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Innovative Methods for Levee Repair

by
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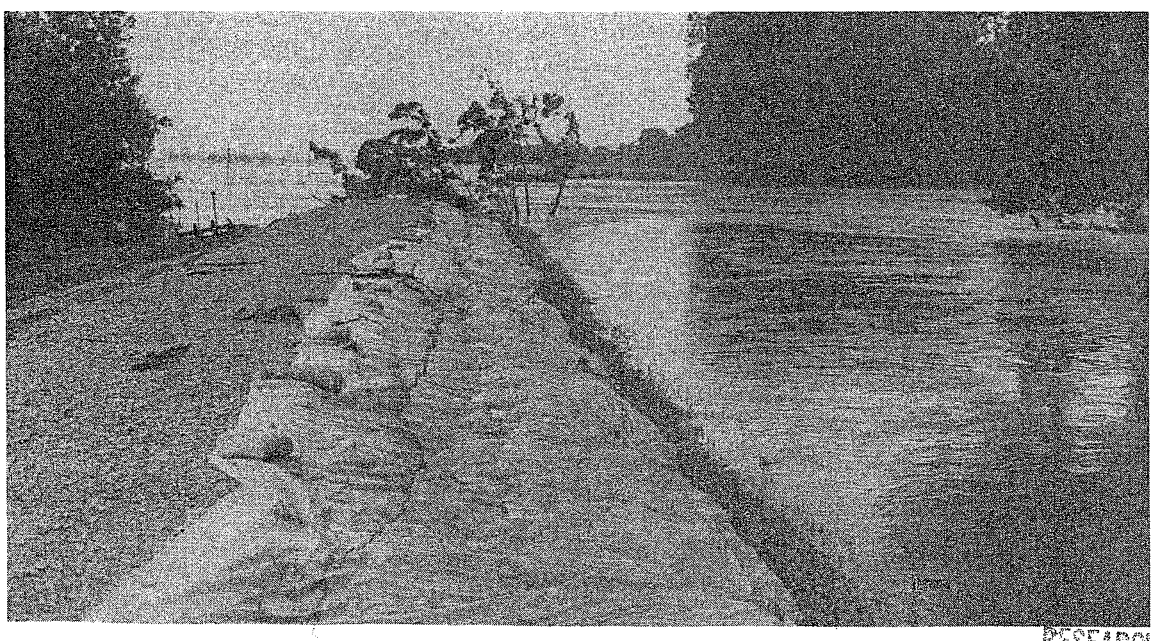
The Flood of 1993 has caused extensive damage to levees in the Upper Mississippi River and Missouri River Basins. With the recession of the flood waters, repairs will have to proceed expeditiously for the levee systems to be restored to readiness prior to the spring high-water stages in 1994. A complicating factor is the extremely short "window" for accomplishment of repairs because of the time required for assessment and categorization of damages, low equipment mobility at some sites for an extended period after cessation of flooding, and the possible onset of adverse construction weather in late 1993 or early 1994. For these reasons, application of innovative methods of levee repair which can contribute to rapid, economical, environmentally acceptable, and permanent restoration of the flood-control system is highly desirable.

Typically, levees are subject to flood damage in six different ways: (a) overtopping, (b) current and wave attack on the riverside slope, (c) surface erosion of slopes and crest resulting from rainfall, (d) through-seepage causing softening and sloughing of the slope in the vicinity of the landside toe and associated piping problems, (e) underseepage resulting in uplift pressures on the landside impervious top stratum with associated sand boils



Overtopping of levee, Columbia, IL (photo courtesy of George Sills, Vicksburg District)

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and piping problems, and (f) slope instability in the form of deep-seated or shallow surface slides. The type of repair selected, whether conventional or innovative, will depend on the cause and extent of the damage which the levee has experienced. Table 1 shows conventional and innovative methods of levee rehabilitation for the various types of damage outlined.

The conventional methods for levee rehabilitation listed in Table 1 have been used for many years. Additional information about these may be obtained in EM 1110-2-1913, *Design and Construction of Levees*, 31 March 1978. Since conventional procedures are often costly and time consuming, innovative methods may offer solutions that are more feasible. While the majority of these techniques have not been used for levee rehabilitation, there is a high probability that they would be suitable for such an application.

Overtopping

Lightweight material for raising levee

Lightweight material such as expanded polystyrene blocks (ESP), shredded tires (or tire chips), and wood fiber (chips or sawdust) may be used to raise an existing levee to prevent overtopping. The weight of the material, ranging from 1.5 lb/cu ft for ESP to 45 lb/cu ft for shredded tires, allows construction over soft foundation soils without appreciable additional settlement. ESP blocks must be protected from flotation and petroleum spills. They have been used as lightweight fill in hundreds of projects in Norway and Japan and by the Colorado Department of Transportation to reconstruct a highway embankment on U.S. 160 near Durango, CO.

Inflatable dams/water structures

Water structures are created by filling two or more flexible inner tubes with water and confining them within a durable and flexible "master" tube. In June 1990, these water structures were used to add height to existing levees along the Trinity River near Liberty, TX. The water structures could also be used in lieu of sandbags around sand boils adjacent to levees. The length of these expedient structures can be virtually unlimited, and heights ranging from 1 to 10 ft can be achieved. The tubes can also be stacked to achieve greater height. They last up to 3 years

Table 1
Conventional and Innovative Rehabilitative Methods for Various Levee Problems

Problem	Conventional Method	Innovative Method
Overtopping	Rebuilding Vegetation Concrete blocks Precast post and panel wall	Lightweight material to raise levee Inflatable dams/water structures/geotextile tubes Geotextile-reinforced grass Geocells Concrete block systems Soil cement/roller-compacted concrete
Current and wave attack	Vegetation Revetment (riprap, concrete rubble, articulated concrete mattress, gabions)	Geotextile-reinforced grass Revetment (used tires, soil cement blocks, etc.) Soil cement/roller-compacted concrete Fabric forms for grout placement
Surface erosion	Vegetation Chemical stabilization	Geosynthetic systems such as erosion nets and excelsior blankets
Through-seepage and underseepage	Pervious toe drain Conventional cutoffs Riverside blankets Landside seepage berms Pervious toe trench Pressure relief wells	Geocells (with vegetation) Biopolymer drains Bentonite sealing Slurry trench cutoffs Jet-grouted cutoffs Inflatable dams/water structures/geotextile tubes
Slope instability	Drainage Removal and replacement of soil (slope flattening and benching) Conventional restraint Structures Chemical treatment	Mechanically stabilized soil Tiresoil (soil and tire parts) Soil nailing with geotextiles Fly ash and lime injections Gravel trenches Slide suppressor walls Pin (micro or root) piles Continuous polymer thread injection Randomly distributed synthetic fibers Prefabricated geocomposite drainage systems Vegetation

and are said to be 95 percent faster to install than sandbags. Costs range from $4/lin ft for a 1-ft-high tube to $88/lin ft for the 10-ft height (Figure 1).

