First use of TRD Construction Technique for Soil Mix Cutoff Wall Construction in the United States

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Abstract

Trench **R**emixing and **D**eep wall method (TRD) developed in Japan was recently used to construct two demonstration test cells at a site in Long Beach, California. Seawater intrusion occurs through a shallow aquifer of 30 meters in depth, which fouls the fresh water supply aquifers farther inland. The physical cutoff wall concept calls for a soil mix wall constructed into the underlying aquifer, and spanning the 3.5-kilometer length of the gap.

During design, hydrogeologic evaluation indicated variability in the aquitard beneath the shallow aquifer; therefore, test cells to depths of 20 and 24 meters were utilized to assess seepage under the wall with respect to wall depth. Testing of 5 different soil-mixes indicated a slag-cement-sepiolite-soil mix as optimal for field application that could achieve a permeability of $1x10^{-6}$ cm/sec or less in the saline environment. Use of the TRD method to construct the test cells proved to be effective at producing a homogeneous soil-sepiolite mix wall to a depth of 24 meters. The resulting permeability of the wall as demonstrated by laboratory and field tests is less than $1x10^{-6}$ cm/sec. During testing, seepage past the wall into the test cells was predominantly through the aquitard sediments beneath the test cell walls with the deeper wall more effective at cutting off the underflow.

Introduction

The US Bureau of Reclamation in conjunction with the Water Replenishment District of Southern California has promoted and financed a demonstration project involving the use of deep soil mixing in the construction of a physical cutoff wall to limit landward intrusion of seawater. The project site is located in the Alamitos Gap between Seal Beach and Long Beach, California, USA. Seawater intrusion occurs through the gap within a shallow aquifer that is less than 30 meters deep (100-ft) and communicates with water supply aquifers further inland (Barneich, 1999). The physical cutoff wall concept calls for a soil mix wall constructed into the aquitard that underlies the aquifer and spans the 3.5-kilometer length of the gap. The purpose of the proposed 30-meter deep passive barrier is to optimize the operation of the existing 140-meter deep injection barrier farther inland.

The demonstration project's primary objectives were to prove the feasibility of constructing a deep soil mix wall and to evaluate the wall's effectiveness at limiting intrusion. Key elements of the demonstration project included 1) careful hydrogeologic evaluation of the selected site to characterize aquifer and aquitard intervals, 2) rigorous laboratory testing of site sediments to determine an optimum mixture of soil, slag, cement and clay, 3) application of the TRD method to construct demonstration test cells, and 4) field testing prior to and following test cell construction to demonstrate the effectiveness of the soil mix wall. TRD machines have been used extensively in Japan where this technology was developed. The Alamitos Gap demonstration project was the first application of this technology for seawater intrusion in the United States.

Program Plan

As part of the feasibility study, a pilot test program was implemented as described in this paper. The pilot test program consisted of: (1) of installing eight monitoring wells and two pump wells as shown on Figure 1; (2) performing aquifer tests using pumping wells PW-1 and PW-2 shown on Figure 1; (3) constructing a soil mix wall in the plan configuration shown on Figure 1 with two cells (a deep cell BEFC and a shallow cell ADFE) using the TRD and support equipment shown schematically on Figure 2 ; (4) completing after wall construction pumping tests; and (5) analyzing the results to evaluate the effectiveness of the soil mix wall in retarding sea water intrusion. The results of the work was reported in Hayward Baker, Psomas and Geopentech (2006).

