REMEDIATION OF BRIDGE FOUNDATIONS IN LIQUEFIABLE SOILS

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10 January 1999

Return to Table of Contents

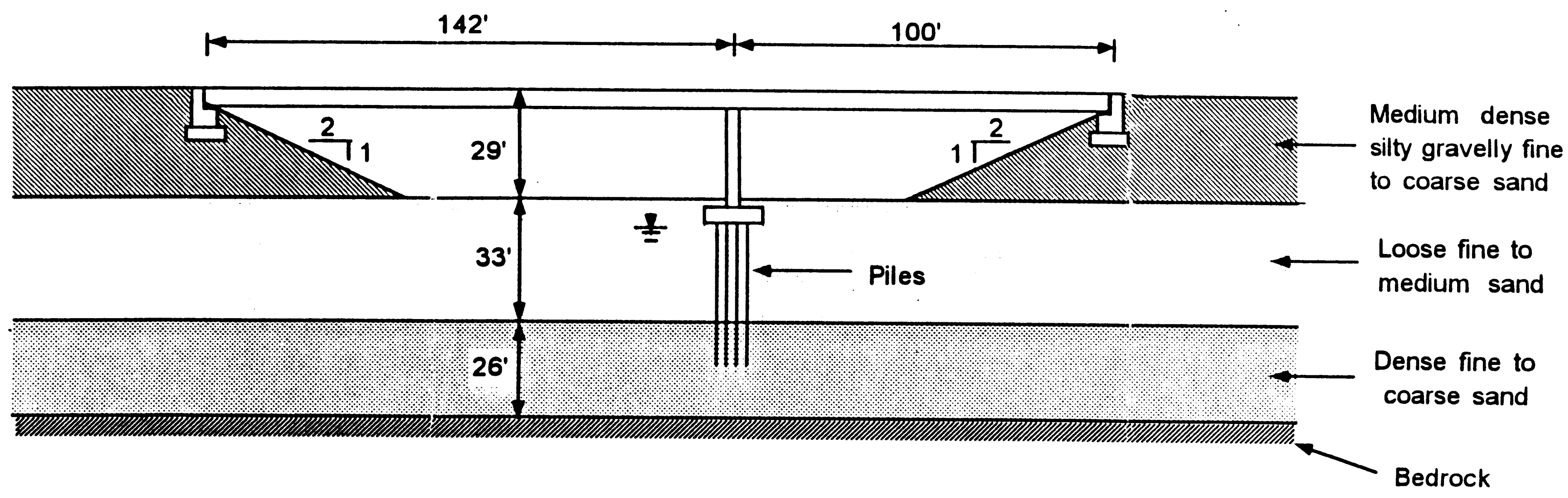
RETROFIT MEASURES—SOILS AND FOUNDATIONS

1. Liquefaction—Retrofit Options
2. Ground Remediation—Vibro Stone Columns
3. Ground Remediation—Compaction Grouting
4. Pile Foundation Retrofit—Lateral Spread Displacement Demand

Return to Table of Contents

LIQUEFACTION—RETROFIT OPTIONS

Return to Table of Contents



Bridge on Deep Foundation

Return to Table of Contents

Mitigation should provide suitable levels of protection with regard to two general types of liquefaction hazard, (1) potential large lateral spread failures, and (2) more localized problems including potential bearing failure, settlements, and lateral displacements (manifested by cyclic ground lurch and ground cracking). Methods for mitigation of lateral spread hazards may include one or more of the following approaches:

1. Edge containment structures (e.g., berms, dikes, sea walls, retaining structures, compacted soil zones);

2. Removal or treatment of liquefiable soils to reduce liquefaction potential;

3. Modification of site geometry to reduce the risk of translational site instability; and/or

4. Drainage to lower the groundwater table below the level of the liquefiable soils.

Return to Table of Contents

Once problems related to potentially large lateral spread failures have been resolved, "localized" potential hazards should be addressed and resolved. Suitable mitigation alternatives if needed, may include one or more of the following approaches:

