CONSTRUCTION, TESTING AND ASSESSMENT OF A SCALED SMART SUBSURFACE BARRIER IN JAPAN

J. Richardson, K. Kostelnik, P. Sloan, R. Nickelson
Idaho National Engineering and Environmental Laboratory

H. Kawamura, M. Noda, S. Sato
Obayashi Corporation

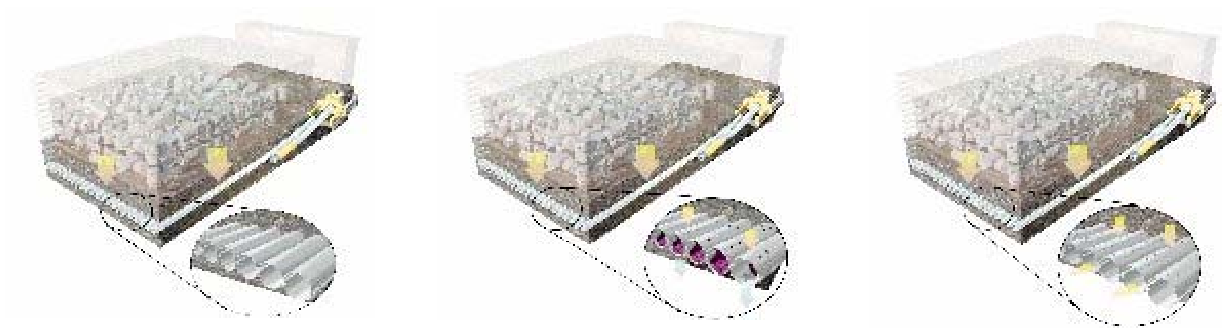
ABSTRACT

Construction and testing of an impermeable segmented horizontal barrier was conducted jointly by Obayashi Corporation and the Idaho National Engineering and Environmental Laboratory in Tokyo, Japan. The 4 by 5 meter Smart Subsurface Barrier© (SSB) was constructed using a tunnel boring machine and inspected by radioisotope and ultrasonic sensors. The system was then characterized for overall hydraulic conductivity. Archeological disassembly and comparison of physical observations with characterization was also performed. Actual performance exceeded expectations and new insights were obtained into success mechanisms of horizontal in-situ installation, grouted assemblies and performance of inspection technologies.

INTRODUCTION

There are thousands of active, inactive, and abandoned environmentally contaminated sites throughout the world. This contamination has resulted from many anthropogenic means such as mining, manufacturing, and waste disposal. Limiting pollution from these areas is a significant challenge facing the world's population. Although various remediation efforts are underway, it is evident that cost-effective techniques for many sites are not yet available. For example, containment techniques for volumes of subsurface contamination have not been adequately demonstrated to satisfy regulatory concerns.

The Idaho National Engineering and Environmental Laboratory (INEEL) and Obayashi Corporation have addressed various limitations of existing subsurface containment techniques and have jointly developed a new technical solution. The Smart Subsurface Barrier System (SSB) is a state-of-the-art technology that can place an instrumented in situ subsurface barrier around and beneath buried waste landfills, contaminated sites, and/or other zones of interest This concept represents a safe, competitive cost, low risk containment alternative that provides significant technical and operational advantages. The SSB approach involves the integration of a series of horizontal tubes that create an isolation barrier and/or a reactive zone. The SSB system design consists of a horizontal floor/wall composed of parallel, interlocked and sealed casing tubes, and four perimeter vertical walls (i.e. tubes and/or diaphragm walls). The interlocked casings are sealed and monitoring instruments are installed in the open casings to validate the barrier installation, monitor the long-term integrity of the barrier, and detect precursors to potential failure so that repairs can be performed. The SSB can be used as an impermeable, semi-permeable, or reactive barrier, as illustrated in Fig. 1.



Impermeable Subsurface Barrier | Subsurface Accumulation Barrier | Permeable Reactive Subsurface Barrier

Fig. 1 Smart subsurface barrier configurations

Installation utilizes micro-tunneling boring machines. This base technology is a mature technology that is currently in use by commercial vendors for placing casing-lined tunnels. It has also been used to construct temporary support structures. As an application of an existing field, the SSB represents an improvement over current barrier technology with minimal development risk.