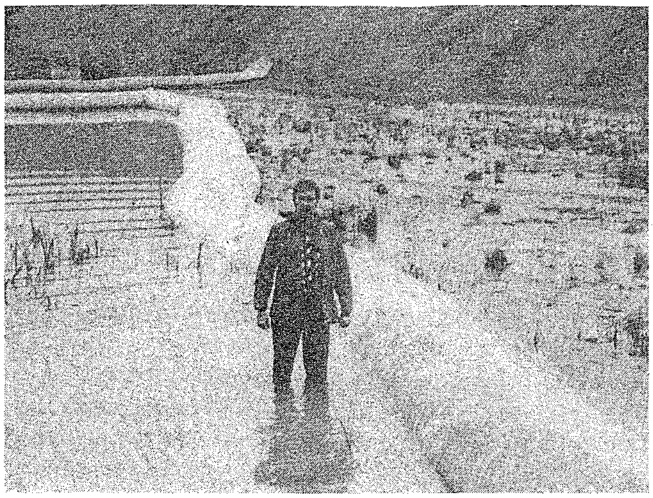


Figure 1. Inflatable water structures

A similar system composed of geotextile tubes has been used to provide dikes up to 4 ft high within dredged material storage areas. Geotextile tubes are constructed of woven geosynthetic materials and are pumped full of dredged material (sand or fines). They can also be stacked to achieve greater height. In a similar way, this type of barrier can be attached to the top of a floodwall to be inflated as the requirement arises for raising the height of the wall. Such inflatable barriers are currently in permanent use at some structures, such as the Jonesville Lock and Dam in the Vicksburg District.

Geotextile-reinforced grass

Grass has long been used to protect and stabilize earth surfaces subject to intermittent flow of water with high velocity, such as embankment overtopping. The use of a geotextile-reinforced grass embankment enhances the engineering functions of grass while retaining its environmental and economic attributes. The entire surface area is grassed, and the roots bind around the geotextile to form a geotextile/soil/root mat. This mat results in improved erosion resistance to overtopping flows. The risk of the mat's being uplifted becomes significant when flow velocities exceed about 16 ft/sec. Disadvantages include root survival during drought and requirements for management of the vegetation.

Geocells

Over steep slopes where vegetation is difficult to establish or the forces causing erosion overcome the strength of the root system, a geocell may be used to ensure that the surface soil is retained on the slope (Figure 2). Geocells are three-dimensional honeycomb structures featuring a unique cellular confinement system formed by a series of self-containing cells. The cells physically confine the soil placed inside the cells, thus avoiding a mass sliding of the surface layer while vegetation is being established.

A larger geogrid-type structure is also available. It is a galvanized (plastic-coated if desired) wire mesh construction on the order of 3 to 4.5 ft square with lengths up to 30 ft. It can be used to raise levees, build ring levees around structures, form closures, and "ring" sand boils. This system is best suited where a relatively firm foundation is available to allow equipment (front end loaders or backhoes) to operate to fill the cells. This technique has been used for shoreline protection at Craney Island, Portsmouth, VA.

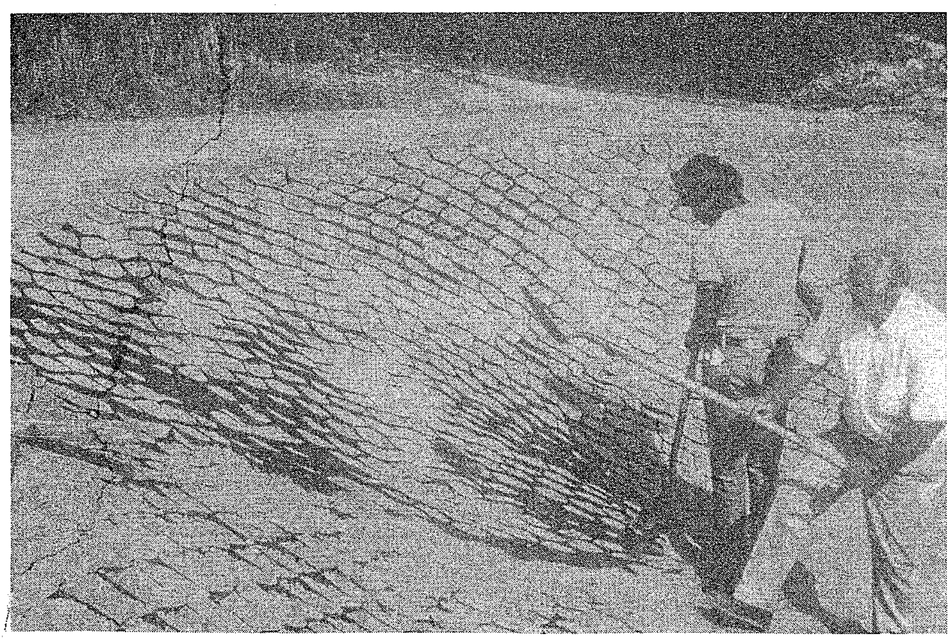


Figure 2. Geocells being installed on slope to prevent erosion and foster vegetation establishment

Concrete block systems

Articulated concrete block revetments (a series of individual blocks placed together to form an overlay) can achieve a high degree of stability under high-velocity flow conditions for a relatively low cost ($3 to $6/sq ft installed).

Soil cement/roller-compacted concrete

When the anticipated flow velocities are large (greater than 25 to 30 ft/sec), the use of soil cement or roller-compacted concrete may provide an acceptable method of protection. The cost is in the range of $40 to $80/cu yd installed. Addicks and Barker Dams in Houston, TX, had roller-compacted concrete installed for overtopping protection in 1988.

Current and Wave Attack

Used tires for revetment

Used auto tires have been successfully recycled as both mattresses and bulkhead to protect streambanks (Figure 3). The tires must be banded together, and the ends of the mattress must be tied into the bank. Used tires are effective except for occasional vandalism problems and sliding of mats on steep granular slopes. Stone rather than random earth fill should be used in bulkheads.

Fabric forms for grout placement

Other systems employ large fabric forms pumped full of grout into pillow shapes and used as artificial riprap for protection of shoreline structures. While these fabric forms are in relatively common use, better methods are needed for anchoring the forms and the molded pods which are produced. Better information on the optimum materials to use in the forms is also needed.

Surface Erosion

Many geosynthetic systems such as erosion nets and excelsior blankets are available for use as surface erosion protection.

Through-Seepage

Biopolymer drains

The biopolymer drain was recently developed in response to the need for an economical method for constructing deep (toe or chimney) drains. This system is based on basic slurry trench technology, but instead of bentonite slurry, a natural or synthetic organic compound is used to maintain an open trench. Natural biopolymers may come from plant, tree gums, or algae. Synthetic biopolymers are generally cellulosic derivatives. Once the trench is excavated, it is backfilled with a drain material. Wells can be inserted and pipe laterals placed under slurry. Once the installation is complete, the biopolymer slurry is chemically and biologically "broken," allowing the system to function as a drain. Although this has never been used for levee rehabilitation, it has great potential for reducing uplift pressures on the landside of a levee.

Bentonite sealing

Bentonitic clay, either pelletized or powdered, can be used on the riverside slopes of levees to seal the levee surface against through-seepage. Deposited in the dry or underwater, the bentonite coating reduces the permeability of the levee. Incorporation into the soil to a depth of 12 to 18 in. is desirable. The Memphis District has applied this technique to reduce the permeability of a reach of levee constructed of silty sand.

