

Seepage Cut-off Walls for Levees and Dams: In-Situ Mixing Methods

Seepage through and under levees and embankment dams is a major problem, and remediation programs of unprecedented scale have begun in recent years in North America. There are various methods used to install cut-offs in both rock and soil. These fall into two broad categories. Category 1 includes cut-offs created by backfilling a trench or shaft excavated under a bentonite slurry or similar supporting methods, and range from the cheapest (backhoe) and the most expensive (secant pile) cut-offs that can be built for levee or dam remedial purposes.

Here we focus on the other category of cut-offs, those created by mixing the fill and/or foundation soils in-situ. There are basically three techniques. The conventional Deep Mixing Method (DMM) uses vertical mixing augers with mixing blades, while there are two newer technologies in this category, the Japanese TRD (Trench Remixing and Cutting Deep) Method, and the Franco-German CSM (Cutter Soil Mix) Method and its Italian sister, CT-Jet. All aim at producing high quality soilcrete in-situ. See a Summary of Characteristics of Various Cut-Off Wall Methodologies on page 55.

DMM (Conventional Deep Mixing) Method

Contemporary DMM methods for seepage control date from Japanese developments in 1972. These techniques for improving foundation soils for strength and stability purposes began in both Japan and in Sweden 5 years earlier. Japanese cut-off technology was introduced into the U.S. in 1986, and U.S. specialists further developed the method in several projects, notably Jackson Lake Dam, Wyo.; Lockington Dam, Ohio; the Sacramento Levees, Calif.; and Cushman Dam, Wash.

DMM technology consists of blending soil with cementitious and/or other materials, or "binders." For the wet methods, a fluid grout is injected through hollow, rotating mixing shafts tipped with some type of cutting tool. On any one

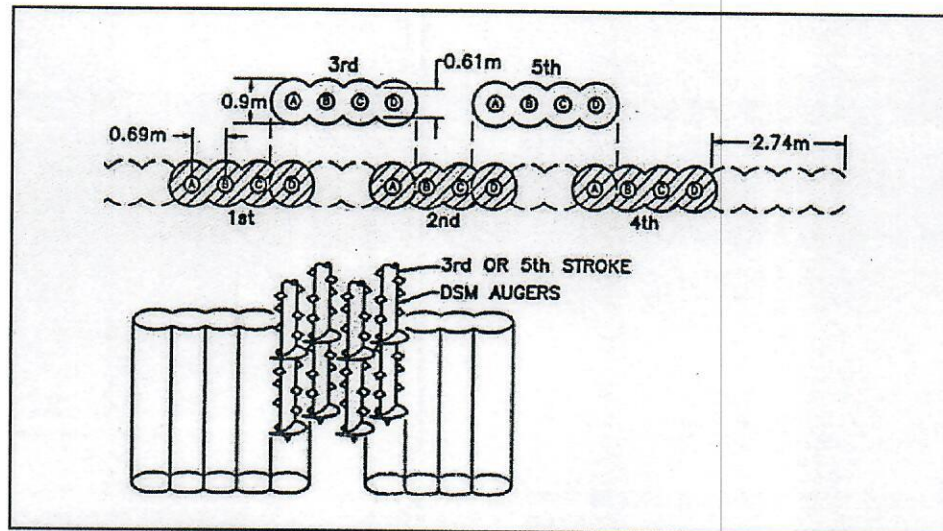
"carrier" there can be between one and eight vertically mounted shafts, but for cut-offs, three or four shaft systems predominate. The type of binder (wet or dry), the energy of the grout injection (rotary only, i.e., low pressure, or jet-assisted, i.e., high pressure), and the mixing principle (all along the shaft, or only at the end), characterize the various methods currently used in the U.S. The original SMW (Soil Mixed Wall) variant is therefore classified generically as WRS (i.e., Wet, Rotary, Shaft mixing).