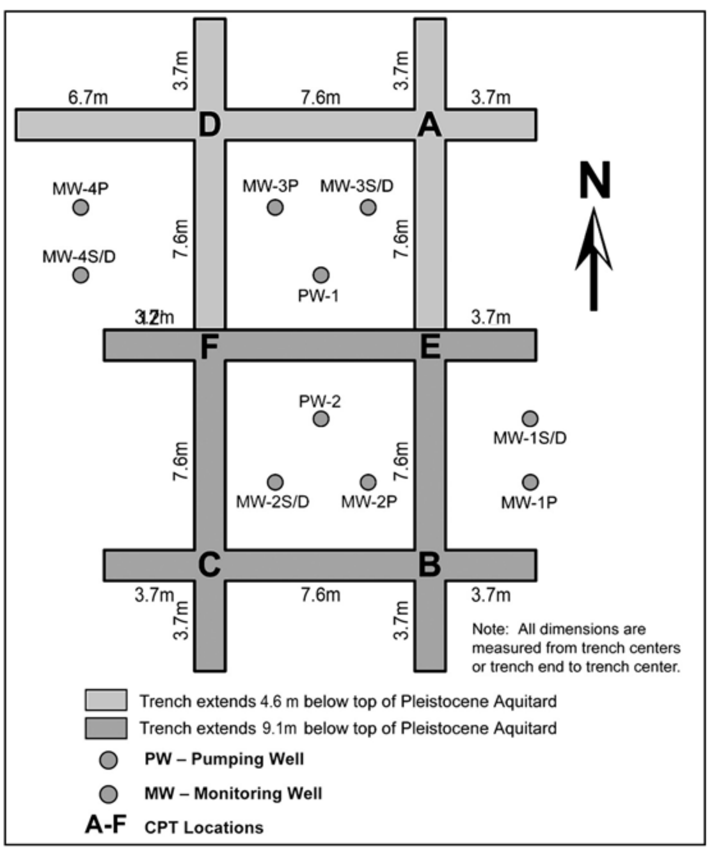

Figure 1. Pilot test layout

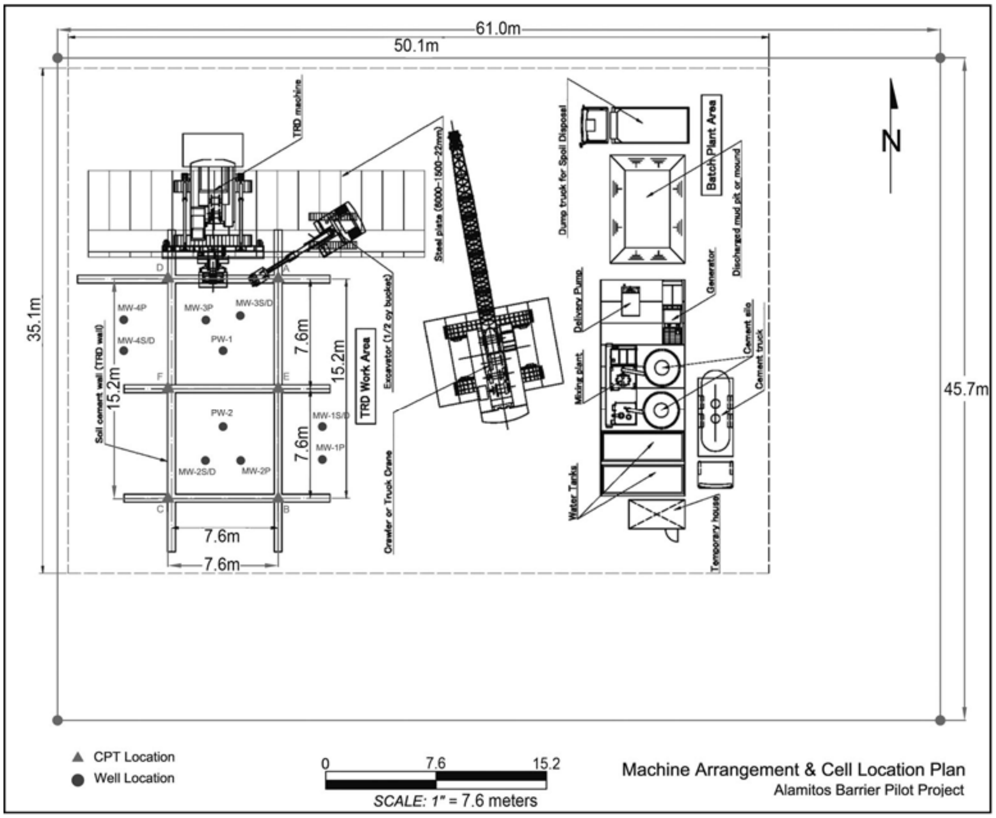

Figure 2. Construction layout of pilot test.

