Engineering Feasibility of In-Situ Subsurface Isolation Barriers

E.E. Carter, P.E.
Carter Technologies Co
9702 Garden Row Drive, Sugar Land, TX 77478
USA

ABSTRACT

In the remediation of radioactive waste disposal sites there are occasional situations where it is not feasible to remove the waste or contaminated soil and a containment approach is more appropriate. This paper is a discussion of a DOE funded research and development study [1] on the feasibility of in situ construction bottom barrier containment structures in soil under and around large contaminated sites.

The evaluated bottom barrier method begins with a conventional slurry trench around the perimeter of a site. The method utilizes high-density slurry grout and a cable saw mechanism to make a controlled horizontal cut at the base of the slurry trench. Gravity alone forces the dense slurry into the horizontal cut and causes the entire block of earth to literally float in a slurry grout that cures into an impermeable barrier material.

The work included evaluation of a completed field test that floated a 50-ton block of earth, development of a computer model of the process, evaluation of structural hydraulic and shearing forces on the earth block, measurement of friction and cutting forces in a field test, hardware design drawings, cost analysis, and an ASME review.

The study evaluated issues such as scalability, and adaptability to various geologic conditions such as soil types and layers, hills, rocks, saturated soil, faults, waste density variations, fractures and unconsolidated soil formations. A method to measure the integrity of the barrier both after construction and periodically in the future was also evaluated. Barrier durability, erosion, bio-penetration, and moisture related cracking, and response to earth movements is also considered. Reactive and adsorptive chemistry to relatively thick layers of barrier material are proposed that may further improve long term containment.

INTRODUCTION

This paper is a discussion of research on the feasibility of the EarthSaw buoyant barrier method of constructing a subsurface isolation barrier in-situ. The paper outlines the method of operation and discuses engineering feasibility in a variety of soil conditions.

A decade ago bottom horizontal barriers were a hot topic of discussion at some environmental technical conferences. [2] There were many ideas and many proposals about how such a thing could be done but most of them were never commercially or technically successful. In time, the demand for such technologies faded in part because of the idea that a barrier would not eliminate risk in the way that removal does. However it is now becoming clear that removal can seldom be so complete that risk is eliminated.

If the life cycle cost of re-disposal at ultra costly sites such as the Waste Isolation Pilot Project is factored in, it become clear why such facilities can only receive a small fraction of the waste presently buried in shallow disposal. Many radioactive wastes are of too low an activity to justify such efforts. Getting poorly documented or widely dispersed waste out of the ground can be a huge technical problem. Many sites have unique orphan wastes that have no legal disposal path at any existing waste facility. In view of this it may be time to re-examine barrier technologies.

The objective of a "bottom barrier" technology was to construct an impermeable barrier under and around a waste burial site, preferably without having to excavate or drill into the interior of the site where the waste was contained. Many approaches relied on cutting a pathway horizontally through the earth and then filling it with grout. One key problem was how to hold up the overburden materials between cutting the barrier and the hardening of the grout. The overburden weight tries to squeeze and pinch out the layer of grout. In hard rock mining this may done by cutting and grouting only narrow width horizontal panels so that the overburden could be supported and then coming back and later to cut between the first panels. However even this approach leaves many cold joints and will generally not work in wet soil or soft non-cohesive soil.

The other key problem was how to keep the cutting apparatus from mechanically failing halfway under the waste site. Complex machines tend to be unreliable ones in subterranean environments. Machines using high-pressure jet grouting techniques also have complexity/reliability issues that can stop them in their tracks just by stopping up a jet nozzle. The author has tested several jet cutting horizontal barrier machines and found that the total energy expended and the volumes of potentially contaminated spoils to be a unacceptably large.

THE FLOATING BLOCK METHOD

The EarthSaw "Floating Block" method is designed for work in most types of soil and is not intended for hard rock. It uses a simple cable saw technique to perform the soil cutting work. A steel wire rope cable is used to mechanically slice or saw a thin pathway through the soil. Since the pathway is quite thin this requires only a small amount of energy and one moving part. This thin pathway is then expanded by introducing grout into it and lifting the overburden upward. However in the EarthSaw technique, this is not done by pressure injection but by simple buoyancy. The grout barrier material is made with a fluid so dense that the overburden simply floats on it and therefore cannot pinch it out. Since the grout is not pressurized it cannot squirt back to the surface.

The "Floating Block" method works as follows:
A conventional slurry trench excavated around the perimeter of the site to be contained. This perimeter trench is excavated in the common manner of civil construction with a large trackhoe or a clamshell trench machine. At some point the bentonite slurry in the trench is replaced with a heavyweight but very fluid grout of greater average density than the soil overburden materials. This heavy weight grout works like a heavy drilling mud to stabilize the walls of the excavation by exerting tremendous hydraulic force against the

soil so that the walls of the excavation cannot cave in. A steel wire rope cable is laid in the perimeter trench around three sides of the block and a pull is exerted toward the forth side to slice horizontally through the soil at the base of the perimeter trench. As this horizontal cut is made, the heavy grout flows into the cut and the block of earth floats free on the heavy grout. The floating block is completely surrounded by liquid grout so when the grout cures it forms a continuous barrier layer.