The secant columns (Figure 1), typically vary in diameter between 20 and 40 in (0.5 and 1 m). "Practical" maximum depths in the range of 80-110 ft (24-34 m) are common, although greater depths are possible using specialized equipment and methods. The cut-off continuity is assured by re-penetrating the inner elements of freshly installed panels. Grout volume ratios of 30 to over 100% are used, depending on the ground conditions, the desired properties of the soilcrete, and the requirements of each DMM variant. Grout volume

fairly massive and require wide and stable access and unrestricted headroom. (Figure 2)

Properties and Characteristics. The grout mix injected during penetration and withdrawal of the mixing tools varies widely. Mostly, the mix is a neat water-cement grout with a water:cement ratio of around 1.0. Bentonite is added where especially low permeabilities (say $< 1 \times 10^{-7}$ cm/s) are needed, or lower strength or stiffness is sought. Strengths vary from 100 to 1,500 psi (0.7 to 10 MPa) and occasionally higher in coarse sands and gravels, and permeabilities are usually in the range 5×10^{-6} to 10^{-8} cm/s. Conventional DMM soilcrete can have a high degree of in-situ heterogeneity.

Notable Advantages. DMM has several advantages, such as wide geotechnical applicability, and low vibrations and moderate noise. With appropriate means and methods and controls, one can build reasonably homogenous cut-offs with good continuity. Productivity can be as high as 2,000 to



ratio is defined as the volume of grout injected divided by the volume of wall.

"Conventional" DMM panels have a range of strengths with depth reflecting stratigraphic variation. In dense or obstructed ground, predrilling or pre-excavation may be necessary to allow efficient DMM cut-off construction. DMM machines are

Figure 1. DMM installation sequence (Bahner and Naguib, 1998)

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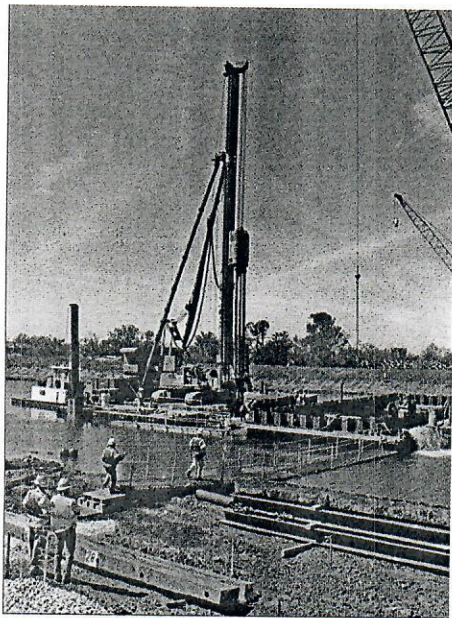


Figure 2. DMM machine (triple axis) operating in river conditions (photo courtesy of Raito Inc.)

3,000 sq ft (200 to 300 sq m) per 10-hour shift. Unit costs are low to moderate, though markedly higher in less favorable conditions. Finally, there are several very competent competitors in North America, with good track records.

Potential Drawbacks. Equipment is large, heavy and incompatible with limited headroom or tight access sites. The practical maximum depth is about 110 ft (34 m) and only vertical diaphragms can be installed. DMM is sensitive to dense, stiff soils or those with many boulders, and soils with high organic contents, or high plasticity can present challenges. Mobilization costs are relatively high.

Overall Verdict. Conventional DMM is a well-researched and resourced technology used for over 20 years in the U.S. Compared to recent DMM variants — such as TRD and CSM — it is more sensitive to variability in the penetrability and composition of the ground, and the product tends to be less homogeneous. Like all DMM technologies, it has a relatively high cost basis due to the specialized large scale equipment and will not be competitive when lower technology systems (e.g., backhoe) can be used. Costs range from \$150,000-\$500,000 for mobilization/demobilization, and unit costs are between \$15 and \$30 per sq ft.

