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Liquefaction Mitigation in Silty Sands at Salmon Lake Dam Using Stone Columns and Wick Drains

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ABSTRACT

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Stone columns are an established method of liquefaction mitigation in clean sands (fines content <15%). Although stone columns are considered less effective in silty soils, an increase in the area replacement ratio or the addition of wick drains may still produce improvement in the normalized blow count. Limited case histories are available with a direct comparison of the use of stone columns with and without wick drains at one location. The Salmon Lake Dam Modification project provided such a scenario. Two test sections were completed at the site prior to construction to determine the area replacement ratio for the final design as well as to compare the application of stone columns with and without wick drains.

Visual observations of water and air escaping from wick drains within a distance of 15 ft of the stone column construction confirmed that drains aided in pore pressure dissipation. Test results indicated that stone column treatment with wick drains produced greater improvement in blow count than stone column treatment without drains. For the overall site, there was an increase in improvement ranging from 3 to 8 SPT blow counts. When compared to the results of a similar evaluation of a site in Ogden, Utah, which had a comparable fines content and an area replacement ratio of 26%, the increase in stone column effectiveness produced by adding wick drains was lower at the Salmon Lake Dam site. The increase in improvement at the Ogden, Utah site ranged from 12 to 18 SPT blow counts. At the Ogden site, wick drains were placed between every stone column while they were only placed between vertical rows of columns at Salmon Lake dam.

Despite the beneficial effects provided by using wick drains with stone column treatment in silty soils, the performance was below what would be expected for stone column treatment without wick drains in clean sands with less than 15% fines. Stone column treatment also proved less effective in layers of sandy silt than in layers of silty sand, which was indicated by lower average improvement and more points of negative improvement in layers of sandy silt.

Although several different area replacement ratios were analyzed (23, 27, 31, and 35%), no consistent trend towards greater improvement in blow count was seen as the replacement ratio increased beyond 23%.

Keywords: stone columns, wick drains, liquefaction mitigation, silty sands, high fines content, Salmon Lake Dam

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1 INTRODUCTION

1.1 Background

On February 9, 1971 a 6.5 magnitude earthquake struck the San Fernando area of California. The result was property damage estimated at $505 million, approximately 2000 injuries, and 65 fatalities (USGS, 2010). Earthquake induced liquefaction occurred at the Van Norman Dam (also known as the Lower San Fernando Dam), causing a failure of the upstream slope of the dam, effectively lowering the dam height by 30 feet. The liquefaction of the loose soil structure of the hydraulically filled dam led to the evacuation of the heavily populated areas downstream for fear the dam might fail (USGS, 2010). Figure 1.1 shows the dam following the earthquake.

The Salmon Lake Dam located in north-central Washington was also a location for concern from damage due to liquefaction caused by a seismic event. Moreover, structures, people and a local national park could be in danger in the case of dam failure. The site's susceptibility to liquefaction resulted in a dam safety modification carried out by the United States Bureau of Reclamation, which included the construction of stone columns and wick drains to improve the foundation of the dam.

Liquefaction occurs in loose, saturated soils when a seismic event causes the soil structure to collapse thereby increasing the pore water pressure. This increase in pore water pressure decreases the strength of the soil, causing it to act as a viscous liquid. Liquefaction can be manifest as boils, settlement, and lateral spreading, all of which can harm dams, structures and foundations.

Figure 1.1 Destruction caused by liquefaction at the Van Norman Dam following the San Fernando Earthquake (source, www.ce.washington.edu).

Destruction caused by liquefaction poses a significant risk to critical structures such as dams, public utilities, transportation infrastructure and emergency response facilities. Due to the critical nature of these structures, it is imperative that their foundations be capable of withstanding likely seismic events. As building sites with ideal soil conditions become increasingly rare, the need to develop and employ effective methods of risk mitigation for potential soil failure is becoming progressively more important. The remediation processes for these areas require additional planning, and can significantly impact the cost and schedule of a contemplated construction project. Considerable research needs to be performed in an effort to improve the mitigation techniques and methods which address soil related problems such as liquefaction.

Various methods have been developed to improve the soil structure and prevent liquefaction. Vibro-compaction, which provides compaction using a vibrating probe, is used to increase the density of the soil. Additional improvement can be achieved using stone columns composed of granular fill to replace the liquefiable soil and stiffen the foundation. Vibro-replacement stone columns are also created using a vibratory probe which compacts the surrounding soil and the granular backfill that is fed into the ground to create a column.

Stone column treatment has become a very common method for mitigating liquefaction hazards. Although this approach has proven effective in creating denser clean sands, the effectiveness typically decreases substantially as the fines content increases above 20% (Mitchell, 1981). Higher fines content tends to decrease the soil permeability and strengthen the soil structure, both of which reduce compaction efficiency. To improve the efficiency of stone column treatment in sands with high fines content, pre-fabricated vertical drains (wick drains) have been employed along with stone columns at relatively high replacement ratios (≈ 25%) (Rollins et al. 2006, Leuhring et al, 2001). Prefabricated wick drains can assist in consolidation of soils and decrease the pore water pressure by aiding the flow of water to the ground surface. Wick drains are comprised of a geotextile filter, which keeps soil particles from entering the molded channels on the strip of plastic that provides a path to evacuate water out of the ground.

While reasonable foundation improvement has been achieved, there is some question whether this is a result of improved drainage provided by the drains or simply the high replacement ratio. Unfortunately, at many sites where wick drains have been employed, comparison tests have not been performed without drains to determine how much of the improvement was associated with the drains. As a result, some uncertainty about the efficacy of the method remains.

1.2 Objectives

The main objective of this report is to investigate the stone column liquefaction mitigation efforts employed at the Salmon Lake Reclamation project where treatment was performed with and without wick drains. Analysis of the existing data will be used to measure the effectiveness of stone columns with wick drains in silty soils. In an effort to reach this goal, the following research objectives were pursued and addressed during the preparation of this report:

1. Determine if wick drains improve the effectiveness of stone columns in silty soils.
2. Determine if increasing the area replacement ratio (A_r) makes it possible to treat silty soils with stone columns and if higher A_r values contribute to greater improvement in $(N_1)_{60\text{-}cs}$ values.
3. Identify associations between stone column effectiveness and soil type.

1.3 Scope

Rollins and Quimby (2009) described stone column case histories from five sites with silty sand where wick drains were used to improve treatment efficiency. Unfortunately, only one of these case histories (Interstate 15 and 24th Street Bridge in Ogden, UT) provided a direct comparison of two adjacent stone column test areas, one having wick drains and one without.

Subsequently, additional reports obtained from the US Bureau of Reclamation on the Salmon Lake Dam project revealed that stone column test sections were also constructed at this site with and without drains. In developing the treatment plan for the dam, two stone column tests sections were used to evaluate improvement without drains and for several stone column replacement ratios with drains. For the purposes of this thesis, the data from these test sections was used to compare the soil improvement obtained using stone columns without wick drains and the improvement using stone columns with the application of wick drains in both the test sections and throughout the entire site. Whereas the soil conditions are less likely to vary between the two test sections at the same site than stone column research with and without drains at different sites, the analysis for Salmon Lake should provide particularly valuable case history data.

In this study, data from the Salmon Lake tests sections were first analyzed through plots of the average pre-mitigation (initial) and post-mitigation (final) SPT corrected blow counts for clean sand or $(N_1)_{60\text{-}cs}$ values versus depth. Plots of improvement of $(N_1)_{60\text{-}cs}$ (change) were plotted against depth, fines content, and initial $(N_1)_{60\text{-}cs}$ values. Final $(N_1)_{60\text{-}cs}$ values were plotted against initial $(N_1)_{60\text{-}cs}$ and compared to similar plots for stone column treatment developed by Baez Satizabal (1995) for clean sands without drains. Finally, averages of the analyzed data were presented in a table to compare the effectiveness of stone columns with and without drains.

Along with an analysis of the test sections, a similar analysis of data from the overall site is presented. The data from the overall site, at locations with pre-mitigation bore holes relatively close to post-mitigation bores holes was first analyzed comparing different area replacement ratio (A_r) values. The process was similar to that used for the test sections. The results for the Salmon Lake, Washington site were then compared with those obtained by Rollins and Quimby (2009) for the Ogden, Utah site.

The final analysis included all pre- and post-mitigation data from the overall Salmon Lake Dam site which was evaluated by segregating the data by soil type in plots of average pre- and post-mitigation blow counts. The properties of all the data were averaged and provided in tabular form to be compared by soils type and area replacement ratios.

2 LITERARY REVIEW

2.1 Development of Stone Columns

The first use of the vibro-compaction technique to strengthen the foundation of a building in non-cohesive soils is credited to the Johann Keller Company, of Berlin, Germany in the 1930s (Sndermann and Wehr, 2004). Vibro-compaction consists of inserting a vibrating probe into the ground to induce a settling effect, thereby compacting the soil. This technique developed into vibro-replacement, in which the hole created by the vibrator is filled with a compacted granular material to support and strengthen the surrounding soil.

The roots of vibro-replacement can also be traced to two earlier forms of deep soil strengthening: vibro-flotation and depth vibration. These methods involved horizontal vibratory action, but did not employ the use of a granular replacement material. In the 1970s, Seed began researching the effectiveness and economical application of stone columns in soils prone to liquefaction (Seed and Booker 1977). A short time later, Barksdale and Bachus (1983) detailed the design and construction of stone columns for the Federal Highway Administration. Since then, further research regarding the application and efficiency of stone columns has been conducted by other leading researchers, construction companies, and multiple state and federal agencies.

2.2 Stone Column Method

The stone column method begins with the insertion of a vibrating probe into the soil. One of two methods is used to ease this process; the wet method and the dry method. The wet method uses hydraulic jets and the dry method employs the injection of compressed air. Vibration is used throughout the entire process to ensure consistent compaction of the column and the surrounding soil. Gravel is then either fed into a bin that supplies a chute which directs the material into the column at the tip of the vibrator (known as the bottom feed method) or is fed into the column at ground level (known as the top feed method). The installation process is divided into a series of separate compaction intervals, or lifts. Following each lift of gravel (approximately 1 meter each), the vibrator probe is raised and lowered to compact the layer and force the column diameter outward. Figure 2.1 provides a schematic of the bottom feed vibro-replacement method, which was the method used at the Salmon Lake site.

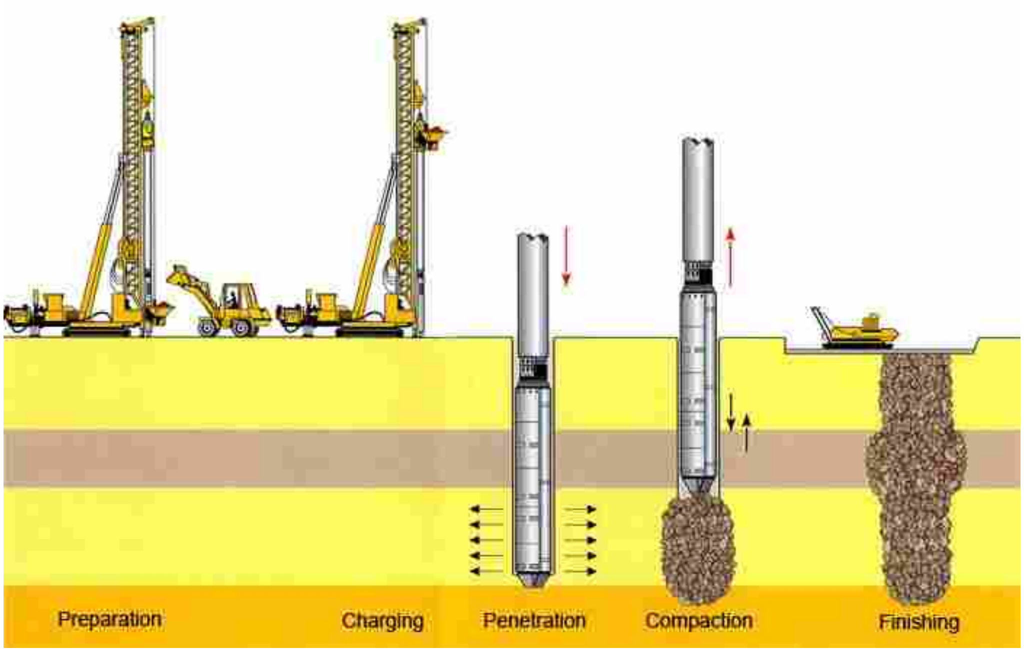


Figure 2.1 Bottom feed vibro-stone column replacement method (source, p3planningengineer.com).

2.3 Stone Column Effectiveness

According to Priebe et al (1995), stone columns have three liquefaction mitigation elements. First, the column provides an escape passage for displaced water, thereby improving drainage and reducing any excess pore pressures. Second, the mechanical compaction and forced expansion of the stone column diameter densify the surrounding in-situ soil, which increases soil strength and decreases the effects of liquefaction during a seismic event. Third, the stone columns themselves are capable of withstanding greater amounts of stress, which further strengthens the overall soil mass.

To evaluate the effectiveness of liquefaction mitigation using stone columns, pre- and post-construction assessment tests are performed at the site. The most common tests are the Cone Penetration Test (CPT) and the Standard Penetration Test (SPT), the latter being the method evaluated in this report. The site is tested before any construction to provide a subsurface condition baseline and provide data for liquefaction triggering analyses (Youd et al. 1997). This analysis uses the geographical location of the site, the maximum magnitude earthquake expected in the area, and the soil properties data collected from the site to determine a minimum post-construction limit of N values for the soil to withstand liquefaction during a potential earthquake.

The post-mitigation test results can be compared to the pre-mitigation testing to evaluate the amount of change or percentage of improvement. Previous researches have used such collections of data to predict the effectiveness of stone columns and aid in the preparation of stone column design.

In a dissertation by Baez Satizabal (1995), a collection of more than 400 data samples of SPT and 1300 data points of CPT tests were used to create a regression analysis, which provided equations to estimate the post-improvement SPT and CPT values for given pre-improvement values. The example of an SPT relationship using fines contents of 15% and A_r values between 5% and 20% is shown in Figure 2.2**.**

Factors which influence the effectiveness of the soil densification created by column installation include the fines content, soil type, soil plasticity, pre-densification relative density, vibratory type, stone shape and durability, stone column area, and spacing between stone columns. Shentham et al. (2004) concluded the critical factors affecting the efficiency of stone columns are area replacement ratio (A_r), hydraulic conductivity and silt content.

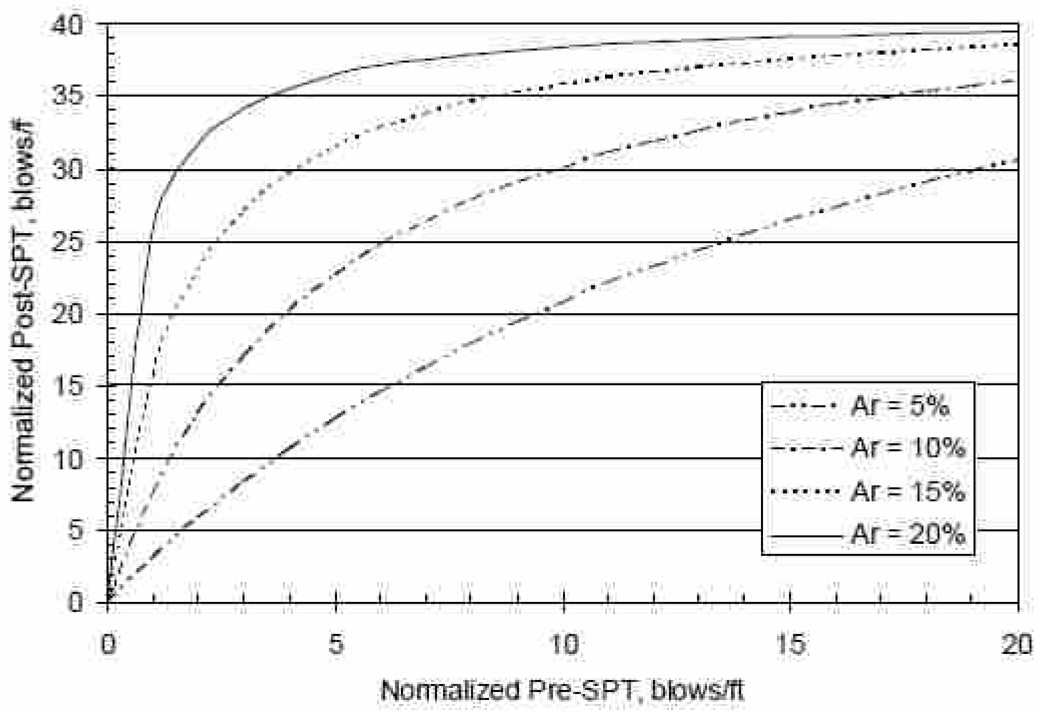


Figure 2.2 Prediction of normalized post-SPT blow count based on normalized pre-SPT blow count and area of replacement for fines content less than 15% by Baez Satizabal (1995).

A major factor considered in this thesis is the fines content. General practice and industry experience with stone columns indicates that the best results occur in soils with a fines content of less than 15% and a clay content of less than 2% (FHWA 2001). Mitchell (1981) indicates that vibratory compaction techniques are relatively ineffective when fines content exceeds 10 to 20%, as seen in Figure 2.3 (included is the range of fines for the Salmon Lake Dam site). This implies that stone columns can only be applied effectively in relatively clean soils. Shenthan's (2005) conclusions regarding the ineffectiveness of stone columns in silty soils states that the low coefficient of consolidation of silty soils slows pore pressure dissipation and prevents the densification of the soil around the stone column during installation, thereby decreasing the effectiveness of stone columns as drainage routes during a seismic event.

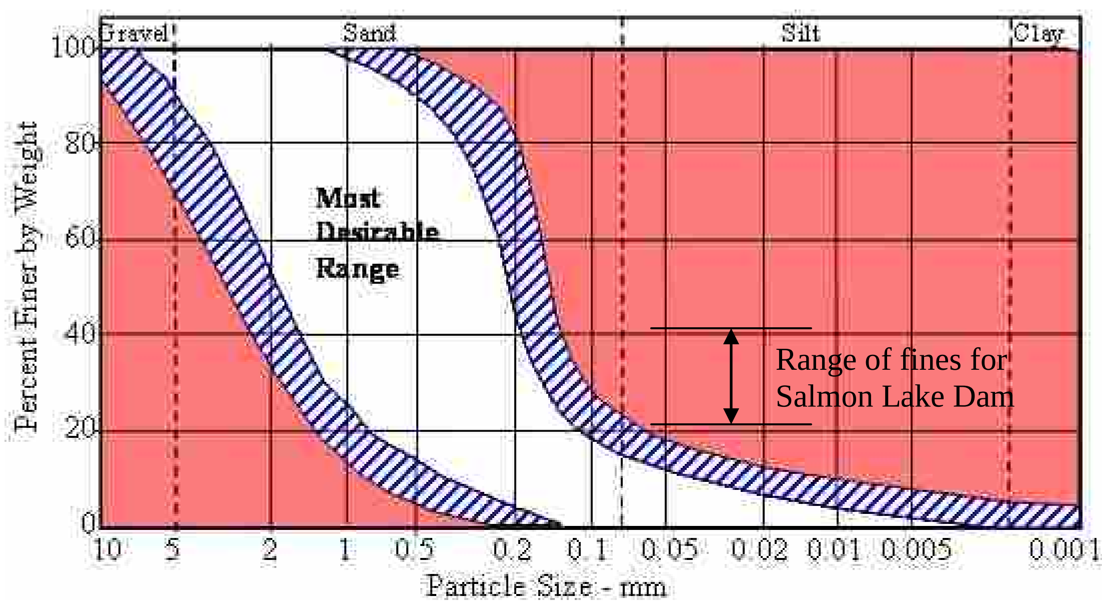


Figure 2.3 Effectiveness of vibratory compaction techniques based on fines content (Mitchell, 1981).

Previous research has suggested that stone column mitigation is less effective in silty soils, but can still improve foundation soil performance (Rollins et al, 2006).

Several methods have been developed in an effort to make stone columns more available for universal soil application. Improvement is possible in soils with a high fines content with the addition of more stone columns, increasing the area replacement ratio, which in turn increases the amount of stiff elements and the amount of soil compacted by displacement (Baez and Martin 1992).

The area replacement ratio, or A_r, is a design aspect considered in this project that has a significant influence on the effectiveness of stone columns. The area replacement ratio (A_r) is used to determine the amount of soil displaced by the stone columns and is calculated using Equation 2.1 below where A_c is the cross sectional area of the stone column and A_e is the tributary area for the stone columns. The equilateral triangle layout of stone columns, which was used at the Salmon Lake Dam, has a tributary area (A_e) which is calculated using Equation 2.2 with an equivalent radius for the tributary area (R_e) shown in Equation 2.3.

$$A_r = \frac{A_c}{A_e} \tag{2.1}$$

$$A_e = \pi R_e^2 \tag{2.2}$$

$$R_e = \sqrt{\frac{0.866 \times S^2}{\pi}} \tag{2.3}$$

where S = center-to-center stone column spacing

Another method of increasing the productivity of stone columns in silty soils is the inclusion of wick drains. This can be seen in Shenthan's (2004) numerical simulations which indicate that wick drains significantly improve stone column effectiveness in soils with high fines content and low conductivity, e.g. 10^{-7} to 10^{-8} m/s, for area replacement ratios greater than

20%. Wick drains are most commonly inserted equidistant between stone columns, as seen at the Salmon Lake reclamation project.

2.4 Effectiveness of Wick Drains Used with Stone Columns

Previous research on the use of stone columns with wick drains was completed for the Utah Department of Transportation to evaluate the benefits of adding wick drains in conjunction with stone columns by Rollins and Quimby (2009). This evaluation of several case histories concluded the following:

- Despite a high fines content (>20%), the foundations were able to be improved using drains with stone columns.
- Locations with higher fines content generally required a higher area replacement ratio (A_r).
- The increase in blow counts was higher when post-treatment testing was completed at least a week later than stone column construction.
- For sites with high fines content (40-50%), to achieve similar results as the Baez Satizabal 5-10% A_r curves for clean sands, an A_r of 23-26% was necessary.
- Stone column treatment with wick drains was found not to be beneficial for soils with clay contents greater than 15%.