Site Conditions and Installation of Test Features

The characterization of the stratigraphy of the site was evaluated using borings and cone penetration tests (CPT). A typical subsurface profile through the site is shown on the interpretive section shown in Figure 3. As shown on Figure 3, the stratigraphy of the site consists of the merged Recent and I-Zone aquifers, a shallow aquitard and an underlying deep aquitard. The existing Los Alamitos Gap hydraulic barrier injects water into the Recent and I-Zone as well as other aquifers extending to a depth of about 140 meters along an alignment about 1.5 Km to the north of the test site. The proposed passive soil mix barrier is to be located to the south of the existing pressure barrier near the Newport-Inglewood fault zone where the aquifers are shallower, extending to only about 30-meters or less below ground surface as shown on Figure 3 where the aquifers extend to a depth of about 15-meters.

Eight monitoring and two pumping wells were installed to depths of between 6.5 and 26 meters at the locations shown on Figure 1. The wells were screened at intervals shown on Figure 4. The wells are designed to monitor piezometric response during the testing of: (1) the aquifer and aquitard sediments prior to the installation of the test cell; (2) the effectiveness of the soil mix wall as a barrier to water movement through the Recent and I-Zone aquifers; (3) the effect of depth of penetration of the soil mix wall into the underlying aquiclude on the effectiveness of the wall as a barrier to the movement of water through the aquifers, and ground water movement laterally and vertically through the shallow sediments. All wells were constructed between August 23rd and August 26th 2005.