TRD (Trench Re-Mixing and Cutting Deep Wall) Method

This Japanese development began in 1993, and within 10 years had been used on over 220 projects. The TRD machine has a crawler mounted base that provides continuous horizontal movement of a trench cutter, basically a chainsaw mounted on a long rectangular section “cutting post.” (Figure 3) Depending on the ground conditions and the model of TRD, walls from 18 to 34 in (46 to 86 cm) thick can be installed to maximum depths of 170 ft (52 m).

After the cutting post is fully inserted into the bentonite-filled starting hole, the cutting chain is activated and the base machine initiates a horizontal movement. The desired cement-based grout is injected from the post into the cut and a soilcrete material created in-situ. The mixing and cutting assures a high homogeneity due to the vertical soil and grout movement generated by the chain. When the operation “rests,” the cement-based grout is substituted by a bentonite slurry again and so the cutting post is safely parked in the trench without being cemented in. When cutting resumes, this section is recut with the cement-based mix to assure

longitudinal continuity of the wall. Most Japanese applications have been for levee repair, and most have been for installing vertical diaphragms, although substantial off vertical can be provided. Hayward Baker, Inc. has used the TRD method to construct miles of cut-off wall in Reach 1 of Herbert Hoover Dike, Florida since 2008.

Properties and Characteristics: The injected grout mixes are tailored to project requirements. The wall's properties also reflect the nature of the virgin ground as the grout volume ratio is usually 35 to 50%. Unconfined compressive strengths of 100 to 3,000 psi (0.7 to 20 MPa) can be achieved, with a wide range of failure strains (0.5 to 3.0%). Permeabilities are typically in the range of 1×10^{-6} to 1×10^{-8} cm/s. There are no vertical or horizontal construction joints and the soilcrete is typically exceptionally homogeneous. The TRD can perform commercially in all soil conditions, in soft to medium hard lithologies, which are still “rippable.” The cutting teeth are changed in response to the ground conditions. Boulders, as for all DMM techniques, are troublesome, but far less for the TRD method than for traditional DMM machines.

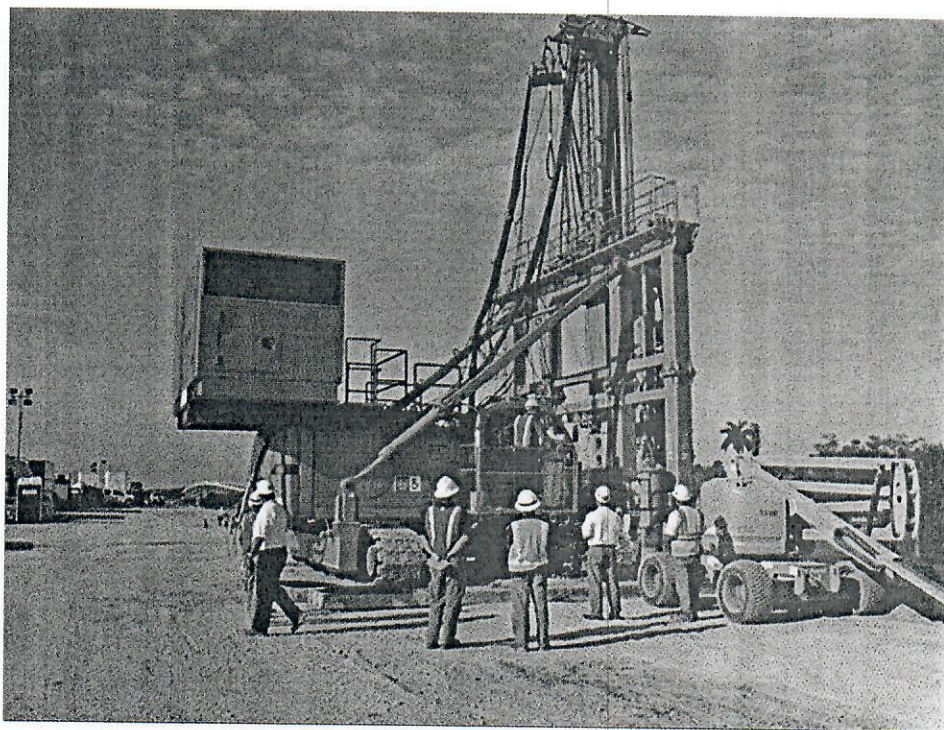


Figure 3. The TRD base machine, with the cutting post inserted into the ground (photo courtesy of Hayward Baker, Inc.)