One case history evaluated by Rollins and Quimby (2009), at the 24th Street Bridge in Ogden, Utah, was unique in that a test section was originally constructed to evaluate the application of stone columns with and without wick drains. The layout of the test section is shown in Figure 2.4. This direct comparison illustrated that there were significant benefits to adding wick drains. Figure 2.5 indicates that adding drains typically increases the improvement in blow counts by about 10. The data from this case history also indicated that an increase in the area replacement ratio to 34% without drains was less effective than using drains while maintaining the same area replacement ratio. Additional benefits from wick drains may not be captured by an SPT blowcount comparison. For example, the wicks will also provide additional drainage in the event of an earthquake.

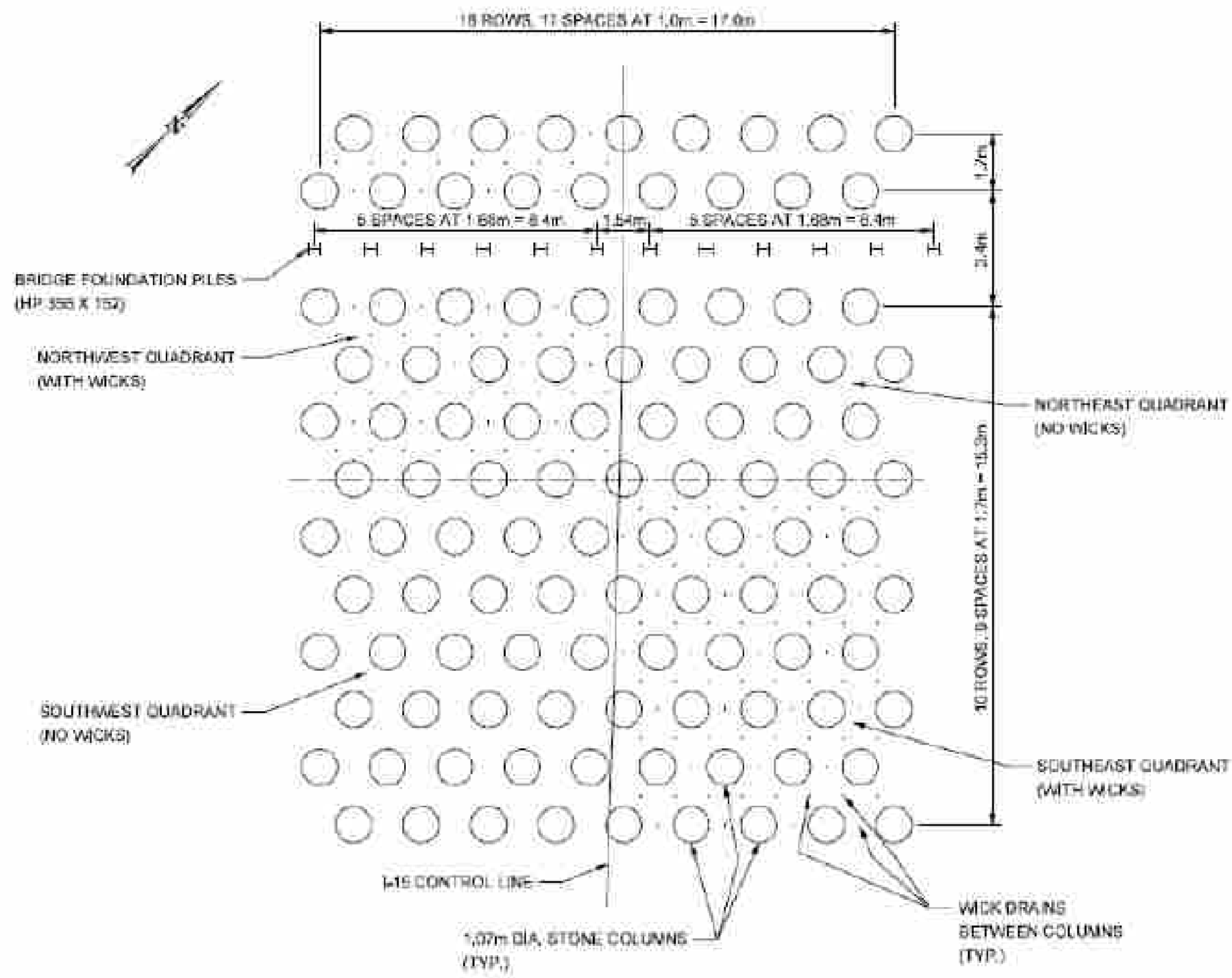


Figure 2.4 Layout of stone columns and wick drains of the 24th Street Bridge test section.

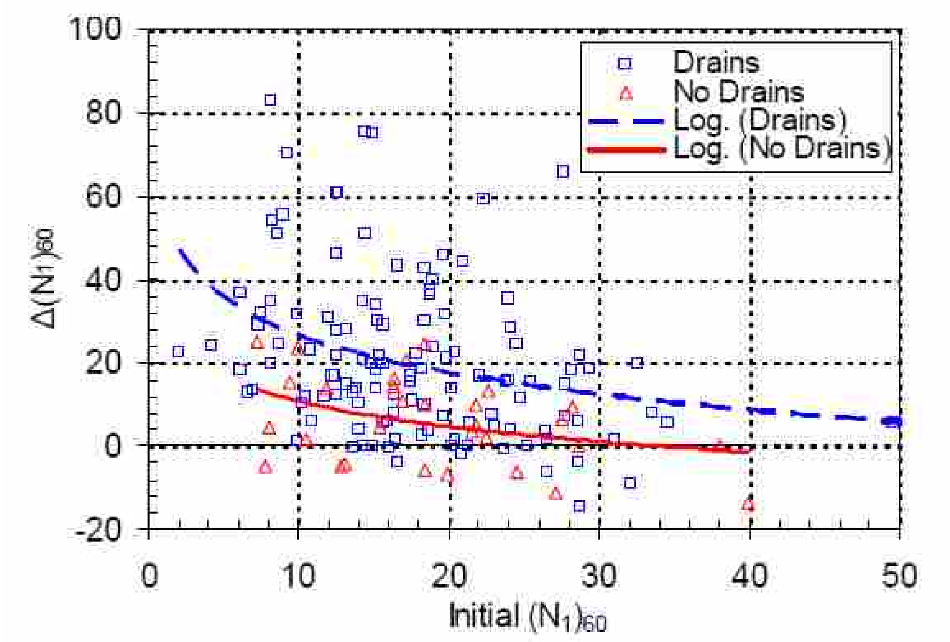


Figure 2.5 $\Delta(N_1)_{60}$ versus initial $(N_1)_{60}$ for the entire 24th Street Bridge site in 26% A_r areas with and without drains (Rollins and Quimby, 2009).

2.5 Previous Salmon Lake Research

Test sections at Salmon Lake, completed years before the actual full-scale construction of stone column mitigation at the site, evaluated not only a variety of stone column diameters and spacing (variations in the area replacement ratio), but also the use of stone columns with and without wick drains.

The result of the Salmon Lake testing for the overall site was analyzed by Luehring et al. (2001). Wick drains were installed prior to the construction of the stone columns. During the construction, the venting of air and water from the wick drains was observed, providing supporting evidence that wick drains were effective in dissipating pore pressure (see Figure 2.6). Leuhring evaluated average improvement but did not evaluate any factors by comparison of companion boreholes. The analysis concluded that the stone columns were effective in increasing the SPT blows counts by 95% on average. Rollins and Quimby (2009) used available data from the entire Salmon Lake site for review of the effect the fines content and initial values had on improvement due to stone columns wick drains. Rollins concluded that the use of wick drains and stone columns with an A_r value of 22.7% generally improved the site. Rollins did not have data for test sections where wick drains were not employed; therefore, they did not compare stone column treatment with wick drains to stone column treatment without wick drains. This data was later obtained and used in the analysis for this project.

Figure 2.6 Water escaping through previously installed wick drains during stone column installation.

3 SITE DESRIPTION

3.1 Overview

The Salmon Lake Dam, built for irrigation, is located about 15 miles northwest of Okanogan in north-central Washington, see Figure 3.1. The dam, which was completed in 1921, is a 30-foot high zoned earth-fill embankment that has a crest length of 1,260 and a crest width of 14 feet. The foundation under the majority of the embankment is made up of Quaternary fluvial-lacustrine sediments, which are cohesionless, interbedded to laminated silty sand, with interbeds and lenses of silt with sand, sandy silt, poorly-graded sand, and silty sand with gravel. Many of these layers were found to be loose enough to liquefy in a potential earthquake (Luehring, 1997).

The earthquake catalog provided a maximum credible earthquake of M_L 6.5 for the area of the dam, with a random event at a distance of 29 kilometers, for an estimated maximum peak horizontal bedrock acceleration of 0.26 g and an annual probability of occurrence of $2x10^{-5}$ (Luehring, 1997). Due to concerns for liquefaction hazards at the site, dam safety modification plans were begun, which would include the construction of stone columns to increase the density of the loose materials in the foundation of the dam.

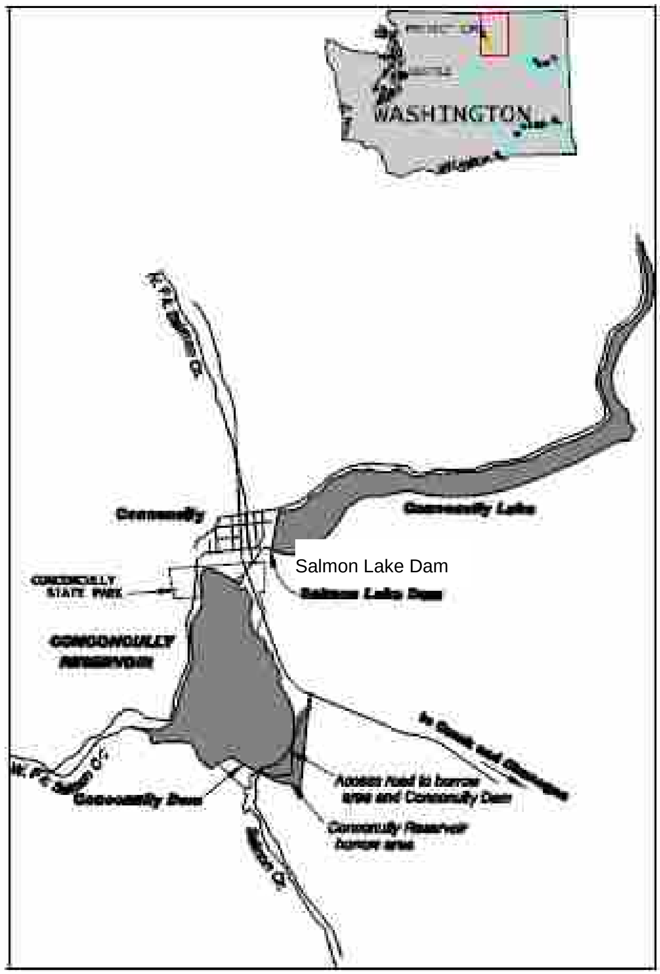


Figure 3.1 Location map of the Salmon Lake Dam in Washington (Luehring et al. 2001).

Geotechnical information for this study was provided by the Bureau of Reclamation through several reports, including the Salmon Lake Dam Stone Column Test Section and Salmon Lake Dam Safety of Dams Modification Summary of Final Designs prepared by Luehring (1997, 1999) and the Geologic Construction Report for Safety of Dams Modifications Salmon Lake Dam Okanogan Project, Washington prepared by Hansen and Link (2002). With respect to all data used in these reports, $(N_1)_{60\text{-}cs}$ values were determined by the United States Bureau of Reclamation from the SPT data using the procedure outlined by Youd et al. (1997) and shown in Equation 3.1.

$$(N1)_{60-cs} = \alpha + \beta(N1)_{60} \quad \textbf{(3.1)}$$

where α and β are coefficients determined from the following relationships based on fines content (FC):

$$\alpha = 0 \text{ for } FC \leq 5\% \quad \textbf{(3.2a)}$$

$$\alpha = \exp\left[1.76 - \left(\frac{190}{FC^2}\right)\right] \text{ for } 5\% < FC < 35\% \quad \textbf{(3.2b)}$$

$$\alpha = 5 \text{ for } FC \geq 35\% \quad \textbf{(3.2c)}$$

$$\beta = 1 \text{ for } FC \leq 5\% \quad \textbf{(3.2d)}$$

$$\beta = 0.99 + \left(\frac{FC^{1.5}}{1000}\right) \text{ for } 5\% < FC < 35\% \quad \textbf{(3.2e)}$$

$$\beta = 1.2 \text{ for } FC \geq 35\% \quad \textbf{(3.2f)}$$

3.2 Treatment Method

Three tests sections, designated as Sites A, C, and D, were initially completed to determine the required diameter and spacing for the stone columns and to compare the use of wick drains in conjunction with stone columns against the use of stone columns alone.

The dry bottom feed vibro-stone column installation method was used for the test sections, due to the high ground water level. The air pressure developed during advancement of the probe and withdrawal during column construction measured up to 60 lb/in^2 and 80 lb/in^2, respectively.

The maximum current for the stone column installation equipment was 300 amps and the desired amperage during the construction process was at least 80% of the maximum amperage, to maximize densification of the materials. For sites C and D the range was about 195 to 260 amps, with some exceptions.

Site A consisted of three stone columns installed in a triangular pattern without any wick drains. The location was chosen based on the high fines content and gravel content, which would make stone column installation difficult. This proved to be the case at installation. To reach the required 80% of maximum amperage for the probe, the contractor installed more stone than specified for the required diameter of 4 feet, resulting in one of the columns being nearly 5 feet in diameter. The specified center-to-center spacing of the columns was 9 feet with an area replacement ratio (A_r) of 21% based on a 4 ft diameter stone column. A 9-foot spacing was not used in test sections at Site C or D or in the final stone column design layout, and the area replacement ratio was not comparable to the A_r for subsequent installations, therefore the SPT results of Site A were not used in this analysis of stone column installation at the Salmon Lake Dam.

Site C was also chosen based on the high fines content in the foundation. The equilateral triangle layout is shown in Figure 3.2, with the number in the circles indicating the sequence of stone column installation. The site consists of two different layouts, one included the use of wick drains and used a column diameter of 3 feet with a center-to-center spacing of 6 feet, while the other did not use wick drains and had a column diameter of 3.75 feet with a spacing of 7.5 feet. Both sections had an A_r of 23%. Wick drains were installed to a depth of 68 feet and for stone column installation in the area where wick drains were used the upstream three rows reached depths of 52 feet while the two downstream rows reached depths of 67 feet. The average installation time for the 3 foot diameter columns at Site C was 76 minutes.

Site D was also chosen because of the significant content of liquefiable foundation materials. The equilateral triangle layout is shown in Figure 3.3. The site consists of three different layouts. The first included wick drains and used a column diameter of 3.75 feet with a center-to-center spacing of 6 feet for an A_r of 35%. The second layout included wick drains and used a column diameter of 3.5 feet with a spacing of 6 feet for an A_r of 31%. The third layout

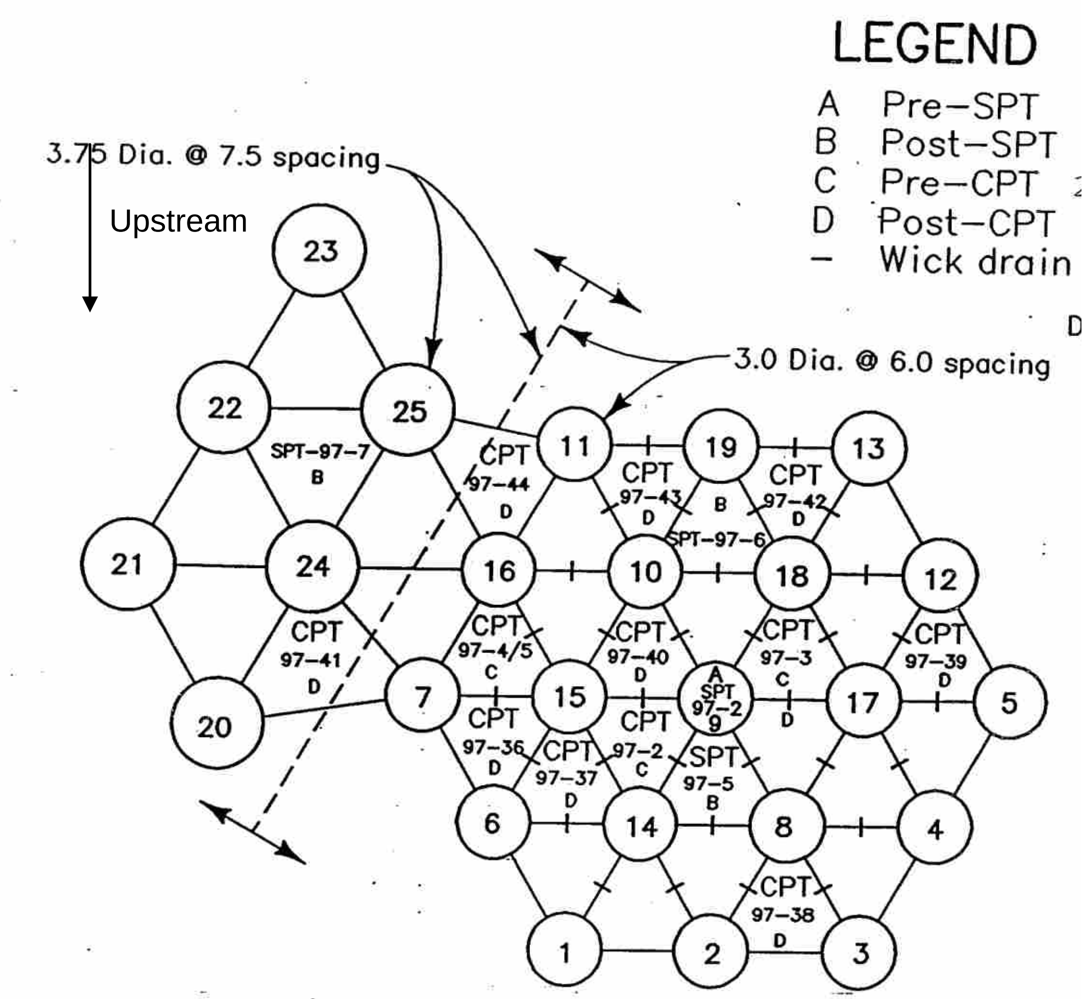


Figure 3.2 Stone column and wick drain layout for test section Site C.

did not include wick drains and also used a column diameter of 3.5 feet with a spacing of 6 feet spacing and an A_r of 31%. Wick drain installation reached full depth (68 feet) in all but five holes where installation was approximately 59 to 60 feet. For stone column installation in the area where wick drains were used, the upstream three rows reached depths of 52 feet while the two downstream rows reached depths of 67 feet. The average installation time for the 3.5-foot and 3.75-foot diameter columns at Site D was 93 and 104 minutes, respectively.

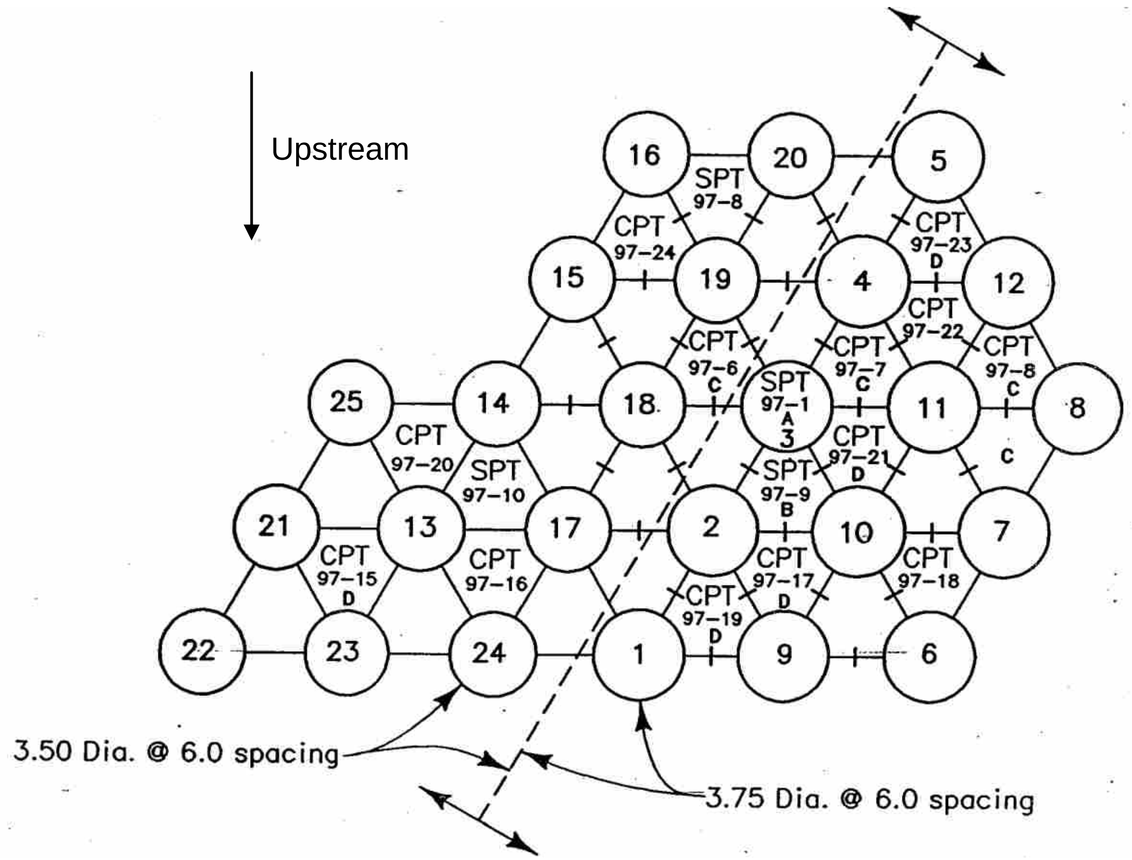
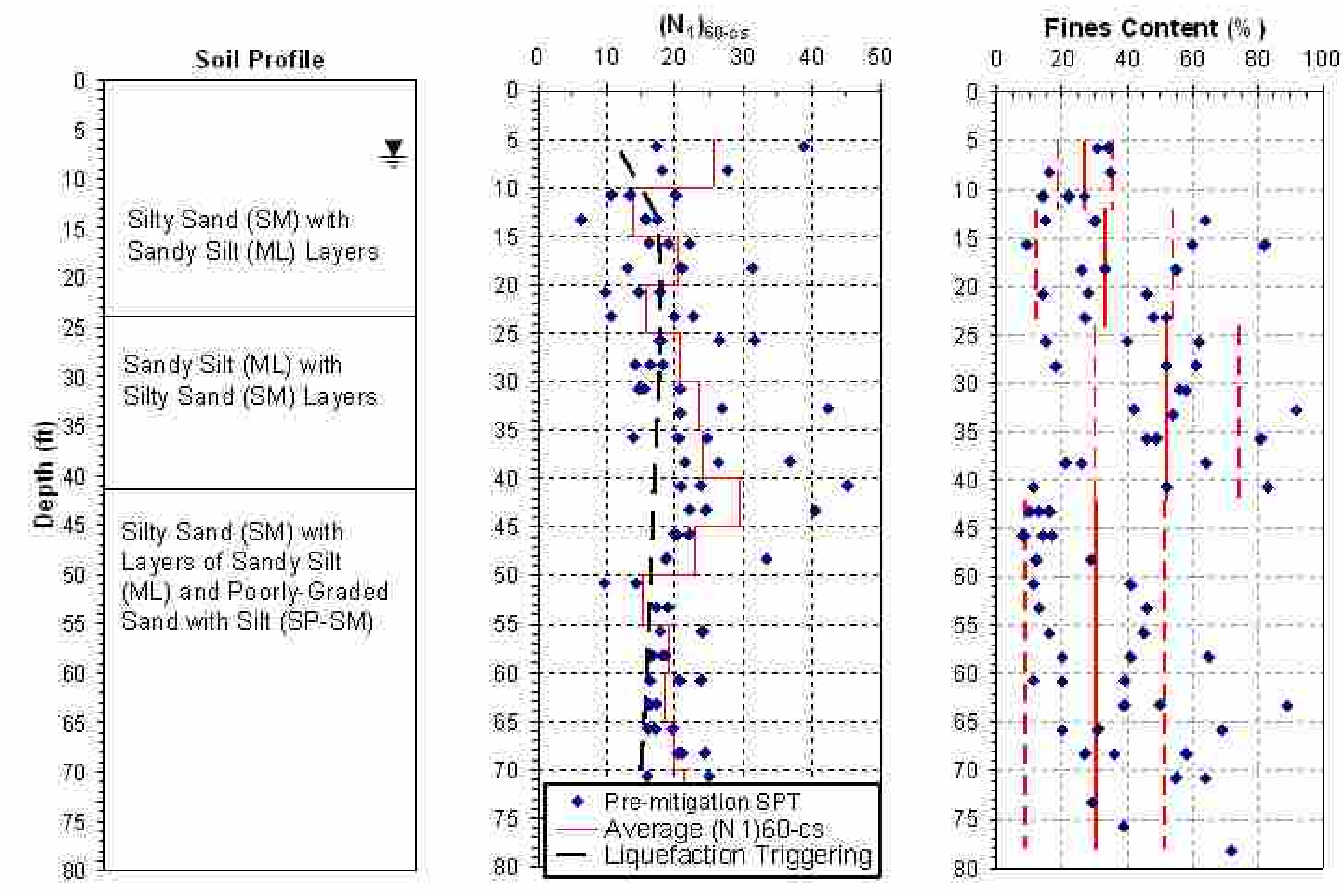