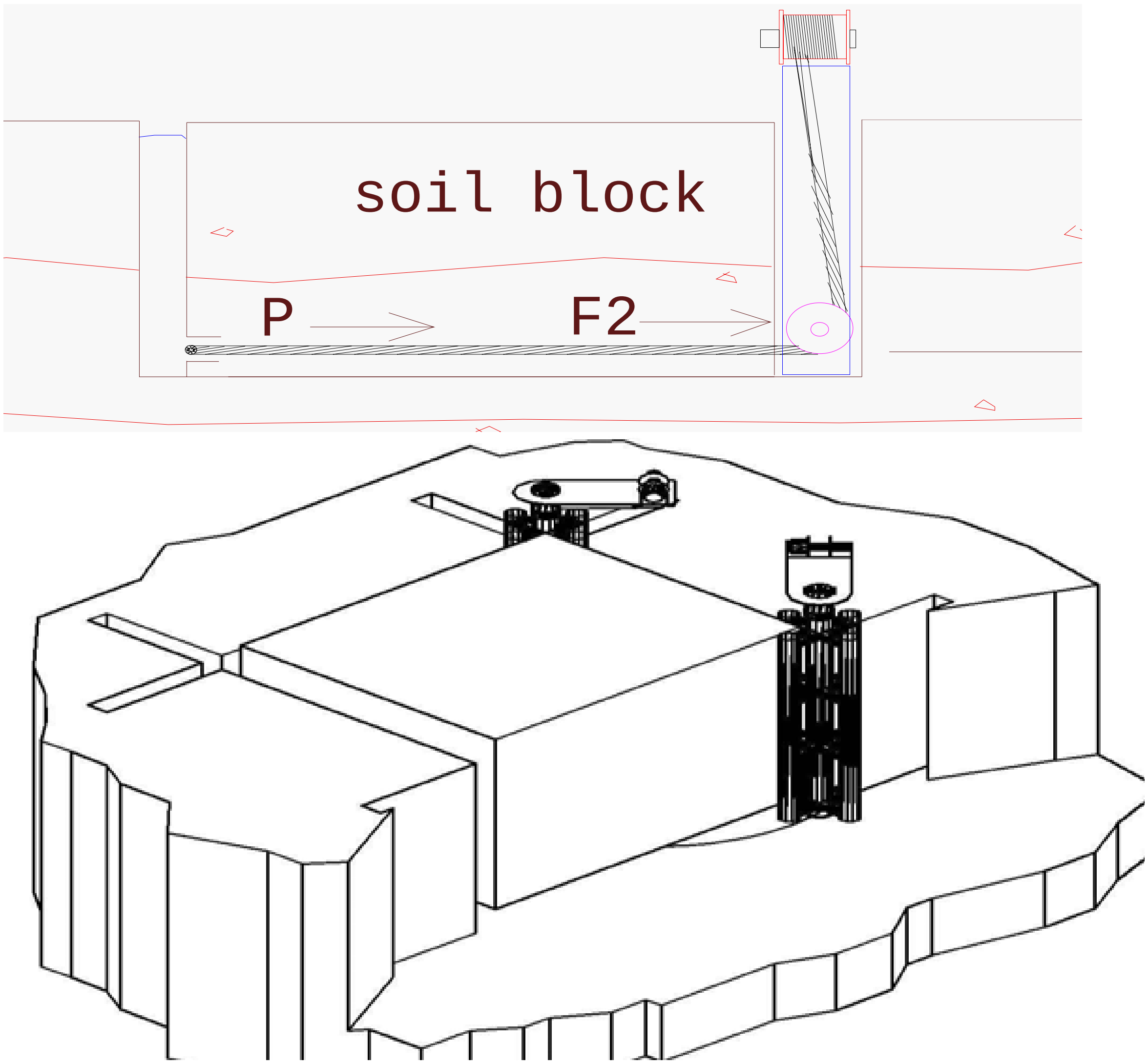

Figure 1: Cable saw force balance concept in 2-D and 3-D illustrations

To form the horizontal cable saw cut the equipment must generate a pulling force on the steel cable at the bottom of the perimeter trench. This can be done with a large winch and pulley mounted on a steel frame that fits into a corner of the perimeter trench. The load frame is lowered into each of two adjacent corners of the perimeter trench. The load frame fits neatly into the cross shape at the corner where two sides of the perimeter trench join. (FIG 1) Each load frame has a large pulley on the bottom and a large winch on the top. A heavy steel wire rope passes from the winch down around the pulley and then around the three sides of the perimeter trench and under the pulley and up to the winch on