1. Excavation and removal or recompaction of potentially liquefiable soils;
2.
3. In-situ ground densification (e.g., compaction with vibratory probes, dynamic consolidation, compaction piles, blasting densification, compaction grouting);
4.
3. Other types of ground improvement (e.g., permeation grouting, columnar jet grouting, deep mixing, gravel drains or other drains, surcharge pre-loading, structural fills, dewatering);

4. Deep foundations (e.g., piles, piers), that have been designed to accommodate liquefaction effects;

The scope and type(s) of mitigation required depend on the site conditions present and the nature of the proposed project. Individual mitigation techniques may be used, but the most appropriate solution may involve using them in combination.

Return to Table of Contents

Ground Improvement Ground Reinforcement Ground Treatment

Developments 1987-1997

Proceedings of sessions sponsored by the
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Return to Table of Contents

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Ground Improvement Techniques for Liquefaction Remediation Near Existing Lifelines

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October 1995
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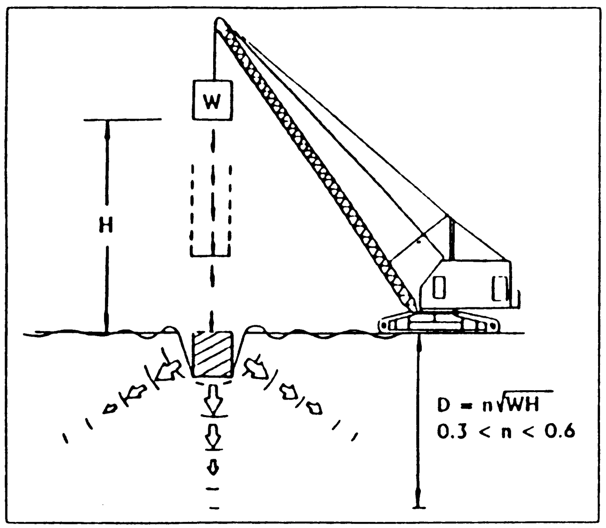
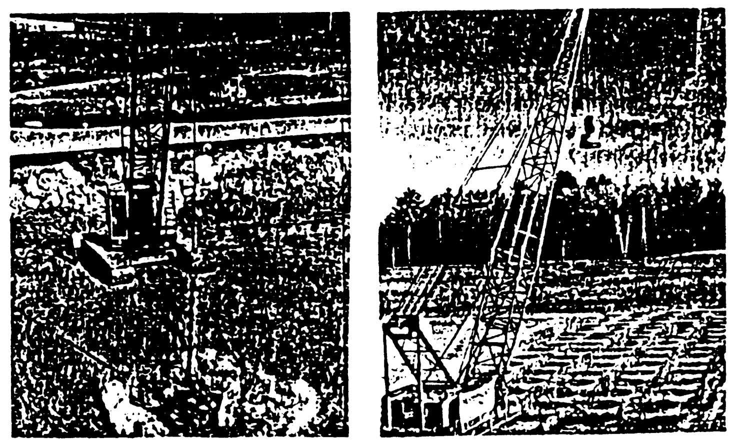
Ronald H. Brown, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati Prabhakar, *Director*

Return to Table of Contents

1. <u>Dynamic Deep Compaction:</u> This method (shown schematically in the figure) entails dropping weights of 10-40 tons from heights of 50-100 feet over impact grids ranging from 7x7 feet to 25x25 feet. The depth that can be effectively improved is a function of the size of weight, height of drop, and the soil type. The effective depth of improvement is limited to about 35 feet and is controlled by the soil type, degree of saturation, permeability, and initial relative density. Levels of ground vibration are an important environmental constraint, and areas treated using this method will probably need to be a minimum of 100 feet from existing structures. A detailed description of applications of dynamic compaction and associated ground response is given by Mayne et al. (1984), Poran and Rodriguez (1992), and Lucas, R.G. (1986).



