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ABSTRACT

The trench remixing and deep wall method (TRD) is a one-phase process for excavation and in situ mixing of a vertical barrier. While the TRD method was developed and has been widely employed in Japan for more than a decade, it has only recently been used in the United States. Since the TRD method mixes the entire depth of the vertical profile, this method can be used to construct a more homogeneous wall than other in situ methods. Using a large revolving chain and cutter bar, the TRD equipment simultaneously excavates and mixes in situ soils and added slurry resulting in a continuous soil mixed wall. The blend of slag, Portland cement and clay-water slurry is added as the excavation moves along the alignment of the barrier and produces continuous vertical mixing of in situ soils with the added blend.

This paper presents a case study of the first TRD project in the United States involved the construction of closed cells to allow full evaluation of the method. This installation was part of a larger evaluation of the use of a vertical passive barrier to prevent the intrusion of salt water into fresh ground water aquifers in Southern California. The paper describes the site characterization, an extensive laboratory study conducted to investigate the appropriate mix design, field construction and post-construction testing. The case study shows the methodology used to develop design mixtures and presents information showing the successful completion of a barrier wall by the TRD method.

INTRODUCTION

This paper describes the first use in the United States of the **T**rench **R**emixing and **D**eep Wall Method (TRD). The TRD method describes a means by which a vertical barrier is constructed in the subsurface by mixing of slurry with in situ soils. The technique employs a continuously revolving chain that both excavates and mixes in situ soils with added slurry (Aoi et al. 1996, Aoi et al. 1998). Depending upon the purpose of the wall, the slurry mixture will vary but generally consists of a clay (such as bentonite) and cement. For this project the clay was Sepiolite, or sea mud a clay closely related in chemical composition and structure to Attapulgite. The cement for this project consisted of a mixture of granulated ground blast furnace slag and Portland cement. The advantage of this method over other methods of *in situ* mixing is the blending of soils from throughout the vertical profile into a homogeneous blend of materials.

The design and construction of the TRD wall described in this paper was undertaken as a component of studies to develop an alternative means to the current method of controlling saline water infiltration into the Los Angeles ground water basin. Currently, injection wells are used to create a ground water mound in an area known as Alamitos Gap. The Alamitos Barrier Deep Soil Mixing Project was devised to evaluate the effectiveness of a physical barrier to prevent the intrusion of saline water in the vicinity of the geologic gap (Water Replenishment District 2006). The design included site and subsurface investigations, laboratory mix design and testing, ground water flow modeling and construction of barrier walls in a box configuration for pump testing. Previous papers on this project include a detailed presentation of the mix design and test results (Evans, 2007) and the project overview focusing on construction methods (Gularte et al. 2007). Professor James Mitchell was a member of the review panel for this project.

TRD METHOD

A number of construction methods have been utilized to form a vertical barrier of low permeability in the subsurface including slurry trench, deep soil mixing and jet grouting methods. In the US, the most common is the slurry trench method for the construction of soil-bentonite cutoff walls while in the UK slurry trench methods to construct barriers of slag-cement-bentonite (Jefferis 1981) are the most common although this technique is finding increased usage in the US. (Opdyke and Evans 2005). In situ mixing using the deep mix method and jet grouting have also been used. The Trench Remixing and Deep Wall Method was developed and has been used in Japan for over 20 years. During this time over 1,500,000 m^2 (16,000,000 ft^2) of wall to a maximum depth of 53 m (177 ft) has been constructed. The TRD method is a one-phase process that consists of excavation of a deep trench while simultaneously mixing in situ soils and added slurry. For the case history described in this paper, the wall was constructed using the equipment shown in Figure 1. While the slurry design can vary depending upon the strength and permeability needs of the wall, for this project the slurry was composed of sepiolite clay, granulated ground blast furnace slag and Portland cement.