Figure 3.3 Stone column and wick drain layout for test section Site D.

SPT tests were performed within the locations of Sites C and D before installation of stone columns and wick drains. The median fines content from the pre-mitigation tests was 36%. Figure 3.4 includes a general soil profile, the $(N1)_{60\text{-}cs}$ values, and fines content information which resulted from the pre-mitigation testing showing the necessity for liquefaction mitigation construction at the Salmon Lake Dam. In addition, Figure 3.4 also includes the liquefaction triggering threshold provided by Luehring et al. (2001). Post-mitigation testing was completed a minimum of two weeks and one day after the construction of the test area stone columns to allow for pore pressure dissipation. An evaluation of the post-mitigation is included in the following chapter. The results from the testing were used to finalize the design of the Safety of Dams Modifications at Salmon Lake with the following conclusions:

- The sites with a stone column diameter of 3.75 feet, which had higher A_r values, demonstrated the most improvement,
- The peripheral stone columns in areas with 3 and 3.5 foot diameters, did not reach the desired amount of foundation improvement,
- Ground water and air were observed to be ejected from most wick drains during stone column construction, which is evidence that they relieved pressure during column construction.

The final design for the foundation of the dam consisted of an equilateral triangle layout with center-to center spacing of 6 feet, a row spacing of 5.2 feet, and an installation depth of 60 feet. Wick drains were also installed to a depth of 60 feet between adjacent stone columns. Of the six rows of columns installed, the two furthest upstream rows and the two furthest downstream rows would have column diameters of 3.75 feet and an A_r of 35% while the middle two rows would have diameters of 3 feet and an A_r of 23%. The stone column installation sequence, employed to maximize pore pressure dissipation during construction and improve the effectiveness of the stone columns, is shown in Figure 3.5 along with the location of wick drains. The typical modified Salmon Lake Dam section is shown in Figure 3.6. Post-mitigation testing was completed at least ten days after construction.



(a) (b) (c)

Figure 3.4 (a) General soil profile, (b) actual and average $(N_1)_{60\text{-}cs}$ values, and (c) fines content with median (solid line) and one standard deviation bounds (dashed lines) for the pre-mitigation standard penetration testing at test section sites C and D.

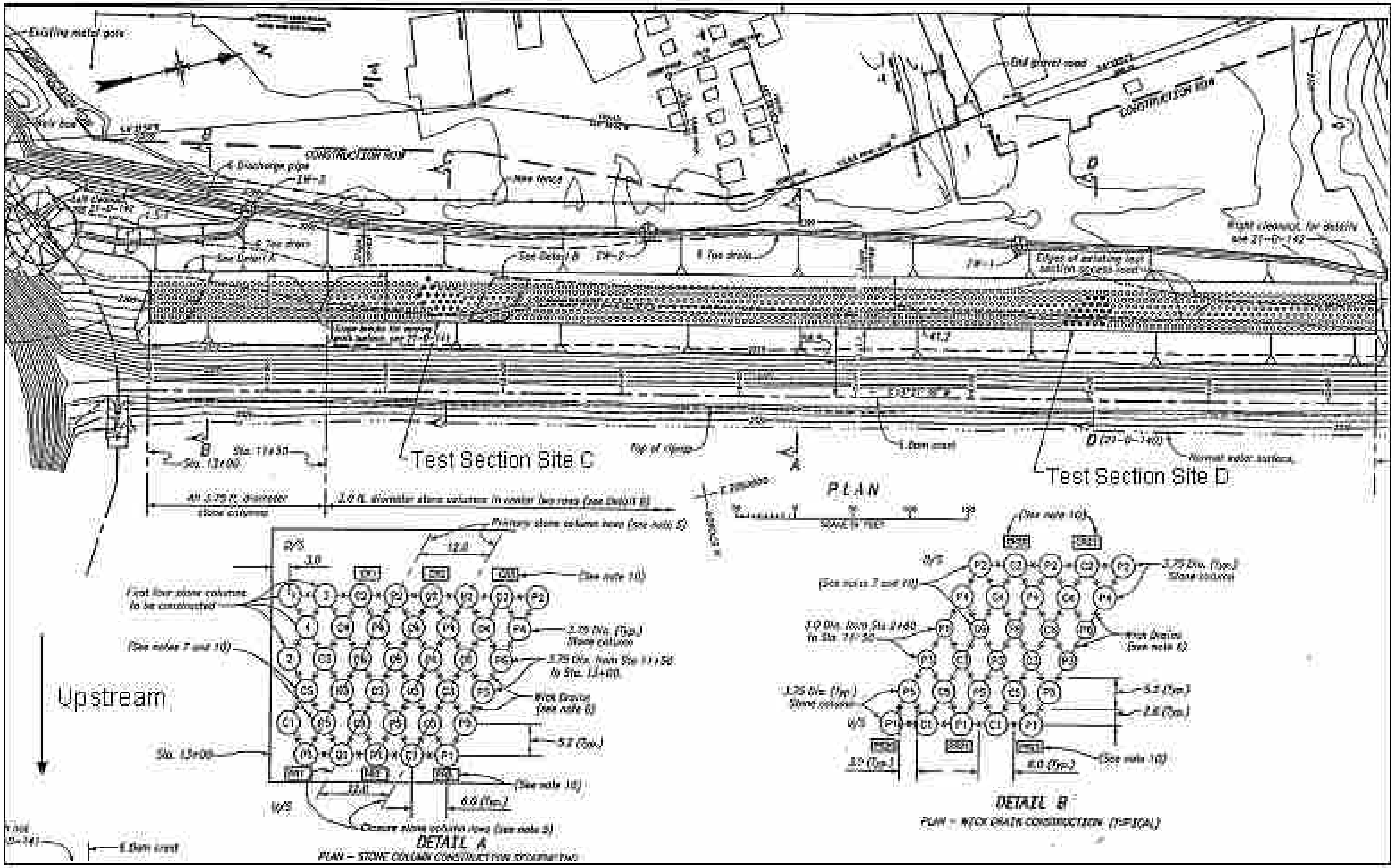


Figure 3.5 Location of test section sites C and D and final design for the overall project, including construction sequencing and wick drain construction details (Luehring, 1999).

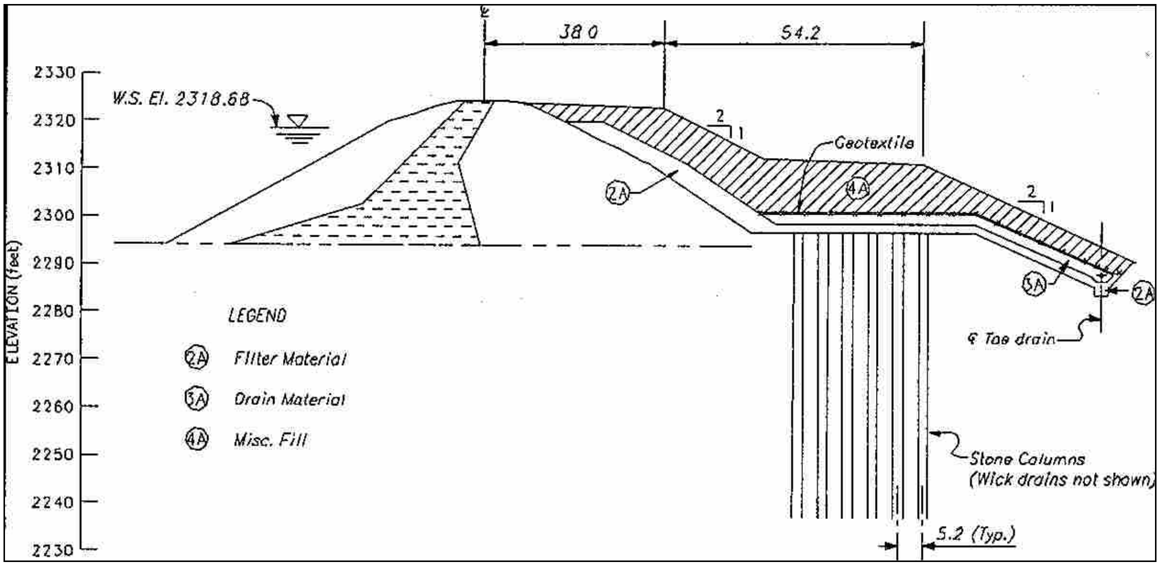


Figure 3.6 Typical cross section of the Salmon Lake Dam project (Luehring et al., 2001).

4 TEST SECTION ANALYSIS AND RESULTS

4.1 Overview

This chapter describes the analysis and results for the data collected from the test sections at Sites C and D. The analysis evaluates the use of stone columns with and without drains and compares different area replacement ratios based on the diameter of columns and column spacing.

4.2 Analysis of Test Section Data

Post-installation SPT data were gathered within each test section at locations of the areas with wick drains at sites C and D, as well as in the areas where drains were not used. Although the diameter and spacing of the columns are different for the areas on each side of the dashed line in Figure 4.1, the area replacement ratio at site C was 23% for all locations. The A_r at site D was 31% for the area left of the dashed line and 35% for the area right of the dashed line, as seen in Figure 4.2 of site D. The SPT blowcounts from bore hole 97-10 at site D with an A_r of 31% may have benefited from drain installation adjacent to stone columns 14 and 17, although those results were considered to be in the no drain area. On the other-hand, SPT results from bore hole 97-8 at site D with an A_r of 31% were at a disadvantage because it was located on the edge of the treatment area and would have fewer stone columns contributing to the treatment of the soil in that location.

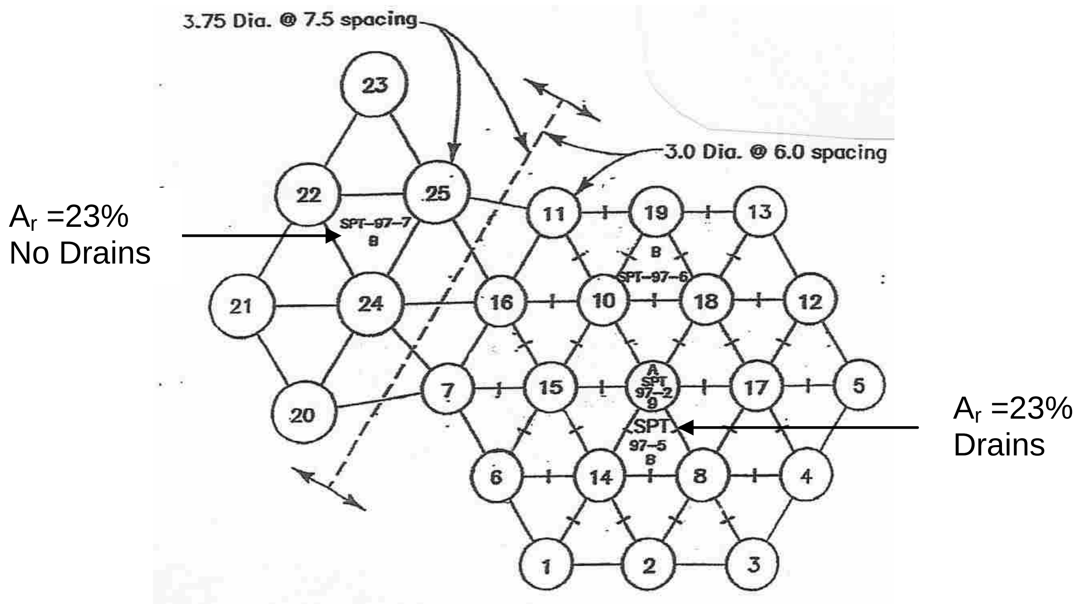


Figure 4.1 Test section site C with an A_r of 23%.

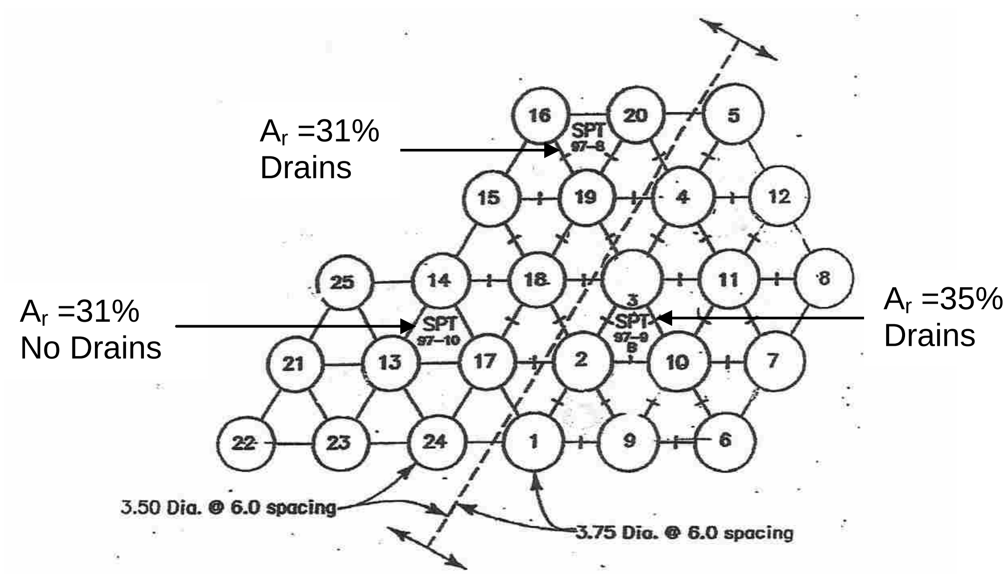
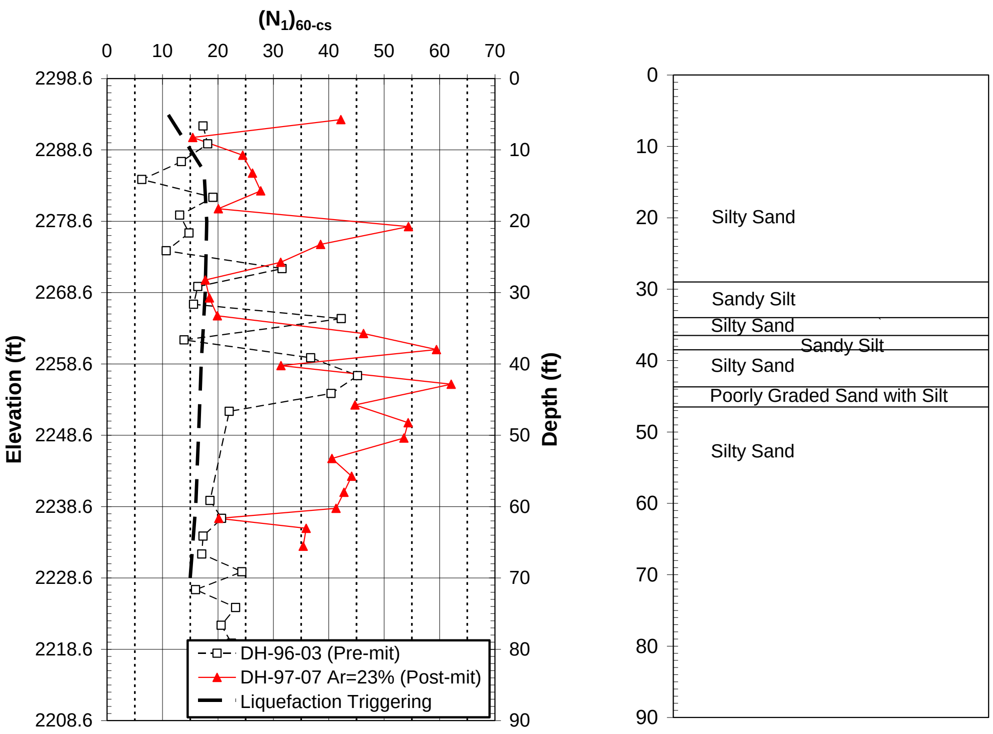
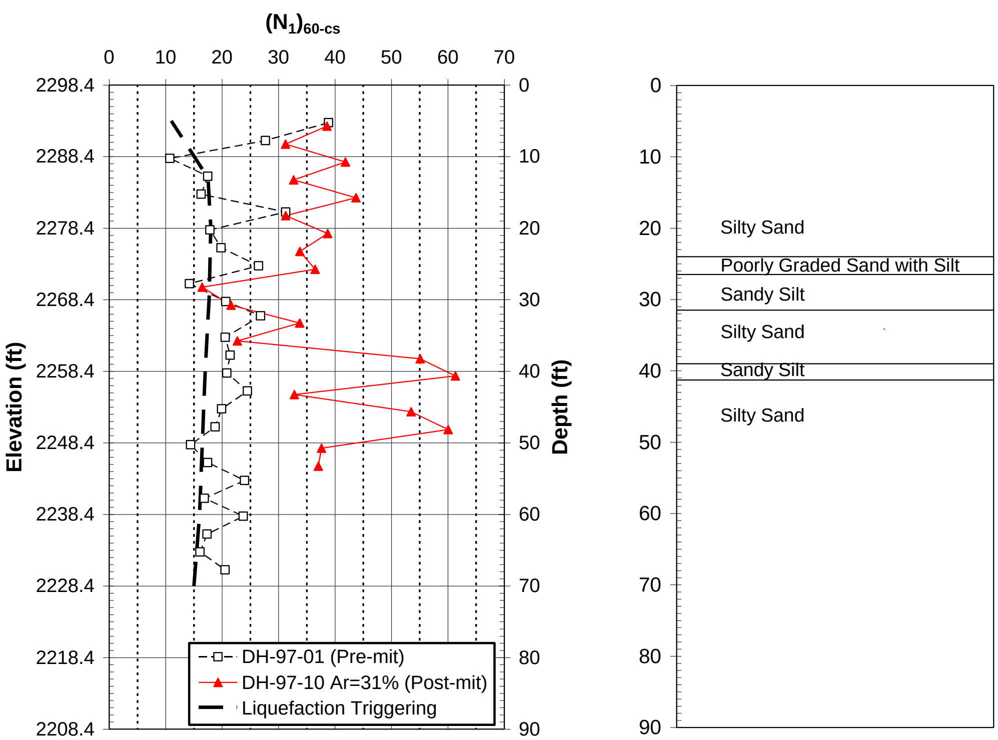


Figure 4.2 Test section site D with an A_r of 31% left of the dashed line and 35% right of the dashed line.

Comparisons of the pre-mitigation and post-mitigation SPT results were created to show the effectiveness of the stone columns and drains. The plots in Figure 4.3 show the SPT results as a function of elevation for the areas without wick drains at sites C and D.