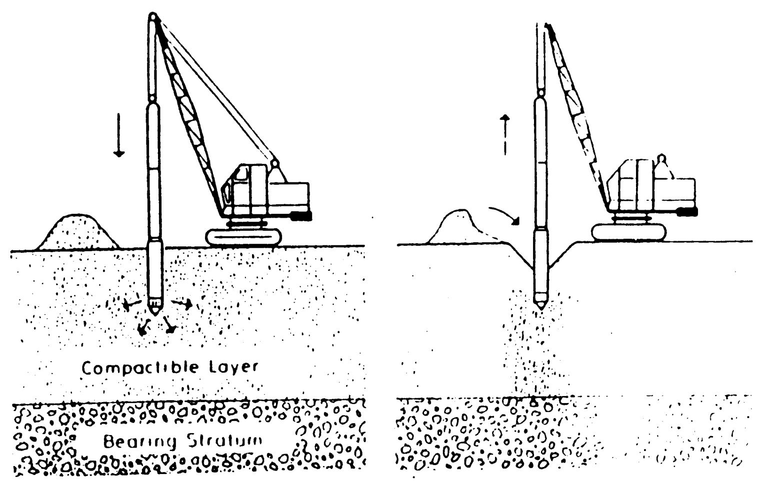
The dynamic compaction process (Lukas 1995)



Typical dynamic compaction equipment

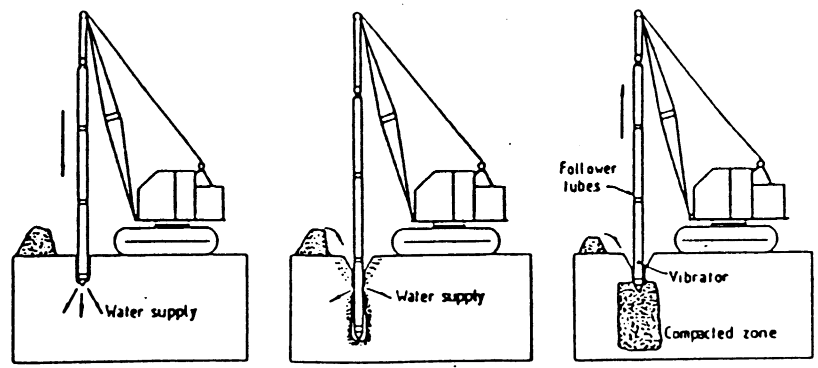
Return to Table of Contents

2. Vibro Compaction: This method (shown schematically in the figure) involves the repeated insertion and withdrawal of a large vibrating probe to be the desired depth of densification. In some cases granular backfill soil is added and densified during withdrawal of the probe. The procedure is repeated over the site using a grid spacing ranging between 6 and 11 feet. The effectiveness of the method depends on the initiation of localized liquefaction followed by reconfiguration of soil particles into a denser packing. Brown (1977) provides general background information on the vibroflotation technique. Dobson (1987) describes several case histories where vibro-systems have been used to minimized liquefaction.



The vibro compaction process.