An integrated demonstration test was conducted at the Obayashi research facility in Tokyo, Japan in the winter of 2003. The overall purpose of the test was to establish the technical applicability for the barrier installation method and to quantify the impermeability of the resulting scaled barrier installation. Other objectives included an assessment of the preferred sealing material injection method, the performance of the sealant, and the accuracy of a proprietary ultrasonic non-destructive inspection technology.

TEST OBJECTIVES

The demonstration test was conducted over a two-month period during January and February, 2003. The test was preceded by a multi-year development process conducted by the Obayashi Corporation and INEEL. Previous work included the design and mechanical evaluations of various interlocks and casing materials, laboratory and bench scale testing of cementitious, thermosetting and thermoplastic polymer sealing materials, development of non-destructive evaluation instruments, interlock sliding force testing, hard rock and cutter evaluation tests, and bench-top hydraulic permeability tests. This previous work contributed to the development of test objectives and the physical design of the integrated demonstration test. There were five objectives of the SSB field demonstration test.

The first objective was to verify that full-scale interlocked barrier sections could be installed through representative rock/soil matrix using a commercial micro-tunneling technology. One specific issue that was to be investigated included the adequacy and dynamic response of alignment and cutting head control sufficient to maintain the interlock without putting undue stress on the structure. Also, there was interest in practical methods for extraction of cuttings from the interlock in the presence of internal interlocks and a sealant injection system.

The second objective was to test the injection system design and the injection control method in an emplaced barrier. Issues such as interlock clearing and segmented injection had never previously been tested because they cannot be simulated in a meaningful manner with small-scale bench or laboratory tests.

The third objective was to minimize the manpower requirements involved in the mud discharge and sealant injection during the installation phase of a Smart Subsurface Barrier. The labor involved in these internal barrier functions provides insight into actual field installation activities and worker safety.

The fourth objective was to empirically measure the permeability of the completed barrier, to investigate any variations in permeability over the 20 m^2 area of the barrier, and to explain these potential variations in permeability.

The last objective was to test a non-destructive evaluation (NDE) technology as a means of validating proper and continuous sealing of the barrier interlocks and to monitor performance of the barrier over time.

In addition, a test of full-scale barrier sections provide actual experience in operation of the integrated tunneling and placement system. This experience provided numerous insights into fielding challenges such as in-situ welding of casing sections and debris removal in the interlocks.

DESCRIPTION OF THE DEMONSTRATON TEST

Figure 2 is a photograph of the demonstration test in progress. The framework container under the tarp is a welded steel assembly four meters wide, five meters long, and 3.5 meters high. Two half-section casings were placed on opposite sides of the framework and welded in place. These were intended to simulate sides of previously installed barrier sections as part of a much larger isolation containment system. "Artificial soil" consisting of an aggregate-rich cementitious mortar with an approximate 15% void ratio was placed in the container and compacted. Compressive strength of the matrix was characterized at 10^{-13} N/mm^2.

Three 812 mm interlocked barrier sections were then emplaced through the artificial soil using a Komatsu TP95S micro tunneling machine and associated jacking system. The cutting rate was approximately 90 cm/hour. Alignment was accomplished using an integrated laser theodolite and positioning control system.

Fig. 2 SSB demonstration test

All barrier sections were successfully installed and interlocked. All end penetrations were then welded so that the box frame to barrier junctions formed a water tight seal. This was necessary to ensure that any movement of liquid would occur through the barrier, not by exiting the test container.

As part of this test, a proprietary cement mortar sealant specifically developed for minimum shrinkage was developed by Obayashi. Laboratory measurements showed the sealant to exhibit an approximate hydraulic conductivity of 0.7×10^{-12} cm/second. This mortar was pressure injected into each of the interlocks through an integrated manifold assembly and allowed to solidify. The injection manifold can be seen in Fig. 3 below just above the internal interlock channel.

During and following mortar injection, ultrasonic NDE measurements were taken along each interlock to verify the absence of voids which could lead to poor barrier performance. The NDE transducer was deployed on a trolley that was fitted to a rail as part of each internal junction interlock assembly. The transducer returned void information as a function of location along the length of each interlock.

After the mortar sealant in the interlocks cured, a fast neutron source and thermal neutron detector were used to measure moisture content just below the interlocks. A total of 19 sets of neutron moisture measurements were taken, each extending along an entire barrier section, and spanning the lower half of each interlocked casing section. Then red dyed water was placed in the upper part of the test assembly above the prototype barrier and the barrier permeability test was initiated. An automated control system maintained head pressure at 1.4 meters. The design was closed to the outside environment to eliminate evaporative losses. Ultrasonic NDE and neutron measurements continued for the duration of the test, and gross water displacement was measured and recorded.