(a)



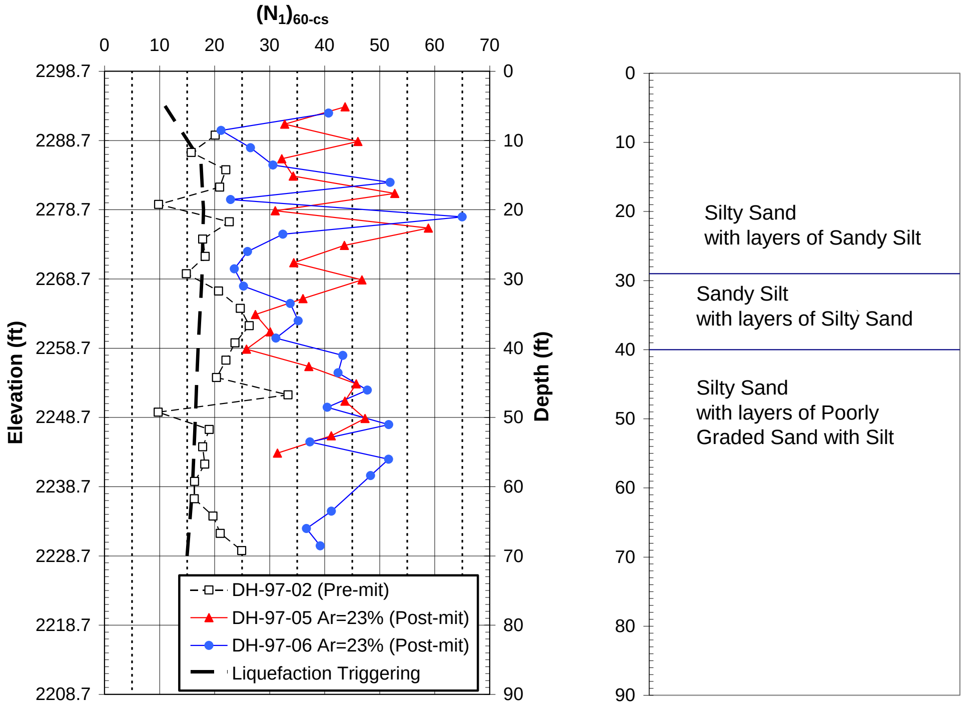
(b)

Figure 4.3 Soil profile and results from pre-mitigation and post-mitigation SPT tests at sites C and D in areas without wick drains with an area replacement ratio of (a) 23% and (b) 31%.

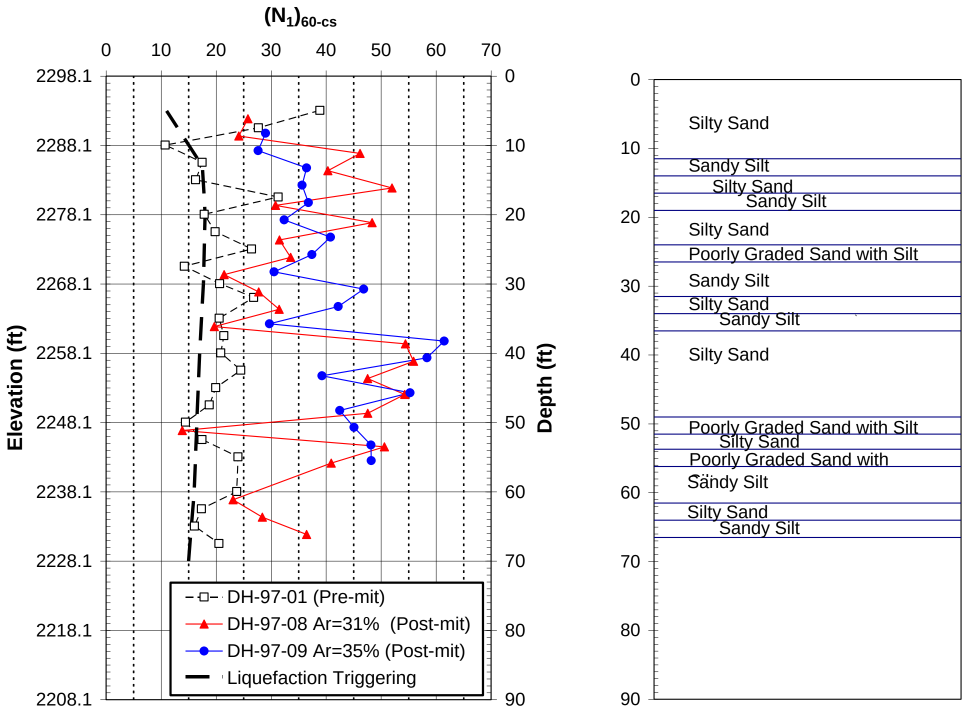
The heavy dashed curve represents the minimum required $(N_1)_{60\text{-}cs}$ value plotted against elevation necessary to prevent liquefaction provided by Luehring et al. (2001). Prior to treatment, a few of the SPT values were below and some were just slightly above the minimum required value. After mitigation with stone columns, the number of values below the minimum decreased substantially; however, the plots indicate that there were still two locations where the minimum requirement was not met in the areas without drains. The one point below the line at bore hole 97-7 was in a layer with a fines content of 59% and the one point below the line at bore hole 97-10 were in a layer of sandy silt but the fines content was not given, (see the soil profile in Figure 4.3).

In contrast to Figure 4.3, Figure 4.4 shows the tests results for the areas with wick drains installed at sites C and D. The heavy dashed line indicates the minimum required final $(N_1)_{60\text{-}cs}$ values. The plots indicate that there was one post-mitigaton location where the minimum requirement was not met in areas with drains at site D where there was a 31% stone column area replacement ratio, in a layer of poorly-graded sand with silt. Although, the SPT tests for DH-97-10 and DH-97-08 were located only approximately 25 feet apart, there is a great variation in soil layers and much more striation from the test results at DH-97-08.

Included in Figure 4.5 are a generalized soil profile and the fines content data for the areas with and without drains taken from the post-mitigation data. The median values and the median ± one standard deviation are included. The two fines content plots both show that there is an increase in fines content from a depth of 24 to about 41.5 feet, but the median fines content for the areas with wick drains is 59% while the median for the areas without wick drains is only 40%. The median fines content for the other layers of soil is also higher in the area with drains than the area without drains.

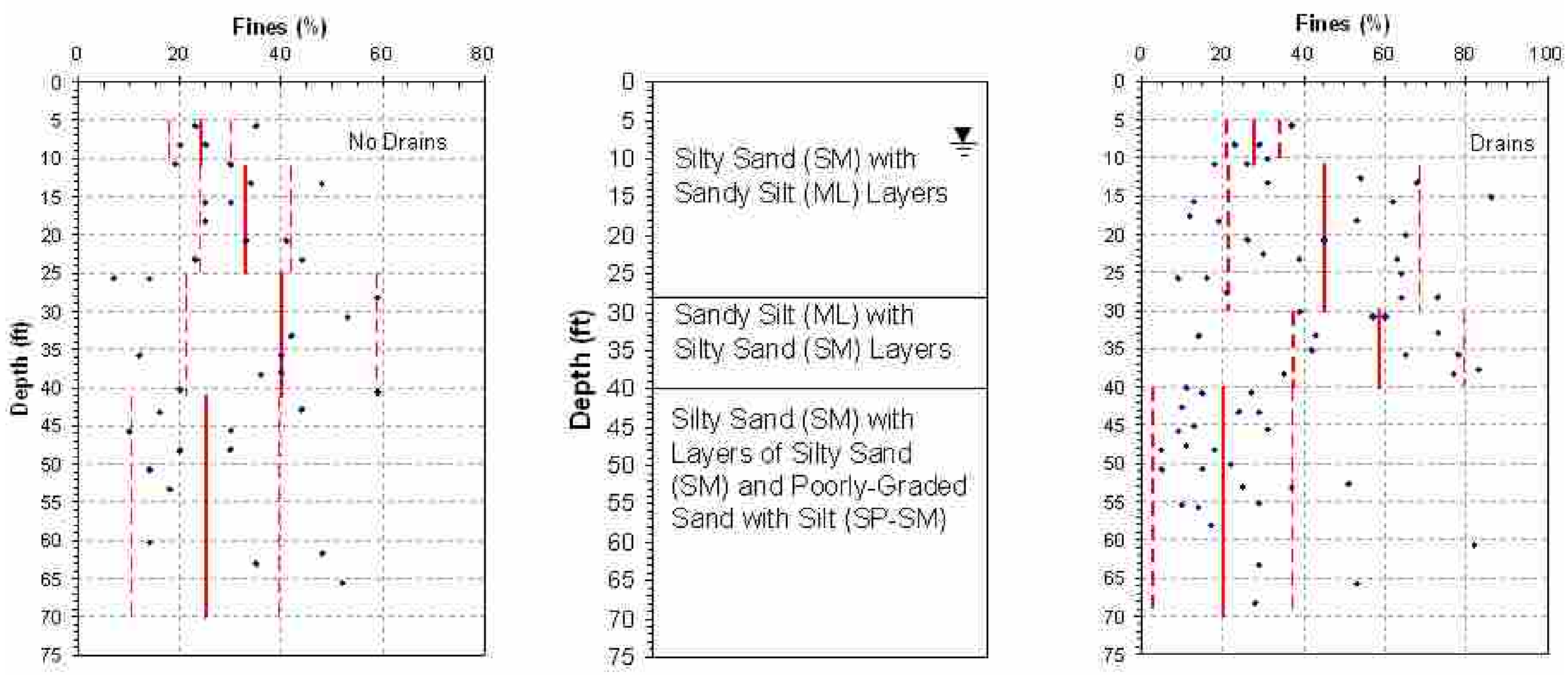


(a)



(b)

Figure 4.4 Pre- and post- mitigation results for areas with wick drains at site C and D including (a) an A_r of 23% with a generalized soil profile for bore logs DH-97-05 and DH-97-06 and (b) and A_r of 31 and 35% with a soil profile for bore log DH-97-08.



(a) (b) (c)

Figure 4.5 Fines content values with median (solid line) and standard deviation bounds (dashed lines) for areas (a) without drains and (c) with drains and (b) a generalized soil profile for the test section areas.

Multi-variable regression was an option for the analysis of the data from Salmon Lake. Unfortunately, due to unavailability of data such as clay content, the large scatter in data (which resulted in low R-squared values), and resulting poor correlations, the effort was abandoned in favor of a more simplified analysis of the results from the SPT testing.

The plot of the improvement in $(N_1)_{60\text{-cs}}$ with respect to the fines content is shown in Figure 4.6. Due to high variation, the trend lines represent the average values across the site rather than an actual prediction of improvement based on fines content. The clean sand blowcount values were used in this analysis, which appears to eliminate the influence of fines on the measured improvement.

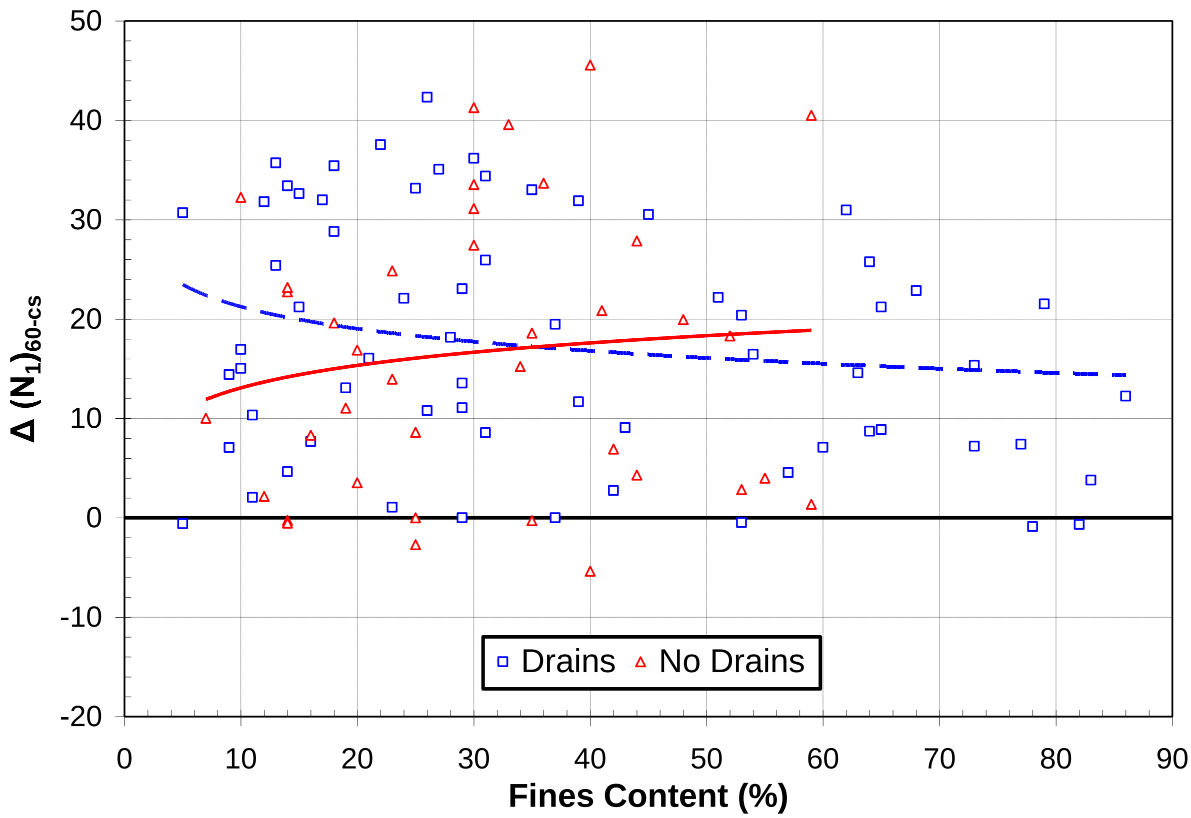
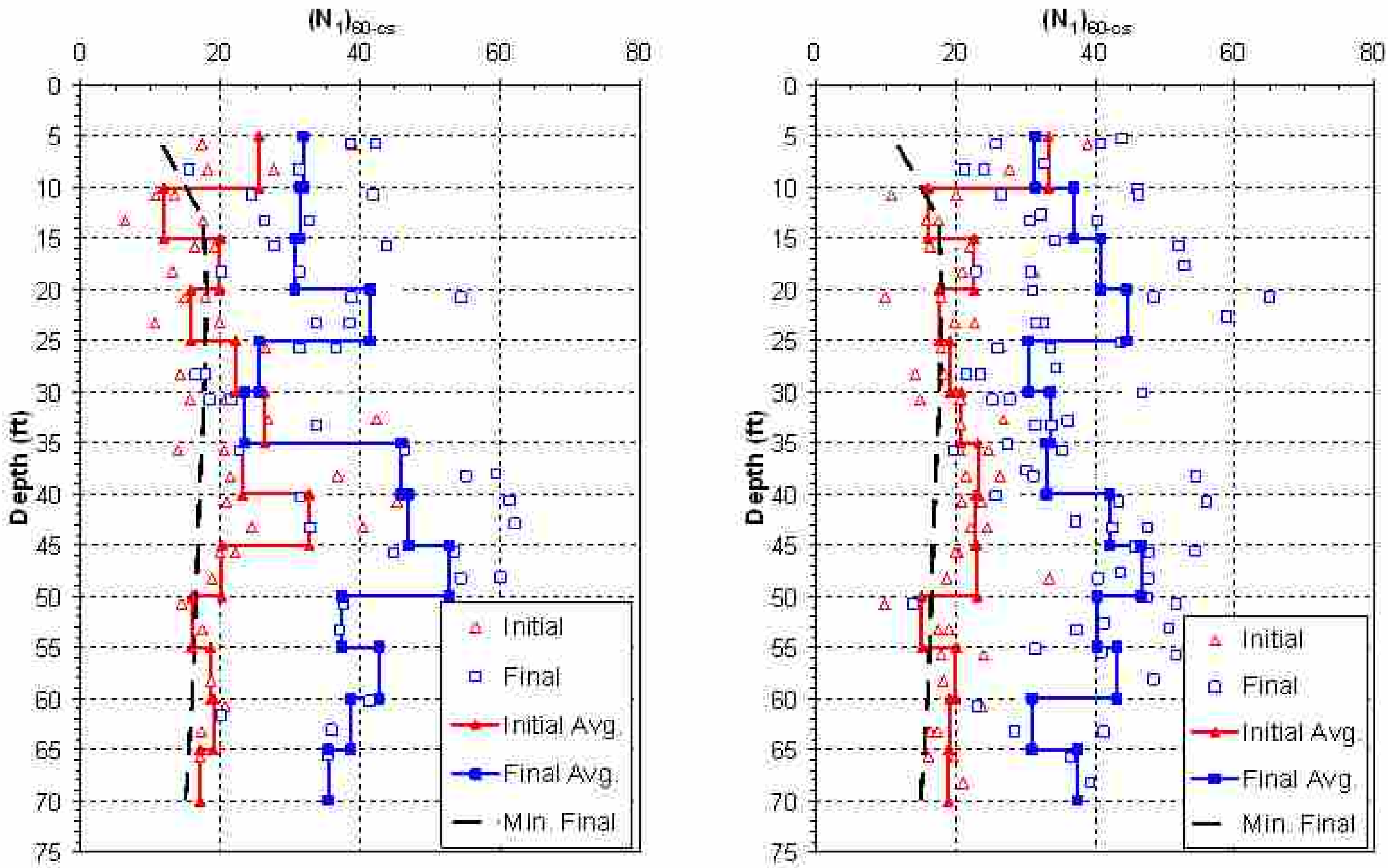


Figure 4.6 Improvement in $(N_1)_{60\text{-cs}}$ versus fines content for A_r values in areas with and without drains.

Figure 4.7 shows the average initial and final $(N_1)_{60\text{-}cs}$ values for test sections C and D for area replacement ratios of 23% and 31% as a function of depth. The dashed line indicates the liquefaction triggering threshold. The averages were computed at 5 ft intervals to provide an indication of the variation with depth and soil type. The data was divided into plots of (a) the areas without drains and (b) areas with drains. Both plots show that there was improvement with the use of stone columns, although the amount of improvement varies within the treatment zone. In the areas without drains, the plots indicate much less effectiveness in the depth range from 25 to 35 feet relative to areas where drains were present. In fact, the average blow count actually decreased between a depth of 30 and 35 feet in the area without drains. Such depths showing a decrease in the final blow counts correlate with the increase in the median fines content shown in the plot of Figure 4.5 for the no drain cases, indicating that a higher fines content decreases the effectiveness of stone columns.

In areas with drains, the plot shows a slight decrease in blow count between a depth of 5 and 10 feet; however, an improvement of at least a 10 blows per foot was obtained throughout the rest of the depth of treatment. The heavy dashed line in the figure indicates the liquefaction triggering threshold. As seen in the plots, the average final $(N_1)_{60\text{-}cs}$ values in both areas with or without drains do not fall below the threshold. However, for two individual SPT locations, the blow count is less than the threshold.

Figure 4.8 was created to analyze the effect that the initial $(N_1)_{60\text{-}cs}$ had on the improvement in the $(N_1)_{60\text{-}cs}$ values. In this instance, only data from Site C was used to compare



(a) (b)

Figure 4.7 Initial and final blow counts versus depth for site C and D (A_r of 23% and 31%) for areas (a) without drains and (b) with drains.

one area replacement ratio (23%) for areas with and without drains to simplify comparisons. Despite the scatter, there were no points of negative improvement at Site C, when drains were used, although there were four instances of negative improvement when no drains were used.

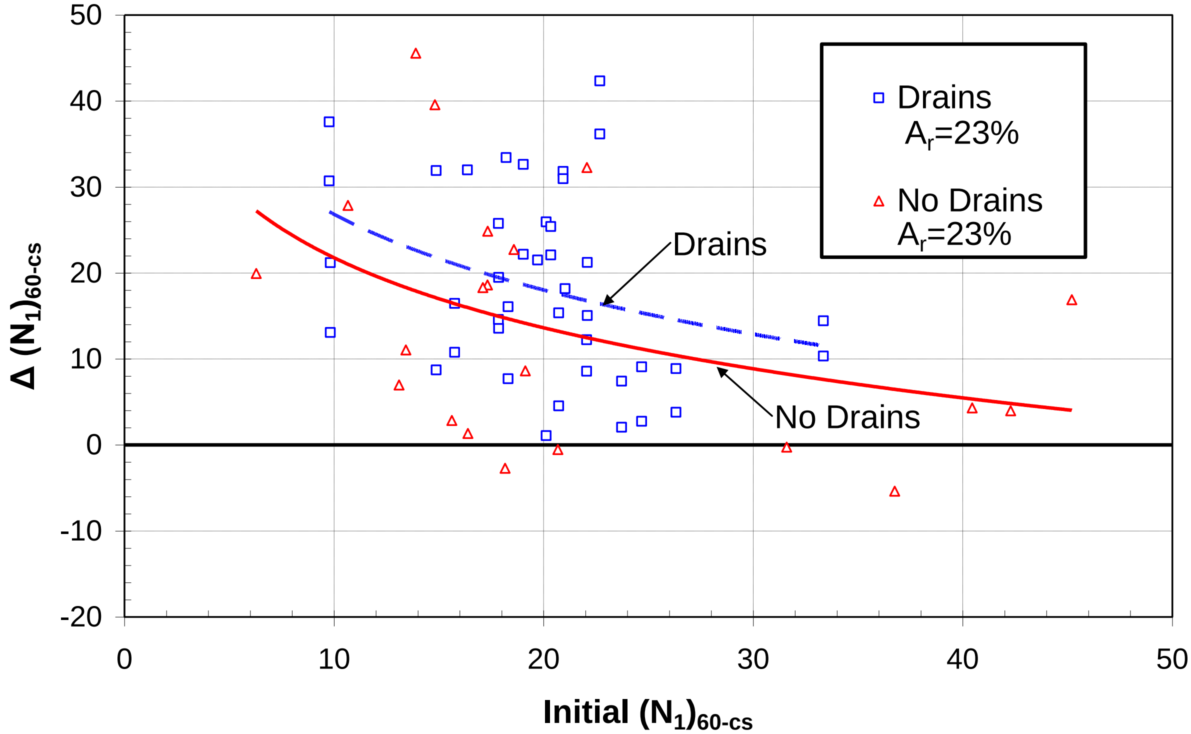


Figure 4.8 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for the test areas with and without drains at site C where the area replacement ratio was 23%.