Fig, 1. Equipment for trench cutting and remixing with the TRD method at Alamitos Gap

DESIGN INVESTIGATIONS

Design investigations were undertaken to evaluate the site and subsurface conditions and to model the impact of wall depth and permeability upon the ground water flow. The overall project objective was to design, construct and evaluate a test section of barrier wall to aid in the selection of the appropriate barrier to passively control salt water intrusion in the Alamitos Gap of the Los Angeles ground water basin.

Boring and testing revealed an alluvial profile. The soils consisted of interbeds of sands, silts and clays of various percentages resulting in a formation of relatively high horizontal hydraulic conductivity.

Laboratory studies were conducted to evaluate 1) properties of the materials to be excavated during barrier wall construction using the TRD method including water content, grain size distribution, and Atterberg Limits; 2) properties of the barrier mixtures prior to curing and their intermediate components including slurry viscosity and density, flow table results, and bleed; and 3) properties of the cured mixtures including unit weight, unconfined compressive strength, hydraulic conductivity, strain at failure and compatibility. In order to execute the mix design studies, samples of site ground water, local potable water to be used in mixing and representative samples of subsurface materials. Mix designs consider bentonite, attapulgite and sepiolite clays in combination with Portland cement and granulated ground blast furnace slag (Evans, 2007).

Design mixes were prepared by first preparing a clay-water slurry. Sepiolite was selected for this project because 1) it was found a sepiolite slurry of suitable viscosity and density could be made, 2) there were concerns between bentonite interacting with the saline ground water environment and 3) sepiolite was available nearer the site resulting in cost savings.

Samples of materials representative of those to be encountered during test barrier wall construction were obtained for characterization and use in preparation of barrier wall mixtures. This work resulting in average properties for a design stratigraphy and model barrier soils were prepared by compositing samples to represent the expected field mixing. To prepare possible design mixtures, the model soil was mixed with 4 different blends of slurry/cement/slag in the proportions shown on Table 1. One additional mix was made with soil as received directly from the field (Mix 4a on Table1). The proportions were based upon the experience with cement-slag mixtures in both the US (Burke, 2005) and in Japan (Ito, 2004). Soils were mixed with slurry blends at a ratio of 1.0 soil to 0.5 slurry by volume.

Table 1. Blend mix proportions

Blend #	Mix			
	Clay (%)	Water (%)	Cement (%)	Slag (%)
1	4	86	2	8
2	6	81	3	10
3	6	77	8.5	8.5
4	4.1	71.5	12.2	12.2
4a	4.1	71.5	12.2	12.2

For the TRD method, the workability of the mixture is measured by the flow table and, as with other grouts, bleed is important. Tests were done using both the Japanese Institute of Standards (JIS) and American Society of Testing and Materials (ASTM) flow tables and, while the flow table results were virtually identical, the means of reporting results is different. The desirable flow for constructability purposes is "between 150mm and 230mm" for the mixtures (Ito, 2005). As shown on Table 2, Blend # 4 falls slightly below this range and blend 4a is well-above the range. Because the mixture proportions were all specified, this was not a controllable variable but rather one measured. Virtually no bleed water was observed in either bleed test except for mixture 4a (which was extremely wet and had a relatively low fines content). After testing the properties of the as-mixed combinations of soil and slurry blends, cylindrical samples of all blends were formed. After initial set and a total of approximately 24 hours, samples were submerged in site ground water for further curing.

Table 2. Bleed and flow results

Mixture/Blend #	ASTM Flow Table (%)	JIS Flow Table (mm)	ASTM 3 hr bleed (mL)	JIS Bleed	
				3 hr ratio	20 hr ratio
1	68.1	167	0	0	0
2	79.2	182	0	0	0
3	109.7	188	0	0	0
4	78.5	146	0	0	0
4a	Overflow	Overflow	26	4.5	4.6

Permeability tests were conducted in triplicate after samples had cured at least one week in site ground water. The site ground water was used as cell water in the triaxial cells and as the permeant. Replicate samples continued submerged in site ground water until tested in unconfined compression after curing approximately 28 days. Results of permeability and strength tests are shown on Table 3 and Figure 2. Note that both the cell water and the permeation water are the saline ground water obtained from the site. As is typical of self-hardening slurries, the materials continue to cure and hydraulic conductivity continues to decline with time. Shown on Figure 2 are the results of the five mixes. All replicates of each of the mixes are shown.

