The Resonant Sonic Drilling Method: An Innovative Technology for Environmental Restoration Programs

by Jeffrey C. Barrow

Abstract

The resonant sonic drilling method offers unique capabilities to the environmental restoration market. By using a drill head that imparts high-frequency, high-force vibrations into a steel drill pipe, continuous, relatively undisturbed cores can be taken through virtually any formation. The resonant sonic method requires no mud, air, water, or other circulating medium for penetration; drills very fast; easily drills at any angle through formations such as rock, clay, sand, boulders, permafrost, or glacial till; and yields no cuttings in the drilling process. Case histories of projects using the method demonstrate excellent results but also indicate several problem areas with the method in its present state. Expanding research efforts to further develop the resonant sonic drilling method should help solve current drawbacks, and could produce a drilling technology for environmental work that significantly changes the way monitoring wells are drilled and constructed.

Introduction

The field of environmental contamination assessment and cleanup has become a multibillion dollar market in the United States over the last decade. Given the magnitude of the dollars that still need to be spent on these problems in the future, there has been a strong desire by most governmental agencies and potentially responsible parties involved in contamination cleanups to develop innovate technologies that are more cost effective, efficient, and expedient.

One major cost sector of the environmental restoration market is drilling boreholes for soil and ground water evaluation as well as for the construction of monitoring wells, extraction wells, and injection wells. Borehole drilling methodologies have not significantly changed within the last century. The standard accepted methods of hollow-stem auger, mud rotary, air rotary, cable tool, reverse circulation, and dual tube percussion, which are currently used for environmental drilling, are all carryover methodologies from other markets. A technology transfer brought these methods into the environmental drilling market from their original fields of geotechnical, oil and gas drilling, agricultural and domestic water well drilling, and mineral exploration. Although these methods can accomplish environmental drilling and sampling, they may not always be the most effective method, yield the best data and product for the project, and/or minimize the generation of waste by-products. A little known but emerging innovative tech-

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nology with numerous potential advantages for the environmental remediation market called the resonant sonic drilling method is quickly evolving. The method provides a drilling technique that is faster, cheaper, and safer than many existing environmental drilling methodologies. It applies the energy of high-frequency sound waves into a steel drill pipe to have that pipe easily and quickly penetrate the ground.

The resonant sonic method is a technologically advanced hydraulically driven system. Through the use of a sonic drill head, a series of high-frequency, sinusoidal wave vibrations are generated into a steel drill pipe to create a cutting action at the bit face which allows a continuous core of the formation to move into a core barrel. Due to the action of the high forces developed by the resonant head and the external flush nature of the specialized drill pipe, excess formation material displaced by the cutting face of the bit is forced into the borehole wall. This eliminates cuttings from the drilling process. It is also possible to resonate a closed-end steel pipe into the ground and displace all formation material much like a pile driver. Through the development of various sizes and types of tooling, boreholes of different depths and dimensions can be drilled. The resonant sonic drilling method can yield continuous, relatively undisturbed cores; requires no air, mud, water, or other circulating medium for penetration; is very fast (up to 1 ft/sec in certain formations); drills through virtually any type of formation; can drill at any angle from horizontal to vertical; and most important, yields no cuttings in the drilling process.

How the Sonic Head Works

The field of sonics refers to the technology of applying mechanical vibratory energy to do useful work in analyzing, testing, or processing materials or products (Hueter and Bolt 1954). Sonics is a specialized branch of acoustics in which the ability to hear the sound wave is irrelevant. In this application, sound waves are mechanically induced vibrations used to do work rather than for communication (Rockefeller 1967).

A mechanically induced vibration is created by an oscillation or a motion that repeats itself periodically, back and forth across a point of equilibrium. This action produces the conditions necessary to create stress wave energy forces. The resonant sonic drill head works by utilizing hydraulic power to create wave force energy. By developing vertically oriented, mechanically induced pressure waves and coupling to a tubular drill steel, the sonic head can deliver forces exceeding 280,000 pounds at rates approaching 150 times per second. The key to the effectiveness of the resonant sonic drilling technology is that the massive vibrational wave energy put into the top of the steel pipe efficiently transfers through the pipe to the bottom cutting edge with very little power loss in the process (Bodine 1967).