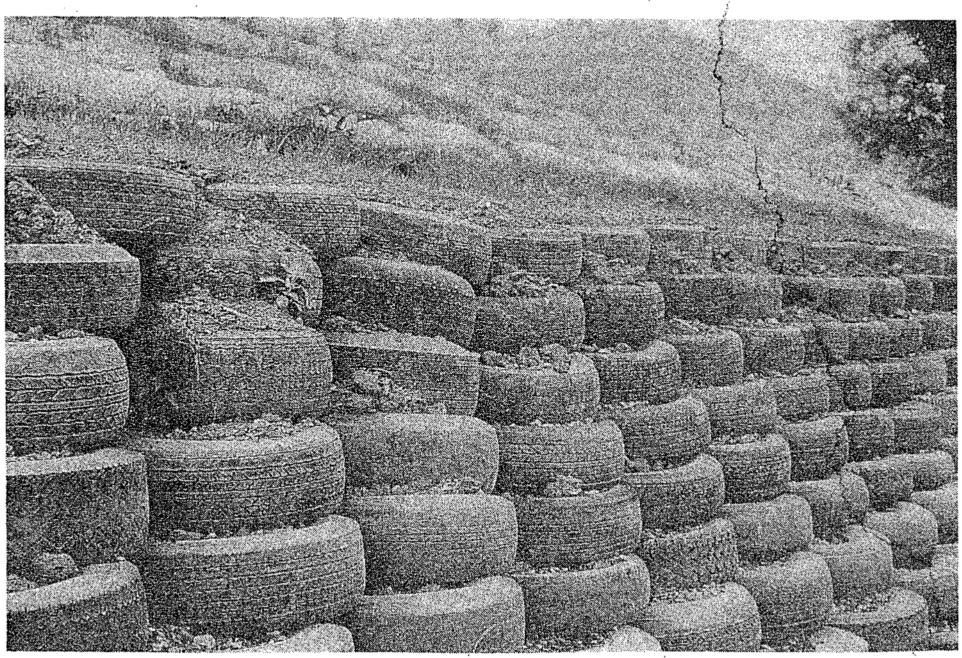


Figure 3. Used automobile tires being recycled as slope revetment

Underseepage

Slurry trench cutoffs

The slurry trench cutoff is a viable method for control of underseepage. A trench is excavated through the pervious foundation, and a sodium bentonite and water slurry is used to support the sides. Alternatively, cement may be introduced into the slurry-filled trench, which is left to set or harden, forming a cement-bentonite cutoff. Detailed guidance on constructing slurry trench cutoffs is given in *Seepage Analysis and Control for Dams*, EM 1110-2-1901, 30 September 1986.

Jet-grouted cutoffs

Under some conditions, such as coarse granular foundation soils underlying a levee, jet grouting may be used for constructing a cutoff wall underneath the levee.

Slope Instability

Mechanically stabilized soil

Mechanically stabilized backfill systems have the potential to stabilize slides in levee slopes. Mechanically stabilized soil is described in *Retaining and Flood Walls*, EM 1110-2-2502, 29 September 1989. Use of mechanically stabilized backfill allows steeper slopes to be constructed, thus requiring less backfill material. Possible problems include the need to wrap reinforcement or place netting around the face of the slope to prevent raveling (Figure 4).

Tiresoil (soil and tire parts)

Tire chips, discussed previously under overtopping, may be mixed with sand to form mechanically stabilized soil. The advantages are a weight reduction of about 25 percent and good adjustment to differential settlements. Research into tiresoil is continuing in Europe.

Soil nailing with geotextiles

The stabilization of slopes by nailing consists of placing inclusions into an existing or potential sliding surface. The inclusions are generally installed with a uniform density either in a critical zone at the toe of an unstable slope or throughout the sliding mass. A wide variety of techniques and reinforcing elements, including timber piles, large-diameter piles, micropiles, and driven rails, have been used. The design of soil nailed slopes, particularly the role of bending moments, has not been resolved.

Fly ash and lime injections

Fly ash and lime injections have been tried as a method for slope stabilization along levees on several projects. Questions to be resolved include the long-term strength of the lime modified soil.

Gravel trenches

A recent method which has been tried to stabilize slopes involves lining narrow trenches with high-strength geotextile and filling the trenches with coarse sand, gravel, or crushed rock. The granular material is compacted in thin layers to increase the effectiveness of the method. Gravel trenches function as drains that will lower the pore water pressure, and the geotextile prevents clogging. They also function as reinforcement and increase the stability of the soil.

Slide suppressor walls

Slide suppressor walls consist of precast, prestressed concrete panels placed behind drilled piles to form lateral support along a slope and thus prevent sliding. This method has been used in plastic clays that are susceptible to shallow surface sliding. Slide suppressor walls are practical

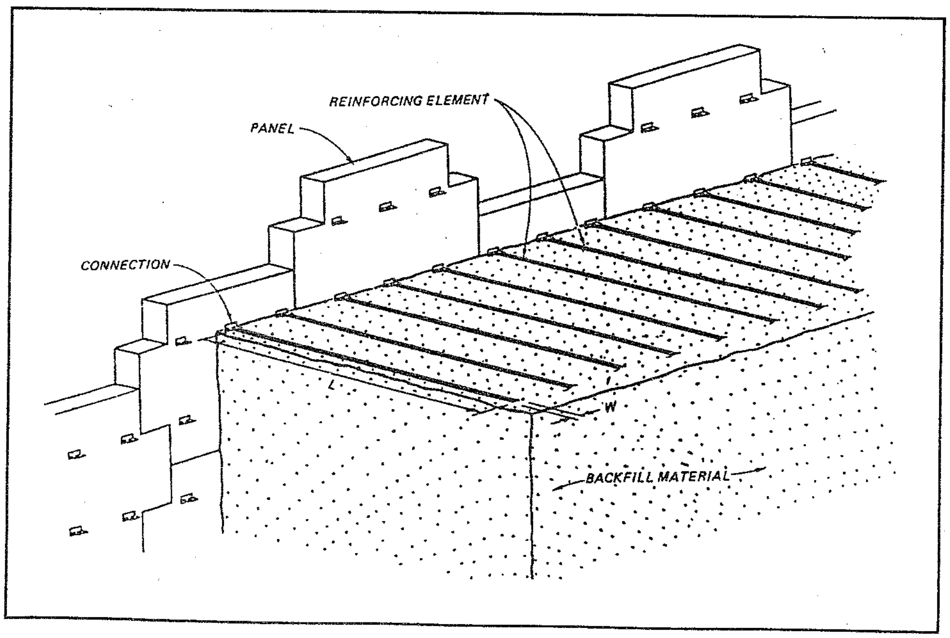


Figure 4. Diagram of reinforced earth retaining wall, a mechanically stabilized backfill system

in areas where right-of-way is restricted and the slide surface is not deep-seated.

Pin (micro or root) piles

Slope stabilization by means of pin piles in cohesive soil may be advisable when conventional methods are not applicable. The loading mechanism between the pin pile and the soil is identical to the passive horizontal loading of pile foundations. However, the boundary condition at the top of the pin pile is not uniquely defined. Therefore, the design methods for this approach are not finalized.

Continuous polymer thread injection

A continuous polymer thread injection where yarn is mixed with sand has been used extensively in France to stabilize soil. This method appears to have possible application for stabilization of levees constructed with an outer zone of sand.

Randomly distributed synthetic fibers

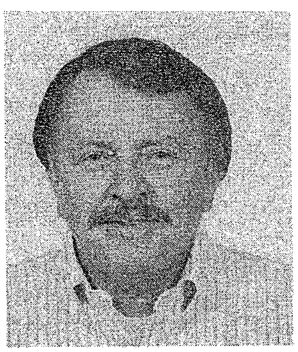
Randomly distributed synthetic fibers are being used in conjunction with various soils in laboratory and field studies to investigate the possible application to slope stability. This technique is experimental at present, and little information is available as to design methods or case histories other than researchers projections.