Best fit curves showing the improvement in blow count [$\Delta(N_1)_{60\text{-}cs}$] as a function of initial normalized blow count [$(N_1)_{60\text{-}cs}$] for an A_r of 23% are also shown in Figure 4.8. Despite the low correlation of the regression analysis, (the R-squared values for the logarithmic trend lines being below 0.17), the plot suggests indicates that the positive improvement in $(N_1)_{60\text{-}cs}$ values decreases as the initial blow count increases. This supports the idea that loose soils will show greater improvement in $(N_1)_{60\text{-}cs}$ values relative to dense soils when this liquefaction mitigation system is employed. Although this may seem to present problems for mitigation, it should be recognized that dense sand also requires less improvement to prevent it from liquefying in an earthquake. Because of the low correlation coefficients, the curves should be thought of as representing averages rather than as equations for predicting improvement. Nevertheless, the best fit curves indicate that the improvement in blow count for the area with drains is consistently about 5 blows per foot higher than that for the area without drains.

Figure 4.9 plots the best fit curves showing the improvement in blow count as a function of initial normalized blow count for an A_r of 31%. The curves indicate the same decrease in improvement with increased initial blow count, but the data do not show any beneficial effect on improvement due to the inclusion of wick drains.

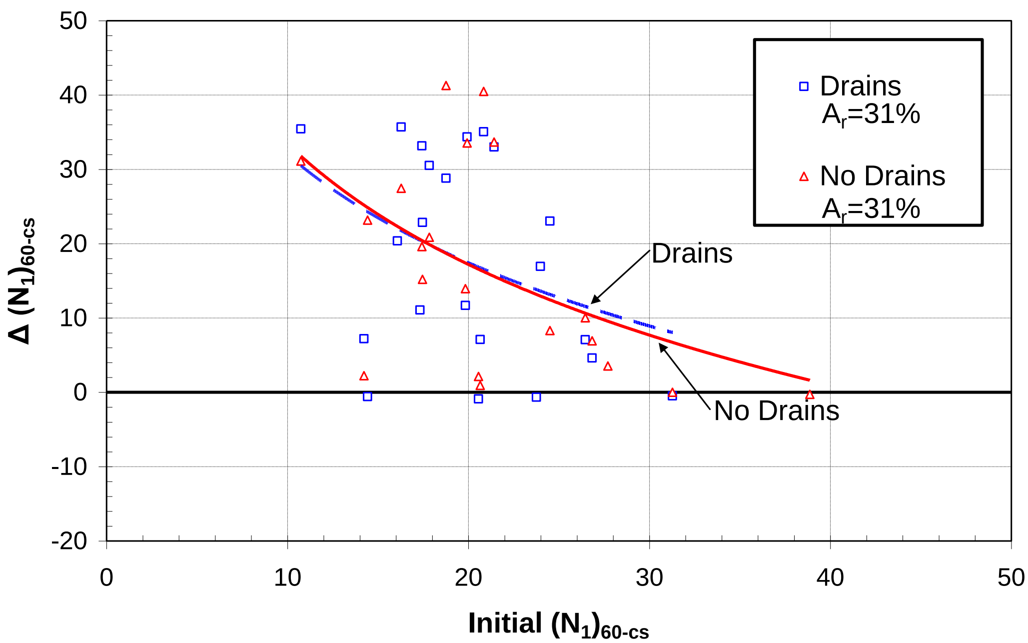


Figure 4.9 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for the test areas with and without drains at site D where the area replacement ratio was 31%.

As seen previously in Figure 4.4, the post-mitigation test results in the areas with drains at site D, which had a stone column area replacement ratio of 31%, proved extremely variable, with results ranging from significant improvement to several points of negative improvement. This greatly affected the results of evaluation of the effect of drains on the improvement. A number of factors may explain the inconsistent results for the tests involving A_r of 31% at site D. First, the soil profile (see Figure 4.5) is extremely variable compared with the soils profile of the other test locations, leading to more variable results. Second, the data set for areas with an A_r of 31% was limited; therefore, the impact of the high variation in the results was more substantial. Third, as mentioned earlier, the SPT test location for the area with drains and 31% area replacement ratio was on the edge of the treatment area and did not receive the benefit of being surrounded by more columns and drains. Finally, although the areas with and without drains have the same A_r, the column spacings and column sizes are different with unknown effects. These factors make it difficult to draw firm conclusions from this set of data.

Figure 4.10 was used to compare the data in areas where drains were used at sites C and D but different area replacement ratios were used. At site C, the area replacement ratio was 23% and the improvement versus initial blow count trendline had a similar shape to the curve at site D where the area replacement ratio was 35% but was offset downward. The logarithmic trendline for the area with a 35% A_r at site D was consistently 3 units higher than the trend for the area with 23% A_r at site C. Due to the variability of the results for the area at site D with a 31% A_r, (includes four points of negative improvement), the trend had a steeper curve than the curves for the areas with A_r values of 23 and 35%. Three of the points with negative improvement had fines content of 78, 82, and 53%. For Figure 4.11 all points with a fines content above 50% were removed from the data set. The points are indicated in Figure 4.10 with solid symbols.

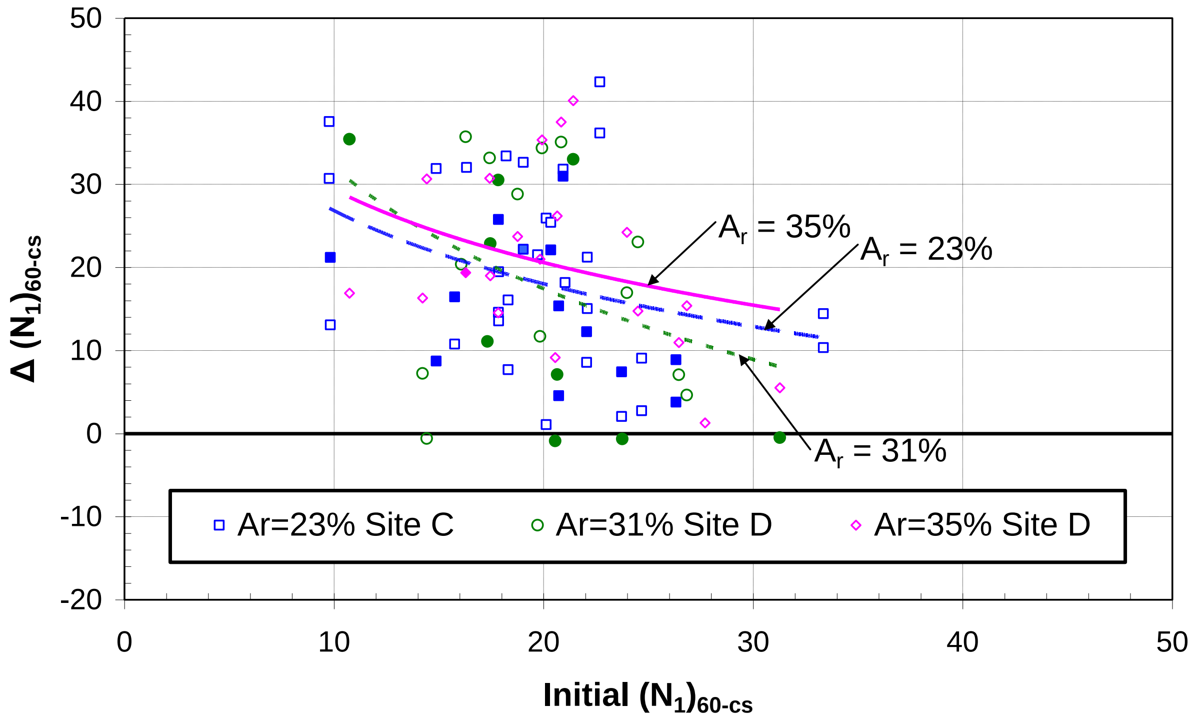


Figure 4.10 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for the test areas with drains at site C with an area replacement ratio of 23% and site D with an area replacement ratio of 31% and 35%. Solid symbols indicating points that with fines contents higher than 50%.

By removing all points which had fines contents above 50%, all of the curves are more congruent. Removing points with higher fines tended to shift the curves upward. Seven points were removed from the A_r of 31% data set, including three of the four points of negative improvement, which resulted in this curve being higher than the curves for the other two A_r cases. The curves for an A_r of 23 and 35% are much closer, due to fourteen points which were removed from the A_r of 23% data set and only one from the A_r of 35% data set. These results suggest that relatively little benefit would be produced by increasing the A_r value above 23% and this was the conclusion of the USBR engineers as well (Luehring, 1997).

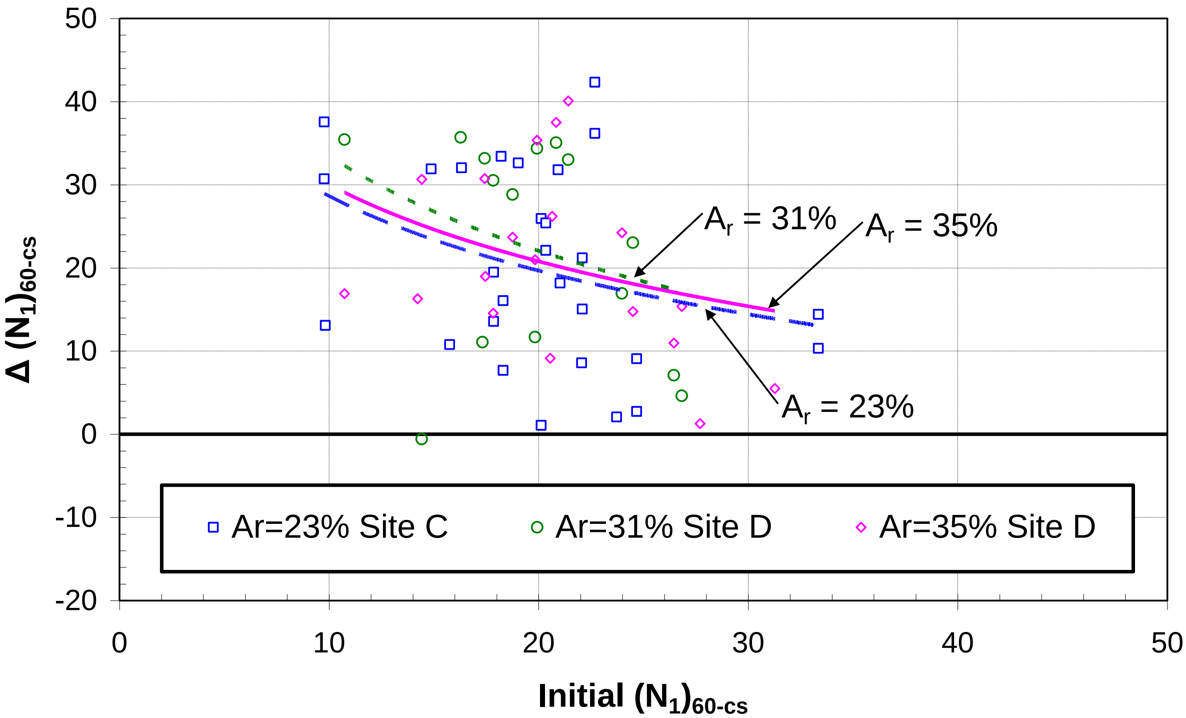


Figure 4.11 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for the test areas with drains at site C with an area replacement ratio of 23% and site D with an area replacement ratio of 31% and 35% with points that have a fines content above 50% removed.

Figure 4.8 and Figure 4.10 indicate that in areas with comparable fines content and soil types, the use of wick drains in conjunction with stone columns or an increase in the area replacement ratio will increase the amount of soil improvement that the stone columns provide.

Figure 4.12 depicts the improvement in $(N_1)_{60\text{-}cs}$ as a function of depth for sites with and without drains. The plot shows significant scatter and therefore provides no apparent trend. The area without drains has a comparable number of negative improvement points to the areas with drains. All of the points of negative improvement in areas with drains came from the data collected at site D in the area with the 31% replacement ratio. Three of these points had fines content values of 53, 78 and 82%.

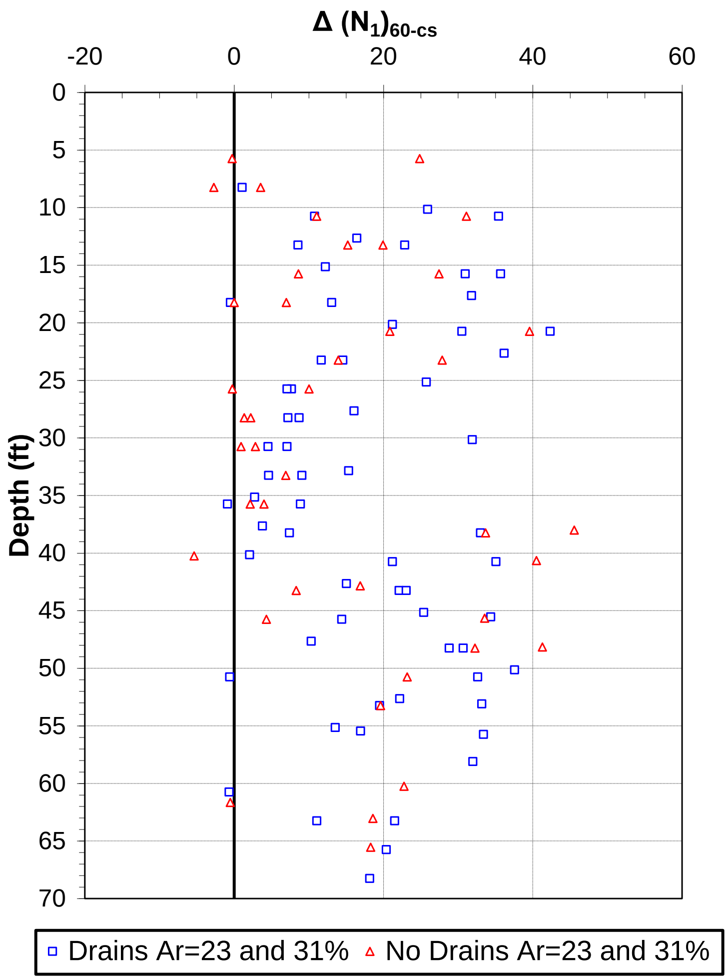
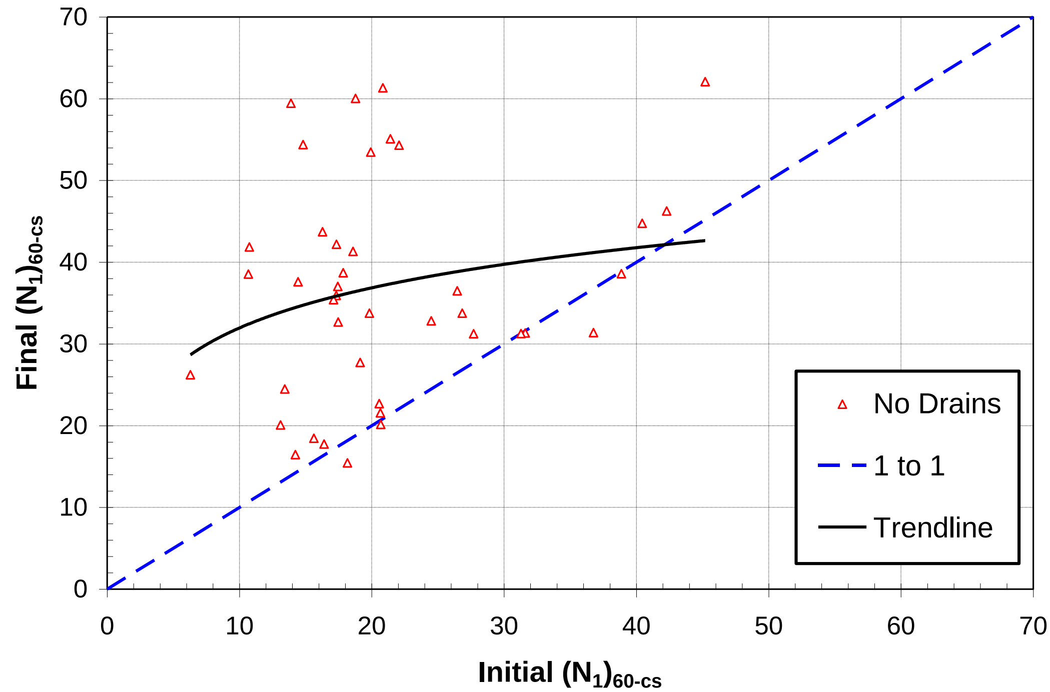
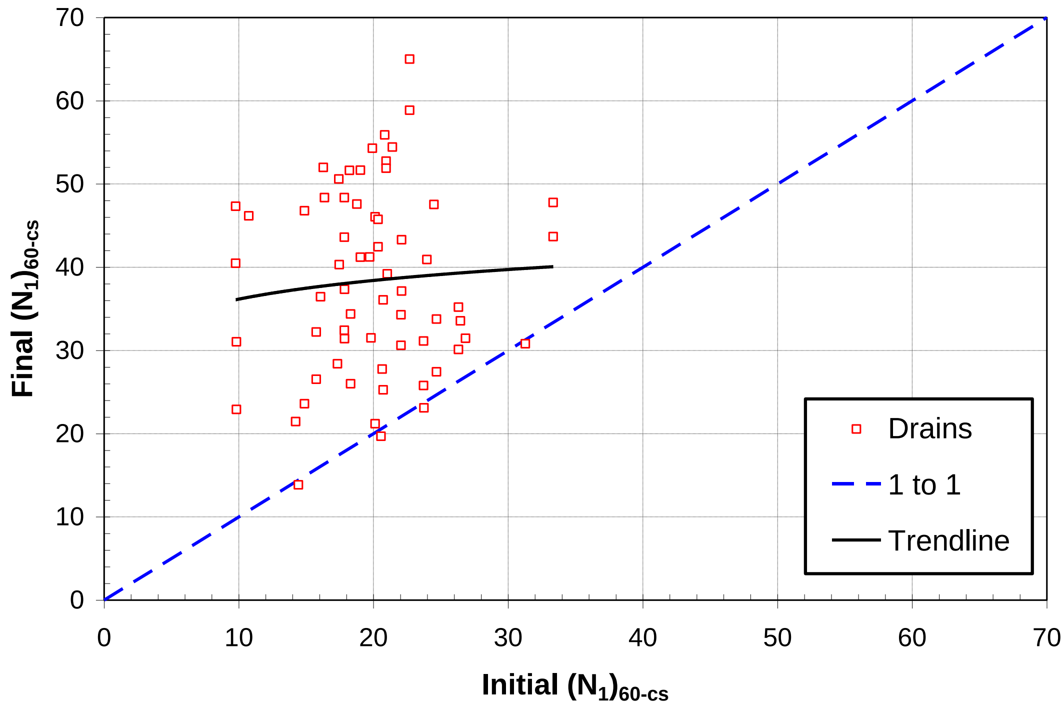


Figure 4.12 $\Delta(N_1)_{60\text{-}cs}$ versus depth for the test areas with and without drains.

Figure 4.13 plots the final $(N_1)_{60\text{-}cs}$ values versus the initial values. The data was divided into plots of (a) the areas without drains and (b) areas with drains, with points above the 1 to 1 line indicating improvement over the pre-mitigation test. A best fit curve is included on each plot to show the trend which indicates that although there is significant scatter, the final value increases as the initial value increases. The data for the areas with drains do not show much improvement over the data with no drains when comparing these charts. Once again, all four points that fell below the 1 to 1 line in the plot for areas with drains came from Site D and three of the points had a high fines content value as indicated previously.



(a)



(b)

Figure 4.13 Final $(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ comparison for the test areas (a) without drains and (b) with drains.

The data from the test section was compared with clean sand (<15% fines) curves developed by Baez Satizabal (1995) by superimposing the final $(N_1)_{60\text{-cs}}$ versus initial $(N_1)_{60\text{-cs}}$ trend lines on Figure 4.14 below. Unlike the curves by Baez, the best fit curves for the Salmon Lake should be thought of as averages rather than statistically valid equations. The trend lines for the data indicate that the higher fines content limited the improvement when compared with a Baez curve for soils with less than 15% fines. Although the areas with drains had area replacement ratios of 23 and 31%, the curves for theses areas were comparable to the Baez curve for an area replacement ratio of 15%. For areas where drains were not used, the trend shows that the data was comparable to the Baez curve for an area replacement ratio of 10%. From this comparison it can be inferred that the area with drains were more effective in mitigating liquefaction, despite the fact that there was a higher fines content in the areas with drains than in the areas without drains, as indicated in the fines content figures in Figure 4.5.

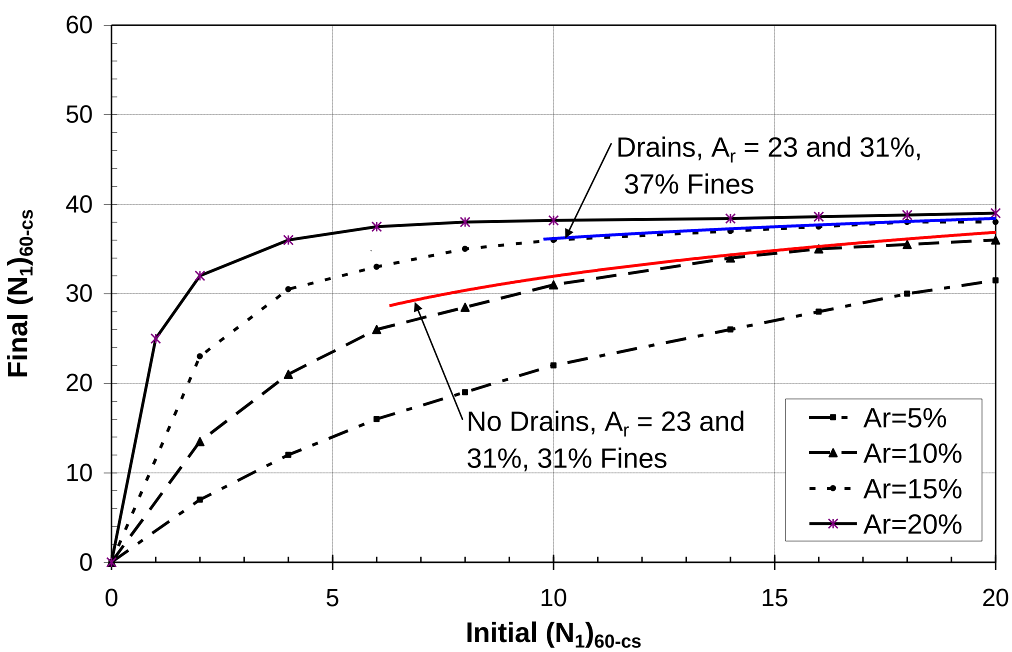


Figure 4.14 Average clean sand results compared with clean sand (<15% fines) curves developed by Baez Satizabal (1995).