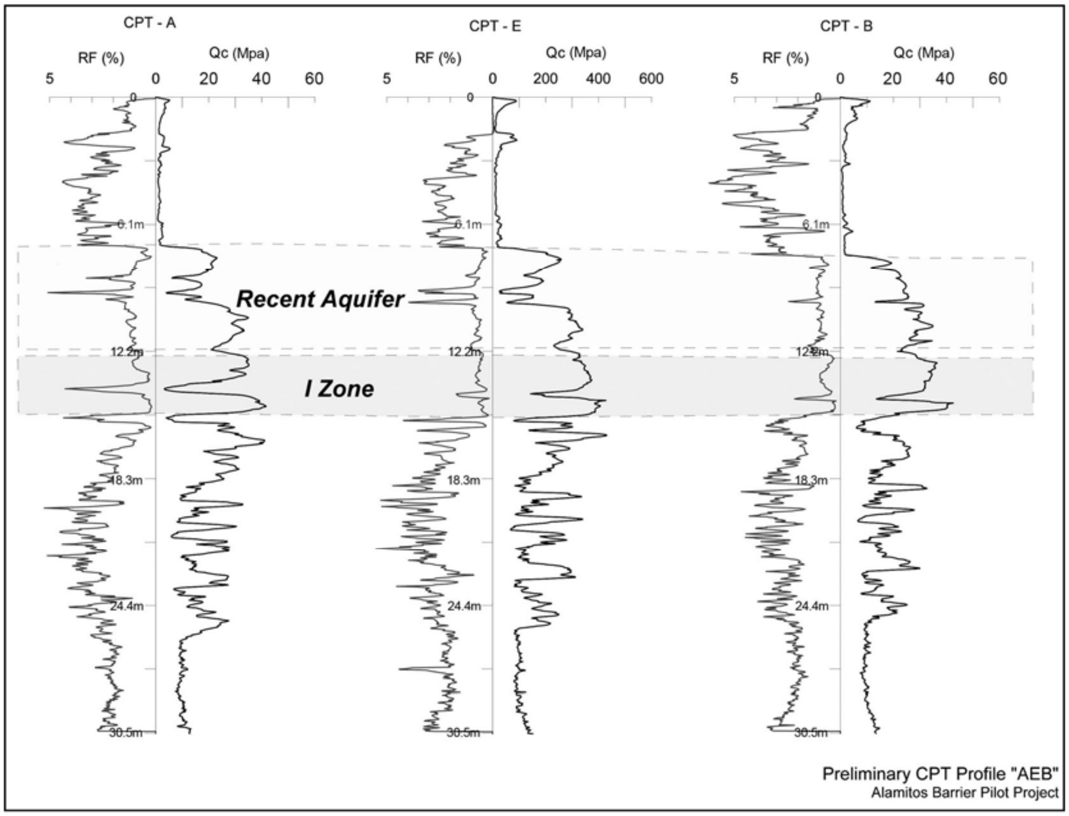

Figure 3. Stratigraphy of pilot test site.

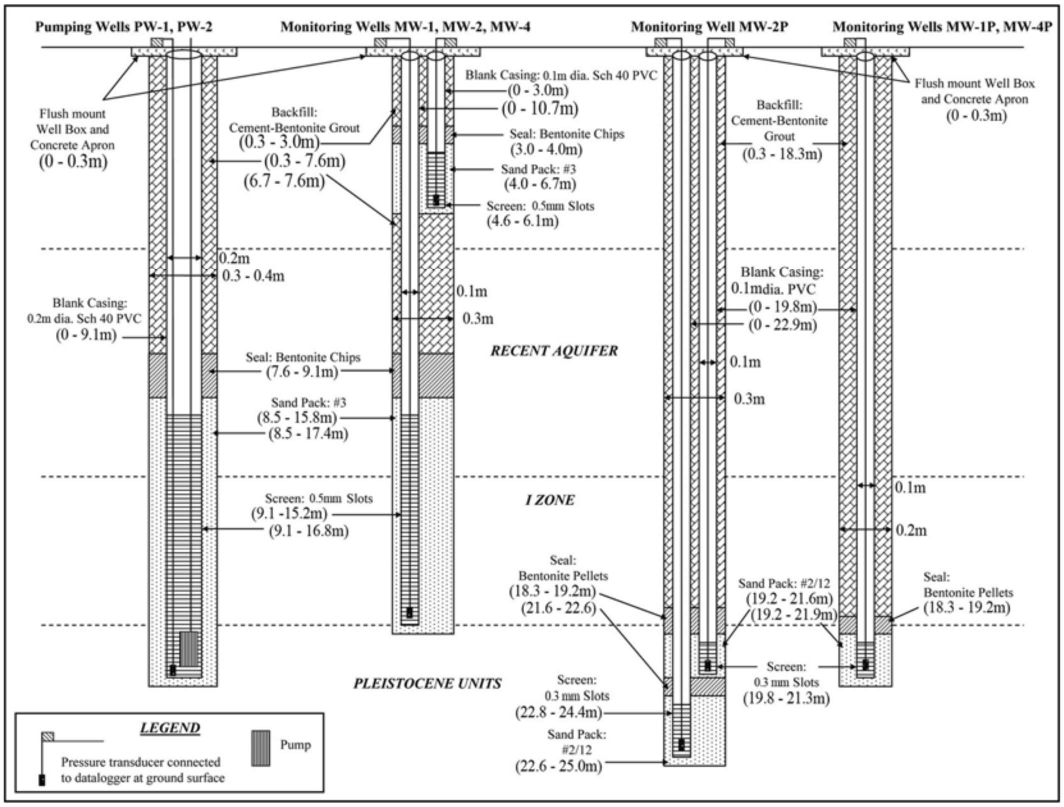

Figure 4. Typical pump and observation well details.

Aquifer Testing

The hydrogeology characterization of the aquifers and aquitards was completed using continuous-discharge pumping tests prior to the construction of the test cells. Two 15.2 cm diameter pumping wells (identified as PW- and PW-2 on Figure 1), were used for aquifer testing by pumping from one of the pumping wells while monitoring from the other PW and all the monitoring wells using automated instrumentation to continuously measure water levels (with periodic physical measurements). The estimates of the hydraulic conductivity, transmissivity and the storage coefficients for the shallow aquitard and aquifers based on measurements made during the aquifer testing are tabulated in Table-1. A typical water level in monitoring wells MW-1D and MW-2D vs. time curve developed from the data during pumping from well PW-2 is shown on Figure 5. As can be observed from Figure 5, the pumping from PW-2 at 128.7 lpm for 18 hours only resulted in a draw down of water in the aquifers of about 1 meter. Also, the recovery of the water level was almost immediate.