Prefabricated geocomposite drainage systems

Prefabricated geocomposite drainage systems are being widely used in pavement edge drain applications. Such drains could be used to construct trench drains to stabilize levee slopes.

Research is currently underway to develop guidelines for applying innovative methods to levee rehabilitation. The opportunity now exists for field testing and demonstrating some of the most promising methods which have been identified.

For additional information, contact Dr. Edward Perry at (601) 634-2670.



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Milton Myers *is Chief of the Soil Mechanics Branch, Soil and Rock Mechanics Division, Geotechnical Laboratory, WES, where he supervises a staff of research engineers and technicians engaged in geotechnical research. He is a graduate of the University of Mississippi and Oklahoma State University and is a Registered Professional Engineer in Mississippi. At press time, he was on temporary assignment to the Office of the Deputy Director of Civil Works for the Middle and Upper Mississippi River Basin, engaged in levee restoration following the 1993 Midwest floods.*

Use of Blended Chemical Heat Treatment (BCHT) Procedure To Clean Contaminated Wells on Superfund Sites

by
Bill Rogers, ARCC, Inc.
Roy Leach, U.S. Army Engineer Waterways Experiment Station

All remediation techniques for groundwater contamination require wells for monitoring. Many techniques require wells to purge the contaminated groundwater for surface treatment, injection wells to induce in situ conditions to allow chemical or biodegradation, and recovery wells to collect the product of the in situ process for disposal or further treatment. Biological action and particularly the action of biomass formation and sloughing are extremely important factors in the success or failure of particular techniques at a given site. The relationships appear to be site, aquifer, and contamination product specific.

Redevelopment procedures

Through a REMR work unit dealing with rehabilitation of relief wells and drains, an effective program of biofilm control for relief wells in toe sections of dams and levees has been established. This redevelopment method is under patent by the Alford Rogers Cullimore Concept (ARCC) and is called the Blended Chemical Heat Treatment (BCHT) method (Figure 1).

The procedures in general include an initial well water diagnosis performed with a prepackaged field bacterial activity and reaction test kit (BART kit), which is designed to give a qualitative indication of the types of bacterial and chemical agents at work in the wells and a very general indication of the concentrations. BART tests generally performed during this project include the tests for iron-related bacteria, sulfate-reducing bacteria, slime-forming bacteria, and a general bacterial count test.

The initial pH and temperature of the water are also measured prior to treatment. Treatment is then designed with the information from the tests in mind, targeting the problematic agents with an appropriate set of chemicals. Redevelopment of the wells using the BCHT method is based upon three principal elements of treatment:

- Shock. This phase can be achieved by adding high temperature (steam) chlorine to the well and surrounding aquifer to "shock" kill or reduce the impact of deleterious bacteria. Chemical guidelines are becoming strenuous, and other disinfectants may be required at specific sites.
- Disrupt. This phase is achieved by the addition of chemical agents and steam to the well and surrounding aquifer and surging to break up organic and mineral clogging in the system.
- Disperse. This phase of treatment consists of removal (by whatever means is most applicable, for example, air lifting or pumping) of the material that is clogging the well and aquifer.

The REMR Research Program has shown that under most circumstances the ARCC patented technique can achieve an order of magnitude improvement greater than with standard or traditional techniques. The period of effective improvement or time span between required major treatments was also improved by using a project-specific preventive maintenance procedure performed by maintenance personnel.

BCHT process at Superfund site

Several agencies were interested in a demonstration project using the BCHT procedures to clean production (plume capture) wells at an

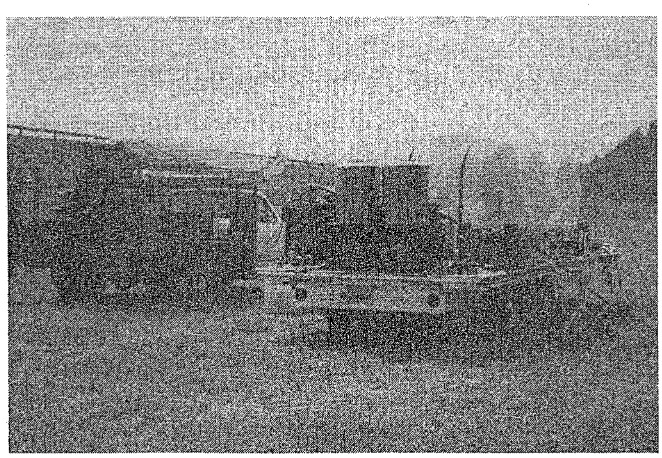

Figure 1. Equipment for BCHT procedure

active Superfund site: the Environmental Protection Agency; the State of Michigan; the Corps of Engineers, Omaha; and REMR. The Bofers-Nobel (BN) Superfund site near Muskegon, MI, had several clogged "plume capture" wells that were in danger of losing the plume without some remediation effort.

The 85-acre site slopes gently north to south except for bluffs along Big Black Creek near the southeast border. The site is sandy alluvium for about 100 ft underlaid by clayey glacial till (an aquitard) for about 140 ft, then Marshall Sandstone (an aquifer with poor water quality) for about 160 ft, and then Coldwater Shale below 400 ft. The surface stratum promotes direct recharge. The sand aquifer is of importance as a source of private and municipal drinking water, and Big Black Creek is important as a fishing and recreation area.

The BN site has been used intermittently for industrial chemical production for 33 years. The site was placed on the Superfund list in 1989 while operated by Bofers-Nobel Company. Reporting was sketchy for several of the past operators, leading to gaps in information on the nature of discharges to the 10 unlined lagoons onsite. Very serious contamination has occurred in the saturated zone of the sand aquifer. This is a direct and present threat to the human and natural environment and will be compounded if significant leachate reaches Big Black Creek and spreads to downstream locations.

Each lagoon (Figure 2) was identified, along with the surrounding impacted area, as a contamination source. The hazardous compounds are methylene chloride, $3,3^1$ dichlorobenzidine, analine, azobenzene, benzene, and benzidine. All are highly toxic. The first four are potential carcinogens in human beings, and the last two are confirmed human carcinogens. About 500,000 cu yd of contaminated soil is involved in the BN site.

In the 1970s, Michigan placed various wastewater disposal restrictions on the site. In 1976, a 12 purge-well net was constructed by the State to contain the contamination plume onsite. Early records indicate "incrustation" and loss of efficiency (later identified as biofouling). Corrective measures included traditional acid treatment and well replacement. When operating properly (seldom), the network is capable of containing the plume. Full production is about 1 million gallons per day to the Muskegon County wastewater treatment plant. Historic information and modeling indicate that system failure will result in discharge to Big Black Creek.

Microbially enhanced corrosion is present at BN and results in mechanical failure of the pumps at perhaps 10 percent of the expected component life and in high levels of iron and sulfide, typical end products of corrosive sulfate-reducing bacteria. These and other anaerobic bacteria as well as more common aerobic bacteria fall within the treatment scheme of the ARCC system. One of the fastest deteriorating of the 12 wells in the network was selected for analysis and model treatment (Figure 3).

The most toxic contaminant at BN is benzidene. The 5-year variation of benzidene in the test well varied from 0.7 to 11.6 mg/L. One microgram per litre is considered carcinogenic. Slime (biofilm) from the time of highest discharge concentration (16.6 mg/L) contained 25 times the benzidene concentration of the water discharge.