The manner in which the resonant sonic drill head reliably creates its force pulses is focal to understanding how the head works. Located inside the outer case of the drill head is a cast steel or aluminum oscillator housing which is affixed to a center column and contains two large precision bores which serve as bearing races (Figure 1). These races provide orbital pathways for two steel rollers of equal weight and dimensionality which occupy approximately two-thirds of each bore volume. The rollers are mounted on shafts off center of the raceway and can freely rotate, like a wheel on the axle of a car, but they are constrained to remain inside the bore as they rotate. The rollers are mechanically attached to a hydraulic motor which causes them to rotate eccentrically inside their race orbits. As they rotate faster and faster, the rollers create equal centrifugal forces against the inside walls of these races. To visualize this force, recall a childhood game of filling a pail half full of water, and with arm fully extended, swinging the pail around and around at such a speed that the water did not spill out even when the pail was upside down. The faster the pail was swung around, the more centrifugal force was created and the heavier the pail felt.

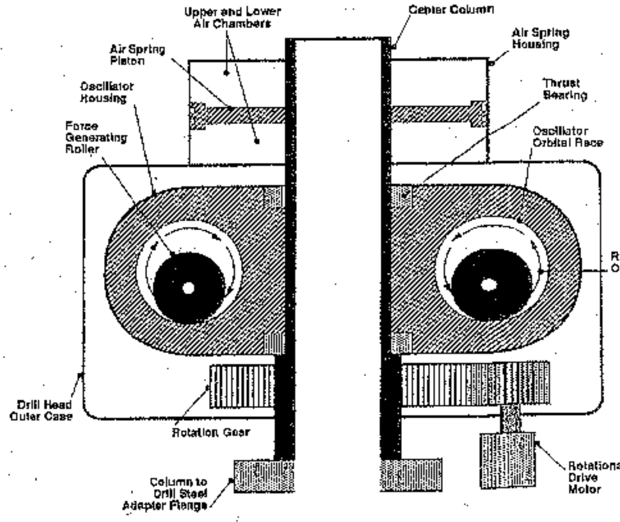

Figure 1. **Resonant sonic drill head.**

The oscillator housing serves to receive the centrifugal force created by the rollers. Much like the pail example, the rotating rollers produce equal centrifugal force at all points along the 360 degree circumference of their raceways. The combined centrifugal forces of each roller create the vertical force pulses that are transmitted into the steel drill pipe by the resonant sonic drill head. This is accomplished by designing the timing and movement of the rollers to be synchronized and counter-rotating; that is, one roller rotates in the clockwise direction while the other rotates counterclockwise. Both rollers are timed by gears so they will be at equivalently balanced points throughout their orbit. By metaphorically replacing the oscillator races with clock faces and the rollers with the big hands of the clocks, it can be shown that when the rollers reach the 12 o'clock or the 6 o'clock position, they do so simultaneously. Likewise, when one roller reaches the 3 o'clock position, the other roller reaches the 9 o'clock position; and when one roller reaches the 7 o'clock position, the other correspondingly reaches the 5 o'clock position, and so on.

The critical point to understand is that as the rollers orbit within their raceways, all radial centrifugal forces generated by the rollers are canceled except at the 12 and 6 o'clock positions where the forces are additive. These positions correspond with and reinforce the vertical motion of the housing to create sinusoidal compressive and expansive force pressure waves which transfer through the center column to the drill rod.

The air spring and rotational drive motor, two other key components of the sonic drill head, are also shown in Figure 1. The air spring piston is attached to the oscillator housing, and the air spring housing provides dual air chambers above and below the piston. Air supplied to the upper and lower chambers is compressed and vented by the piston which cushions the oscillator housing as it cycles through its upward and downward movement. This cushion of air isolates movement and vibration of the oscillator housing from the rest of the machine, preventing destructive metal-to-metal contact, and provides a lifting and supporting function for the weight of the suspended drill rod. The rotational drive motor and its associated gears attached to the bottom of the center column provide rotational capability for connecting threaded drill rods as each section is added and for assistance in drilling through certain formations.

As a point of reference, the total vertical distance of movement of the oscillator housing and center column in response to the force of the rollers varies from ⅛ to ⅜ of an inch. However, even with this small amplitude of movement, depending upon roller weight and rotating speed, forces ranging from 50,000 to 280,000 pounds can be generated up and down over 150 times per second. The uniqueness of the resonant sonic drill head is that a relatively small physical unit can reliably generate extremely high energy outputs at variable rates. As a result, coupling the sonic head to the drill rod creates tremendous potential for easily penetrating formations.

