2011).

**Time Lag in Ship, Pipe Bottom, and Miner While Making 90° Turn**

An example of a turning maneuver of a ship-pipe-miner moving at a slow mining velocity (Fig. 12) is discussed below. With the self-propelling miner turning 90° to the left, the ship and buffer maneuver to keep the moving buffer at the pipe bottom end close within the buffer-to-miner link length or the slant range. The timing for turning for each of them is different. There is a time lag while maneuvering between the ship (pipe top) response and buffer (at the pipe bottom end) response and the miner (Fig. 12).
A 90° Concurrent Turn Maneuver of a Ship-pipe-miner: Pipe Length \( L = 18,000 \) ft

While the ship (pipe top) and pipe bottom (buffer-miner) move along the preset track path to the west, the miner on the seafloor makes a sharp 90° turn to the south. The ship and buffer turn while maintaining the buffer-miner position within the slant range or the buffer-miner link length. There is a time lag in subsequent ship (pipe top) and buffer (pipe bottom) motion or position relative to the miner in action on the seabed.

The track path of the self-propelling screw miner is preset by the set-point management, according to the nodule-collection, track-path-keeping control plan. The full-scale test of the OMCO self-propelling miner (Fig. 4) proved that nodule mining is possible with the miner track-keeping control operation along the set-point track path. Brink and Chung (1981) presented the control simulation of ship and buffer responses to various miner turning maneuvers, including a buffer thruster control.

Mining Track Path, Track-keeping and Track Crossing

There can be many different mining track-path scenarios. Among a few, two types of track-keeping are discussed here.

Sweep or collection efficiency. Maximum collection or production of nodules depends on the miner’s track-keeping ability for maximum recovery of nodules in a given distribution area. Here, one of the most important parameters for the miner is to maintain the track path and to not skip the intended area of the nodules on the seafloor.

One advantage of the self-propelled, remote-controlled miner over the tow-sled collector is its track-keeping control ability to stay on the planned (set-point) track, not missing areas of nodules on the track path. The tow collector-miner may deviate from the intended track path and cross over and run into its previous track, departing from the pre-planned track separation (Fig. 13). Such a situation can pose two technical issues. When a miner crosses over the previous track path, it can further damage the near-seabed surface soil of the crossed-over previous track(s), which are partially fluidized and the original shear strength lost. In case the soil behaves as Bingham plastic, the surface sediment or soil can be further fluidized. For a tow sledge miner, it can more likely run into the previous disturbed track. If this happens with the self-propelling miner-collector, the miner or nodule collector can lose some traction force, and in extreme situations, the miner may sink there.

Bingham Plastic Shear of Sediment Soil: Non-Newtonian Properties and Miner Traction Force

Understanding the sediment’s (or soil) shear stress-strain relationship (Chung, 2021) in the deep seafloor is one of the critical design and operational parameters. In an extreme sediment-fluidizing situation, the miner may significantly lose traction force in fluidized sediment. There are reports that the sediment sample taken from the deep seafloor in the Pacific Ocean showed Bingham plastic-type surface sediment behavior: beyond the yield point of the sediment shear stress, the sediment behaves like fluid with the increase of shear strain. This can reduce the miner traction force and even cause loss of its mobility.

Khripounoff et al. (2006) reported the actual measurements of water content in the sediment of facies C (Fig. 14), at sediment depth in the range of 30 cm. The water content of sediments in the top 10-cm layer ranges from 66% to 80%. The top layer is nearly fluidic, and this can be an important miner traction design parameter in “blade” design in achieving effective traction power. Depending on the miner traction blade size and geometry, the associated miner traction force can greatly change the shear force, traction force, or propulsive power. Furthermore, once the miner or its blades damage or disturb the top surface sediment layer, the miner (vehicle) may have little traction power.

Miner-Collector Track Path and Turning Maneuver: Set-point Management and Learning

The zig-zag track path of the miner and the ship under autonomous track-keeping control simulation was previously reported...
as follows: (1) a set-point management for ship-miner position control (Brink and Chung, 1981) and (2) position control by learning (Chung and Qi, 2000):

- Start at slow (0.5 to 2 knots) miner speed to move to the right
- Stop and wait until the pipe bottom end stops moving, and the miner makes a 180° turn and completes its reverse of direction
- Enter and follow the set points next to and along the previous track
- Stop, reverse, and move along the previous track

For such maneuvers, azimuth thruster systems for the ship and possibly for the buffer at the pipe bottom end may be preferred (Chung, 1981).

During these slow-speed mining operations, the ship is further subject to various levels of directional Sea States, and the pipe along its length is subject to the current velocity and headings varying along the long vertical pipe in deep-water column. For such a case, the ship heading is not necessarily bow-forward in achieving minimum drag of the ship and the long pipe. Note that total drag along the long pipe and ship during the ship-pipe maneuver can be in the same order of magnitude as the ship drag in beam sea (Brink and Chung, 1981).