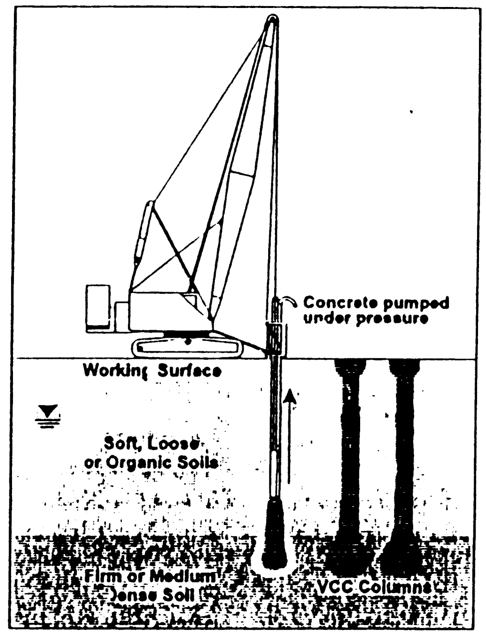
3. Vibro Replacement: This method (shown schematically in the figure) is suitable for soils containing more fines (silt) than can be effectively densified using dynamic compaction or vibro compaction and provides a more efficient vibratory process able to be used at greater depths. Gravel or crushed stone is backfilled and compacted during withdrawal of the vibrator leaving a dense "stone column" about 3 feet in diameter. These columns are installed in a grid with spacings ranging between 6 and 11 feet. The columns may also act to induce drainage and provide reinforcement of the soil. In the case of silty soils, wick drains may be used to enhance drainage during vibrations. Design approaches are described by Baez and Martin (1993).



Vibro-replacement equipment and process (Welsh, et al., 1987)

Return to Table of Contents

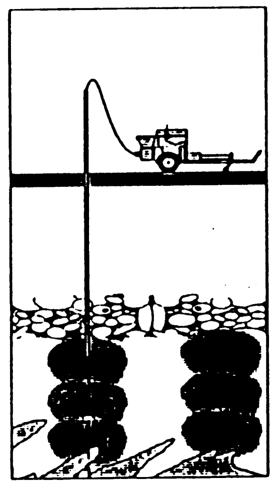
4. Vibro Concrete Columns: This technique (shown schematically in the figure) uses the advantages of vibrations for densification of loose granular soils and the addition of ready mix concrete for increased vertical and lateral support (Barksdale and Bachus, 1983). The method is specifically suitable for soil profiles which include soft silt and clay layers where a ground reinforcement approach may be needed to prevent lateral spread. The column can be compared for analysis with a driven concrete pile.



Vibro concrete column construction.