Figure 2. Lagoon at Bofers-Nobel Superfund site near Muskegon, MI

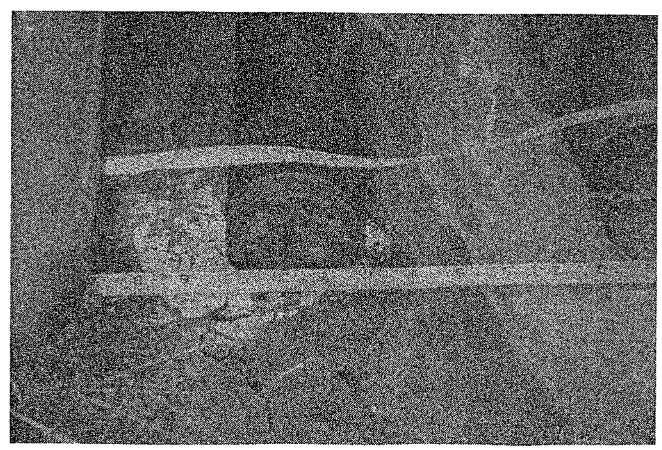

Figure 3. Fast deteriorating well selected for analysis and model treatment

At the lowest discharge, the concentration in the bifilm was 8,000 mg/kg. The bio-accumulation at the lower rate (higher concentration in pumped water) represents 400,000 times that considered toxic to human beings. This observation points out the monitoring distortion potential that can occur due to bio-accumulation.

Biofilm is one of the main factors in turbidity from recovery wells. The turbidity masks ultraviolet (UV) disinfection and O_2 treatments, interfering with aboveground and some in situ systems. At BN where UV is being used to treat the pumped water, filters must be used before UV treatment to collect the biofilm. The material pumped is approximately the color and viscosity of cola soft drinks from top to bottom.

The ARCC test well was developed to 100 percent of original pumping capacity (Figure 4), and a preventive maintenance program involving acetic/sulfamic acids and a setting agent on a 3- to 4-month cycle allows continued pumping at over 100 percent of original well capacity. The previous maintenance cycle had dropped to as low as 2 weeks to keep the pump operating. The ARCC remediated well pump rate must be reduced to produce only the flow that the treatment system can handle. Monitoring appears to indicate that the flow is "improving with time." The key elements for accounting for differences in results are site-specific chemical selection and improved application with the BCHT process.

Problems with free product removal

The BCHT process is being used at another contaminated site located at Shaw Air Force Base near Columbia, SC, in the Savannah District.

Figure 4. The ARCC test well developed to 100 percent of original pumping capacity

Biofilm management is particularly critical when dealing with a free product contaminant such as pure jet fuel. Following several rest days for the production wells, a see-through bailer will indicate about 1/2 product (J-P4) and 1/2 water, with a thin red line between. The red line is iron bacteria, which thrives on site oil conditions and J-P4 and is present all over the site.

One of the nine Shaw wells, a well designed for product recovery, is pumping water out and leaving product behind. This is an interesting study in selective separation, but the reverse of the objective at Shaw. The iron bacteria shield is prohibiting entrance of the product into the well. The separation might be helpful in some applications, but here the product is held back by the biofilm. The BCHT process will remove the biomass and allow the free product to be pumped to the surface.

Observations

The biomass culture expands until limited by nutrients and energy source or by their vital life requirements. Microbes are stunned or killed by substances toxic to the culture. Heat, cold, mechanical agitation, and internal competition for prime life essentials also cause an ebb and flow in the culture life cycle. Bio-accumulation, sloughing off, release of original or altered products, shell building, and changes in mass characteristics, corrosion potential, and effect on surrounding groundwater or solid environment are ongoing phenomena in response to site, product, and treatment condition.

Microbial activity is almost assured in wells because bacteria are present in most soils; the well provides an oxidation/reduction regime; the contaminants or naturally occurring organics and metals provide an energy source; and flow to the wells brings the energy source to the microbes. The only questions are how long the well will take to clog and whether the clogged well presents a safety or life-threatening situation. Pumping a well brings nutrients to it; the microbes use these nutrients and form biomass; and the biomass filters out contaminants that remain in the well. The amount of contaminants found in biomass would indicate that if a well is abandoned, it may have to be considered a point source for the contaminant.

Summary

The REMR well remediation study has developed an efficient well rehabilitation procedure using the BCHT process and has shown that this process can be used to clean contaminated wells by refining it to be site specific. All wells including nonflowing and monitoring wells are affected by microbial activity, and the activity should be considered during design and monitoring.

For further information, contact George Alford at (904) 258-5695 or Roy Leach (601) 634-2727.

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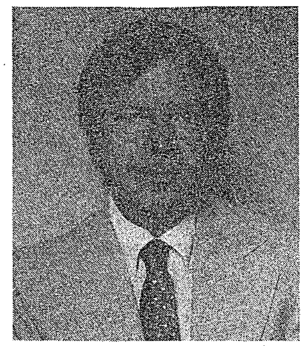


Roy Leach *is a research civil engineer in the Soil Mechanics Division, Geotechnical Laboratory, WES. He has been with the Corps of Engineers for 27 years. He received a B.S. degree in civil engineering from Mississippi State University. Leach is Principal Investigator for REMR Work Unit 32313, "Restoration of Relief Wells and Drainage Systems."*

Fifth REMR-II FRG Meeting a Big Success

"Technology on the move" was the key phrase during the Fifth REMR-II Field Review Group (FRG) Meeting held July 28-30 in Omaha, NE. Innovative new methodologies, such as Core-Loc armor units, used to patch dolos slopes and reduce coastal erosion, kept FRG members attentive and motivated during the 2-1/2 day session. Approximately 75 people were in attendance.

Slide presentations were made on each ongoing work unit under the six REMR problem areas: concrete and steel structures, coastal, geotechnical, electrical and mechanical, operations management, and hydraulics applications. Also included in the agenda were presentations on eight Construction Productivity Advancement Research (CPAR) Program projects that are producing technology useful for the maintenance, repair, or rehabilitation of Civil Works projects.

The major emphasis at the meeting was on the need to get information to the field as quickly as possible. Research on maintenance and removal of lead pigmented paints from hydraulic structures received considerable attention from the attendees, who stressed that field guidance in this area is needed immediately. Another area where research needs to be accelerated is levee rehabilitation. The results from this work unit can play an important role in the rehabilitation of levees that failed during the 1993 floods. Other technologies found noteworthy included techniques for underwater surveying, cleaning of relief wells, high-performance concretes, and numerical modeling of high-velocity channels.

Use of Ground-Penetrating Radar in Nondestructive Testing for Voids and Cracks in Concrete

by Falih H. Ahmad and Richard Haskins, U.S. Army Engineer Waterways Experiment Station

Accurate evaluation of the condition of concrete structures such as locks and dams is necessary for their continued serviceability, especially those approaching their design life. In the past, methods to obtain these evaluations depended on destructive techniques that were often costly and sometimes unacceptable. Now, nondestructive techniques (NDT) are being developed to determine the need for repairs to these structures. A typical scenario using NDT testing under the REMR Research Program is the examination of a vertical concrete wall for the containment of voids and cracks. Size, depth, and orientation of such anomalies in the concrete wall have no particular pattern and are therefore very hard to predict. Better tools for investigating a given concrete wall and showing the locations of these voids and cracks inside the wall are needed.