Table 1. Aquifer test results

Well ID (Analytical Method)	Estimated Transmissivity (m^2/sec)	Estimated Hydraulic Conductivity (cm/sec)	Estimated Storage Coefficient (Dimensionless)
Average for Combined Recent and I-Zone Aquifers (MW 1D-4D) [1,2]	0.0021	2.74E-02	5.00E-04
	3 Hydraulic Resistance (day)	Estimated Vertical Hydraulic Conductivity (cm/sec)	Estimated Storage Coefficient (Dimensionless)
Average Shallow Aquitard (MW 1S-4S)[3]	6.28E+03	1.25E-06	1.20E-04

1. **Hantush and Jacob, 1955**
2. **Hantush, 1956 and 1960**
3. **Witherspoon and Neuman, 1972**

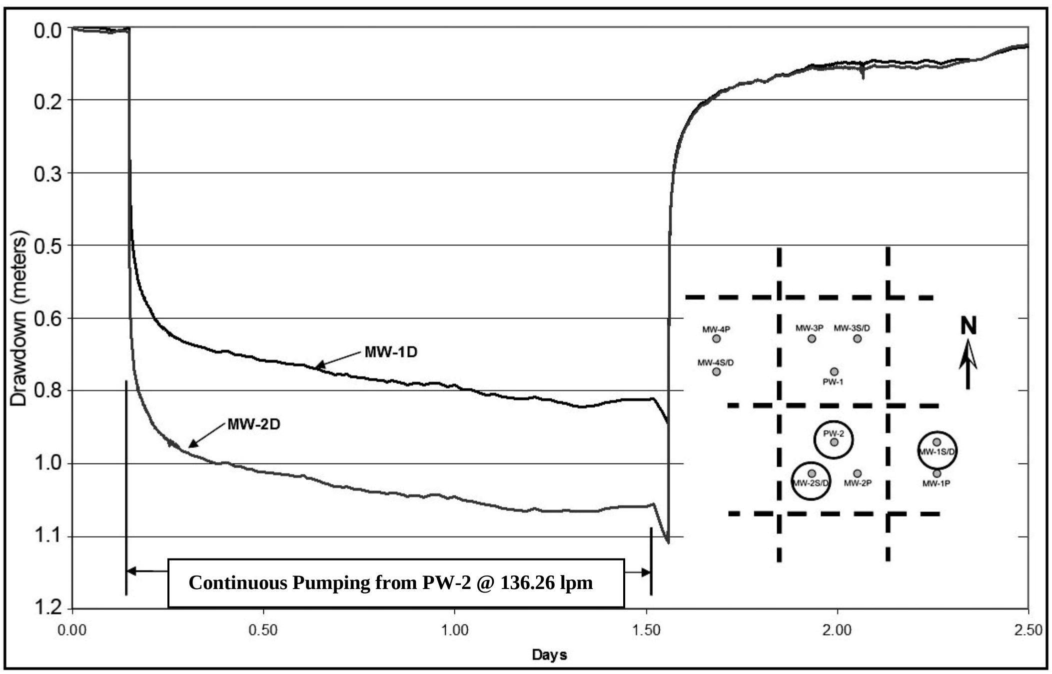

Figure 5. Aquifer test results.

Construction of Soil Mix Wall Using the TRD

In preparation of soil mix construction site soils are sampled and laboratory tests performed to design for permeability and strength. This aids 1) construction-related performance, 2) end-of-construction performance, and 3) long-term performance. Testing from field samples during soil mix construction is shown in Tables 2 and 3 [Jeff Evans (2007)][i]. The results on duplicates are very consistent and illustrate the quality of mixing from the TRD method. Where time of testing relative to mixing is a variable, the data shows permeability decreasing with time and strength increasing with time over the duration of the test as shown on Tables 2 and 3, respectively.