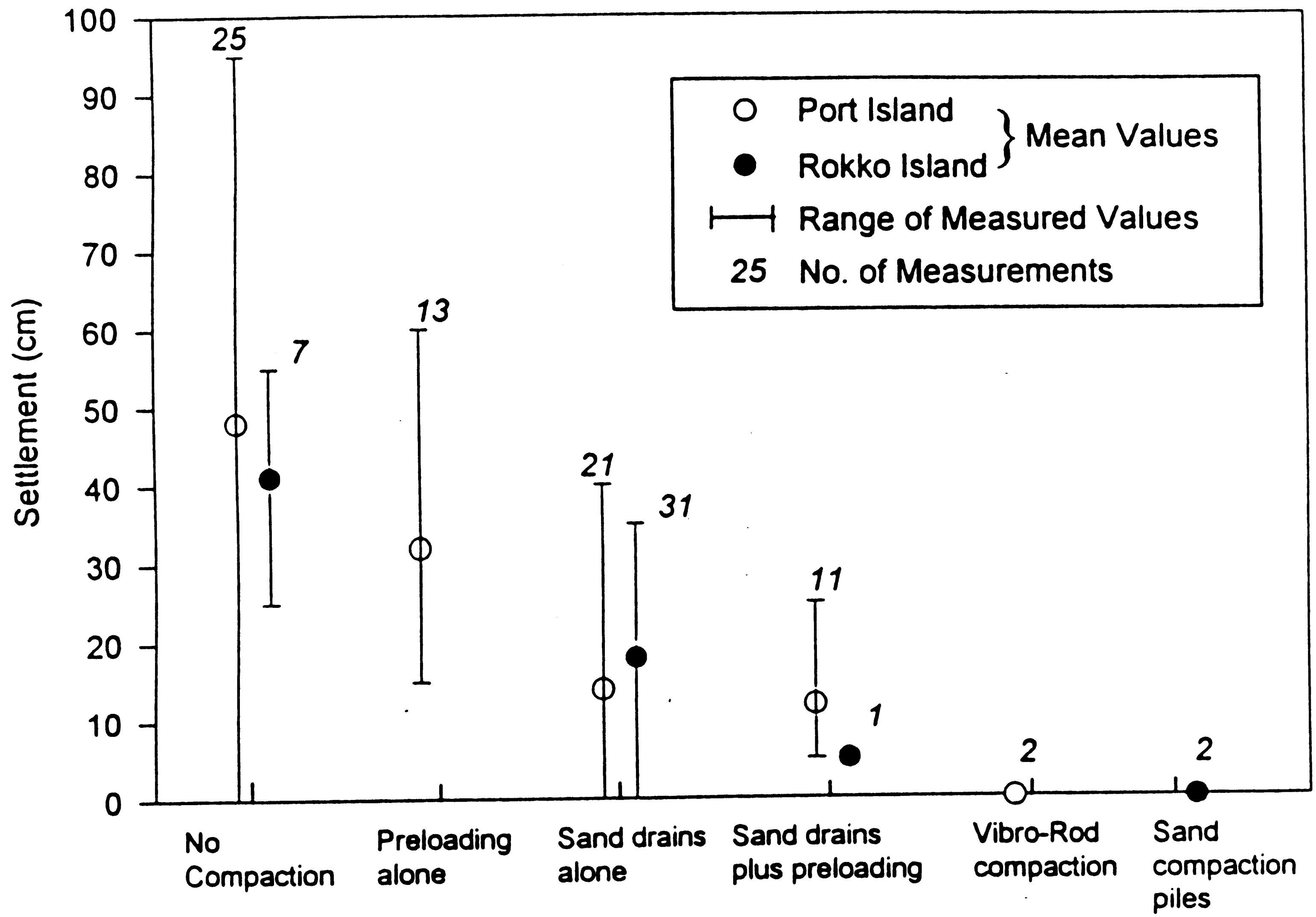
Return to Table of Contents

5. <u>Compaction Grouting:</u> Compaction grouting (shown schematically in the figure) involves pumping a stiff mix of soil, cement and water into the ground under high pressure to compress or densify the soil. For sites where dynamic compaction and vibratory techniques may be impractical, particularly those with deep layers of loose liquefiable soils, compaction grouting can be used to displace and densify the soil. Typically, a very stiff (1-2 inch slump) soil-cement-water mixture is injected into the soil, forming grout bulbs which displace and densify the surrounding ground, without penetrating the soil pores.



Compaction grout bulb construction.

Return to Table of Contents



Measured settlements at improved sites due to the 1995 Hyogo-ken Nambu (Kobe) earthquake (after Yasuda et al., 1996).