Notable Advantages. TRD provides continuous, homogeneous, joint-free walls through all soil and many rock conditions. Productivities can be very high in appropriate conditions, as high as 100 sq ft (10 sq m) of wall per hour. The machine is best suited to "long runs." A very high degree of real time QA/QC assures verticality, continuity and in-situ properties. Post-construction verification of as-built properties (strength, permeability, homogeneity, elastic modulus) is readily conducted with conventional, quality coring. In addition, the cutting teeth on the chain can be readily adjusted to suit ground conditions, and the TRD can operate in headroom as low as 20 ft (6 m). Finally, the machine and mixing plant are modestly sized, and extremely quiet.

Potential Drawbacks. Sharp changes in alignment necessitate extracting, reorienting and replacing the cutting post. Abrasive, hard, or massive rock markedly reduce productivity and increase wear on the chain, the driving wheel and the bottom idler. Also, the cutting post can become trapped in soilcrete that hardens unexpectedly rapidly, or it may refuse on hard boulders or hard rock.

Overall Verdict. TRD is a highly-specialized technology with a proven track record in Japan and the U.S., and can provide a cut-off with exceptional quality. In site and soil conditions that permit lower technology approaches (e.g., backhoe), the method cannot be competitive. Costs range from \$250,000-\$500,000 for mobilization and demobilization, and the unit price is in the range of \$25-\$50 per sq ft.

CSM (Cutter Soil Mix) Method

This joint development by Bauer Maschinen and Bachy Soletanche began in 2003. The first prototype machine was field tested in Germany in 2004, and a patent was granted the same year. Bachy Soletanche now refer to this system as "Geomix." By mid-2007, 25 units had been built and over 50 projects had been completed in Europe, Japan, New Zealand and North America, totaling around 1.4 million sq ft (140,000 sq m) of wall. The first use in North America was at the Vancouver Island

Conference Center in 2006, (Figure 4) while the highest profile current CSM project in the U.S. is for sections of a cut-off wall at Herbert Hoover Dike, Florida.

CSM uses hydromill (or cutter) technology previously developed for conventional diaphragm walls to create vertical soilcrete panels, rectangular in plan. The cutting and mixing is done by special wheels mounted on horizontal axes, as opposed to the conventional Deep Mixing equipment, which uses single or multiple vertical axis equipment. Different lengths and widths of panels are possible, and the original Kelly-mounted cutters can reach about 100 ft (30 m) maximum depth. Recent researches into cable suspended machines permit a maximum depth potential of 180 ft (55 m).

Panels are created in the sequence used in conventional diaphragm walling. Each one cuts about 12-16 in (30-41 cm) into each of the adjacent panels. During insertion, either bentonite slurry (to loosen/precondition the ground) or the target cement-based grout is injected through nozzles mounted between the wheels (about 50-75% of the total foreseen grout volume). Mixing continues with the balance of the grout injected during extraction, with the counter-rotational directions of the wheels reversed. Spoils collected in the pretrench are removed by backhoe. In difficult ground conditions, predrilling with closely spaced rotary drilled holes may be required to break up the ground or remove the organics.

The cutter has instruments that monitor and control the construction of each panel. For deep panels requiring the cable suspended cutter, directional stability and control is provided by a series of movable steering surfaces on the supporting frame.

Control of verticality in 3 axes to a tolerance of 0.2% is claimed. A further new development is the "Quattro" machine with two additional mixing wheels mounted on the frame above the lower two wheels. These enhance mixing efficiency during withdrawal from deep cut-off panels.