Two major properties of these tools are desired: capability of testing without destruction of the structure and ease of application. In addition, the tool must provide enough information to the user so that decision-making regarding the concrete structure under investigation is fruitful and economically sound. Pulse echo is one example of such a tool. Energies that can propagate in concrete include two kinds: electromagnetic and mechanical. Radar can provide the former in many forms. The study of the propagation of electromagnetic energy in concrete has been shown to be helpful in NDT. Due to the characteristics of radar, this energy can take many shapes or forms; hence, it is a versatile tool for NDT.

Ground-penetrating radar

The full capacity of the application of different kinds of radar to NDT of concrete is not fully known. The Structures Laboratory (SL) at Waterways Experiment Station (WES) is investigating the feasibility of using ground-penetrating radar (GPR) for this purpose. Ground-penetrating radar is used as a tool to impinge a given amount of electromagnetic energy upon a concrete structure. The reflected energy carries information about the tested structure. The degree of complexity by which the electromagnetic energy is transmitted and received is a function of many parameters, such as the type of radar used (for example, pulsed, impulse, or continuous radar) and information used from the signal being transmitted and received (for example, the signal's amplitude, polarity, frequency, or phase).

Criteria

The following criteria have been established for the SL research:

- Objective: To detect, locate, and identify voids and cracks in concrete through the use of GPR. The current GPR has a pulse repetition frequency of 5 million pulses per second and a pulse width of 1 or 0.5 nsec. The desired results are that all true targets are detected and the probability of false alarm is minimized.
- Methods for target discrimination: High azimuth and range resolutions and application of polarimetric techniques. The desired result is that scattering characteristics of different voids and cracks are determined.
- Methods for target recognition: Solution of the inverse scattering problem, information theory, and signal processing applications. The desired result is that identities of different voids and cracks are known.

The Structures Laboratory's GPR (SLGPR) is a monopulse radar; this means that the width of the transmitted pulse occupies the full period of the transmitted signal. The SLGPR has two transducers, each containing a transmitter and a receiver. One transducer generates a signal with a frequency of 1 GHz and hence a pulse width of 1 nsec. The second transducer generates a signal with a frequency of 2 GHz and hence a pulse width of 0.5 nsec. The pulse repetition frequency of the SLGPR is 5 MHz. Only one transducer can be operational at any given time. The SLGPR antenna works over a range from 200 MHz to 2 GHz. Since it is a TEM wide-beam antenna, it has a poor cross-range resolution. On the other hand, the range resolution of the SLGPR is a function of the width of the transmitted pulse. The user of this SLGPR can select either a 1- or 0.5-nsec pulse width. Between these two pulse widths, the shorter pulse provides a better range resolution. The user, however, sacrifices the depth of penetration capabilities of the SLGPR. In this phase of the investigation, the SLGPR is used to detect voids and cracks that exist in concrete walls.

In tests conducted at WES, multiple radar scans were taken on the east and north faces of a concrete monolith constructed on station (Figure 1). Data were collected and displayed using customized scanning software written for the SLGPR system. During the scanning, continuous returns from the SLGPR are collected and used to generate real-time scans on the monitor of the computer. In these scans, amplitudes, in volts, of the different returns are mapped into a 16-color set from which the scans are made in both horizontal and vertical directions.

Field scan 1

Figure 2 shows a captured scan image in the vertical direction for the east face of the test structure. The SLGPR was successful in detecting an air void inside the concrete wall. This void was generated by burying a polyvinyl-chloride (PVC) pipe, 3.5 in. in diameter and 54 in. long, in the structure at a depth of 16.5 in. from the east face surface. This PVC pipe was buried at a height of 59 in. from the bottom. Coordinates of the void that were deduced from the scan and the actual location of the void are in good agreement.

Field scan 2

Returns from vertical scans on the north face of the test structure are indicated in Figure 3. Returns from a clustered reinforcing steel mat about 2 in. below the north face of the test structure prevented the radar from detecting a void that existed behind the reinforcing steel at a depth of about 20 in. Dimensions and configuration of the reinforcing steel beneath the surface of the concrete are shown in Figure 4. In an effort to remedy a situation like the one presented in this scan, a well-known technique in radar application, the constant false alarm rate (CFAR), was considered.

CFAR

In any radar system, there are false reflections that can mask the signals of interest. Returns from reinforcing steel, for example, are considered false reflection. The interference resulting from false alarms (reflections) limited the performance of the SLGPR used in this investigation. For voids and cracks to be identified in radar returns, the corresponding returns must be large enough to exceed a set threshold. In the meantime, it is desired that this threshold be exceeded by a minimum number of false reflections.

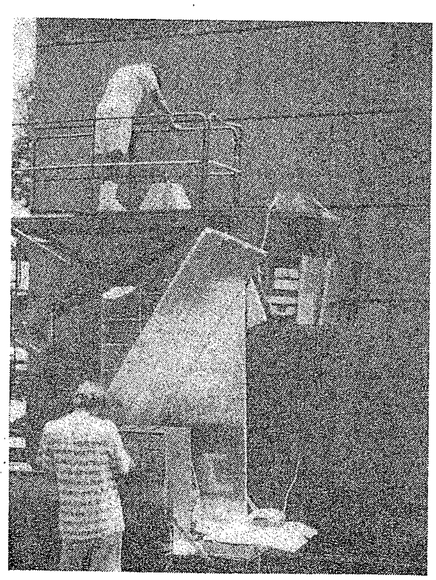


Figure 1. Concrete monolith at WES

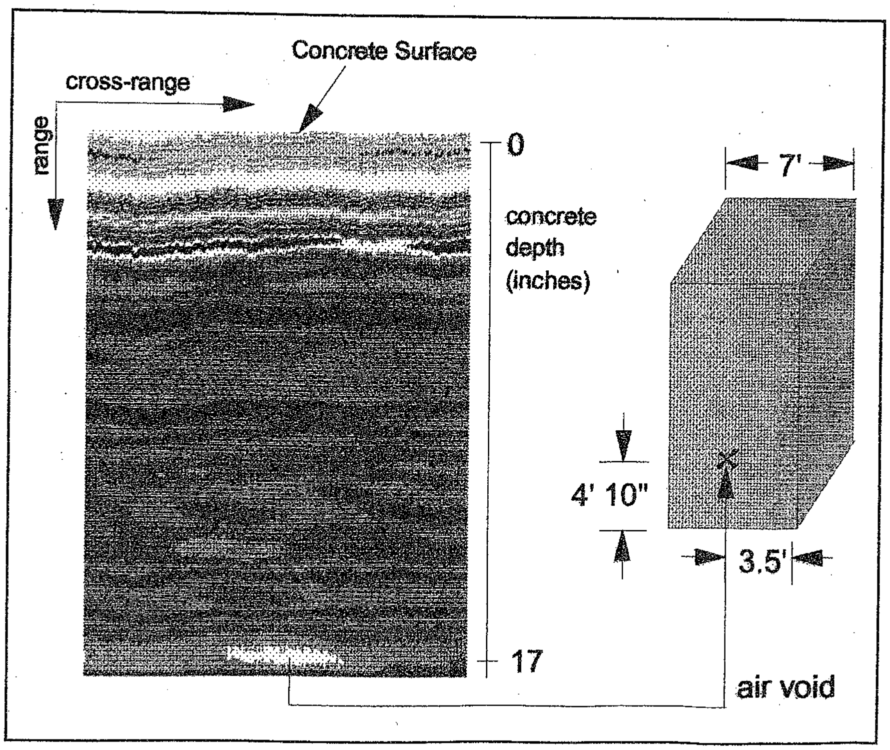


Figure 2. Vertical radar scan, east face of structure

Extra sources of false returns are the connector joints in the SLGPR cables and the discontinuity that is represented by the interface between the antenna of the SLGPR and air. Another discontinuity generating false alarms is clutter that is laterally displaced from the radar, for example, a mobile cart on which the antenna of the SLGPR is mounted. Additional clutter that may generate false alarms include personnel in the vicinity of the radar or even nearby vehicles. When detection is considered, clutter is one source of contamination. During the detection process, the electromagnetic energy reflected from the clutter competes with that reflected from the object that needs to be detected.