Table 4.1 summarizes the average initial and final blow counts, the percentage of increase, the average fines content, and the number of final values that did not meet the minimum required $(N_1)_{60\text{-}cs}$ value. Results are provided for areas with and without drains that had area replacement values of 23% and 31%. In areas with and without drains the initial values were about the same at 20 and 21. The average fines content for the area with drains was 6% higher than the area without, yet the area with drains still averaged an increase in $(N_1)_{60\text{-}cs}$ values that was 11% higher than the area without drains. The areas with drains had 4 values (6%) that fell below the minimum required final $(N_1)_{60\text{-}cs}$ value, while the areas without drains had 6 values (15%).

Table 4.1 Blow counts, fines contents, and other values for Sites C and D with area replacement ratios of 23 and 31%.

	Average $(N_1)_{60\text{-}cs}$				Ave. Fines Content (%)	Values Below Lique. Trigger.	Sample Size	Standard Dev. (Final)	Coeff. of Variation (%)
	Initial	Final	Change	Increase					
Drains	20	38	18	92%	37	1	64	11.1	29
No Drains	21	37	16	75%	31	2	41	13.1	36

Table 4.1 does not show that stone column treatment with drains was significantly more effective than in the areas without drains, as was the case in Figure 4.14. The trendlines in Figure 4.14 were truncated at an initial $(N_1)_{60\text{-}cs}$ value of 20. Looking back at the same data without the curves truncated, (see Figure 4.13), the curve for the areas without drains continues to increase above a final $(N_1)_{60\text{-}cs}$ value of 40 while the curve for the areas with drains remains level around a final $(N_1)_{60\text{-}cs}$ value of 38. Therefore, for final $(N_1)_{60\text{-}cs}$ relative to the initial $(N_1)_{60\text{-}cs}$ values, the no drain cases performed better than cases where drains were used above an initial $(N_1)_{60\text{-}cs}$ value of about 25.

The standard deviations for the final $(N_1)_{60\text{-}cs}$ values are 11.1 to 13.1 in Table 4.1 and the coefficients of variation are 29 and 36%. These values are consistent with the findings of Kulhawy (1992) that the coefficient of variation for SPT blow counts range from 15-45%.

As was done in Figure 4.11, a second table was created with the same analysis, but removing data with fines content values above 50%, shown in Table 4.2. By removing these data points, the difference in percent increase between the areas with and without drains increased from 11 to 37%. These results indicate that the effect of the drains on improvement is more pronounced for cases with fines contents less than 50%. For higher fines contents the beneficial effect of the drains may not be sufficient to allow adequate drainage. This result is consistent with results obtained by Rollins and Quimby (2009) which showed greater effectiveness for drains in soils with lower fines contents. They reported on the test site at the 24th Street Bridge in Ogden, Utah where stone columns were used with and without wick drains. They found that for an average fines content of 29% in the area with drains and 27% in the area without drains the average percent improvement increased only 35% in areas without drains but increased 148% in areas with drains. For soils with the higher average fines content of 32% in the area without drains and 40% in the area with drains the amount of improvement was not as pronounced with an average percent improvement of only 8% in areas without drains and 69% in areas with drains.

Table 4.2 Blow counts, fines contents, and other values for Sites C and D with area replacement ratios of 23 and 31%, removing the data set with fines content above 50% removed.

	Average $(N_1)_{60\text{-}cs}$				Ave. Fines Content (%)	Sample Size	Standard Dev. (Final)	Coeff. of Variation
	Initial	Final	Change	Increase				
Drains	20	41	21	106%	23%	44	11.3	0.28
No Drains	22	37	15	69%	27%	37	12.4	0.33

The following observations can lead to a conclusion that the use of wick drains in conjunction with stone column increased their effectiveness.

- The visual observation of water and air escaping the wick drains during stone column installation.
- The improvement in $(N_1)_{60\text{-}cs}$ values as a function of the initial $(N_1)_{60\text{-}cs}$ values plot for an A_r of 23% is approximately 5 blow counts higher for the curve for areas with drains over the no drain curve.
- The improvement in final $(N_1)_{60\text{-}cs}$ relative to initial $(N_1)_{60\text{-}cs}$ for tests involving drains relative to the case without drains, particularly when compared to the Baez Satizabal curves for clean sand.
- The higher average percent improvement for stone columns treatment with drains.

5 OVERALL SITE ANALYSIS AND RESULTS

5.1 Overview

From the analysis completed on the test section, it was determined that for the remainder of the treatment area, wick drains would be used. In addition, six rows of stone columns would be used with the two outer rows on each upstream and downstream side of the dam using columns with 3.75 ft diameters and the inner two rows using columns with 3 ft diameters. Whereas, center-to-center spacing of the stone columns would be 6 ft for all columns so that the outer rows would have an A_r of 35% and the inner rows would have an A_r of 23%. In areas between the outer and inner rows an average of the three nearest A_r values was calculated. The average A_r for the stone columns on this boarder was 27%.

Following construction, SPT tests were used to determine if the mitigation plan was effective. The following comparisons summarize the initial and final SPT data for the overall site, including both the areas from the test sections as well as the entire mitigation project, for all the areas where wick drains were used.

The SPT data for the entire site was evaluated using two comparisons. First, pre- and post-mitigation data was analyzed by different area replacement ratios where there was a pre-mitigation bore hole near a post-mitigation bore hole, (which will be referred to as a matching pair). The distance between the pre- and post-mitigation bores holes was no more than 20 feet. Second, all pre- and post-mitigation data was analyzed after separating the data by soil type.

5.2 Analysis by Area Replacement Ratio

To add to the matching pairs from areas with wick drains at the test section there are were three other matching pairs to include from the overall site. The SPT results for these matching pairs and the soil profile from the post-mitigation testing are included in Figure 5.1 and 5.2. The heavy dashed line indicates the minimum required final $(N_1)_{60\text{-}cs}$ values. The plots indicate that there were three post-mitigaton locations where the minimum requirement was not met in areas with drains for the three locations of tests. The point that did not meet the minimum criteria in the area with an A_r of 27% was in a layer of silty sand and had a fines content of 56%.

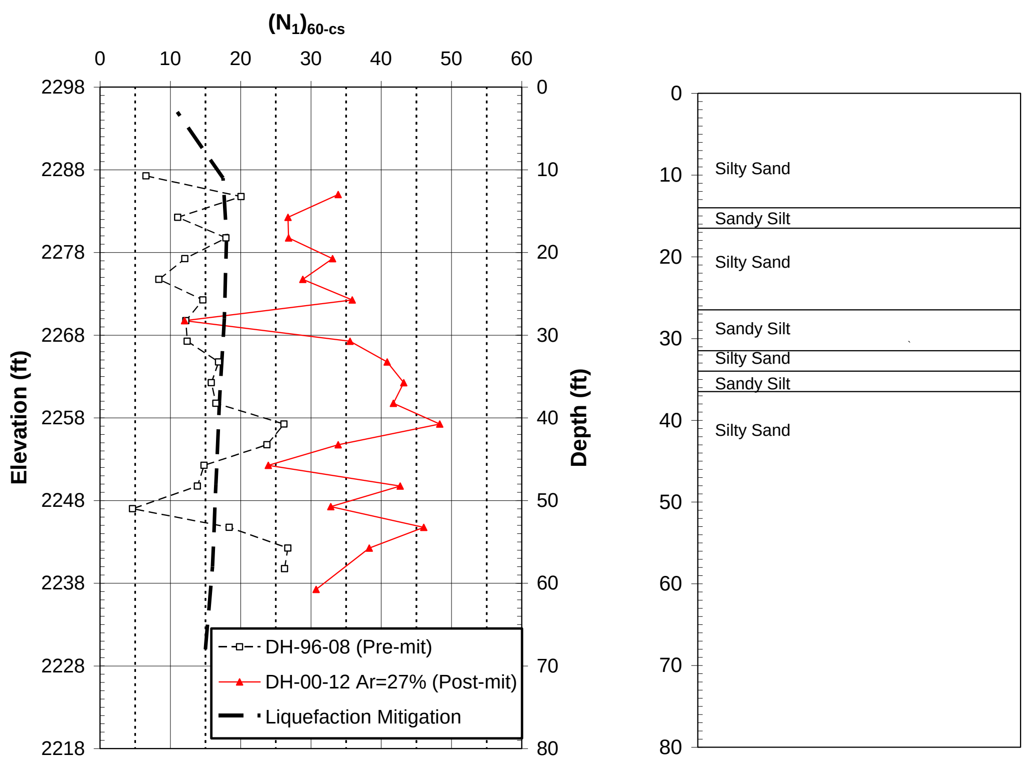


Figure 5.1 Soil profile and results from pre-mitigation and post-mitigation SPT tests with an A_r of 27%.

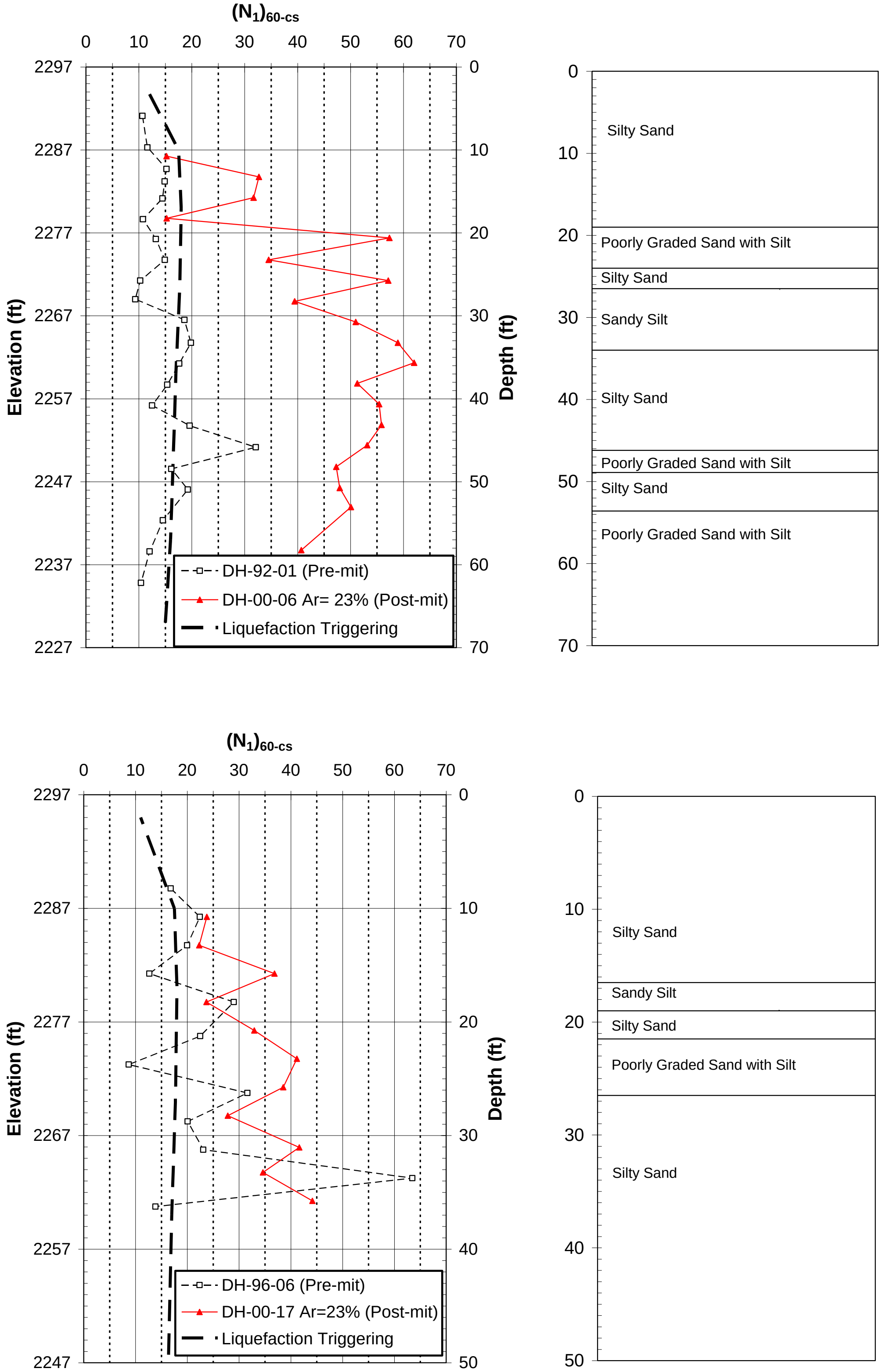


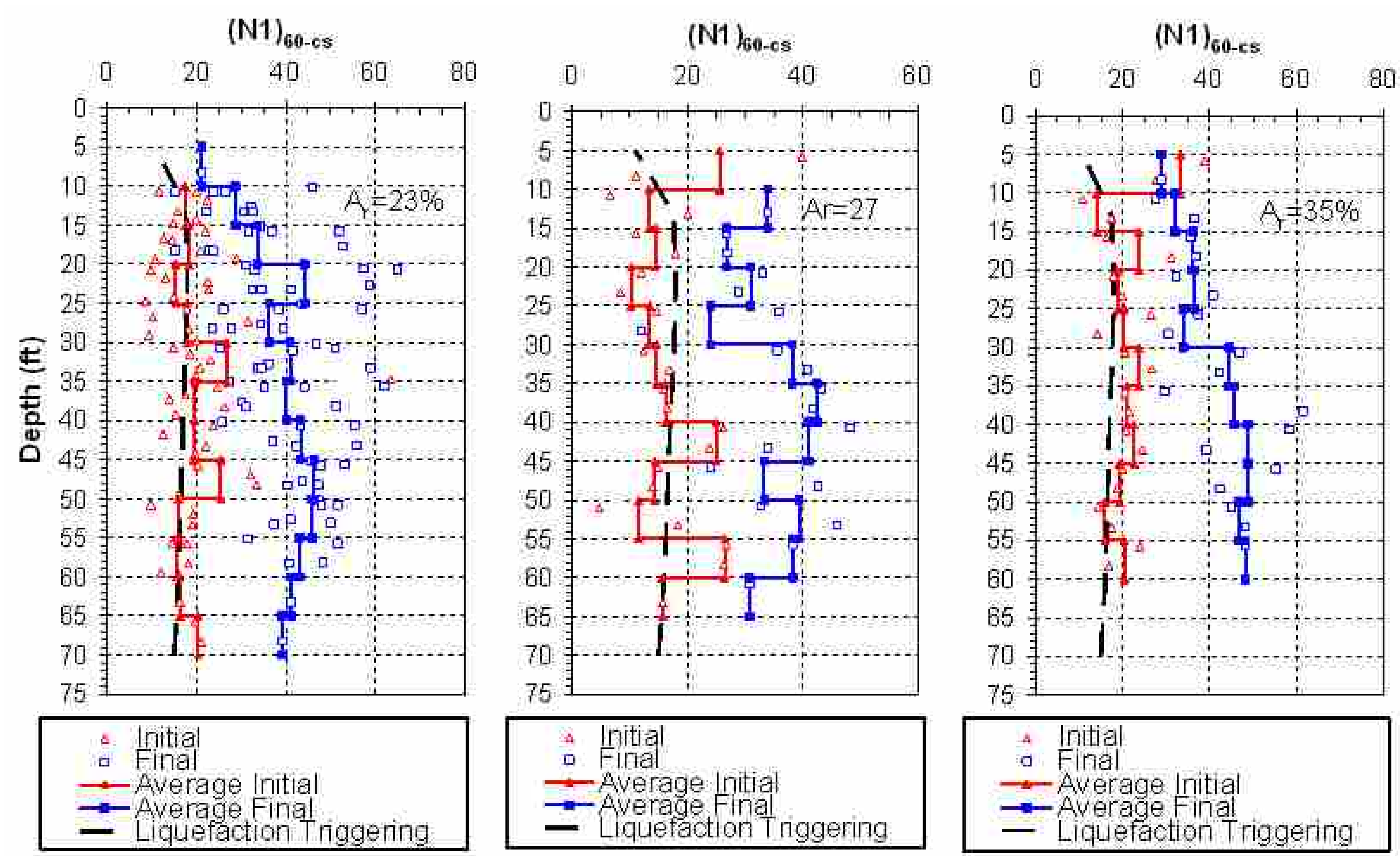
Figure 5.2 Soil profile and results from pre-mitigation and post-mitigation SPT tests for remaining areas with an A_r of 23% from the overall site.

Figure 5.3 shows the initial and final results of the SPT tests as well as the averaged results for bore holes with matching locations. Matching pairs were used with the expectation that if the tests were in close proximity to each other, the soil conditions would be similar. Each plot represents a different A_r value of 23, 27% and 35% which resulted from the final overall application of stone columns.

Each comparison of the averages shows improvement, except for depths of 5-10 ft for the areas with an A_r value of 35%. With the exception of that section, the average improvement for areas with A_r values of 23, 27 and 35%, from the above plots, were at least 11, 11 and 12 blowcounts, respectively. The heavy dashed line indicates the liquefaction triggering threshold at the site. As seen in the plots, in each of the areas with different area replacement ratios, the $(N_1)_{60\text{-}cs}$ values after treatment do not fall below the threshold.

Figure 5.4 plots the fines content data with a median value and mean ± one standard deviations for different layers in the profile. From 7 to 30 feet the median was approximately 22 and from 40 to 70 feet the median was approximately 19. Similarly, from 30 to 40 feet the median was about 41, which corresponds to the layers of sandy silt seen in the previous figures of soil profiles. The median fines content for the entire soil profile was 27%.

A plot showing improvement in $(N_1)_{60\text{-}cs}$ versus fines content is shown in Figure 5.5. The trend lines are relatively constant because the clean sand value was used for this analysis, although the curve for an A_r of 23% shows a decrease in the improvement as fines content increases. The greatest variation occurs due to a high amount of improvement in the $(N_1)_{60\text{-}cs}$ values for fines content less than 20%.



(a) (b) (c)

Figure 5.3 Initial and final blow counts versus depth for areas with an area replacement ratio of (a) 23, (b) 31% and (c) 35%.

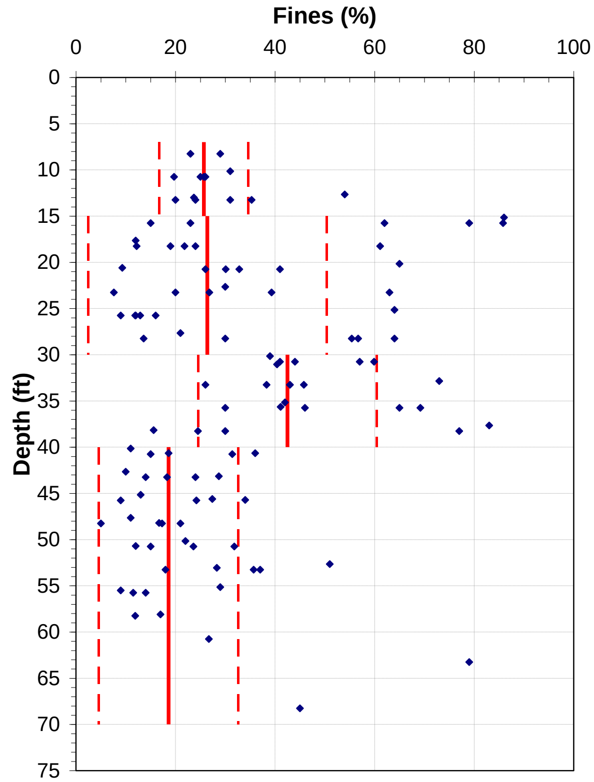


Figure 5.4 Fines content values with median (solid line) and one positive and negative standard deviation (dashed line) for areas with matching locations of SPT tests.

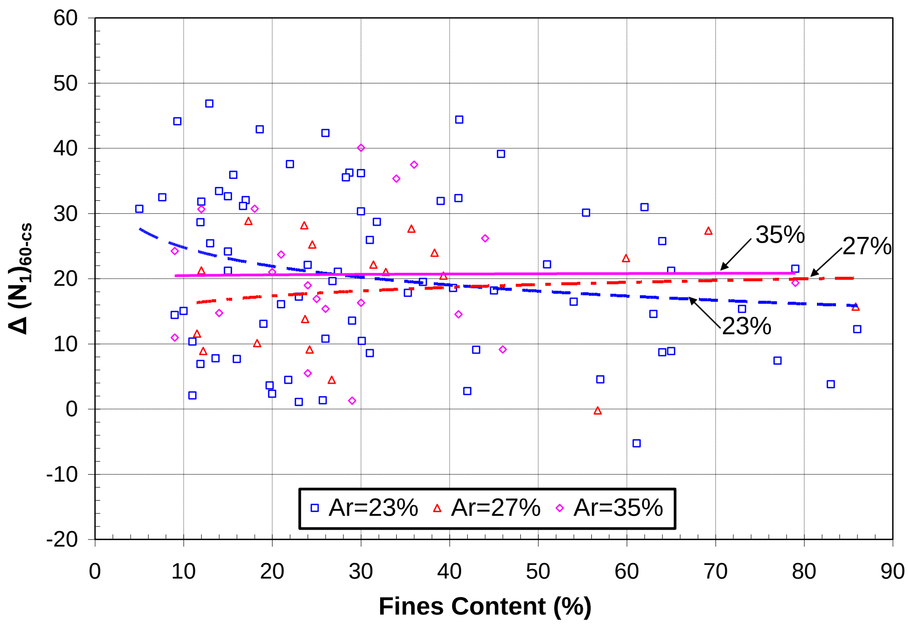


Figure 5.5 Improvement in $(N_1)_{60\text{-}cs}$ versus fines content for A_r values of 23, 27, and 35% for the overall site.

Once again, the initial $(N_1)_{60\text{-}cs}$ values were compared to the improvement in the $(N_1)_{60\text{-}cs}$ values, as seen in Figure 5.6. Although the results are not as consistent as those found in the test sections, some similar results can be observed. The improvement curve for the area with an A_r of 35% showed a slight improvement over the area with an A_r of 23%. Below an initial $(N1)_{60}$-cs value of approximately 13, the 23% curve is higher than the 35% curve. This is due to a significant improvement in blow counts at low initial values for the areas with an A_r of 23% (three points showed improvement over 300%). The area with an A_r of 27% had the lowest improvement curve of the areas with wick drains. The improvement versus initial blow count curve for the area with an A_r of 23% where no drains were installed in the test section is also shown on this plot to allow comparison with all the matching pairs where drains were used. The trend lines indicate that the areas with drains performed better except for the areas with a 27% area replacement ratio for initial $(N_1)_{60\text{-}cs}$ values less than about 12. This resulted from the lower initial $(N_1)_{60\text{-}cs}$ in the areas with an A_r of 27% which skewed the best fit curve for 27% to the left in the plot.