The Effect of Energy Waves on Steel Drill Pipe

The characteristics of wave movement through the steel drill pipe used in the resonant sonic drilling method are such that energy is stored in the elastic properties of steel. The sonic method uses the elasticity of steel drill pipe to make it behave, in part, like a spring. The method uses the natural elasticity and inertial properties of a steel drill pipe to allow wave propagation that will make the drill pipe expand and contract due to these waves. These characteristics, coupled with the effects of bringing the pipe into resonance, are what allows the drill pipe to penetrate through virgin earth formations with little resistance, often like a knife through soft butter. Furthermore, it is the rate at which these expansion and contraction cycles occur in the steel drill pipe that establishes the condition of resonance, and what sets this drilling method apart from any other.

The resonant sonic drilling method induces vibrational stress waves into the steel drill pipe at a rate commensurate with its natural ability to accept and reflect each wave. Since a single stress wave travels up and down the steel pipe to establish a resonant condition, successive waves must be added in phase, or timed to coincide with the movement of the waves already traveling in the pipe. When this timing is achieved, a standing wave will be created in the drill rod, and the benefits of using resonance for drilling can be realized.

In a resonant condition, stress waves moving through the drill rod will appear to stand still because each induced energy pulse wave is exactly superimposed on each reflected energy pulse wave (Figure 2). In this condition, the direction and magnitude of movement of each steel molecule in relation to another stays the same and creates a situation where the energy being stored in the pipe can greatly exceed the energy being dissipated in the form of work on the medium being drilled. In the standing wave condition of resonance, the drill pipe molecular interspaces can be expanded and compressed to their greatest amplitude, and the pipe will accept maximum power from the hydraulic power source. Consequently, the most effective penetration can be accomplished by the drill rod when the standing wave condition of resonance is achieved and maintained.

The purpose of the resonant sonic drill head is to impart as much force as is needed to the top of the drill pipe, and have as much of that energy flow to the bottom of the drill pipe where it can do the most useful work

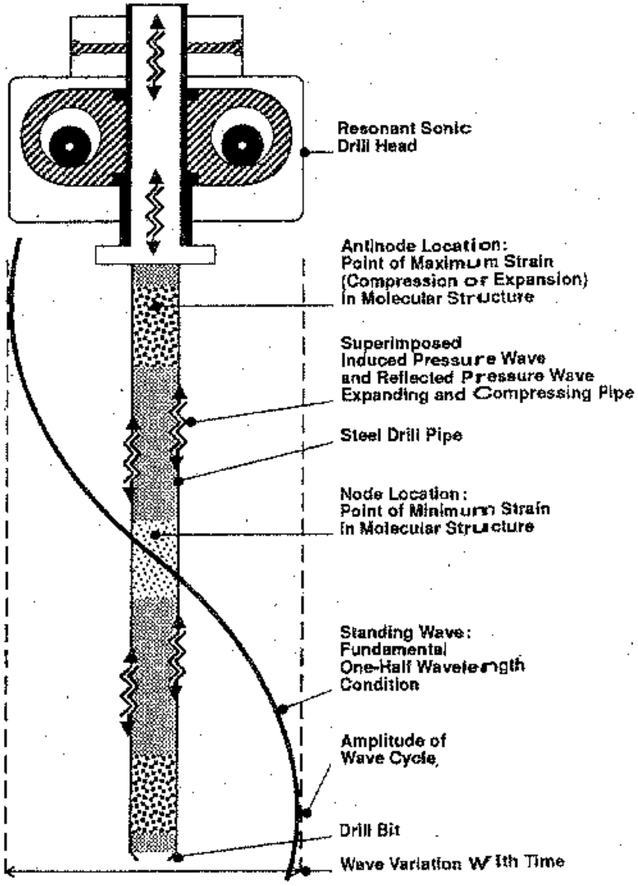

Figure 2. One-half wavelength resonant conditions with no dampening.

in penetrating the formation. The most effective rate of penetration occurs when the cutting face of the resonating steel pipe receives the largest amplitude of movement possible through the center column from the oscillator housing. As shown in Figure 2, in the standing wave condition of resonance in a steel drill pipe, there are points of maximum molecular movement and velocity called antinodes (i.e., locations where the amplitude of expansion and contraction of the elastic molecular interspaces is greatest), and points of minimum molecular movement and velocity called nodes (i.e., locations where the amplitude of expansion and contraction of these same interspaces is least). The objective in resonant sonic drilling is to operate the sonic head so the antinodes are located near the top and bottom of the length of drill steel and the node is located near the middle (Newfarmer 1966). In this situation there is maximum strain in the pipe at the top and bottom, and minimum strain at the center. The alternating compression and expansion of the drill rod causes the pipe to dilate and contract over its length with each alternating phase, and thus the outside diameter of the pipe continually gets larger and smaller. Simultaneously, the top and bottom of the pipe move in opposite directions at any instant of time.