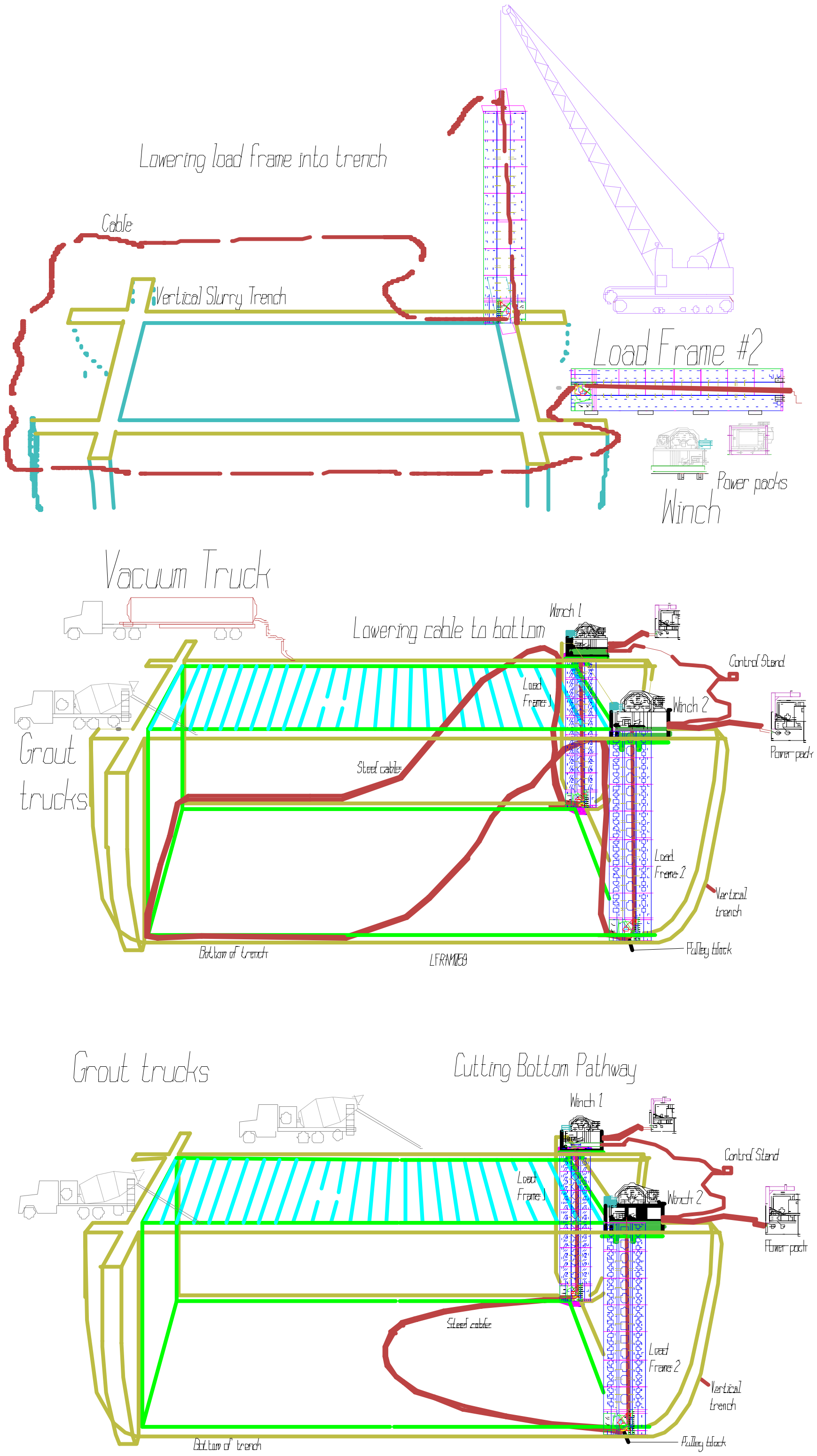

Fig 2: Sequence of installing load frame in trench and cutting bottom pathway

the second load frame. (FIG 2) Tethers, (not shown) in the other two corners of the perimeter trench hold the cable at a precise depth at those corners to control the initial depth of the cut. In this way the depth of cut at each of the 4 corners is precisely controlled. The load frames are made so that they fit down into the intersection of two trenches that cross at each corner of the perimeter trench. The reaction force for the soil-cutting load is transferred to the soil through this structure so that there are no unbalanced forces and no ground anchors are required.

When the winches are activated, the steel cable slices through the horizontal pathway at the base of the perimeter trench. As the cut progresses, gravity will force the heavy grout to follow the cable and fill the void by lifting the overburden earth. In larger sites it may be desirable to use the winches to reciprocate the cable back and forth to make the cut, though this is much slower. The design of the system is such that the cable transitions from slicing to sawing mode automatically, when high resistance is encountered, with no adjustment of hardware.

Before the bottom cut is made, the level of the grout in the perimeter trench is adjusted to provide enough positive buoyancy to lift the block as it is cut loose. A topographic survey is then repeated on previously placed survey markers on top of the block. Heavy and light areas of the block will not rise equally. Variations in the depth of the bottom cut can also cause this. The floating block is "*balanced*" by using earth-moving equipment to move surcharge topsoil around on the top of the block until all survey markers have risen to the same elevation. This step of verifying that the top of the block has risen uniformly also verifies that the bottom barrier is of uniform thickness. Additional grout is then added to each of the 4 sides of the perimeter trench. This causes the block to uniformly rise in the same way a docked boat rises when the tide come in. If desired, the entire block may be displaced sideways by adding the extra grout from only one side. After the barrier has reached full thickness, the perimeter trench and the top of the block are capped with a synthetic liner, which becomes part of the full cap.