The best fit improvement curves for areas with drains and no drains at an A_r of 23%, including the data from the entire site, is shown in Figure 5.7. This plot also shows the difference between the two curves at initial $(N_1)_{60\text{-}cs}$ values of 10, 20, and 30. The curves show a similar trend to those presented in the test section chapter for improvement versus initial normalized blow counts. Although the absolute increase in blow count obtained from adding drains decreases from 8 to 3 as the initial value increases, the percentage increase remains about the same, only ranging from 33 to 36%.

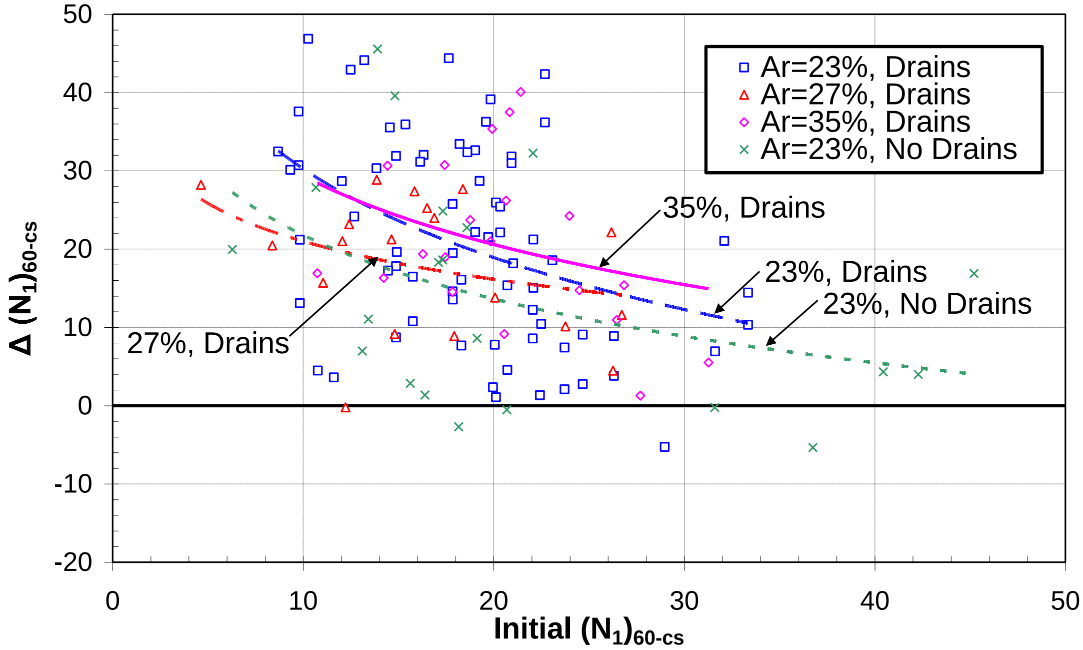


Figure 5.6 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for areas with area replacement ratios of 23, 27 and 35%.

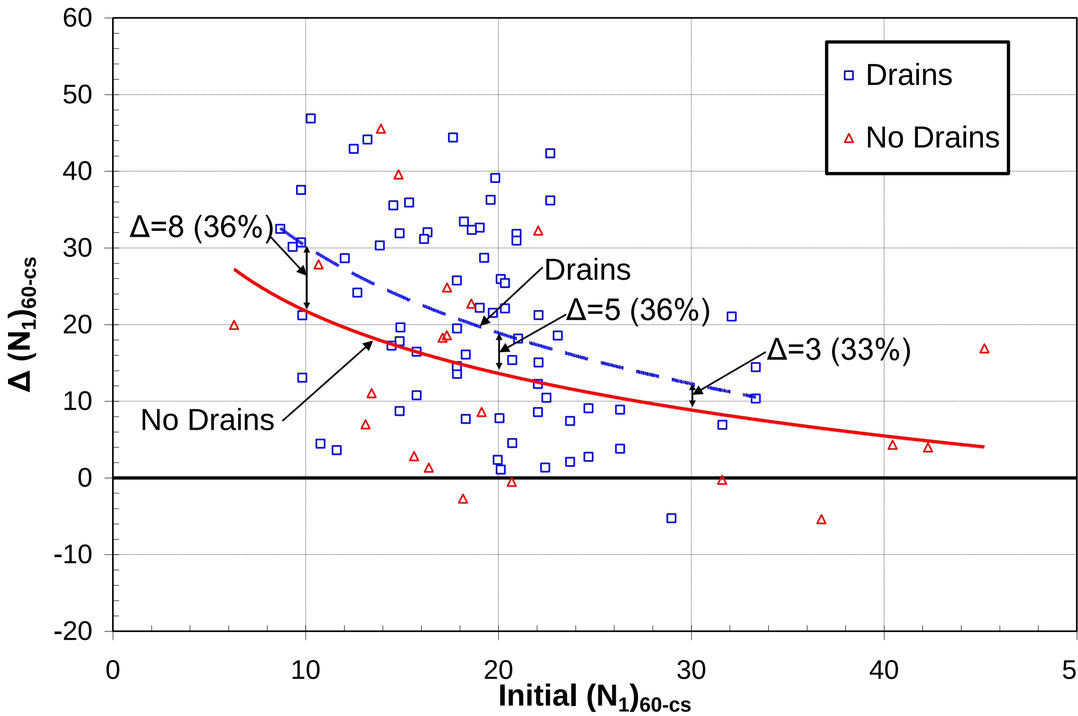


Figure 5.7 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ curves for areas with and without drains with replacement ratios of 23%. The change in the improvement and the percent change in improvement between the two curves is shown at initial $(N_1)_{60\text{-}cs}$ values of 10, 20 and 30.

The improvement in $(N_1)_{60\text{-}cs}$ versus the initial $(N_1)_{60\text{-}cs}$ for the case history at the 24th Street Bridge in Ogden, Utah (Rollins and Quimby 2009) is shown in Figure 5.8 for comparison to the results from Salmon Lake. The 24th Street site had a 26% area replacement ratio with a fines content of 34% in the area with drains and 29% in the area without drains. The results for 24th Street show similar trends to those of Salmon Lake and also indicate that there is increased effectiveness when drains are used in connection with stone column treatment in silty sands. However, the amount of benefit from adding wick drains is greater, ranging from approximately 12 to 20 blows per foot higher in the 24th Street Bridge case. The increased spread between the drain and no drain curves for the 24th Street Bridge site could be a result of the difference in wick drain layouts. Although, wick drains were installed between every column in the test section at

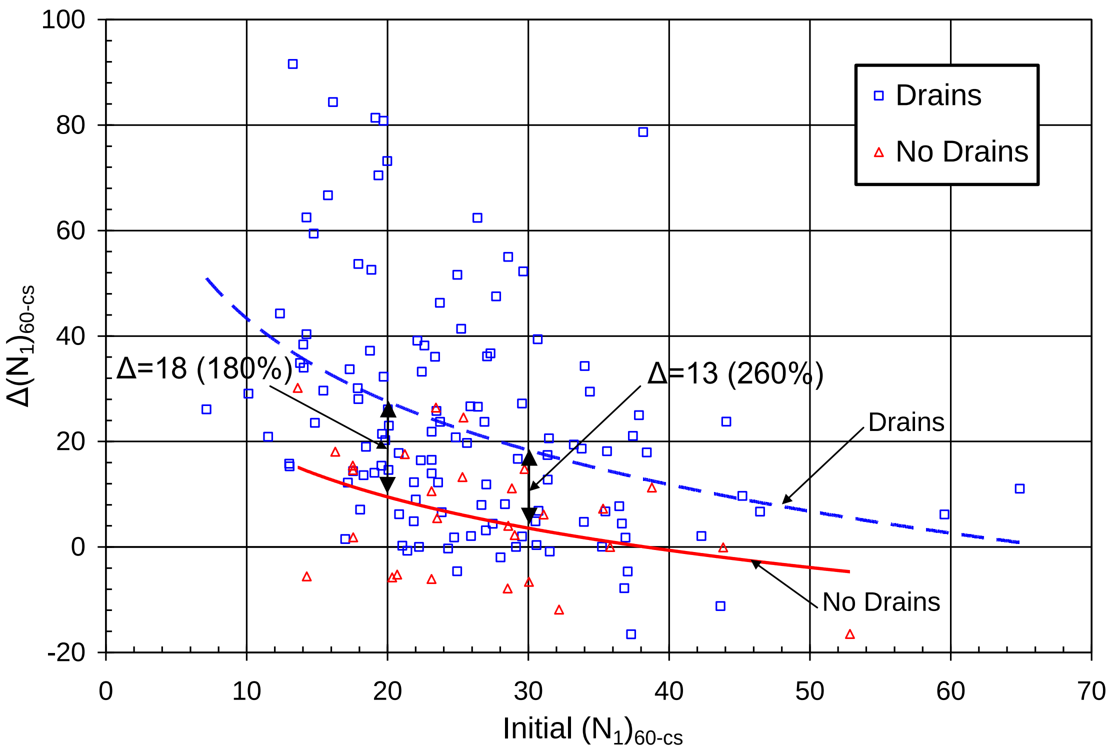


Figure 5.8 $\Delta(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for the overall site at the 24th Street Bridge in Ogden, Utah with and without drains where the area replacement ratio was 26% (Rollins and Quimby 2009).

Salmon Lake; in the final design, wick drains were only installed between stone columns diagonally and not between stone columns horizontally (see Figure 3.5). Wick drains were installed on all sides of the stone columns at the 24th Street Bridge location (see Figure 2.4).

The improvement in $(N_1)_{60\text{-}cs}$ for matching pairs throughout the overall site was plotted to look for trends relative to depth, as seen in Figure 5.9. The plot shows significant scatter and therefore provides no relationship to depth. The areas with a 23% area replacement ratio had one point of negative improvement, areas with 27% A_r had one point with zero improvement, and areas with 35% had none.

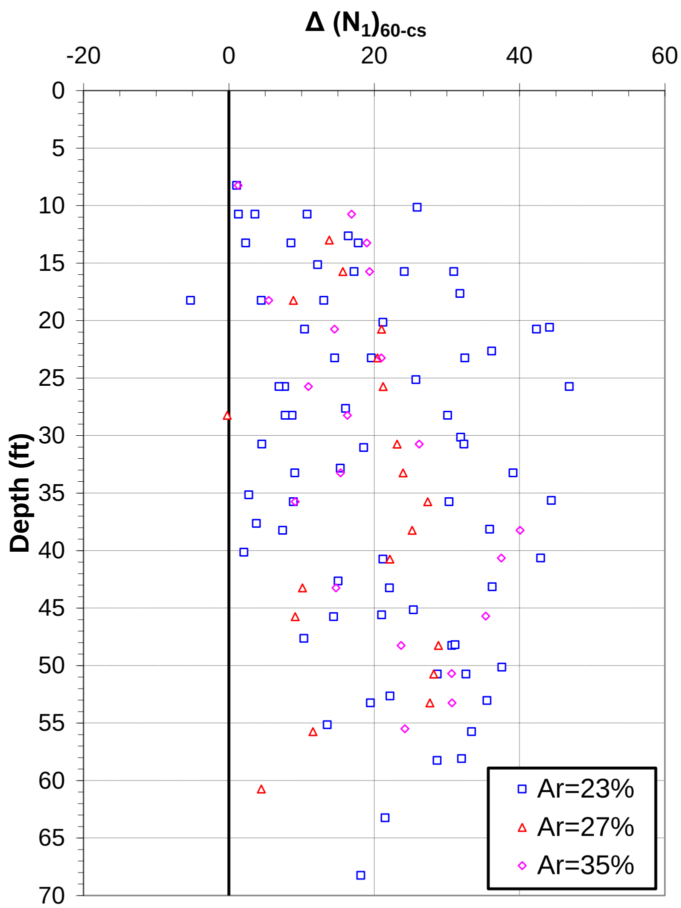


Figure 5.9 Depth versus $\Delta(N_1)_{60\text{-}cs}$ for areas with area replacement ratios of 23, 27 and 35%.

Figure 5.10 plots the final $(N_1)_{60\text{-}cs}$ values versus the initial values, with points above the 1 to 1 line indicating improvement over the pre-mitigation test. A logarithmic best fit curve is included for each area replacement ratio. As in the previous figure, the areas with an A_r of 23% and 27% each show one point of negative improvement and areas with A_r of 35% shows none. Although, the best fit curve for the final blow counts were higher for the A_r value of 35% than for the A_r of 23%, the best fit curve for the A_r of 27% was below both curves. These results are inconsistent with the improvement that would be expected to accompany an increase in the stone column area replacement ratio.

The inconsistency in the results in Figure 5.6 and Figure 5.10 may be influenced the small SPT data sets for A_r of 27 and 35%, clay content variations, variation in installation procedures, and difference in soil profile and fines content from site to site.

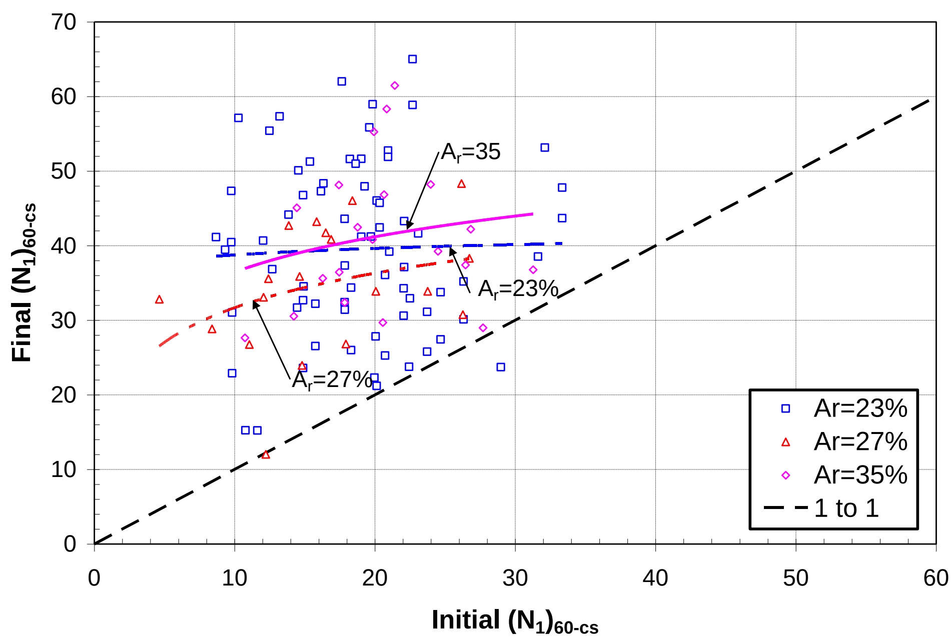


Figure 5.10 Final $(N_1)_{60\text{-}cs}$ versus initial $(N_1)_{60\text{-}cs}$ for areas with area replacement ratios of 23, 27 and 35%.

The initial and final SPT data for all the matching pairs at the stone column mitigation site were compared with the curves developed by Baez Satizabal in Figure 5.11, as was done for the test section data. The best fit curves in Figure 5.11 suggest that the higher fines contents of the soil at the Salmon Lake site limited the improvement when compared with a Baez curve for soils with less than 15% fines. This conclusion is similar to that observed from the trend lines at the test sections. The areas with A_r values of 23 and 35% had average fines content at 33 and 29% and were comparable to the Baez curve for an area replacement ratio of 20%. The curve for areas with A_r of 27%, which had 34% average fines, fell along Baez's curve for an A_r of 10% and less than 15% fines. This result is reflective of silty soils, with higher fines contents that would not respond to stone column mitigation as well as other types of soils. While these results indicate that the drains are producing a beneficial effect on stone column treatment, the treatment is still not as effective as that obtained for clean sands.

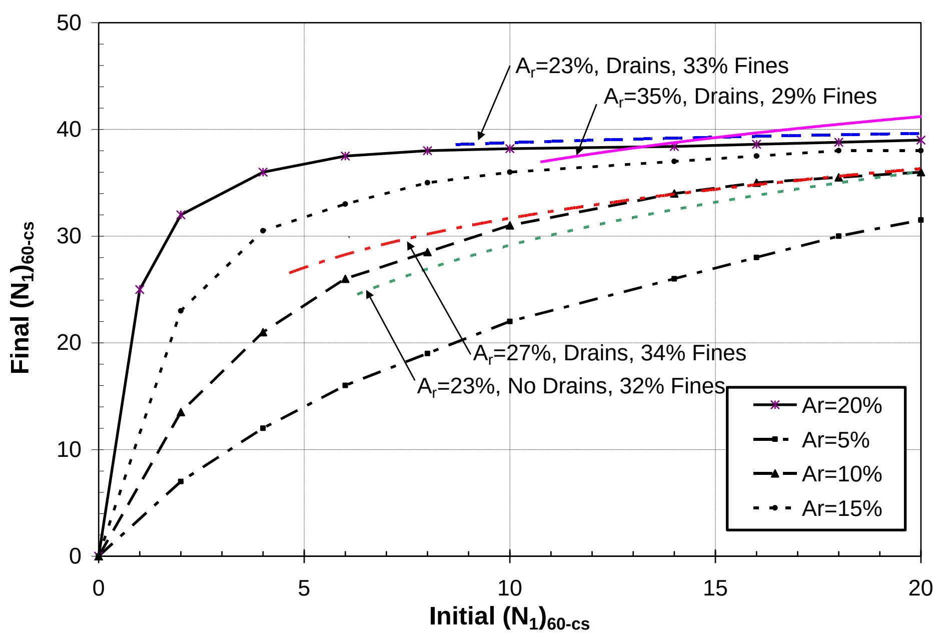


Figure 5.11 Average clean sand results for areas with area replacement ratio of 23, 27 and 35% compared with clean sand (<15% fines) curves developed by Baez Satizabal (1995).

Figure 5.12 includes the best fit curves for only the areas with an A_r of 23% with and without drains. The curve for the area without drains with a 23% area replacement ratio and 32% fines fell just below the 10% curve, as apposed to the areas with drains (33% fines) that lies just above the Baez clean sand curve for an area replacement ratio of 20%. Similarly to the test section plot, this figure indicates that stone columns do benefit by adding wick drains.

The residuals from the final blow count versus initial trend line for the areas with an A_r of 23% are plotted versus fines content in Figure 5.13. A linear trend line is also shown for the data for cases with and without wick drains. Once the influence of initial blow count is accounted for, it can be seen that influence of fines content is negligible with an R-squared value of 0.0352 for areas with drains and 0.0053 for areas without drains.

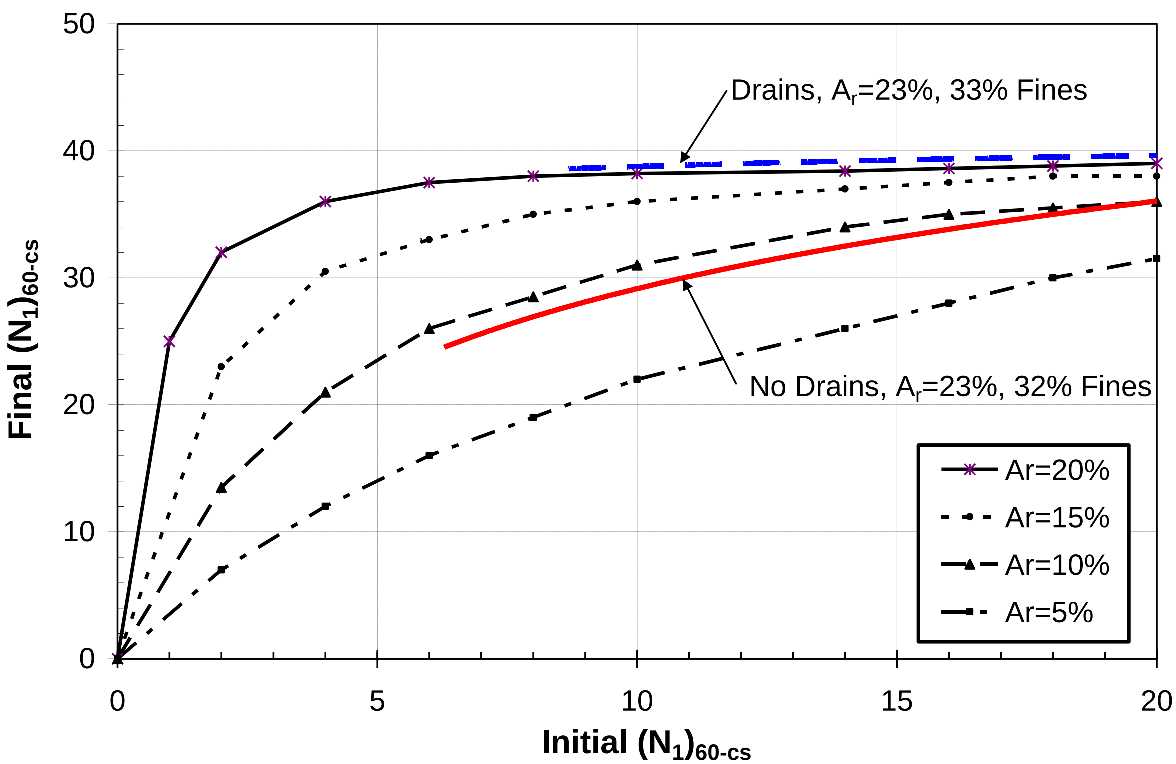


Figure 5.12 Average clean sand results for areas with area replacement ratio of 23% with and without drains compared with clean sand (<15% fines) curves developed by Baez Satizabal (1995).