The location of the nodes and antinodes is related to the length of the drill pipe and the frequency (cycles per second) at which the sonic head delivers vibrational energy to the pipe. Since the speed of sound through steel is approximately 16,500 ft/sec, the fundamental resonance point of any length of steel drill pipe is determined by the following simple formula:

$$\frac{\text{Speed of sound through steel pipe}}{2 \times \text{length of the pipe}} = \begin{array}{l}\text{Cycles per second}\\ \text{(hertz) necessary to}\\ \text{resonate steel pipe}\\ \text{at its fundamental.}\end{array}$$

This formula defines the "one-half wavelength resonance" condition and is strictly true only when the pipe is free at the top and the bottom (Newfarmer 1965). Thus for a steel pipe which is 100 feet long, the frequency required for resonance becomes:

$$\frac{16{,}500}{2 \times 100} = 82.5 \text{ cycles per second.}$$

Assuming no other intervening variables, a 100-foot length of any size or weight of steel drill pipe will resonate when cyclic force impulses are introduced into it at a rate of 82.5 cycles per second. This fundamental one-half wavelength resonance condition creates the situation where a single node will be located near the middle of the pipe length, and the two antinodes will be located near the top and the bottom. As drilling progresses and more pipe is added, the cycles per second of energy input must change according to the formula in order to maintain the one-half wavelength condition. Therefore, if a 20-foot length of steel drill pipe is added to the 100-foot length, the new operational frequency to reach the one-half wavelength resonant condition in the combined 120-foot length of pipe would be:

$$\frac{16{,}500}{2 \times 120} = 68.75 \text{ cycles per second.}$$

As the length of the drill pipe increases, adding multiples of the fundamental one-half wavelength frequency (called overtones) yields the desired condition of resonance, keeping the antinodes near the top and bottom of the length of steel drill pipe. More important, however, as drilling gets deeper, operating the resonant sonic head at higher frequency levels produces the necessary larger force output to allow continued penetration to greater depths. In resonant systems, the peak power of each subsequent overtone will be substantially higher than that of lower overtones (Rockefeller 1966).

Effects on Soils of Resonating Steel Pipe

My focus to this point has been on how the resonant sonic drill head creates cyclic force and on the effects that occur in steel drill pipe as a result of coupling these two elements. When downward-weight bias is applied by the sonic drill head and the steel drill pipe is brought into a condition of resonance, events occur which allow the pipe to effortlessly penetrate most formations. The resonating drill rod literally fluidizes the surrounding soil within a quarter of an inch of the drill pipe wall only, and reduces frictional forces that constrain the pipe (Dance 1982).

By operating the sonic head and drill steel at frequencies ranging from 80 to 150 cycles per second, as the drill steel penetrates the formation, the soil particles cannot vibrate in unison with the drill steel. Consequently, the earth grains vibrate in random directions which fluidizes these particles along the wall of the steel pipe, producing a remarkable reduction in the friction of the soil against the drill rod. The resonating drill rod easily moves the vibrating particles aside by exceeding and breaking their elastic bonds and causing the soil to have only a minor resistive impedance to the advancing drill steel. If a boulder is encountered, the resonant sonic drilling method will core right through it if the correct bit is attached (Figure 3).

Although the drill rod fluidizes the soil and creates a thixotropic transformation of clayey soils, the area affected around the drill rod is minimal. Studies show that the zone of influence of fluidization around the drill rod and on the core does not exceed a few millimeters (1/32 to 5/64 inch) in width. Furthermore, the transformation, particularly in clays, is reversible once the vibrations cease. If proper sonic drilling procedures are followed, excellent quality cores of most formations can be generated with minimal disturbance, if any, to its structural and physical integrity (Gumenskii and Komarov 1961).

Representative Projects Using Resonant Sonic Drilling

The resonant sonic drilling method has been used in place of conventional drilling methods on a number of environmental projects. A study and several case histories attest to the versatility of the method.