In an example scenario, detection of a void under a slab of concrete is sought in the laboratory under controlled conditions. The slab of concrete has reinforcing steel in it. In this case, the void is considered the object that needs to be detected and the reinforcing steel that exists in the concrete is considered the main source of clutter. The energy that reflects from the clutter confuses the SLGPR as to whether the void is present or not. This confusion produces false alarms, and the integrity of the SLGPR is questioned. The probability of declaring the detection of a void underneath the concrete when no void actually exists is called the probability of false alarm. This probability depends strongly on the noise and/or clutter power. A process that keeps the average number of false alarms constant in spite of the unpredicted changes in the background in which the void exists is called a CFAR process.

For the SL investigation, the application of a well-known

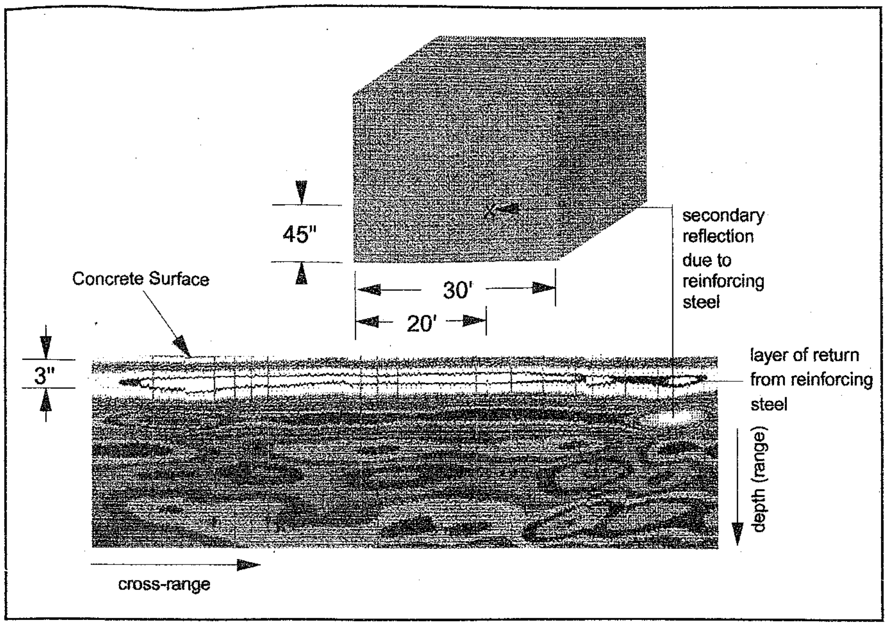


Figure 3. Vertical radar scan, north face of structure

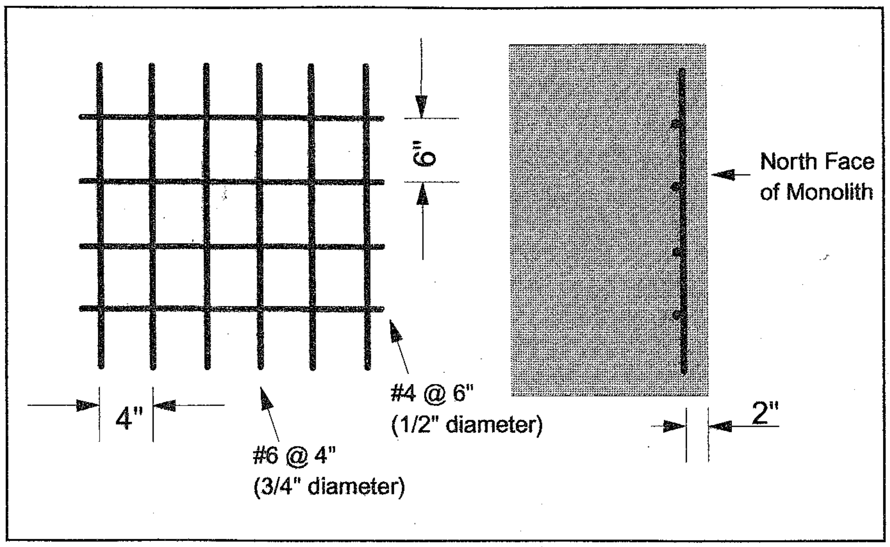


Figure 4. Dimensions and configuration of reinforcing steel beneath the surface of the concrete

CFAR method was used, and comparison between the results from the use of such a process and those from a conventional method was demonstrated. Improvement of the SLGPR detection capability was desired to allow for better recognition of voids or cracks in concrete. To increase the detection capability of the SLGPR, a clutter map constant false alarm rate (CM-CFAR) process was implemented. This CM-CFAR processor uses adaptive thresholding. The threshold that this process produces is calculated from previously returned signals and allows the GPR to detect buried objects in or under concrete in the presence of clutter. A block diagram describing CM-CFAR is presented in Figure 5.

As indicated in Figure 5, the CM-CFAR processor has memory, and the relationship between the n^{th} return of the SLGPR at point I and that at point P is given by the following:

$$TH_n = \alpha\,\omega \sum_{j=0}^{\infty} (1-\omega)^j E_{(n-j)|r}$$

where

TH = threshold value generated by the process

α = gain set by the radar user

ω = feedback parameter

j = index of accumulation

E = radar return

Due to the n^{th} return, the output from the comparator is:

$$E_{n|r} - \alpha\,\omega \sum_{j=0}^{n} (1-\omega)^j E_{(n-j)|r}$$

If the return of the SLGPR is assumed to be constant (e.g., reflections from the same spot), the output from the comparator due to the n^{th} return is:

$$M - \alpha\,\omega \sum_{j=0}^{n} (1-\omega)^j M$$

where M is the constant SLGPR return. Knowing that $(1 - \omega) < 1$ and considering large n, one can approximate the above output as:

$$M(1-\alpha)$$

The simple form of the output from the comparator is zero when α is selected to be one. This means no detection is declared, and physically this means that the antenna is not moving at all or that it is scanning a perfectly homogeneous medium. This could be used as an indication of the signal-to-noise ratio of the system. The following test was conducted in the laboratory to investigate the advantages, if any, of the application of CM-CFAR in NDT of concrete.