Trevi has developed a similar machine, CT-Jet, which combines the cutting action of the wheels with the high kinetic energy of grout injected at elevated pressures, similar to those used in jet grouting and jet-assisted

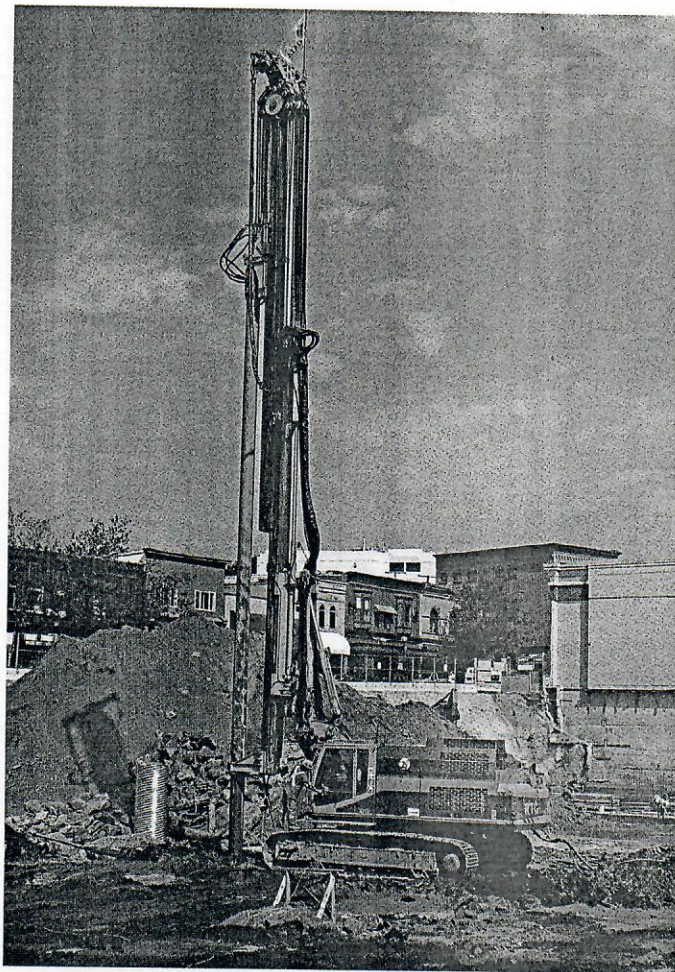


Figure 4. CSM used at a Vancouver Island site

DMM (Turbojet system). The jetting accelerates and optimizes the disaggregation of the soil, improving productivity and homogeneity. The jets above the mixing wheels are adjustable for different soil types. Side jets can be used during withdrawal. Cable-suspended CT-Jet equipment can reach over 250 ft (76 m) in depth. Panels range from 25 to 60 in (64 to 150 cm) wide, and 8 to 10 ft (2.4 to 3.0 m) long.

Ongoing research focuses on the geometry of the cutting and mixing wheels. Three standard types are readily available, while two other types are being investigated. Relatively low headroom machines are also being developed.

Properties and Characteristics: CSM has been successfully conducted in the whole range of soils from organics and clays to gravels and cobbles. A typical grout mix, as used in a cut-off in Germany, involved 373 kg (822 lbs) cement, 40 kg (88 lbs) bentonite and 858 kg (1,891 lbs) water per cubic meter, while the mix being used at Herbert Hoover Dike has a high replacement of Portland cement by slag cement. For another example, 54 wet grab samples from the CSM wall installed in 2006 in the fine estuarine, silty and clayey sands of the Venice lagoon provided the data in Figure 5.

The soilcrete is typically more homogeneous than the equivalent material produced by conventional DMM methods and, of course, there are fewer inter-element joints and less waste since re-penetrations are not required.