Anderson and McBane (1991) with the U.S. Corps of Engineers compared and evaluated various environmental drilling methods with regard to such technical factors as drilling speed, ability to obtain maximum core recovery, control of cuttings and dust, well construction capabilities, costs, mobility, and amount of labor required. They evaluated solid-stem continuous-flight auger, hollow-stem continuous-flight auger, bucket auger, air rotary, air hammer (down-the-hole hammer), casing advancement system with air drilling methods, mud rotary, reverse circulation rotary, dual-wall reverse circulation rotary, cable tool, core drilling, jet drilling, and sonic drilling. They concluded that sonic drilling, "from past environmental investigation work and monitoring well installations at the radioactive waste management complex at the INEL [Idaho National Engineering Laboratory] site in Idaho and the Rocky Flats Site in Colorado, has been demonstrated to be superior to conventional drill methods for environmental work. Some of the advantages of sonic drilling include: Rate of penetration (15 ft/hr in boulders); high sample integrity; requires limited drill operating crew (two); conventional methods can be employed as attachments if/when needed; there is controlled/complete contaminant containment; it can be operated dry or with drilling fluid; the equipment is easily moved and operated; and this method has shown to be more cost effective per foot than most conventional methods. Sonic drills are capable of angle holes and can be remotely operated.... Because of its ability to maintain contaminant control, its speed and versatility, and its ability to be operated remotely, this drilling method is highly recommended for environmental investigations and monitoring well installation" (Anderson and McBane 1991).

At the Sandia National Laboratories in Albuquerque, New Mexico, the resonant sonic method was used to continuous core and construct monitoring wells to depths exceeding 550 feet through arid region type formations. A sonic drill rig modified to handle a large diesel pile driver was used to alternately continuous core and then drive 10-inch diameter temporary casing to the deep water table. Inspection of the continuous cores showed interbedded, fine sand lenses approximately 1/16-inch thick and other in situ anomalies that had never been recovered in coring that had previously been performed at this site. Additionally, no fluid was used in the drilling process resulting in no liquid waste generated. An angle well was continuously cored and constructed to 545 feet to evaluate and monitor potential contamination under a mixed waste disposal area. The data derived from the resonant sonic coring method used in this project yielded excellent results for defining the formation lithology of the basin, generated very little waste, did not inject any fluids into the formation, and allowed for the dry borehole construction of 5-inch monitoring wells to fairly significant depths (relative to remediation projects).

Resonant sonic coring equipment was utilized on an environmental project at a large military base in northern California from 1991 to 1992. Approximately 15,000 feet of continuous core drilling was performed with boreholes averaging from 30 to 100 feet deep. Analysis