Table 3. Average Density, Hydraulic Conductivity, Strength and Strain at Failure (28 day samples)

Blend	Sample Preparation Date	Bulk Density (g/cm^3)	Water Content (%)	Hydraulic Conductivity k (cm/s)	Unconfined Compressive Strength q_u (kPa[psi])	Strain at Failure ε_f (%)
1	12/9/04	1.65	55.8	$3x10^{-7}$	124 [18]	2.6
2	12/10/04	1.71	48.3	$2x10^{-7}$	386 [56]	2.3
3	12/10/04	1.63	55.6	$5x10^{-7}$	317 [46]	2.4
4	12/13/04	1.70	45.8	$7x10^{-9}$	903 [131]	2.8
4a	12/13/04	1.82	38.4	$9x10^{-6}$	248 [36]	2.7

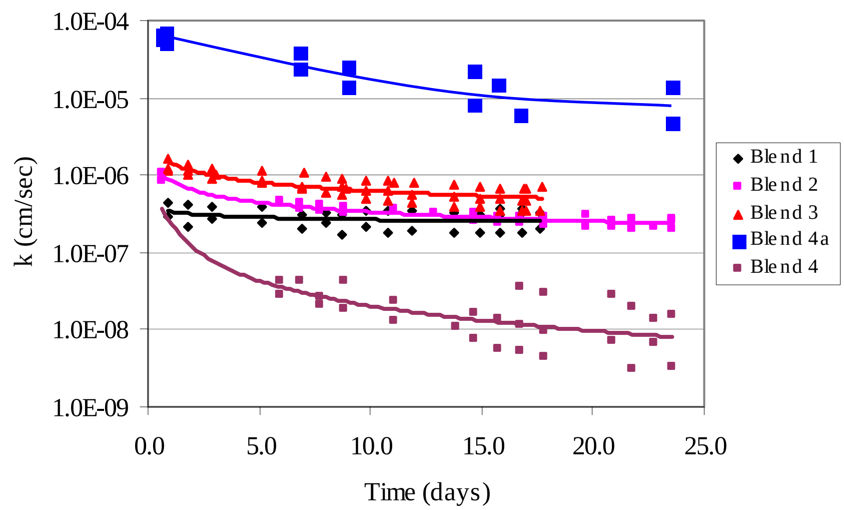

Fig. 2. Permeability test results

In order to consider the longer-term impacts of permeation with saline ground water, permeation of all samples shown on Figure 2 and Table 3 continued for 60 days. Hydraulic conductivity continued to remain steady or decline for all samples. Since mix 4 exhibited the lowest hydraulic conductivity, it was tested for a longer period (six months). The results of this testing of replicates (a, b, and c) are shown on Figure 3 and had a pore volume displacement of 0.84, 1.5 and 1.9 respectively. From these results it was concluded that a barrier constructed of a mixture of slag, cement, sepiolite slurry and soil from the site could be blended and a low permeability material would result and remain compatible with the site ground water.