Table 2 - Los Alamitos field sample permeability test results

Mix Date	Wall No.	Lab No.	Age (days)	Hydraulic conductivity (cm/s)	Age (days)	Hydraulic conductivity (cm/s)	Age (days)	Hydraulic conductivity (cm/s)
9/5/05	1	FS-1	28	2.1E-07	60	1.6E-07	77	9.1E-08
9/5/05	1	FS-2	28	1.5E-07	60	1.1E-07	77	8.0E-08
10/11/05	5	FS-3	30	3.1E-06	41	2.4E-06		
10/11/05	5	FS-4	31	3.4E-06	41	2.8E-06		

Table 3 - Los Alamitos field samples with unconfined compressive strength reults

Mix Date	Wall No.	Lab No.	Test Date	Age (days)	UCI (psi)	Strain at Failure (%)	Water content (%)	Unit weight (pcf)
9/5/05	1	FS-1	11/21/05	77	242	1.2	44.0	121.6
9/5/05	1	FS-2	11/21/05	77	215	1.1	44.5	109.3
10/5/05	4	FS-5	12/18/05	72	86	1.8	47.9	104.6
10/5/05	4	FS-7	12/19/05	73	82	2.0		105.0
10/11/05	5	FS-3	11/21/05	41	63	2.0	62.3	102.2
10/11/05	5	FS-4	11/21/05	41	58	1.6	60.1	102.2
10/11/05	5	FS-6	12/18/05	69	72	1.3	55.3	100.5

Field operations consisted of: 1) checking for utilities; 2) surface grading to clear and level area; 3) layout of walls; 4) form guide/spoils trench; 5) setup TRD machine with laser alignment; 6) insert TRD cutter post; and 7) production milling of the soil mix walls. Photos of the milling operation are shown on Figures 6a and 6b. Soil mix operations start with test milling to adjust water, cement, clay, and additives and then move on to production soil milling and mixing. Rigorous quality control and assurance measures from depth-of-wall checks through real time density monitoring of the slurry mix ensured compositional consistency. For overnight shutdown or wait periods, the slurry is modified and/or retarders added to "shelter" the cutter post. Upon completion the cutter post is extracted while backfilling with richer slurry. The TRD technique provides for higher quality wall intersections due to its controlled advanced milling action. Advance rates for the short test walls ranged from 30 and 45 minutes per meter for 19.8 and 24.3 meter depths, respectively. Spoils produced during the milling ranged from 35% to 50% of the re-mixed wall volume. The sequence of milling of the 5 soil mix walls is shown on Figure 7.

Figure 6a. TRD milling wall, and excavator removing spoils

Figure 6b. TRD milling wall.