Return to Table of Contents

GROUND REMEDIATION—
VIBRO STONE COLUMNS

Return to Table of Contents

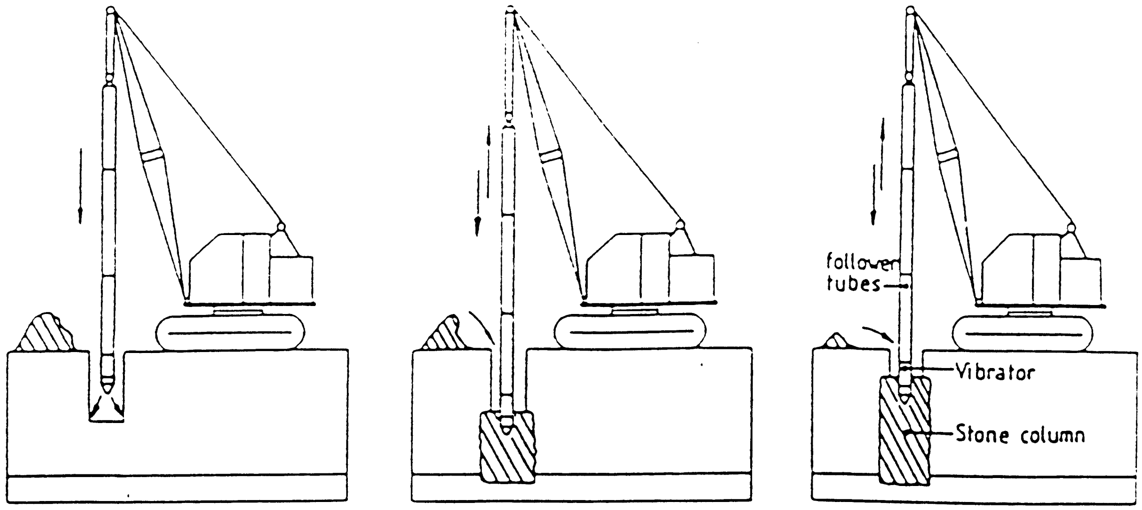
Ground Remediation using the Vibro-Replacement Method

- Most extensively used ground remediation method in the United States

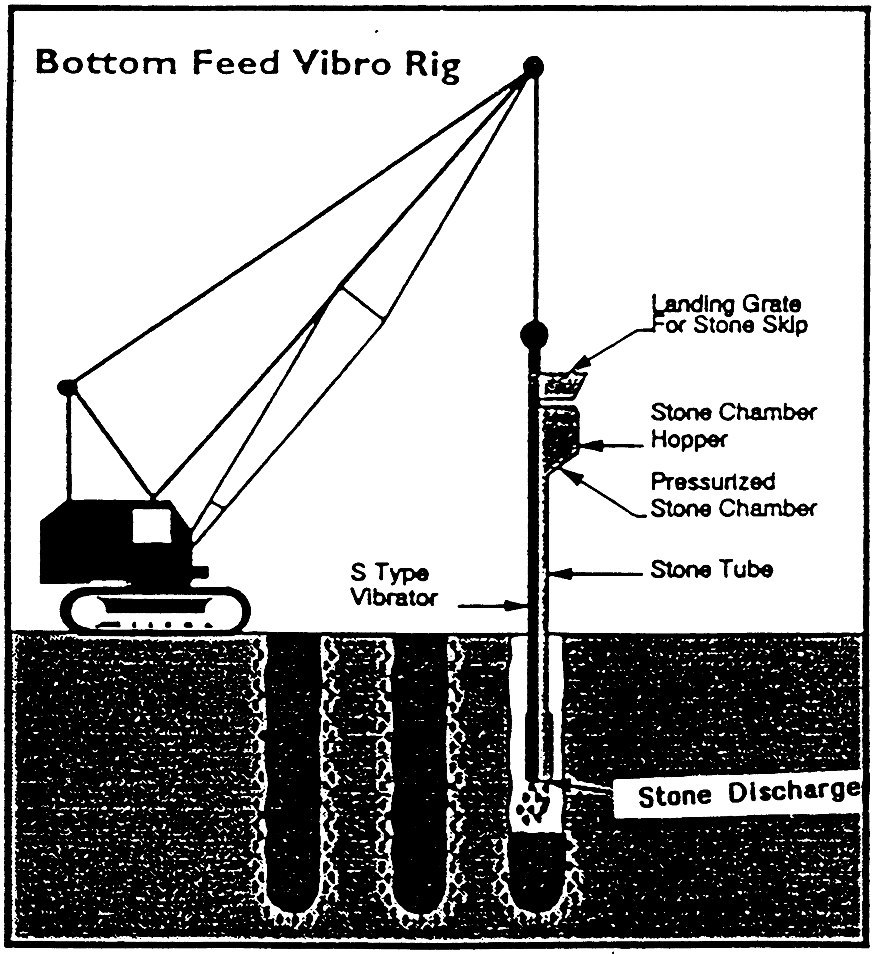
- Mechanics of densification?