Following the test, the entire assembly was archeologically disassembled. Three 0.7 m^2 samples of interlocked sections were cut out and hydraulic conductivity measurements were made on each sample using blue dyed water. This was followed by further disassembly and physical examination.

TEST RESULTS

As noted above, there were multiple project test objectives. These were intended to answer various technical questions about the feasibility of installing and verifying an in-situ installation of a segmented and interlocked horizontal isolation barrier. In addition, the test was intended to provide operating experience that only a near full-scale test can reveal. Below is a summary of the data and experiences gained during the integrated demonstration test. Each of the objectives and the test results obtained to meet that objective are summarized.

Barrier Installation

The first objective was to verify that full-scale interlocked barrier sections could be installed through representative rock/soil matrix using commercial micro-tunneling technology. Some specific issues that were to be investigated included the adequacy and dynamic response of alignment and cutting head control sufficient to maintain the interlock without putting undue stress on the structure Also, is the overall installation process compatible with the internal integral structure necessary for subsequent injection of sealant and fast neutron and ultrasonic inspection?

For the purposes of this demonstration test, the interlock section were located inside the casing due to application into a relatively hard matrix of artificial ground. The injection pipes were also located inside of the casing. Because the interlock and injection pipes are obstacles for a screw auger method, a vacuum method for mud (excavated soil) discharge was applied. This directly contributes to worker safety (and lower cost) because it requires less manpower. The tunneling direction was easily controlled without undue stress and no particular differences were observed nor unique difficulties experienced between 'inner-type' interlocks and 'outer-type' interlocks. At a field application the lithography is not expected to be homogeneous like the demonstration test, and the distance will be much longer. Therefore the directional control may become more difficult.

Injection System

Fig. 3 Interlock injection manifold

The second objective was to test the injection system design and the injection control method. Issues such as interlock clearing and segmented injection had never previously been tested because they cannot be simulated in a meaningful manner with small-scale bench or laboratory tests. In the demonstration test, an internally configured junction was used. This junction was an Obayashi design incorporating features used in earlier Obayashi and INEEL tests. The design included a single grout injection manifold that extended along the entire length of the interlock. The injection method was a double packer system. Figure 3 shows the interlock, injection manifold, and several injection channels. The cement mortar used as the injectable sealant consisted of a 4:10:7 mixture of water, slag cement, and sand with small amounts of an air entraining water-reduction agent and a thickening agent.

Previous laboratory tests indicated an average compressive strength of 96.2 N/mm^2 and a hydraulic conductivity of 0.69 x 10^{-12} cm/sec. Total injected volume was monitored, and compared with the 41 liter volume of each interlock. This was used as a minimum volume reference during the injection process. The injection was accomplished in two stages, with the interlock being filled to the halfway vertical point, and then completely filled the following day. Air was vented and filling was monitored by observing overflow through valved taps at the end of the interlock.

Injection proceeded at a rate of approximately 2 L/min., with each of the interlocks filled in sequence. A double packing injection method was used to fill sections, called steps, along the length of each interlock. Both volumetric rate and pressure were monitored continuously. The second injection on each interlock was discontinued when injection pressure increase was observed in each step, and the total volume injected into the interlock exceeded 41 liters. All four interlocking assemblies were successfully filled with cement mortar. Actual injection volumes varied from 57 to 128 liters, with the additional volume flowing into void area outside the interlock (i.e. void space created by the cutter head being slightly larger in diameter than the casing) and external to the barrier.

Mud Discharge and Sealant Injection

The third objective was to minimize the manpower requirements involved in the mud discharge and sealant injection during the installation phase of a Smart Subsurface Barrier. A vacuum method was applied in this demonstration, which is not complex and is flexible in the presence of internal assemblies such as injection manifolds and internal interlocks. Under the current design, this alternative needs more work. The single grout injection manifold and double packer injection scheme worked well, and certainly minimizes the manpower requirements inside of the casing for injection. As in the demonstration test, the injection is done outside of the casing and requires no direct access to the inside of the channel, thus contributing to worker safety.