Laboratory scan

The location and size of an air void under a reinforced slab of concrete along with the dimension of the slab are shown in Figure 6. The antenna of the SLGPR was traversed over the surface of the slab of the concrete. The returned signals were collected, and a real-time, color-coded scan was displayed on the monitor of the computer. Two versions of a computer program were used, one with CM-CFAR implementation and the other without. Data collection was carried out using these two versions to study the effect of CM-CFAR on the detection of the void. The conventional scan is shown in Figure 7. As can be seen, it is impossible to declare the detection of the void under the concrete. In Figure 8, however, two CM-CFAR scans are shown. In Figure 8a, the CM-CFAR scan is shown where no void existed under the slab of concrete. In the CM-CFAR scan shown in Figure 8b, the void under the slab of concrete is evident. The conclusion from the data available as demonstrated in Figures 7 and 8 is

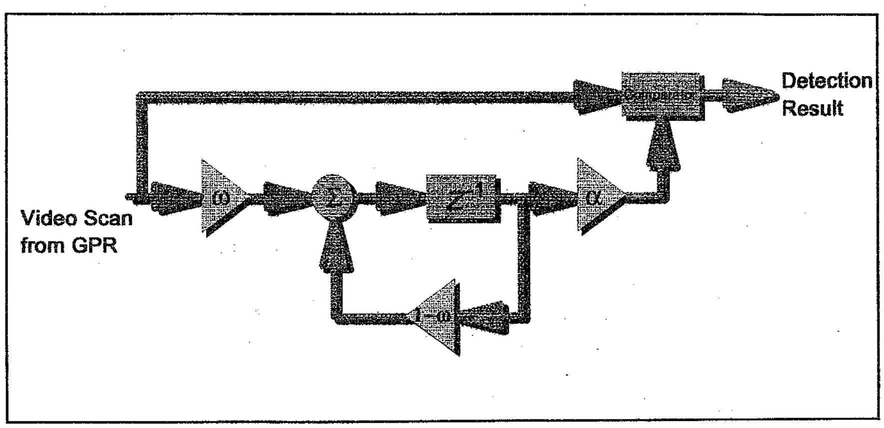


Figure 5. Clutter map, CFAR processor

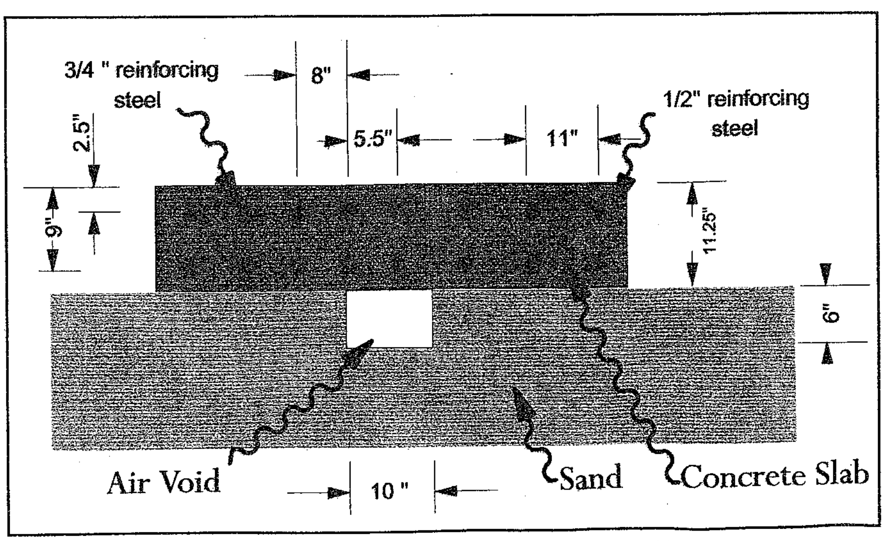


Figure 6. Air void under a reinforced slab of concrete

that CM-CFAR improved the detection capability of SLGPR.

For additional information, contact Falih Ahmad at (601) 634-4100.

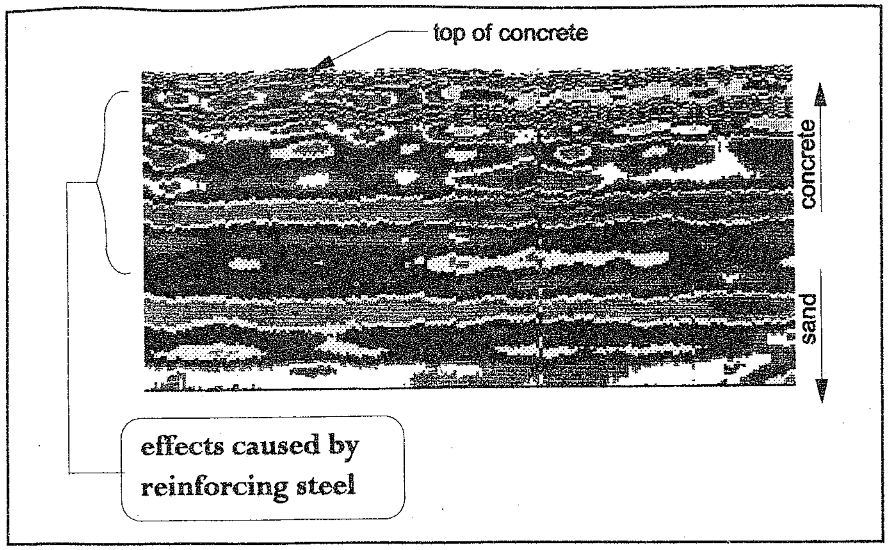


Figure 7. Conventional scan

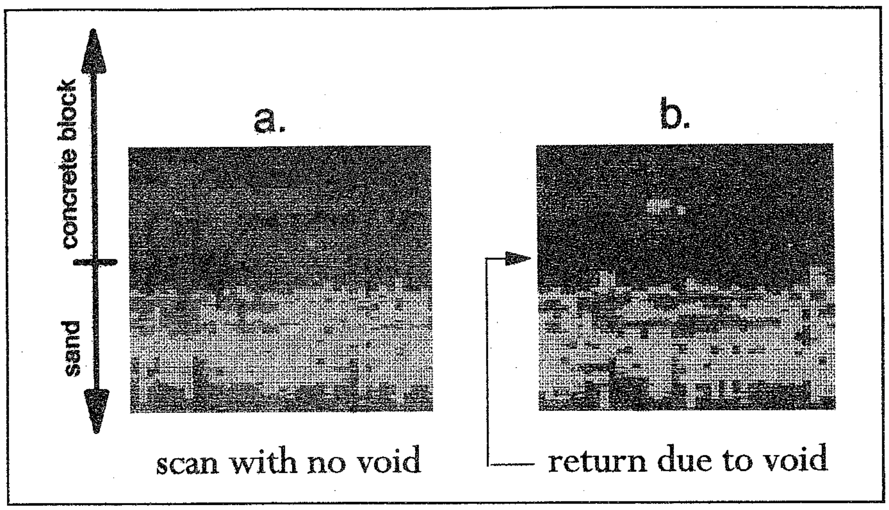
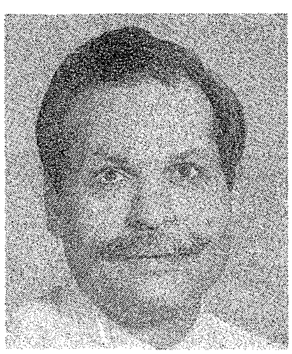


Figure 8. CM-CFAR scan



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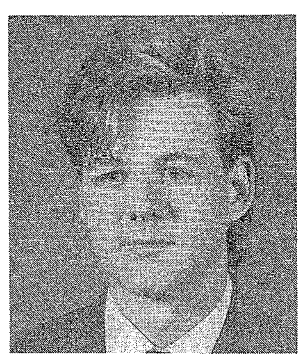

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