Notable Advantages. CSM provides strict control of panel verticality in real time. The soilcrete is relatively homogeneous and the grout properties can be designed for specific parameters. The method is applicable in all soil conditions, including dense/stiff deposits. Cutting teeth can be quickly adjusted to soil conditions. The equipment operates on a wide range of conventional carriers. Productivity can be very high. The method easily accommodates sharp changes in wall alignment. Finally, the equipment is relatively quiet and vibration free.

Potential Drawbacks. Boulders and other obstructions, and very dense deposits or rock-like layers will severely impact feasibility and productivity. Homogeneity will be challenged by very plastic and/or organic sediments. The typical machine requires considerable headroom and access.

Overall Verdict. CSM, in its various evolutions, has spread very quickly across several continents over the last few years,

	COMPRESSIVE STRENGTH (PSI) [MPa]			PERMEABILITY (CM/SEC)		
	MAXIMUM	MINIMUM	AVERAGE	HIGHEST	LOWEST	AVERAGE
28-day	570 [4]	51 [0.3]	214 [1.4]	8.75×10^{-7}	7.25×10^{-8}	3.27×10^{-7}
60-day	760 [5.5]	68 [0.4]	286 [1.9]	4.63×10^{-7}	4.49×10^{-8}	2.04×10^{-7}

Figure 5. Data from CSM wall installed in Venice lagoon (Fiorotto, 2007)

indicating the system's attractiveness. However, it will not be competitive in situations where low technology approaches can be used. Unit costs are from \$20-\$40 per sq ft, and mobilization and demobilization costs range between \$50,000-\$100,000.

Summary

The characteristics of Category II in-situ cut-offs were presented here, including estimated costs, advantages and best

applications. The text is condensed from a much longer document, "Seepage Cut-offs for Levees and Dams, the Technology Review," which was presented at the ADSO Dam Safety conference in 2009. The original paper also included an analysis of Category I cut-offs, which were defined as cut-offs involving backfilling of a trench or shaft previously excavated under bentonite slurry or a similar supporting medium. Examples include the use of backhoes, grabs, hydromills and secant piles.