Permeability

Perhaps the most important objective of the demonstration test was to empirically measure the permeability of the completed barrier. The approximate planar area of the barrier was 20 m^2. Figure 4 provides an overview of the in situ permeability test. During the permeability test, a pressure head of 1.4 meters water relative to the bottom of the barrier was applied. Water level and temperature were measured and logged at regular intervals. The system was sealed to eliminate errors due to evaporation. The water was dyed red to provide a visual record of water migration within the matrix and barrier sealant during subsequent archeological disassembly.

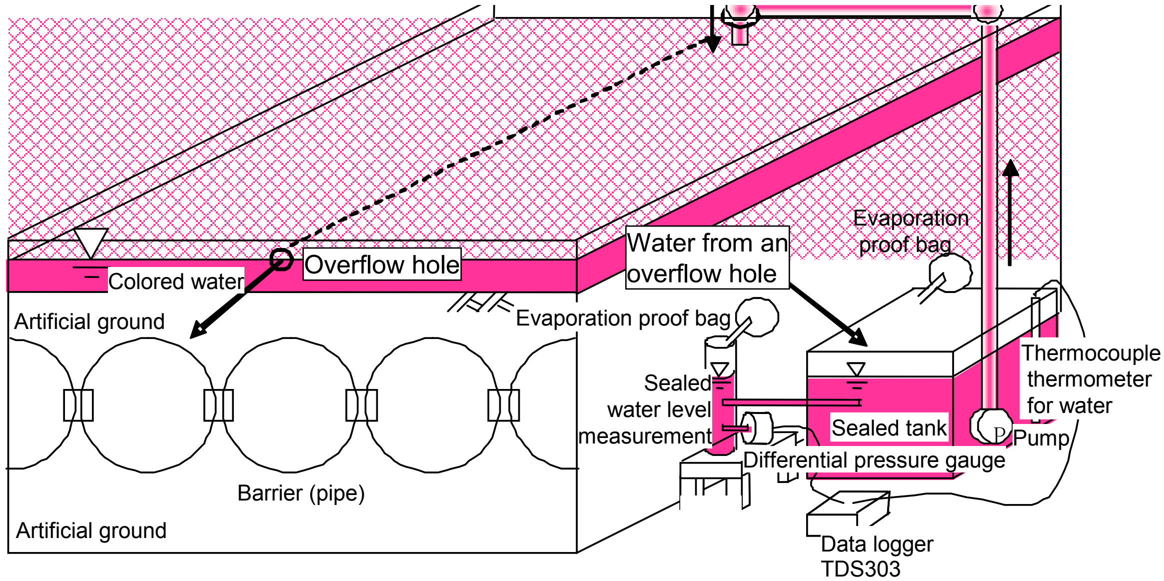


Fig. 4 Barrier permeability test configuration

The barrier permeability test continued for 19 days. Minor leakage was observed at the ends where welds between the containment box and the casing sections were imperfect. This was not accounted for, and hence the gross conductivity number is conservative. Hydraulic conductivity was measured to be 7.2 x 10^{-8} cm/sec after being corrected to 15 degrees Celsius.

Following the conductivity test, the barrier was cut into 0.7 m^2 sections with a large wire saw. Three of these sections were transported to a test laboratory, including one section where neutron interrogation had indicated some leakage. Each of these sections was placed sequentially in a test fixture and hydraulic conductivity was again measured at various head pressures. Two sections exhibited hydraulic conductivities of less than 10^{-8} cm/sec. The 0.7 m^2 section where leakage was postulated was measured at 3.7 x 10^{-6} cm/sec., thus validating for this case the neutron measurement as a means to infer migration.

Neutron and Ultrasonic NDE Measurements

Another important objective was to test a non-destructive evaluation (NDE) technology as a means of validating proper and continuous sealing of the barrier interlocks. Both neutron and ultrasonic based instruments were used for this purpose.

Fast neutron interrogation was used to detect the presence of water below the barrier structure. Obayashi engineers deployed a fast neutron source and thermal neutron detector. The detector was self-propelled along the length of the interlock. Following each interrogation, the collision of fast neutrons with light atoms creates thermal neutrons. Comparisons of detected levels of thermal neutrons can be used to calculate water content in the artificial earth and unconsolidated volume immediately below the barrier. Neutron interrogation scans along the length of the barrier were conducted at a total of 19 different locations within the four barrier sections. These were positioned immediately below both sides of each interlock, at the bottom of each casing section, and half-way in between. Each of these 19 scans was taken before and after the in situ permeability test. The measured values were subtracted and the differences were plotted versus position along the barrier length.