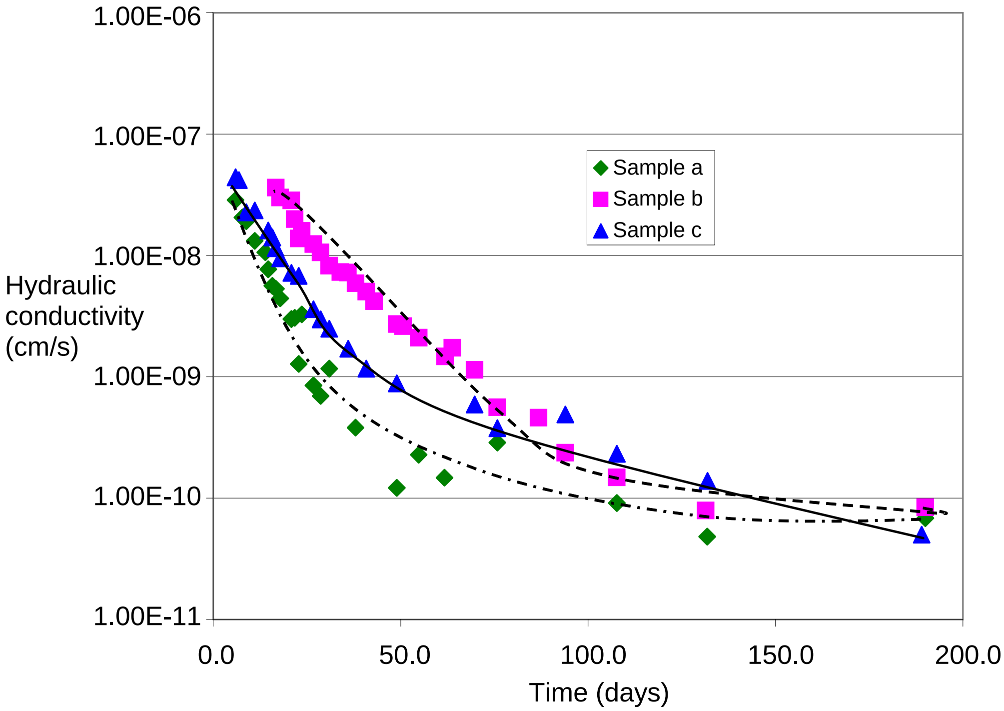

Fig. 3. Long-term Permeability (Compatibility) Test results

CONSTRUCTION

The next phase of the project involved the construction and field testing of test cells using the TRD method based upon the geotechnical investigations and laboratory test results described above. The configuration of the test cells along with a key to field testing are shown on Figure 4. As indicated on Figure 4, the cells were constructed to two different depths to evaluate the effectiveness of the barrier as a function of depth.

After checking the site for subsurface utilities, grading the surface, laying out the wall locations and mobilization of the TRD machine and mixing plant, construction began by installing a guide trench which also was used to contain excavation spoils. The first step after machine setup is the insertion of the cutter post test milling to adjust water-cement-soil mix proportions. Trenching (milling) then proceeded along the alignment while simultaneously conducting quality control sampling and testing. At the end of any given wall section, the cutter bar was withdrawn, the TRD machine repositioned and the process repeated. Rates of advance were approximately 30 to 45 minutes per meter. Spoils produced were approximately 35% of the remixed wall volume.