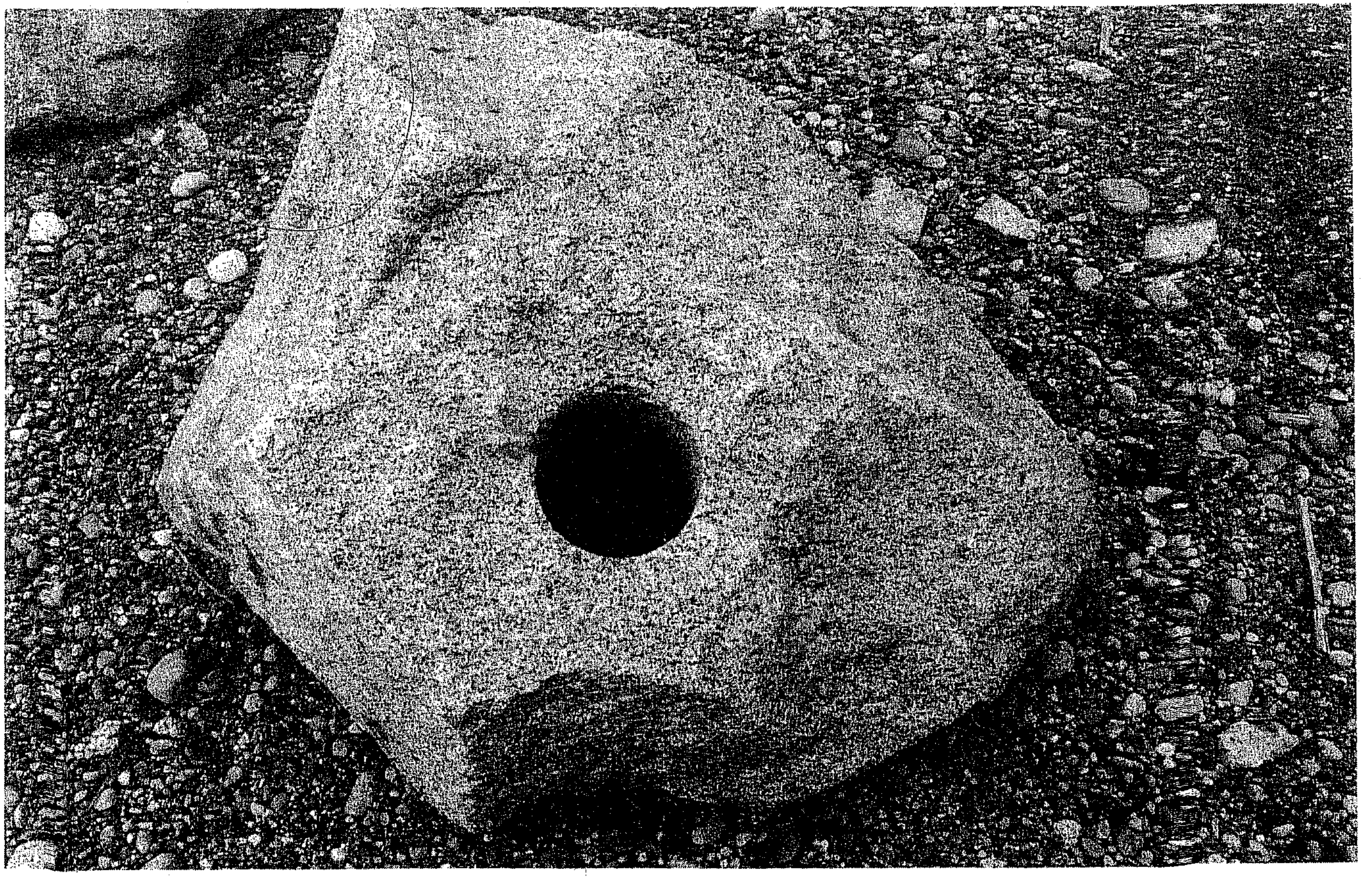

Figure 3. Four-inch diameter sonic core hole drilled through a large granite boulder.

of data collected during this project indicated the following results: first, approximately 120 feet of continuous core was drilled by one rig each day in only two hours of drilling and core retrieval with the sonic method. The remainder of each day was consumed with soil gas sampling, standby, decontamination, mobilizing between sites, and other nondrilling type activities. Second, the average sonic core temperature was 81 degrees Fahrenheit; no excess cuttings were generated; and the core recovery rate was 100 percent. On the same project, data were also collected on a hollow-stem auger rig performing continuous coring at the same time, in the same general area. Using 8-inch diameter flight augers, the auger rig collected 3-inch diameter continuous cores, which was the same as what the sonic rig collected. The auger data showed that approximately 55 feet of continuous core was generated in eight hours of drilling and core retrieval. The average core temperature was 76 degrees Fahrenheit; however, the cuttings generated averaged 4300 pounds per 100 feet of drilled borehole (approximately seven 55-gallon drums), and the core recovery rate was 85.5 percent (Barrow 1993).

INEL reports the use of the resonant sonic drilling method to characterize potential environmental problems (O'Rourke et al. 1992). The primary objective of this drilling project was to retrieve core samples of the highest integrity without exposing the samples to the environment. Constraints were that no air or fluids could be introduced during the drilling stage, and no excess drill cuttings could be generated. Once the formation was drilled and cored, each individual sample could not be exposed to air at any point along its path to laboratory analysis. Procedures were developed for the use of specially designed lexan liners as core barrels that were held down and retrieved by weighted wireline techniques. In a high risk area, the resonant sonic drilling rig was adapted to be operated from 100 feet away with no personnel at the borehole location.

O'Rourke et al. reported results of the INEL sonic drilling project that showed "all aspects of the effort were highly successful. Sample recovery rates were on the order of 100 percent. Some compaction of the unconsolidated sediments did occur as a result of the method, so a direct correlation between sample length and depth is not possible" (1992). The authors go on to conclude that "as this system is designed to mitigate the threat of contaminant release to the environment and to minimize the generation of waste materials, it is suitable for use in high contamination areas. The fact that no air nor fluids are introduced and the use of high rotation or impact is not necessary greatly reduces the risk to personnel working in the area. The remote applications eliminate the need for any personnel to be in the area during penetration" (1992).