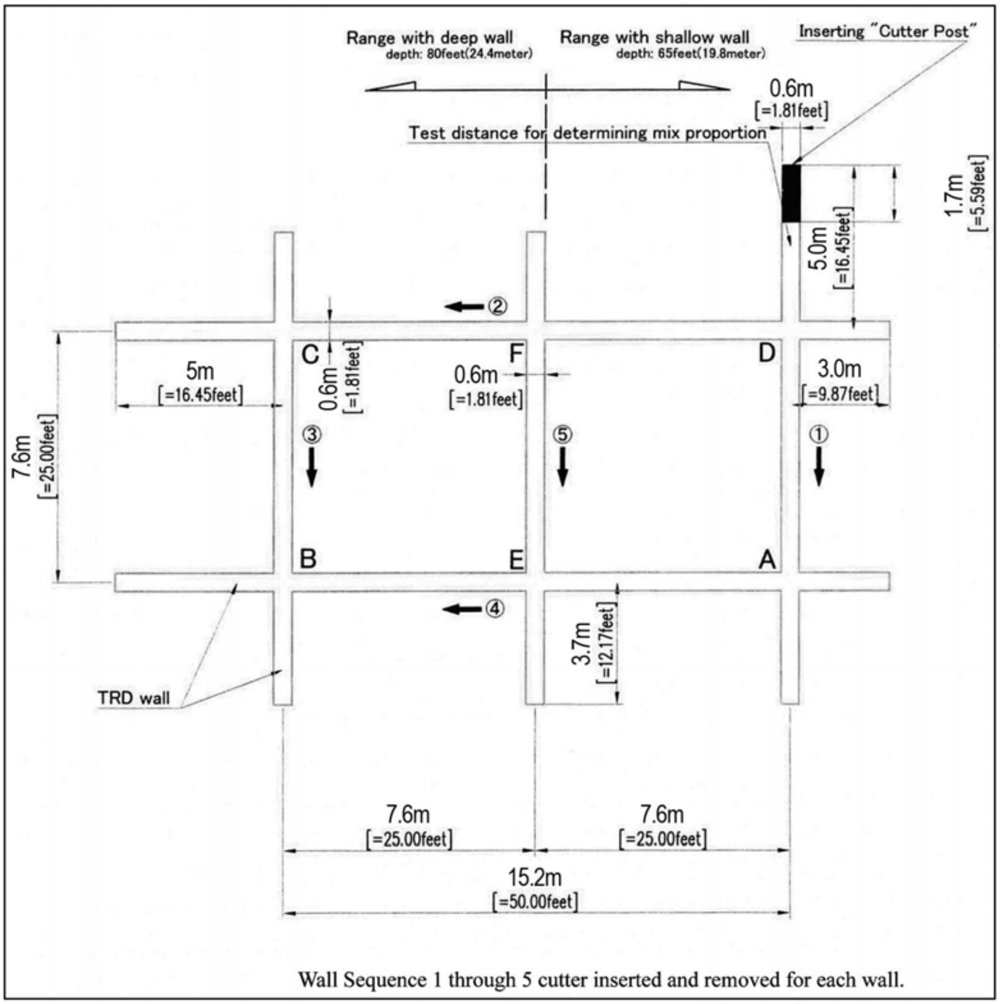

Figure 7. Construction sequence.

Pump Testing to Evaluate the Effectiveness of the Wall as a Water Barrier

After the completion of the cell construction discussed above, pumping tests were completed by pumping from wells PW-1 and PW-2 and monitoring water levels in the remaining wells. A typical water level vs. time curve measured in monitoring wells MW-2 and MW-1 resulting from pumping water from PW-2 at a rate of 17 lpm to 26.4 lpm in 9-to 12-hour increments over a period of 3.5 days is shown on the right side of Figure 8. As can be seen from Figure 8, water in the cell BEFC in MW-2D is drawn down over 30-meters while the water in nearby well MW-1D is unaffected by the pumping from within the cell. Also, the recovery of the water in well MW-2D after turning off the pump in well PW-2 is very slow (about 0.3 lpm). To compare the results of the before cell construction pump tests with the after cell construction pump tests, the results on Figure 5 have been re-plotted on the left side of Figure 8 to the same scale as the right side of Figure 8. As can be seen by comparing the before and after cell construction results, the cell walls are very effective in stopping water from flowing through the aquifer into the cell. The hydrogeologic modeling [Eric Fordham

(2006)] of the tests conducted showed that the average permeability of the wall was 1 to 2 X 10^{-7} cm/sec which is in good agreement with the testing of samples from the wall in Table-2. Other similar testing conducted by pumping from PW-1 in the shallow cell ADFE shown on Figure 1 gave similar results as shown on Figure 8 for cell BEFC, except that the recovery rate was 1.1 lpm (over three times as fast as for cell BEFC), indicating more water flow under the cell walls.