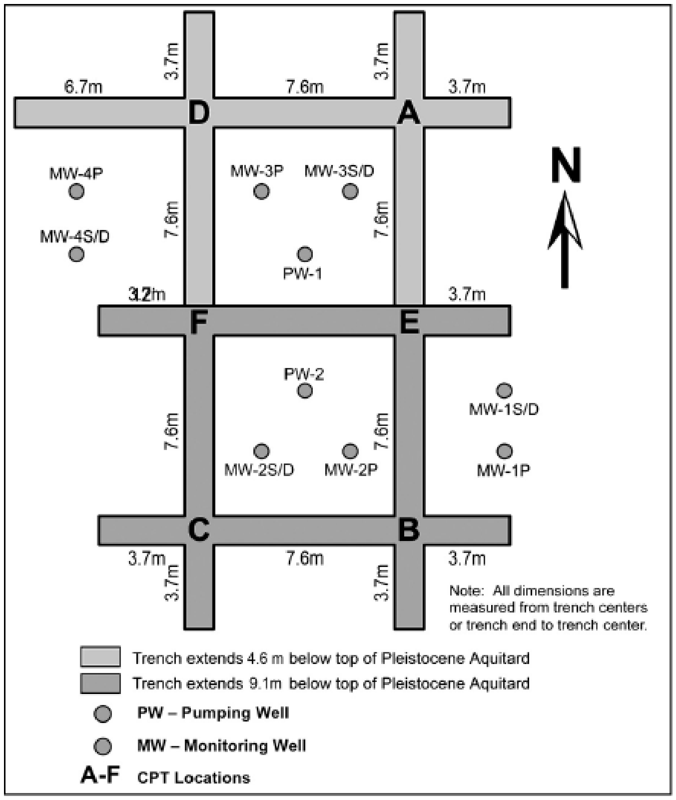

Fig. 4 Layout of test cells and testing (from Gularte, et al., 2007)

Quality control measures for the field phase of this work included measurement of cutter post dimensions, machine alignment using laser, and continuous cutter post verticality with built-in inclinometers. Testing on field mixed samples included flow table, bleed, density, and formation of samples for subsequent curing and laboratory testing.

The method was evaluated both through testing of individual samples and by pump testing the cells. From the analysis of pumping test data, the hydraulic conductivity of the TRD constructed barrier was estimated at 1.3×10^{-7} cm/s. At the time of testing the barrier wall had been installed about one-month or less so the hydraulic conductivity is expected to decrease with time. In addition, samples formed in the field were tested in the laboratory the results are shown on Tables 4 and 5. The strength results are reasonably well correlated to data from the design studies. They hydraulic conductivity in Field Samples 1 and 2 correlate well to both results from laboratory design studies and from result of the field pumping tests while Field Samples 3 and 4 were more permeable.

Table 6. Strength test results for field mixed samples

Lab Identification number	Sample age (days)	Unconfined compressive strength (kPa [psi])	Strain at Failure (%)	Water content (%)	Total Density (g/cm^3)
FS-1	77	1669 [242]	1.2	44.0	1.95
FS-2	77	1482 [215]	1.1	44.5	1.75
FS-5	72	592 [86]	1.8	47.9	1.68
FS-7	73	565 [82]	2.0		1.68
FS-3	41	434 [63]	2.0	62.3	1.63
FS-4	41	400 [58]	1.6	60.1	1.63
FS-6	69	496 [72]	1.3	55.3	1.61

Table 7. Hydraulic Conductivity test results on field mixed samples

Lab Identification number	Sample age (days)	Hydraulic conductivity (cm/s)	Sample age (days)	Hydraulic conductivity (cm/s)	Sample age (days)	Hydraulic conductivity (cm/s)
FS-1	28	2.1E-07	60	1.6E-07	77	9.1E-08
FS-2	28	1.5E-07	60	1.1E-07	77	8.0E-08
FS-3	30	3.1E-06	41	2.4E-06	Not tested	Not tested
FS-4	31	3.4E-06	41	2.8E-06	Not tested	Not tested

SUMMARY AND CONCLUSIONS

The TRD method has been used to construct a vertical barrier for the first time in the US. Mix design studies were described and the result presented to show both the methodology of mix design and the results for this case study. For the saline ground water conditions and the site soils on this project hydraulic conductivity values of less than 1x10-7 cm/s and strengths greater than 345 kPa (50 psi) were achieved. Long term laboratory tests showed the hydraulic conductivity of the mixtures continue to decline with time and that the mixtures were compatible with the saline ground water. Based upon concerns with the saline ground water and the results of slurry testing, the barrier mix design used sepiolite clay instead of bentonite or attapulgite to form the clay-water slurry. To the clay water slurry, 25% of a slag-Portland cement material was added. The cementitious material consisted of 50% Portland cement and 50% granulated ground blast furnace slag. These mix proportions were based upon the experience of the Japanese using the TRD method. The TRD method was then used to construct vertical barrier walls in the form of two test cells for evaluation. Pump testing and laboratory testing of field mixed samples confirmed the laboratory results could be achieved on samples mixed in the field.

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