At the Department of Energy's Hanford, Washington, facility the sonic drilling system was used between September 1991 and May 1992 to drill and complete eight ground water monitoring wells, one carbon tetrachloride monitoring/extraction well, and two vadose characterization boreholes. The drilling ranged in depth from 30 to 227 feet. The method met most of the project objectives and the results are summarized as follows (Westinghouse Hanford Co. 1993):

1. Sonic drilling was used with large-diameter pipe to drill to depths of 227 feet through the Hanford semiconsolidated sands, gravels, and cobbles without the addition of water or air into the borehole.
2. Sonic drilling penetration rates were double the average for cable tool drilling, which has been used at the facility for the last 45 years.
3. The sonic system was able to drill and retrieve dry, near in situ samples.
4. For a typical 100-foot ground water well drilled by resonant sonic, 2.2 drums of soil would be generated. For the same well, the cable tool method would produce 10.4 drums of soil.
5. The sonic drill was shown to be a more cost- and schedule-effective method of drilling, sampling, and completing wells drilled for hazardous waste site characterization.
6. The method met all Washington State Ecology regulations, and Westinghouse Hanford Co. specifications and procedures for drilling and constructing wells.
7. The sonic equipment used on site was plagued with downtime problems, lack of maintenance support, and spare parts availability.

Resonant Sonic Method Problem Areas

Although there are numerous advantages to using the resonant sonic drilling method in environmental remediation investigations, there are several potential problems associated with it.

First, the resonant sonic equipment is relatively expensive. As a package, a fully tooled rig with support equipment costs in the range of $500,000 once it is ready for field operations. Additionally, replacement parts for the high-technology sonic drill head are expensive, and significant costs in preventive maintenance and repairs are required to maintain the resonant sonic system in peak working condition.

Second, the resonant sonic method does not have deep hole drilling capability at this stage in its evolution. The types of formation encountered in the drilling process determine to a large extent how deep the steel drill pipe will penetrate the earth. The deepest borehole using resonant sonic energy was performed by Guild Construction; they penetrated the earth with a 10-inch casing to 700 feet on the Rhode Island coast. Unless the sonic method is combined with a casing advance system which reduces sidewall-friction damping, it is currently best to consider using sonic drilling for boreholes not exceeding 400 feet in depth. The method performs most efficiently and quickly in the 50- to 300-foot range.

Third, the sonic drilling method is a displacement method. Since it uses no circulating medium to lift cuttings up the borehole to the top of the ground, all formation material must either move into the core barrel or out into the formation wall as the resonating steel pipe penetrates. The more consolidated the formation, the more material will move into the core barrel since the formation wall is too compact to re-orient itself and accept a greater volume. When the bit face cuttings take this path of least resistance by moving inward, it is not uncommon to recover more core than the footage drilled.

Fourth, the speed with which the resonant sonic drilling method generates significant quantities of core can easily overwhelm the field geologists responsible for logging and data collection. Although good for the contractor who has a footage rate contract, high production can create resistance to the method by field people. In addition, it can outstrip the capacity of laboratories to analyze the samples on a timely schedule if they are not prepared to handle large quantities of core samples from daily drilling activity. If project managers recognize this problem, they can easily solve it by proper planning before drilling starts.

Finally, many environmental drilling projects evaluate areas which might contain volatile organic compounds (VOCs) in the soil. The resonant sonic drilling method can create elevated temperatures in core samples of certain formations. Since the sonic drilling method uses no water, mud, or air as a cuttings transporter and therefore as a cooling medium, it creates friction in a manner similar to hollow-stem auger methods. Ongoing research is showing that through proper bit design and operator procedures, core temperatures in most formations can be maintained at their in situ levels or only a few degrees above.

Future Directions

Even in its current state of development, the resonant sonic method offers advantages over existing conventional drilling methods, including the rotasonic method. Like any evolving technology, however, the resonant sonic drilling method requires ongoing research and development programs to fully realize its potential for the environmental restoration market.

The ideal state for resonant sonic drilling to yield top quality core samples will be achieved when all the characteristics of a sonically derived core sample are comparable to the industry accepted standard penetration test core sample. Little work has been done to date on statistically comparing the properties of the different sample types.

In some consolidated type formations, the high frequency movement of steel against the formation in the absence of any circulating medium can result in elevated core sample temperatures. This may have an impact on sample analyses, especially for VOCs. Future work is needed to add an element of cooling to the coring process in more difficult formations. Investigative work is currently under way to utilize the cooling effects of liquid nitrogen to prechill core barrels and cool the core barrel in situ during the drilling cycle. Although preliminary results are encouraging, more research is needed to advance this procedure.