MECHANICAL ANALYSIS OF FLOATING BLOCK

The overburden of earth above the horizontal cut and inside the perimeter trench is called "*the block*" but the actual perimeter trench may have more than 4 sides and they do not have to be at right angles or straight.

After the heavy grout is in the perimeter trench, the sides of the block are uniformly pressed by the hydrostatic force of the grout, much as they are by adjacent soil loading in plastic soil. The grout exerts this force against the walls of the excavation regardless of the soil qualities. If the soil is highly permeable the grout produces a seal known as "filter cake" on the face of the soil and the force acts on this seal. This mechanism is how drilling fluid keeps an oil well open as it is being drilled through soft sand. This force acts over the entire side surface of the block reinforcing its structural integrity so it behaves as a cohesive block even if it is made of loose wet sand. As the bottom cut is made, gravity forces the grout to flow into the cut and there it provides the same balanced force strengthening the bottom of the block. If the cut passes through a void too large to be immediately plugged by the filter cake of the grout, then the grout will flow into the void and fill it. This does not alter the net buoyant forces acting on the block.

Like the action of a rising tide on a floating object, buoyant rising does not induce any change in stress or loads in the block. The final stress condition of the block is the same as its initial condition before starting the horizontal cut. Cracks or discontinuities in the block will have no effect on the stability or buoyancy of the block. Voids with in the block, which connect to the perimeter trench, will simply fill with grout and will not affect buoyancy. The bottom barrier thickness is equal to the distance the top of the block raises. The block surface rise is proportional to the depth of the cut so a deeper block floats higher. In uniform ground, and angled bottom cut will cause the block to raise more on the deep end. If one side of the block were known to contain denser soil or waste, the barrier deeper could be cut deeper on that side compensate and achieve a uniform rise height.

Figure 3: First Field Demonstration Floating a Block of Earth Severed With Steel Cable

GROUT REQUIREMENTS

The grout for the EarthSaw process is the most complex part of the work. It must be of higher density than the earth material that is to float on it. It must also form a barrier material that will not crack and is sufficiently impermeable to meet the containment requirements. The grout must also remain liquid until the bottom cut and the balance and fill is complete. The grout must be able to resist premature changes in its properties due to fluid loss to the soil formation. The grout must be able to resist the environmental conditions for the design life of the project. The grout must also serve as a lubricant and heat transfer fluid for cutting the bottom pathway.

Grouts for the EarthSaw method include "TECT A", a set-delayed cement-based grout that hardens like concrete. The grout is essentially a high strength concrete and is available with internal micro fiber reinforcement. Another cement-based version is available that cures to a low strength similar to hard clay, but retains a malleable capacity allowing for significant deformation without fracture.

There is also a molten wax based grout known as Waxfix that cures to form a sticky and malleable solid with self-healing properties. Waxfix grout contains no water is not affected by soil moisture. Waxfix has good capacity to form barriers in fractures and open formations because the wax entering the formation quickly cools and solidifies even in vertical fractures. Large quantities of Waxfix have been used in grouting programs at the Idaho National Laboratory to isolate highly radioactive buried waste. Operating methods for molten grouts are different form conventional grout because the set of the grout is a heat transfer process and instead of a chemical reaction. Wax based grout is more damage resistant and impermeable than any other kind of grout but it is also more expensive so it is used in thinner layers.

TECT B grout is a non-hardening clay based grout with iron oxide weighting agents. TECT B is applied as a flowable slurry with high lubricity properties similar to a heavy drilling mud. The grout cures to a stiff peanut butter like condition over a period of months. It is fully self-healing and should offer a very high level of containment integrity over long time periods. This grout actually provides three means of containment at once. The grout's high hydrostatic gradient prevents groundwater from flowing into the grout. The grout's low permeability impedes contamination permeating the grout. Finally, the optional reactive zero valiant iron in the grout may treat contaminants that eventually diffuse into the grout. The grout barrier may easily be made as much as a meter thick. The grout may be formulated using sufficient zero valiant iron to treat essentially the entire inventory of organic solvent to be contained. This grout is called a semi-permeable reactive barrier. Unlike other permeable reactive barriers this barrier has a very low native permeability that is likely to continue to become more impermeable as it ages. However since there is no pathway around the barrier, the contaminants have to pass through it if they are to escape and the passage will take a long time so they have much time to react with the iron.

Laboratory data were developed to validate the performance of examples of the three main classes of grouts. Lab testing of the TECT B grouts indicates that permeability is approximately 1.9×10^{-8} cm/sec for field-cured grout excavated from the test barrier 6 months after installation. The grout is essentially made out of clay and rust, two materials that are known to be highly stable and not subject to deterioration over time.