Minimum fuel consumption during ship track-keeping is one of the goals. To achieve this minimum fuel consumption goal, the ship heading is kept steady to maintain minimum total drag of the pipe as well as the ship for the lowest power and the low fuel consumption. Note that the ship supplies power to the miner, buffer, and pumps or compressor for the nodule lift.

**Zig-Zag Mining Track Path**

A zig-zag track-keeping control operation with a ship has been used with the continuous line bucket (CLB) in mining/collecting minerals and sands offshore. An actual CLB system (Chung, 2021) has been in operation in offshore Southeast Asia in mining the mineral particles buried in mud. A similar zig-zag track path was tested with the OMCO miner on the deep seabed. For the purpose of the present zig-zag path control, an example of a 100-m track path and track-keeping control by set-point management is utilized for deep seabed mining. The track path (Fig. 15a) is an example target track path for a self-propelling, remote-controlled miner to track-keep on the deep seabed.

**Ship and Miner Track-keeping Speed**

The miner track-keeping speed range $V_m = 0.25$–2.0 knots is one order of magnitude slower than the ocean-going ship speed. It is primarily a function of (1) the seabed surface sediment properties with shear stress variation that directly influences the miner screw’s or track-belt’s traction force, and (2) the variation of local nodule abundance distribution. The terrain maneuver and obstacle-avoidance maneuver will be reported later.

**Target Track Path and Autonomous Track-keeping by Learning and Set-point Management**

Nodule collection efficiency. Maximum seabed coverage or sweep by the miner increases the manganese nodule recovery or pickup rate. Precise automatic miner track-keeping ability is the focus of the entire deep-ocean mining system (Brink and Chung, 1981).

**A Miner Maneuvering Simulation Along Zig-zag Track-keeping Path: Set-point Control and Learning Control**

Set-point control. The miner turns at the end of the initial 100-m track, with the first 90° turn to the left and proceeding 10 m, followed by another 90° turn to the left, and then it follows the set points set along the previous track path and repeats the zig-zag turns. The set-point control in full-scale was successfully tested at sea.

Track-keeping control can also be automated by set-points along and next to the miner track path. When returning, the miner follows the set-points recorded along the previous tack and continues or repeats along the immediate past track path, and so on.

In track-keeping simulation by learning (Fig. 15b), the initial miner track can be off the target track. Its initial track is as much as 3 m off a target track of 5-m width (Fig. 15b). It takes five track cycles for the present example to correctly track-keep along the target track for this learning method, and the miner crosses over the previous track of the disturbed seabed soil surface, which reduces the tracking force.

The effect of variation of miner velocity and nodule (and soil mixture) collection rates with the seabed soil property variation is discussed in Chung and Qi (2000). More examples of detailed miner track-keeping control simulation by learning will follow in Chung (2022).

**CONCLUSIONS**

This paper reviews and discusses some important design and position-control parameters and issues of commercial seabed mining since the 1970s for the development of deep seabed nodule collector-miners, including the subsystems–self-propelling,
remotely-controlled miner or mining vehicles as part of OMCO (-Lockheed)'s development of its commercial mining system and technology. It includes OMCO's 1978 and 1979 full-scale at-sea tests of design, deployment, and touchdown of its self-propelled, remote-controlled miner on the 16,000-ft-deep seabed. There must still be many unknown issues to identify.

OMCO conducted two full-scale at-sea tests in the North Pacific and concurrently developed a commercial deep-ocean mining system and technology of automatic ship-pipe-buffer-link-control with a self-propelled, automatic track-keeping miner or mining vehicle. This proves that deep seabed mining will be a reality.

OMCO's commercial mining system incorporated more recent automatic track-keeping control computer operation simulations. The miner speed control accounts for varying seabed sediment properties and nodule abundance distribution to maximize nodule recovery. This is incorporated in the integrated system of ship-pipe-miner subsystems as well as design and control operation, and some will be made public in the future.

As for the concern for the seabed disturbance by screw miners, this paper shows a remarkable change made on the sediment track surface. That track was elevated or disturbed in 1978 by OMCO's Archimedean-screw miner track blades. Over a 26-year period, the elevated seabed surface became flat, i.e., no longer elevated.

More technical details will be discussed in follow-up papers on the miner track-keeping control simulation, the miner-links-buffer, hydraulic nodule lift to the ship, and the buffer-to-miner link.

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REFERENCES


Chung, JS (2013). “Commercial Mining System Development for Manganese Nodules: Take Direct-to-5,000-m Approach or Incremental to 5,000-m Approach for a Target Year?” Proc 10th ISOPE Ocean Mining Symp, Szczecin, Poland, ISOPE, 1–4.