Current resonant sonic drill rigs are operated somewhat by feel and by ear. Although the rigs are usually endowed with numerous gauges monitoring all system hydraulic pressures, much successful sonic drilling is accomplished because of the skill of the driller. For the method to achieve future widespread use and driller acceptance, more automated control over critical system parameters will need to be developed. Through the use of devices such as accelerometers and strain gauges transmitting information to a small, programmed computer, it should be possible to gain control over critical resonant sonic activities. By developing automated controls that could react to formation changes more quickly than does the drill operator, it would be expected that less experienced drillers could successfully operate the sonic equipment. The mechanically harmful effect on the system of being out of resonance during drilling would be minimized thus increasing the useful life of all system components, and the quality of the core taken during drilling should also be improved.

The resonant sonic drill head currently can operate at any angle from vertical to horizontal, but the longitudinal axis of the borehole is always linear. Future work needs to be oriented toward developing a directional drilling system using resonant sonic technology. Developing such a system would allow continuous coring and horizontal monitoring well installations under trenches, buildings, waste ponds, buried tanks, and other hazardous waste sites that are difficult to remediate with vertical borehole technology. Furthermore, directional resonant sonic methods could allow for the construction of horizontal grout curtains under hazardous waste sites that need to be contained.

The need for more advanced drill steel tooling is of paramount importance. Research is currently underway to develop a flush-type tool joint that can be machined on steel pipe and reliably withstand the cyclic forces it will experience. Metallurgical analyses will need to be performed to identify the best available material to stand up to the forces of the resonant sonic head. As these horizons are conquered, more powerful sonic heads will be needed to achieve greater depths of drilling, and this will require re-evaluation of the sonic operating parameters.

Perhaps the most important future development for sonic drilling lies in reorienting how environmental wells are presently constructed. All current environmental drilling methodologies are carryover techniques from other markets. Each method requires the drilling of an oversized borehole in order to place a casing in the ground. Given this requirement, an annular space is created between the borehole wall and casing which must be filled to prevent cave-ins and to prohibit migration of any substance down along the walls of the casing. Because of the way conventional methods must drill a borehole, state and federal regulations have established requirements that the annular space must be sealed with an appropriate medium (grout, cement, or other impervious material). The resonant sonic method has the unique capability of inserting the well casing directly into the ground by displacing the formation and thus creating a bond between the borehole wall and outside of the casing that is as tight or tighter than a cement seal. Due to shrinkage of cement as it sets up, its sensitivity to pH and salinity, and its questionable adherence to a smooth PVC casing wall, it is debatable how competent a seal the cement provides against cross migration of borehole fluids (Kurt and Johnson 1982).

Extensive records maintained by companies using sonic pile drivers demonstrate that load tests performed on sonically driven piles were always significantly higher than those performed on conventionally driven piles. This was postulated to occur because of the fluidization of formation medium at all points along the wall of the resonating pipe and subsequent resorting and compaction of this thin layer. Upon stopping resonant action in the pile, the affected formation area ceased moving against the pile and created a strong bond (especially in heavier clay content soils) through the hardening of the formation as the thixotropic action reversed.

In extrapolating these findings, future research needs to focus on constructing a well without the need for sand packs or cement seals. Bond logs and vacuum or pressure tests could be performed to determine the seal integrity between the formation and the casing. Since resonating the casing into the ground would displace cuttings into the aquifer to be screened, any aquifer damage could be evaluated and procedures developed to minimize its occurrence.

The bottom line is that the resonant sonic drilling method has the potential for constructing any type environmental well — monitoring, vadose zone, extraction, injection, neutron access — without generating any cuttings, and without requiring the sealing of annular spaces.

Acknowledgments

The author greatly appreciates the assistance of Terry Stapleton for his work in the preparation of this manuscript. For those readers wishing to receive more information on this drilling method, an expanded version of this article is available from the author which discusses historical developments, the physics of how the system works, in-depth sonic drilling core retrieval methods and other technical data too detailed to present in this condensed version.

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Biographical Sketch

Jeffrey C. Barrow *(president, Water Development Corp., 1202 Kentucky Ave., Woodland, CA 95776) received his B.S. in business administration from the California State University, Chico, and his M.B.A. and doctoral degrees from the Graduate School of Business, Indiana University. He works in the area of environmental remediation and construction, and focuses much of his attention on the research and development of environmental restoration methodologies using high force orboresonance machinery. He serves on the Policy Advisory Council for Governor Pete Wilson's California Environmental Technology Partnership, leads a Cooperative Research and Development Agreement (CRADA) program with DOE's Pacific Northwest Labs/Westinghouse Hanford Co., and is involved with Sandia National Laboratories on a D.O.E. Office of Technology Development TTP research program. He is the author of numerous articles on leadership.*