Ultrasonic NDE was used to detect voids and poor seals adjacent to the walls. During the past several years INEEL performed scoping studies assessing attenuation and propagation characteristics of ultrasonic signals in various types of sealants and grouts. The Laboratory designed a trolley configured to track along a modified interlock structure. The transducer acoustically characterized the grout/sidewall along the length of the interlock. Signal energy losses were correlated with presence or absence of good bonding between the sealant and the interlock wall. A computer software package and data system were also designed to measure, display, and log the test results. Ultrasonic NDE measurements included four groups of ultrasonic scans of each interlock. These were taken at the completion of the first grouting injection (when the interlocks were filled approximately ½ full), at the completion of the final grouting injection, one week later prior to initiation of the barrier hydraulic conductivity test, and one month later following almost three weeks of 1.4 meters head pressure for hydraulic conductivity testing.

Ultrasonic results indicated progressive curing of the cementitious grout in each of the interlocks. Data indicating 500 mm defects were observed at one location, and debonding was observed at various locations along the length in another location. These do not translate necessarily into barrier permeability because the region examined only constitutes part of the sealed structure. However, it does provide an indication of the status of the seal, and observation of significant lengths of debonding indicates a generally questionable seal of the barrier interlock. Two neutron scans were taken near each interlock, and they were averaged to obtain representative values. Since neutron interrogation cannot discriminate between leakage and migration, averaging was not done for scans performed at or near the bottom of the barrier sections, since the presence of water there could result from migration from another location along the barrier casing section. Interlock 3 was chosen for more detailed study because two sections were physically disassembled after the tests and detailed information on physical status of the sealant and dye traces were observed and recorded. Peaks in neutron interrogation data were correlated with red dye stains resulting from water migration during the hydraulic conductivity test. Physical examination revealed a 30 cm void along the outer wall, and this was found to be coincident with a peak in the ultrasonic data. Other parts of the interlock revealed no dye or physical indication of leakage, and exhibited no ultrasonic or neutron peaks.

Operating Experience

A test of full-scale barrier sections provides actual experience in operation of the integrated tunneling and placement system. This field demonstration provided numerous insights into field application issues such as in-situ debris removal in the interlocks. Any debris remaining in the interlocks potentially has an impact on impermeability of barrier. For debris removal, the air jet method with air compressor was particularly effective. In the demonstration test, the barrier length was five meters and a small compressor (gauge air pressure was around 0.02 MPa) worked well. In real construction, debris can be removed with a larger compressor.

Cutter face design affects tunneling speed. During the first tunneling, the opening ratio of the cutter face was inadequate for the artificial ground and the tunneling speed was slow (5mm/min.). The cutter bit type, bit allocation and the opening ratio had been improved repeatedly, and as a result the speed at the third tunneling was 15mm/min. (900mm/hr.).

SUMMARY AND CONCLUSIONS

The 4 by 5 meter Smart Subsurface Barrier was constructed using a Komatsu tunnel boring machine operating in a contained volume of aggregate-rich cement media. It was then inspected by radioisotope and ultrasonic sensors to establish a baseline. Work proceeded smoothly and the original operational schedule was maintained. Boring became routine and advancement rates were close to predictions. No problems were encountered with alignment or interlock placement. The double-packer mortar injection system intended to seal the interlocks also performed as predicted. The entire barrier was characterized for overall hydraulic conductivity over a one-month period. The mean value was measured to be 7.2×10^{-8} cm/sec. Subsequent testing and archeological disassembly successfully provided insight into sealant performance and variation in performance within the barrier.

The full-scaled demonstration test described in this paper has shown that a near full-scale barrier system can be installed, verified, and meet commonly accepted performance requirements. The choice of barrier dimensions, media, and methods of sealing and verifying the installation provide empirical data for broad applicability of this technology in a wide variety of media. The operating experience reveals and quantifies actual operational details necessary to perform a field installation of such a barrier.

Obayashi and INEEL both view the impermeable version of the Smart Subsurface Barrier demonstration Test to be an unqualified success. The next development steps will be to field deploy the impermeable SSB and perform additional laboratory tests on the semi-permeable and reactive barrier components.