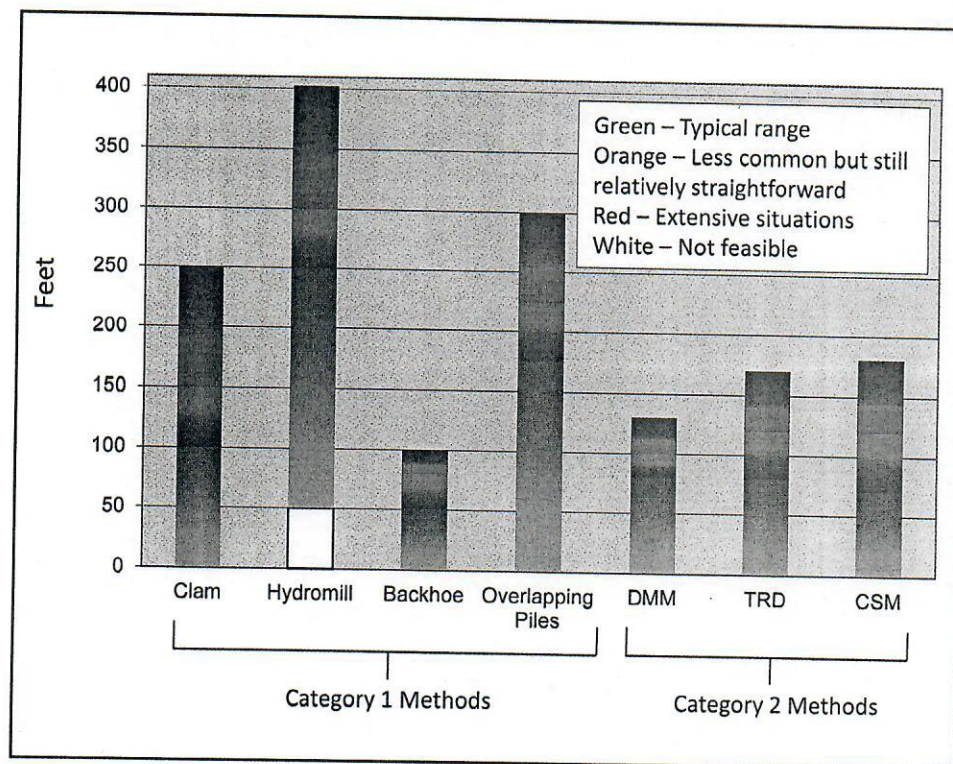


Figure 6. Comparative depth capabilities of the various cut-off wall methodologies

Conventional DMM

Vertically mounted shafts are rotated into the soil creating panels of soilcrete

Wall Dimensions

Depth: Maximum practical about 120'
Width: 20-40"

Typical Properties Of Soilcrete

UCS: 100-1,500 psi
K: 5×10^{-6} to 1×10^{-8} cm/s

Costs

Mob/Demob: Moderate-High
Unit Prod: Low in sympathetic soil conditions to Moderate-High in difficult conditions

Pros

- Low vibrations and noise
- Experience
- Several practitioners in U.S.
- High productivity
- Good homogeneity

Cons

- Large equipment needs good access and substantial headroom
- Depth limitation
- Very sensitive to obstructions
- Variable homogeneity with depth due to limited vertical mixing

TRD

Vertical chainsaw providing simultaneous cutting and mixing of soil to produce continuous soilcrete wall

Wall Dimensions

Depth: Maximum 170'
Width: 18-34"

Typical Properties Of Soilcrete

UCS: 100-3,000 psi
K: 10^{-6} to 10^{-8} cm/s

Costs

Mob/Demob: Moderate-High
Unit Prod: Low-Moderate

Pros

- Continuity of cut-off is automatically assured (no joints)
- Homogeneity (especially vertically)
- Productivity
- Quality
- Quick adaptability to wide range of ground conditions
- Low noise and vibrations
- Low headroom potential (20)
- Inclined diaphragms possible
- Wide range in cut-off properties can be closely engineered
- Very high degree of real time QC
- Relatively compact equipment

Cons

- Difficult wall geometries (sharp turns)
- Medium-hard rock, and boulder nests (will reduce productivity and increase wear on key components)
- Currently only one U.S. contractor
- Requires very specialized equipment
- Cutting post may become trapped in the wall or may "refuse" on nests of boulders or hard rock

CSM

Cutting and mixing wheels mounted on horizontal axes create vertical soilcrete panels

Wall Dimensions

Depth: Typically 140 with Kelly but Maximum 200' with cable suspension
Width: 22-47" with trials to 60"

Typical Properties Of Soilcrete

UCS: 70-3,000 psi
K: 10^{-6} to 10^{-8} cm/s

Costs

Mob/Demob: Low-Moderate
Unit Prod: Moderate

Pros

- Panel continuity/verticality closely controlled
- Homogeneity
- Productivity
- Adaptable to conventional base carriers
- Wide range in cut-off properties can be engineered
- Can accommodate sharp geometry changes
- Applicable in nearly all soil conditions
- Cutting teeth can be quickly adapted
- Relatively quiet and vibration-free
- Fewer joints than conventional DMM
- Can change parameters for different soil types
- Low headroom potential (15 min)

Cons

- Rock, boulders and other obstructions
- Requires considerable headroom

Summary of Characteristics of Various Cut-Off Wall Methodologies

Key to Costs (2010 Figures)

Mob/Demob		Unit Costs (i.e., cost per square foot of cutoff)	
< \$50,000	Very Low	< \$10	Very Low
\$50,000-\$150,000	Low	\$10-\$20	Low
\$150,000-\$300,000	Moderate	\$20-\$50	Moderate
\$300,000-\$500,000	High	\$50-\$100	High
> \$500,000	Very high	> \$100	Very High