COMPUTER MODEL OF EARTH BLOCK DISPLACEMENT

A computer model was developed in Microsoft Excel to help evaluate the parameters of a potential project. The computer model calculates friction, buoyancy, and displacement and provides the means to control buoyancy design so that the EarthSaw process generates minimal differential stress on the soil block as it is being cut. The model assumes that no large earthen block will remain rigid but will eventually conform to the load placed on it by breaking, bending or deforming. Therefore the computer model need only calculate the final displacement of the block due to buoyancy. This model does not evaluate stress because the barrier does not require any structural support from the soil block. The soil block mechanical properties for contaminated sites are typically unknown and must be assumed to have many crack defects, vertical discontinuities, vertical lithological heterogeneities, planes of weakness, large-scale voids, large rocks and other non-homogeneities. A key feature of the EarthSaw technology is that it does not depend on the mechanical integrity of the soil block. Relative bulk density is ultimately all that matters. The entire floating block could be a pile of loose rocks, a mass of sand or a hard rock mass riddled with fractures before during or after the buoyant cut and lift and it would make no difference at all. The mass would still be floating and contained within the perimeter barrier. Flow of grout into the floating block's interstitial voids will not alter the buoyancy of the total block.

Density data can be obtained by continuous coring around the perimeter of a block before excavating the perimeter trench. The models input fields allow for variation in density by depth and by quadrant as well as estimated densities for interior waste volumes. As an example assume a very large but relatively shallow soil block where one corner of the block is lighter than the rest of the block, perhaps due to buried waste or a buried tank, then that area will rise more than the perimeter areas. The buoyancy computer model graphically shows the magnitude of this rise assuming the block is large enough to be fully elastic. This will make the bottom barrier thicker under that area of the block. The model helps us determine how much extra soil must be added on top of that area of the block to keep the barrier thickness uniform. The model contains two main output graphics. One shows the thickness and surface contour of the bottom barrier and the other shows the elevation and contour of the top surface of the block. In uniform conditions, they look much the same. However, if we have re-contoured the surface soil to make the barrier thickness uniform, then these two surfaces may no longer match so the survey markers are pegged to the original surface, regardless of how the surface may be re-contoured.

If the soil within the block is sufficiently strong, the elastic response might be reduced or eliminated causing the block may act as a rigid body listing to one side instead of deforming. Fortunately we do not need to determine if the block will be rigid or flexible. The same computer model automatically allows us to determine correct surcharge loadings to adjust for this and produce a uniform lift with no excess deformation or tilt on the block. In order to construct a uniform thickness bottom and side barrier using buoyancy, the earth block's top surface must float parallel to the original ground surface. This implies that the final buoyant position of the block is not listing to one side or bent by unbalanced forces. Any forces that would tend to change the original surface slope of the block must be counter balanced to achieve our objectives of a uniform barrier. This inherent requirement for balanced forces limits the need for stress analysis on the floating earth block since proper balancing of loads is a functional part of the work progress and its success is measured with a surveyor's precision.

Under certain conditions an unfinished EarthSaw block may be subject to mechanical stresses sufficient to cause deformation. These include: a non-flat bottom cut, large variations in waste density and excessive buoyancy during the horizontal cut process. The mechanism for this deformation is differential buoyancy. This is undesirable because it causes variation in the thickness of the barrier. Some reviewers expressed concern that the floating earth block could be cracked by these stresses and that calculating the stresses would require invasive studies. The project team discounted this concern by pointing out that the earth block probably has many cracks already and that additional cracks in the block do no harm since they will all be filled with grout. In the field tests it was observed that the hydraulic forces of the grout on the surfaces of the block reinforce the structural integrity of the block and tend to close cracks that are intentionally induced. If workers balance the block keeping the top of the floating block parallel to the original surface topography, then loads and internal stress are substantially the same as before the block was severed from the earth.

COMPUTER MODEL OF FORCE AND FRICTION

Friction is a critical factor in EarthSaw project design. The cable used to cut soil is a standard type of non-rotating steel wire rope. The cable is much stronger than ordinary steel for its cross-sectional area and since it is used in a remote underground environment it can be stressed to within a significant percentage of its breaking strength, without the typical 4 to 1 safety factor used in load lifting applications. The cable can be operated by the remote controlled winches as a knife in what we call "slicing mode" cutting a pathway through soil like a knife or cheese slicer. Without the hydrostatic head of grout this pathway would immediately close behind the cable as it passed through the soil. However the grout, which is locally pressurized by gravity, is forced into the cut and holds it open. The width of the cut increases the amount of force required to make the cut. This effectively limits how wide of a cut can be made in a given soil.

If the cut to be made is very wide, the cable can be reciprocated back and forth in a sawing motion or circulated continually in one direction. When a sawing action is used to make the horizontal cut, the cable functions not only as a mechanical saw but also as a pump to create a flow of grout across the face of the cut. This flow is facilitated by using a cable made with three bundled strands. The spiral strands act like a progressing cavity pump. This grout flow carries soil cuttings from the face and dumps them in the perimeter trench where they are dispersed into the much larger volume of grout. Much of the actual cutting action is done by the abrasive particles in the grout. Sawing still causes the cable to wear so the design of the overall system is such that cables can be replaced an unlimited number of times during a cut. The cable friction depends not only on the roughness of the cable and the lubricity of the grout but also on the total contact angle between the soil and the cable. The computer model, which is freely available and runs on any computer equipped with Microsoft Excel or compatible spreadsheet program, provides a quick method of estimating the total friction and determining if slicing or sawing motion is required as well as the size of cable and power of the winches.