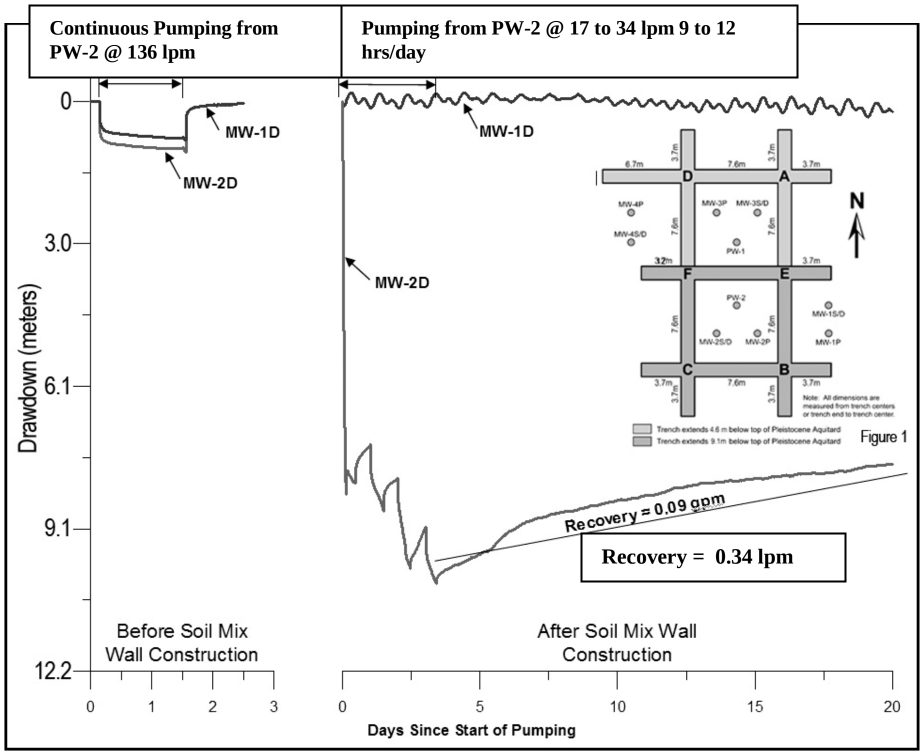

Figure 8. Pumping test before and after wall construction.

Permitting

Securing permits for any project is an essential component of the overall process. The first step in the permitting process was to identify the jurisdictional agencies for each component of the work to be completed. Several potentially sensitive resources were identified in areas adjacent to the pilot test site. Specific concerns involved with the testing and construction activities in this area included potential impacts to aquatic and wildlife resources, degradation of water quality to the San Gabriel River, impacts to sensitive vegetation and wildlife of special status, and impacts to sensitive archaeological resources in the vicinity.

Based on an intensive environmental and archaeological review of the area no significant concerns were identified to preclude implementation of the Alamitos demonstration project. The following table outlines the regulatory requirements addressed for the project:

Table 4. Regulatory Requirements Addressed for Project

Regulatory Component	Agency	Required
Well Permit	Local City	**Yes**
National Pollutant Discharge Elimination System	RWQCB	Yes
Coastal Development Permit	CCC	No
CEQA	WRD	Yes
NEPA	USBR	Yes
Clean Water Act Sections 401/404	RWQCB/ACOE	No

Conclusions

The following conclusions were developed with respect to the effectiveness of the construction of a passive barrier against sea water intrusion using the TRD from the pilot test:

(1) Based on the aquifer testing before cell construction the aquifers were estimated to exhibit a permeability of 2 to $3x10^{-2}$ cm/sec and the aquitards to exhibit permeabilities in the range of 10^{-6} cm/sec.
(2) The TRD provided an extremely effective barrier to water intrusion as evidenced by the difference in drawdown and recovery of water levels for the before and after barrier construction pump tests shown on Figure 8. Specifically, the before pump test resulted in a 1 meter draw down when pumped at 128.7 lpm compared to the 9 to 10 meter drawdown within the walled cell in the same wells when pumping was at a rate of 17 lpm to 26.4 lpm and no drawdown in the well outside the walled cell.
(3) Based on the field recovery rate, on the after cell construction pump test shown on Figure 8, the average permeability of the TRD wall was computed to be 1 to 2x 10^{-7} cm/sec. The laboratory permeability tests on samples of the wall material yielded the same results indicating that the wall was well mixed and uniform with respect to permeability.

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