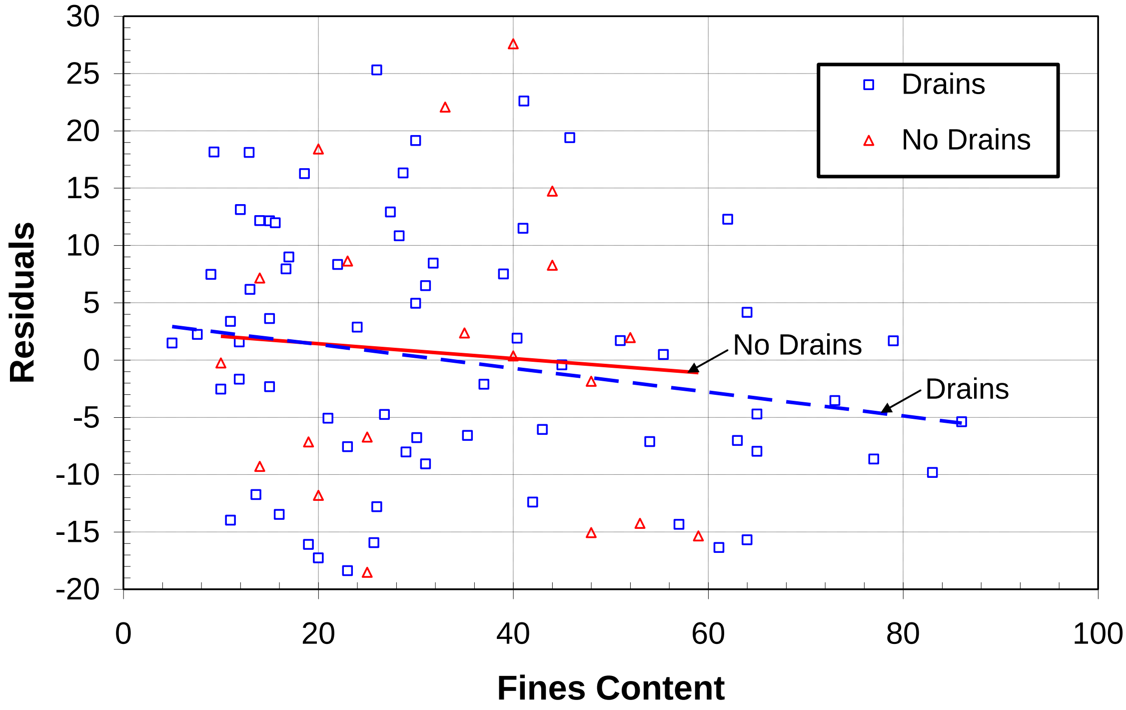


Figure 5.13 Fines content versus the residual values from linear regression on final blow count values using initial blow count as the predictor.

The summary of data from the matched pairs for the overall site is included in Table 5.1, which gives the average initial and final blow counts, the percentage of increase, and the average fines content for areas with A_r values of 35, 27, and 23% with drains and for an A_r value of 23% for areas without drains. In the areas with an A_r of 23%, the areas with drains performed more effectively than the areas without drains. By adding drains the change in blow count increased from 15 to 21 and the percent improvement increased from 70% to 108%.

Table 5.1 Blow counts, fines contents, and improvement for area replacement ratios of 23, 27 and 35% with drains and 23% without drains.

A_r	Average $(N_1)_{60-cs}$				Ave. Fines Content (%)	Sample Size	Standard Dev. (Final)	Coefficient of Variation (%)
	Initial	Final	Change	Increase				
23% No Drains	21	36	15	70%	31	21	14.3	40
23% With Drains	19	40	21	108%	33	71	11.6	29
27% With Drains	16	34	18	110%	34	19	8.7	25
35% With Drains	21	41	20	97%	29	20	9.7	24

In Figure 5.6 and Figure 5.10 the areas with an A_r of 27% were the least effective of all the cases where drains were used. In Table 5.1 these areas have the lowest average final $(N_1)_{60-cs}$ and average change at 18, compared to 21 for an A_r of 23% and 20 for an A_r of 35%. Because the average initial $(N_1)_{60-cs}$ was so low, at 16, compared to the other initial $(N_1)_{60-cs}$ values, which were 19 and 21, the percent increase is slightly better than that for other A_r values. Figure 5.6 and Figure 5.10 also indicate the area with an A_r of 35% was the most effective. The curves for areas with an A_r of 23% showed comparable or slightly improved results at low initial $(N_1)_{60-cs}$ values where the high final blow counts for A_r values of 23%. In Table 5.1, the area with drains and an A_r of 23% exhibited a similar amount of change as the areas with an A_r of 35%, but with a higher percent improvement, due to its lower average initial $(N_1)_{60-cs}$ values.

As seen in the table, the sample size for the areas with A_r of 27% and 35% was limited due to the lack of matching pairs for the available SPT data. This limited amount of data may explain why the results do not show an improvement as the A_r values increase.

The coefficient of variation (COV) for the areas with drains ranged from 24 to 29% for the three different A_r values which is again consistent with the findings by Kulhawy (1992). These COVs are considerably smaller than the 40% value for sites where drains were not used.

5.3 Analysis by Soil Type

The final analysis of the SPT data from the Salmon Lake liquefaction mitigation project includes all of the pre-mitigation and post-mitigation data where wick drains were used. The data was divided by soil type in an effort to identify any correlations between soil type and increased improvement in SPT values.

The individual fines content values for the entire site are included in Figure 5.14, along with a median and standard deviation range. Similar to the previous fines content profiles, this figure shows that there is a substantial increase in fines at depths of 26 to 40, where the median is 38% fines.

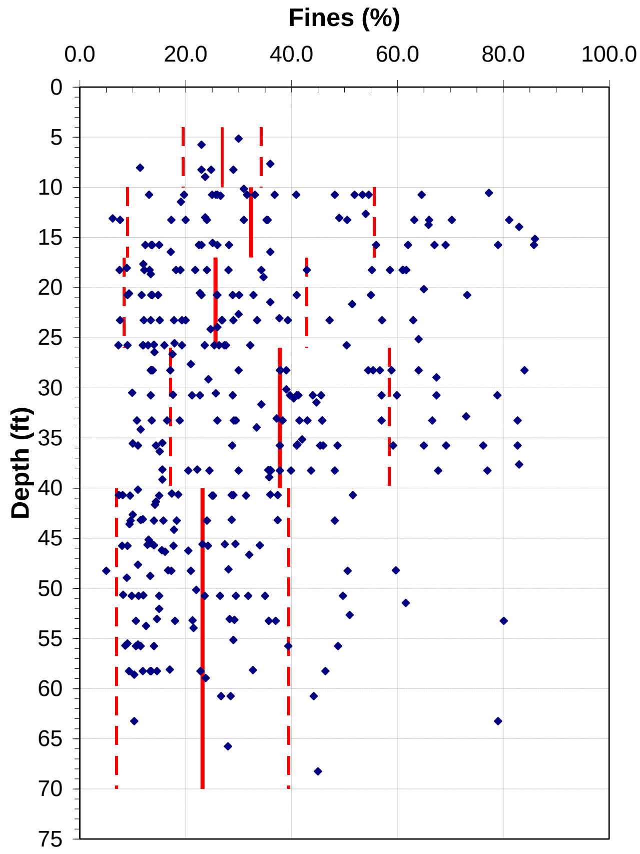
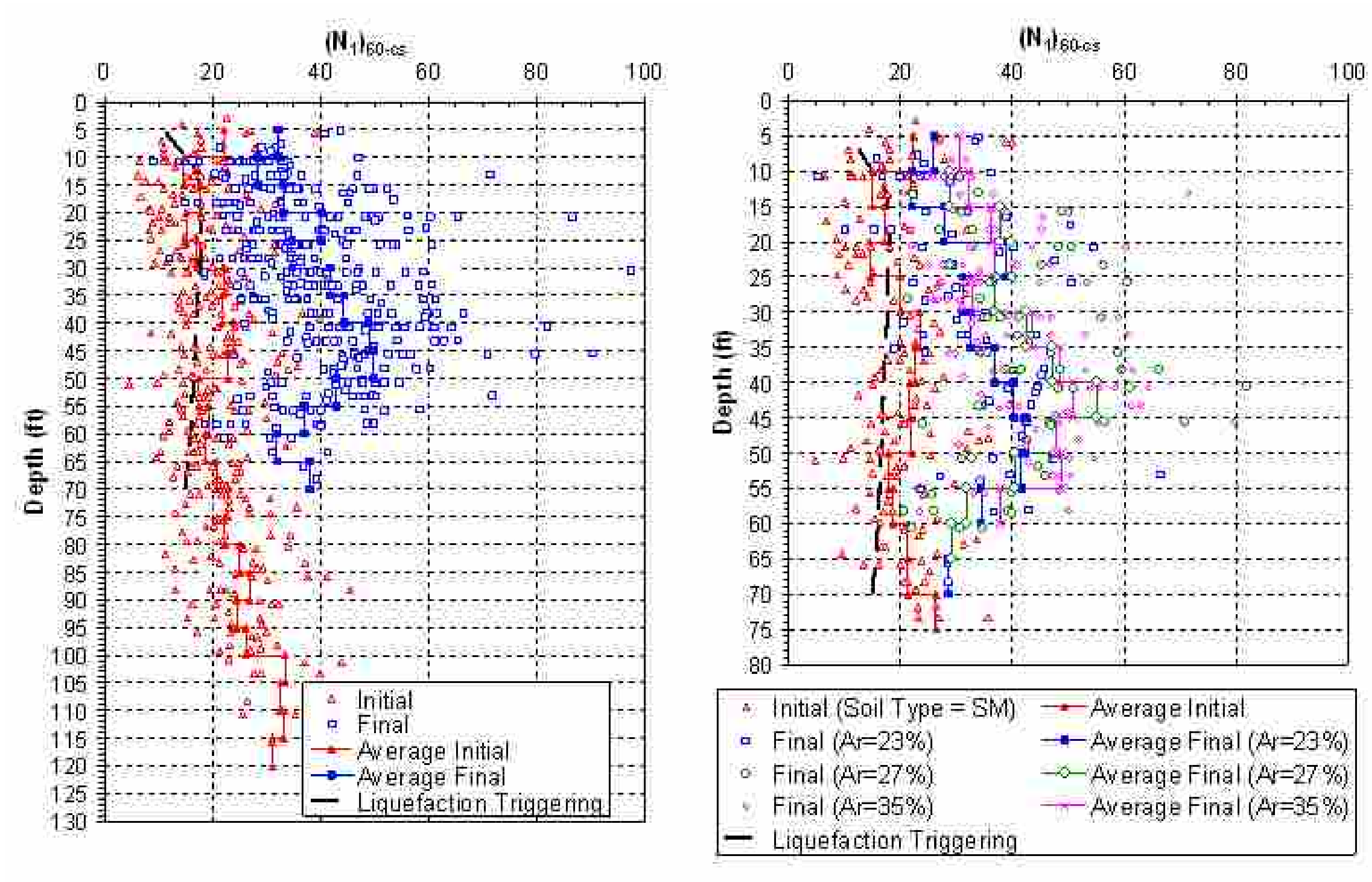


Figure 5.14 Fines content values with median (solid line) and one standard deviation bounds (dashed lines) for all post-mitigation data at the dam site.

Figure 5.15 includes the average initial values for all of the areas where drains were used. Plot (a) shows the results for all soil types and has a minimum average improvement of 9. The other plots show averages for the following soil types: (b) silty sand (SM), (c) silt (ML), and (d) poorly-graded sand with silt (SP-SM). Due to the low number of data points, silty gravel with sand (GM) was not included. Plot (b), (c) and (d) show averages for the different A_r values that resulted from the design of stone column diameter and spacing applied at the site: 23, 27, and 35%. The heavy dashed line indicates the liquefaction triggering threshold at the site. None of the plots exhibited an instance where the average post-mitigation blow count fell below the triggering threshold.

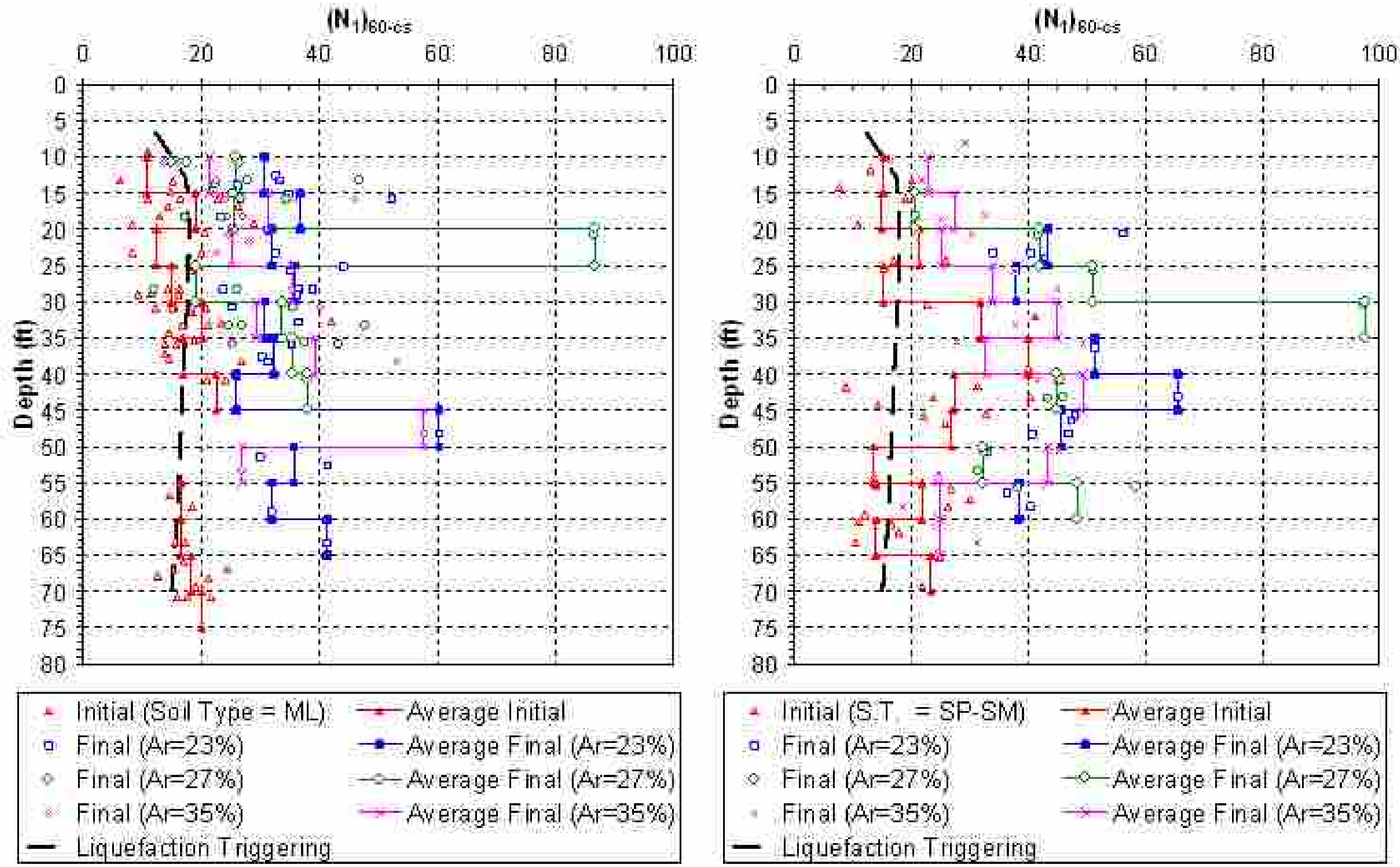
Plot (b) generally shows higher post-mitigation values associated with a higher A_r value as would be expected based on test results for clean sands (Baez Satizabal, 1995). However, plots (c) and (d) do not indicate any consistent increase in improvement with increasing $A_{r.}$ At this point, it is unclear whether this is a result of the influence of the soil type negating the effectiveness of the stone column treatment or simply the limited data set leading to unreliable averages.

A comparison in foundation improvement based on soil type and A_r is available in Table 5.2 for all pre- and post-installation SPT data where drains were used. The same values for the area with no drains and an Ar of 23% are also included for comparison. The average clay content data was provided by Luehring et al. (2001). The silty gravels (GM) had the lowest average initial $(N_1)_{60\text{-}cs}$ value and the lowest average fines content while exhibiting the highest final $(N_1)_{60\text{-}cs}$ values, change, and percent increase. The silty soils (ML) had the lowest amount of improvement. The soil types SM, ML, and SP-SM had similar average initial $(N_1)_{60\text{-}cs}$ values



(a) (b)

Figure 5.15 Initial and final blow counts versus depth for areas with area replacement ratios of 23, 27, and 35% for (a) all soil types (b) SM soils, (c) ML soils, and (d) SP-SM soils. The dashed line indicates the liquefaction triggering threshold.



(c) (d)

Figure 5.15 Continued from the previous page.

of 21, 20, and 22 respectively. Although the average final blow count increased for the silty sands (SM) as the Ar increased, soil types ML and SP-SM show the opposite outcome.

As seen in the table, the sample sizes for areas with A_r of 23, 27, 35% is limited for soil types GM and SP-SM. The limited amount of data, as well as the high variability of fines content (29-37%) could explain why improvement did not increase as the A_r values increased.

Table 5.2 Blow counts, fines contents, and improvement compared by soil type and area replacement ratios of 23, 27, and 35% for areas with drains and 23% for areas without drains.

Soil Type	Average Initial $(N_1)_{60-cs}$	Average Final $(N_1)_{60-cs}$ / Change / Increase			
		Drains A_r=35%	Drains A_r=27%	Drains A_r=23%	No Drains A_r=23%
SM	21	41/20/92%	41/20/91%	41/19/90%	37/15/71.1%
ML	20	30/10/49%	32/11/55%	35/14/71%	33/13/64%
GM	17	62/44/255%	52/34/199%	52/34/199%	---
SP-SM	22	32/10/46%	45/23/104%	45/23/105%	---
Soil Type	**Average Fines Content (%)**	**Average Clay Content (%)**	**Number of Samples**	**Standard Dev. (Final)**	**Coeff. of Variation (%)**
SM	26	5	262	13	34%
ML	64	11	76	12	38%
GM	10	2	5	19	32%
SP-SM	13	3	44	14	36%

The COV values from this data fell on the higher end of the range for SPT blow count (N) values, which is from 15-45% (Kulhawy 1992). However, because these COVs for the stone columns with drains at the Salmon Lake Dam are likely associated with the fact that the penetration resistance (mechanical property) is dependent on the soil permeability (fluid flow property). The COV values do fall on the low end of the range for properties dealing with fluid flow in soils (coefficients of permeability and consolidation), which have COV values from about 33% to as high as 90% (Duncan 2000).

6 CONCLUSION

6.1 Overview

In preparation for the Salmon Lake Dam reclamation project, test sections were constructed to determine the diameter and spacing (A_r value) of the stone columns and if wick drains should be used in conjunction with the stone columns. Following analysis by the Bureau of Reclamation, a final design was constructed involving outer rows of stone columns with an A_r of 35% and inner rows of stone columns with an A_r of 23% in a triangular pattern, with wick drains installed on the diagonals between columns. Post-mitigation testing was then conducted to check the effectiveness of the procedure.

6.2 Conclusions

The purpose if the investigation was to evaluate the use of stone columns with wick drains in soils containing high fines content. The fines content at the Salmon Lake Dam ranged from 5 to 86%. The average fines content for the test section data was 31% for cases with drains and 37% for cases without drains. In the final design, the average fines content ranged from 29 to 34% for matched pairs with different area replacement ratios, and for the overall site the average fines content was 32%.

The conclusions from the analysis of the two sets of data, test sections data and final design data, are summarized below:

1. Visual observations of water and air escaping from wick drains within a 15 ft diameter of the stone column construction confirmed that that drains aided in pore pressure dissipation.
2. Test results indicate that stone column treatment with wick drains produced greater improvement in blow count than stone column treatment without drains.
   a. For the test sections, best fit curves of improvement in normalized blow count versus initial normalized blow count indicate a consistent improvement of 5 blows/ft for the drain case over the no-drain case for an A_r of 23%.
   b. For the overall project, best fit curves of improvement in normalized blow count versus initial normalized blowcount indicate an improvement of 3 to 8 blows/ft for the drain case over the no-drain case for an A_r of 23%.
   c. The averages for the overall project indicate a greater amount of average improvement in $(N_1)_{60\text{-}cs}$ values for areas with drains (21 compared to 15 for areas without drains) and areas with drains had a greater average percent increase in $(N_1)_{60\text{-}cs}$ than areas without drains (108% compared to 70%).
3. The increase in stone column effectiveness achieved with drains at Salmon Lake Dam, Washington (3 to 8 blows/ft) was less than that obtained with drains at 24^{th} Street in Ogden, Utah (12 to 18 blows/ft) as reported by Rollins and Quimby (2009). Although the fines content was comparable in both cases, at 24^{th} Street drains were placed between each column which provided greater drainage. This increase in drainage capacity could explain the improved effectiveness.
4. Despite the beneficial effects provided by using wick drains with stone column treatment in silty soils, the improvement was still less than that which would be

expected for clean sands with less than 15% fines based on curves developed by Baez Satizabal (1995). At the test section, the areas where drains were used (which had 37% fines) produced improvement similar to the Baez curve for a 20% $A_{r,}$ and the areas without drains (which had 31% fines) produced improvement similar to the curve for a 10% A_r.

5. Although substantial improvements in the average blow count were obtained in silty sands with stone column treatment and wick drains, the coefficient of variation (COV) was 34% which is on the high end of the COV range for standard penetration test blow count. These high COV values are likely associated with the fact that improvement is connected with the soil permeability and consolidations which typically have even higher COV values ranging from 33 to 90% (Duncan, 2000).
6. For stone column treatment with and without drains, improvement in normalized blow count decreased as the initial normalized blow count increased. However, this finding is not particularly problematic because less improvement is necessary to prevent liquefaction for soils which are initially denser.
7. There was no consistent trend towards greater improvement in blow count as the replacement ratio (A_r) increased beyond 23% as would be expected. However, it is unclear whether this finding is entirely reliable because the sample size for higher A_r values was quite small and often involved geometries with limited extent.
8. Stone column treatment was less effective in layers of sandy silt (ML) than in layers of silty sand (SM).
   a. Average percent improvement in SPT $(N_1)_{60\text{-}cs}$ ranged from 49 to 71% in sandy silt and 90 to 92% in silty sand.

b. Points of negative improvement from the plot of improvement based on initial blow count were most often in layers of sandy silt (ML).

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