Friction is a critical variable in cutting soil. The project team developed the mathematical relationship to describe the cable friction in an EarthSaw™ application and verified it with field data using a friction sled and also actual horizontal cuts through both sandy soil and hard clay soil. The friction rises exponentially as the contact friction angle and the coefficient of friction increase. We were able to build these factors into the Excel spreadsheet, which displays a table showing how changing parameters results in stuck cables, or slicing on either side of optimal sawing conditions.

Analysis with the computer model indicates that very large size barriers may be formed with this method. Maximum site size with 25 millimeter, (1-inch) diameter cable and 100,000-pound winches is limited to about 152 meters (500 feet) square by total friction imposed by the friction due to the weight of the cable itself. It is of course possible to use winches that are more powerful and larger cable. If the total friction exceeds the strength of the cable or the power of the winch, the cable will be effectively stuck. In this case the winches would be permitted to pull the cable in two and another cable would be re-installed from the beginning.

This size limitation can also be avoided by reducing the coefficient of friction between the cable and the soil. Optional traveling block devices (not shown) can be used in the trench to reduce the typical contact angle to less than 110 degrees to enable construction of even larger width horizontal cuts. The friction factor is an exponential function of the angle of contact, with the soil (in radians) times the coefficient of friction. This factor defines the ratio of power lost to friction due to the contact angle. The drag friction is the weight of the cable on laying horizontal in the ground times the coefficient of friction. In the model, this drag friction subtracts from whatever force remains after applying the friction factor and can cause it to fall below zero, indicating a potential for a stuck cable.

Pounds Total Friction = $\mathbf{e^{\lambda\alpha} + W_h \times \lambda}$ **Where λ is the coefficient of friction and α is the angle of contact in radians, and W_h is the weight of the cable laying on the ground surface and in the horizontal cut.**

Reducing the contact angle can dramatically decrease the friction. The typical illustrations of the method (FIG 2) show a rectangular block with the cable extending from two adjacent corners. This produces an effective contact angle of 180 degrees. This contact angle can be reduced by using a traveling block pulley in the bottom of the trench to make the cut, thus reducing contact angle to nearly 90 degrees. This technique allows continuous cut barriers to be increased to over 609 meters, (2000 feet) square, though such large spans require a tedious reciprocating saw action rather than a rapid slicing action. The cost/benefit of this approach versus breaking the site up into many smaller blocks may also be evaluated using the Excel computer model spreadsheet.

CRACKS, DISCONTINUITIES AND VOIDS

The grout acts like a drilling fluid in that as it is pressed against a soil formation it will do one of two things. If the pore size of the fracture or porosity openings are small as in sand and small gravel, the grout colloidal particles will plug the openings and allow pressure force to bear against the formation. However, if the pore size opening is large enough the grout will flow into the opening, filling it until it finds a surface it can plug. The net hydrostatic force of this grout inside the opening is always zero. To better understand this, consider that a large solid block of wood that floats 70 percent submerged in water. If many random holes are drilled through this wooden block, making it look like Swiss cheese, it will lose some of its potential weight carrying capacity but it will still float 70 percent submerged in the water. Thus fractures and voids in the floating block that connect to the barrier grout perimeter and fill with grout do not alter the buoyant condition of the block.

An EarthSaw barrier can be constructed around a large field composed of soft mud on one end, loose pea gravel in the middle, and fractured soil on the other end. As the trench is excavated, the grout in the trench will create a hydrostatic force against the soft mud soil preventing the trench from collapsing. The grout will flow a finite distance into the surface of the pea gravel and bridge off to form a similar pressure bearing surface, preventing the pea gravel from sloughing off. While excavating around the fractured soil section, the grout may flow a significant distance into the larger fractures before bridging off and perhaps one or more large voids inside the block will fill with grout. The hydrostatic pressure of the grout exerts a slight compressive force on all sides of the block keeping it from falling apart or sloughing into the trench. As the bottom pathway is cut the grout will also exert force against the bottom of the block causing it to float.

CRACK SEALING MECHANISMS

The TECT A cement based grouts and the TECT B clay-based grouts are thixotropic fluids that are designed to seal off in narrower cracks while flowing freely into large ones. Molten Waxfix grout is not thixotropic but gets the same effect through greater heat loss in the smaller cracks. If cracks form in the bottom or sides of the soil block during the horizontal cut, or the soil already contains such cracks connected to the cut barrier area, they will be automatically filled and sealed off by the barrier grout. The grout can never rise higher in a discontinuity than the elevation of the grout in the trench. Fractures and cracks which do not contact the barrier will, of course not be sealed or filled with grout.

EFFECT OF WATER TABLE

The computer buoyancy model shows that water table and porosity of the soil prior to operations, affect density and thus buoyancy quite significantly. If data on the net wet bulk density of the entire soil interval is collected from borings in the four corners of the site then the water table variable may be overridden by setting porosity to zero. Once the barrier is constructed, water can no longer enter or leave the earth block and increases in the external water table will have no effect on the barrier because the barrier grout and all that is in its perimeter are much heavier than water. Removal of ground water within the block will reduce the weight of the block and thus tend to increase the thickness of the barrier if a non-hardening TECT B grout was used.

MAKING BARRIERS ON SLOPED GROUND

When making a barrier on sloping ground the uphill end of the barrier must be deeper to compensate for the fact that the trench on that end cannot be filled to the surface. The computer model takes the elevation change into account and allows an easy "what if" evaluation of multiple options. Significant elevation changes are difficult and more costly to compensate for so the utility if this method is limited with trench sites that run down hillsides. Such sites would have to be broken up into smaller areas with limited elevation change.

PROPOSED TEST SITE

Prior to redirection of funding in 2002, the C749 Uranium burial Ground at Paducah was selected for a proposed field test of a 50 foot square area about 35 feet deep. This site is underlain by a relatively soft wet soil layer that should allow the cable saw to work in the more rapid "slicing mode". The site contains air sensitive uranium turnings in drums with a very detailed inventory detailing the weight of each waste package and where it was disposed. The site was near a river and the seasonal water table inundated the waste. The soil was considered unstable and difficult to excavate. The site has the potential for earthquakes so the soft non-hardening TECT B grout was selected for its potential to construct an earthquake resistant barrier. Since many of the wastes could be packed in TCE or other oil, the grout was to be made with sufficient zero valiant iron to treat any long-term permeation migration. This site is an example of an ideal candidate for the floating block method because the process will also lift the waste above the water table.

APPLICABILITY LIMITATIONS DISCUSSION

The study indicates that the EarthSaw is applicable to both wet, dry, and water saturated soil and that the water table has little impact on construction. For EarthSaw to work the cable saw must be able to cut through the soil and the grout must not leak out into the formation. Rocks in a soil matrix can generally be broken or pushed out of the way by the cable saw while some softer rocks can be sawed through. Soft shale formations that can be easily excavated with a backhoe should be feasible to cut abrasively with the cable reciprocating back and forth. Generally the EarthSaw method is not recommended for rock because cutting would be slow. Sand and soft soils appear to be easy for the process to handle. Gravel mixed with sand should not present a problem but clean gravel formations might not be feasible without special grout because the grout could leak away into the formation.

In field tests, it was easy to saw through a cubic foot size limestone rock with a plain steel cable. The wire rope cable easily cut through a sample of volcanic Tuff received from Los Alamos National Laboratory. Cutting in soft rock such as weathered shale of Tuff appears to be quite feasible. Hard soils containing many large rocks may be slow to cut with standard wire rope. If the rocks are frequent or the soil surrounding them is hard enough to resist pushing the rocks around, the cable would require frequent replacement. Cutting in harder rocks would require further testing on special cable with an abrasive grout for the application and is not recommended.

There are buoyancy limitations on the method that restrict the application to sites that are not mounded up above grade. Very dense soil would also impose economic limits based on the fact that the cost per gallon of grout rises for higher specific gravity grout. One simple way to minimize required grout density is to simply increase the depth of the bottom barrier. This also may be desirable when working with buried tanks that have leaked. Large voids and discontinuities within the soil block will be automatically filled with grout if they are in contact with the barrier layer or so close to it that they collapse.

The maximum size of a barrier is limited mostly by friction. Reducing the friction or increasing power can make larger cuts possible. Use of a the traveling block in the trench to reduce the contact angle can increase the maximum size significantly. Reducing the contact angle from 180 degrees to 110 degrees could allow sites as large as 609 meter, (2000 feet) square to be cut by cable sawing action.

There are possible economic limitations regarding the minimum size of an EarthSaw containment barrier. As EarthSaw projects become larger, the cost of the grout and other factors is greatly reduced. As the surface area to volume ratio decreases the economics improve dramatically.

The technology is limited to sites that are relatively flat. Working on a hillside with slopes greater than 10 feet from one side of the site to another is probably not feasible because the cuts have to be deeper and the grouts denser to compensate for the larger volume of the block that will be above the fluid level. This could complicate application at some of the Oak Ridge Bear Creek Valley trenches. These trenches would have to be done in two separate sections. Breaking the trench into multiple sections.

A with a building on it would not be a problem because the weight of a building is generally small compared to the soil block. However, the method is difficult to apply to landfills that rise like a tall hill above the surrounding landscape. The problem of attaining sufficient buoyancy may be addressed to some degree by making the barrier deeper, to increase the vertical lift. However, the vertical block method would tend to make the barrier thicker at the edges. A directional drill based version of the technology offers a means of dealing with this type of site but discussion of it is beyond the scope of the current discussion, which focuses on the vertical block method.

Another limitation concerns sites that have require the perimeter barrier to be constructed in contaminated soil. When constructing the vertical slurry trench in contaminated ground, some of the inherent safety of the method is not realized because contaminated spoils are still produced to dig the vertical trench. Again this can be addressed by using the directionally drilled holes method.

SITE APPLICABILITY

The Floating Block EarthSaw method is recommended for well-defined and relatively level sites that have little or no rock at the desired depth of the bottom horizontal cut. The method may be especially useful when adjacent soil is unstable or saturated such as areas next to a river or other water-inundated site.

The following conditions could make work significantly more difficult:

- Significant Rock formation in the path of the bottom horizontal cut
- Contaminated perimeter that requires side wall spoils to be managed as waste
- Site elevation variance more than 10% of barrier depth
- Cobble and boulder layer in zone in or just above bottom horizontal cut
- Very hard soil and a very wide site requiring a single continuous cut
- Soil with a very high bulk density, such as iron or uranium ore
- Sites that are mounded up above grade
- Sites that have pits excavated into rock
- Sites consisting of a pond of liquid underlain by very soft soil
- Sites that are made of dense rock
- Sites where access to the perimeter is too restricted
- Sites where perimeter trench excavation is not feasible
- Small sites where waste can be economically removed
- Non-removable monitoring wells through the barrier path
- Non-removable utility lines through the barrier path
- Clean gravel formation or Karsts limestone with large leak paths

The method should work well in the following conditions:

- Wet soft soil at the depth of the bottom horizontal cut
- Dry sandy soil at the depth of the bottom horizontal cut
- Wet sandy soil or non-cohesive soil
- Rock strata above the depth of the bottom horizontal cut
- Sites with highly variable types of strata, mixed soil types
- Volcanic tuff and soft sandstone
- Glacial till or clayey silt with flat rocks
- Sandy gravel type soil with some cobbles
- Very deep sites up to 30 meters deep
- Very long and narrow trenches
- Soil containing many fractures and animal holes
- Sites with tree roots and de-energized decommissioned utility lines
- Sites containing large buried tanks
- Sites containing mostly boxes or drums
- Sites containing unknown waste forms
- Sites containing air sensitive materials
- Sites containing energetic or explosive material
- Site that are seismically active
- Sites that are triangular, rectangular or trapezoid shape

- Sites that contain buildings or basements
- Water table in contact with waste, evacuated after construction

The speed of construction of the bottom horizontal cut can be a matter of hours in "slicing mode" which is possible typically with widths less than 30 meters. Wider sites up to 100 meters wide are almost always limited to a much slower "sawing mode" action to make the bottom cut.

VERIFICATION

Verification of the thickness of a bottom barrier can be done using standard surveying methods. The vertical movement of the surface directly corresponds to the movement of the bottom of the block. Prior to making the bottom cut, topographical survey markers are placed on a grid over the site. This markers stick up above the surface so that they are not affected by extra soil placed on top of the soil block. After the bottom cut is made and the block is floating a second survey is done to determine if every part of the block has risen evenly. Soil on the surface of the block is then moved around to calculations from the computer model to balance the block so that all areas have risen equally. After this additional grout may be placed in the perimeter trench to cause the block to rise higher and increase the thickness of the fluid bottom barrier layer before it sets.

A synthetic liner cap may be placed over the top of the block and keyed into the side walls of the barrier before it sets. Vacuum dewatering wells may be installed within the confines of the block to remove leachate or to permanently dry out the entire waste site. Barometric pressure sensors may be placed under the cap and also in adjacent areas to monitor and log the daily air pressure variations outside the barrier versus inside the barrier. Humidity sensors and trace gas detectors may also be used to provide long term monitoring.

The optional cap structure can be an integral part of the barrier and may be formed by a combination of a top synthetic liner, which is keyed into the vertical wall, a concrete or clay perimeter ring placed in the upper portion of the trench, and an earthen cap. For 1,000 year durability, we suggest that a rock armor layer and nontoxic bio-intrusion-resistant materials mixed with cap soil may be more effective than traditional vegetative caps for applications where institutional control can not be maintained. Mixing 5 percent powdered sulfur into the clay soil used for the cap can be an effective bio-deterrent. Lime is also useful but can reduce the plasticity of clay soil. For saturated sites, a monitor well within the block may be used to remove ground water from the interior, and then verify that additional ground water does not leak in through the barrier. For dry sites, the airtight cap structure allows the integrity of the vault to be monitored by air pressure differentials that occur naturally with changing weather.

A computer model was prepared to simulate collecting barometric pressure data from a monitor well inside the block and comparing it to data from the soil outside the block. Statistical tests were used to infer if the data had a significant correlation.

CONCLUSIONS

The EarthSaw floating block method offers a feasible engineering method of forming a verifiable barrier under and around a waste landfill in many common soil conditions. The method is mechanically simple and robust but field experience with the application is limited. Most engineering and construction companies should be capable of applying the method with minimal technical assistance. Unit cost of the method declines dramatically with increasing project size but small demonstration projects are less economical. This factor has limited commercial application of the method. The first commercial projects are therefore likely to be large ones where the method produces a dramatic cost savings.

1: Final Report, Research and Development of EarthSaw, www.cartertech.com, 2002
2: IEELL Forum on Remediation of Pits and Trenches, Idaho Falls, ID 1997
Annual Containment Technology Conferences, Florida State University 1997 –2001