- Design Applications

Return to Table of Contents



Formation of stone columns provides more effective transmission of vibration to densify soil and also provides means for radial drainage.



VIBRO-REPLACEMENT (STONE COLUMNS)
(FROM HAYWARD BAKER SEMINAR NOTES, 1992)

Return to Table of Contents

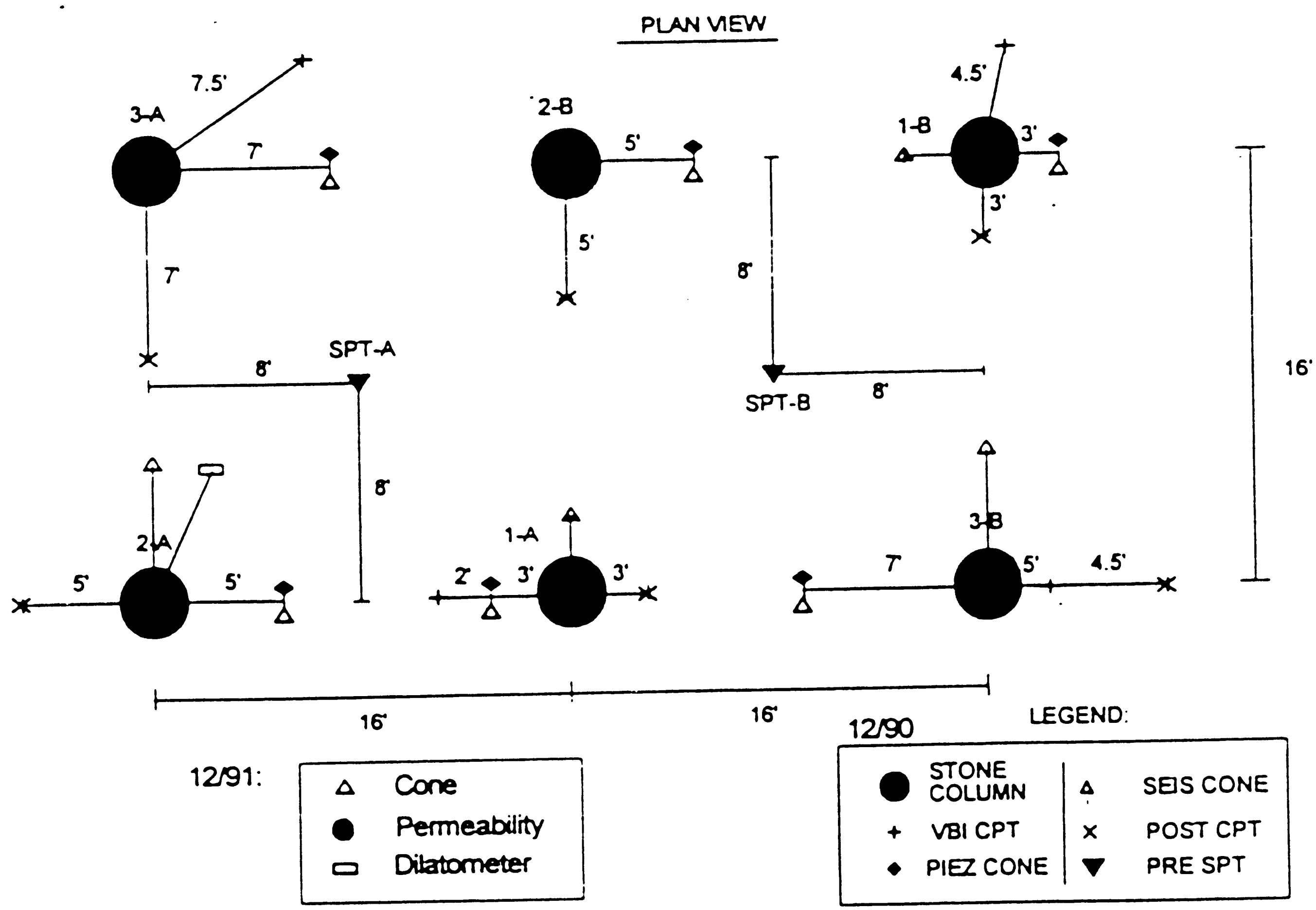


Figure 3.1 Stone Column and Instrumentation Locations for Monterey Field Study

Return to Table of Contents

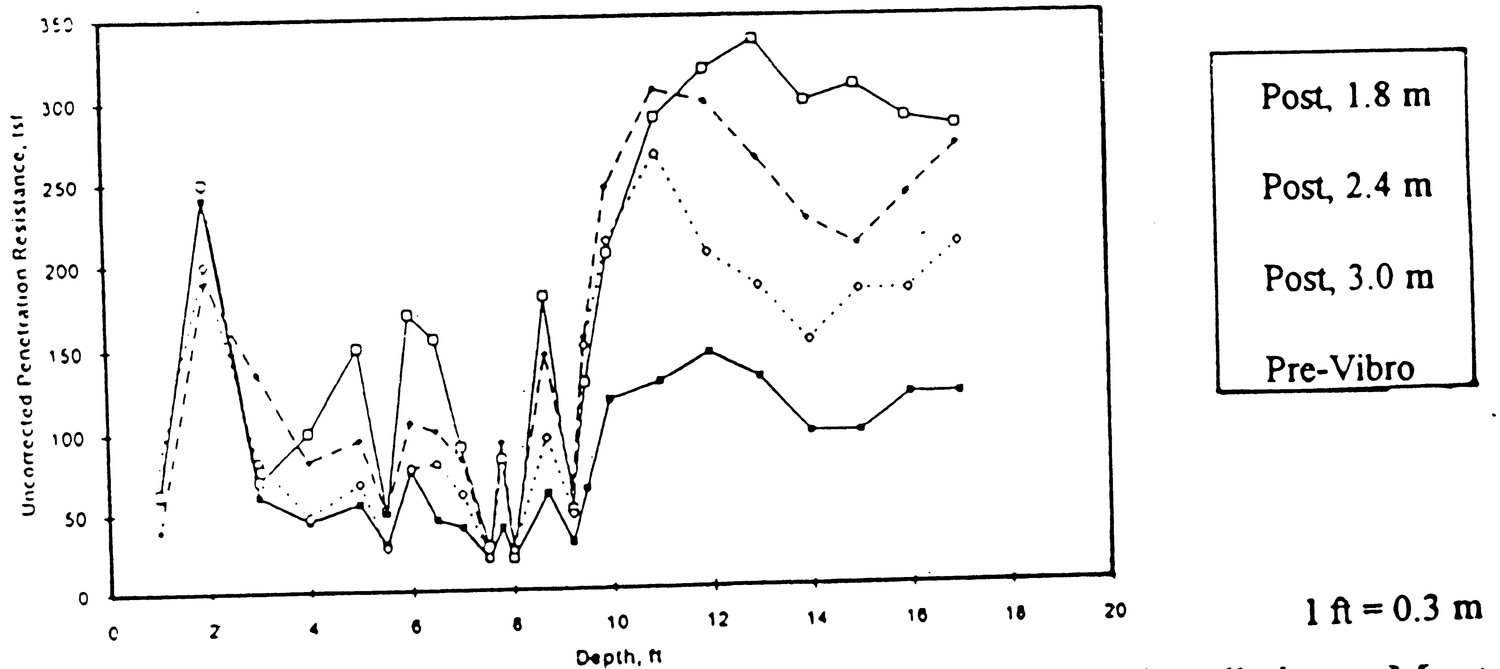


Figure 5. Results of Penetration resistance following stone column installation at Monterey site

Return to Table of Contents

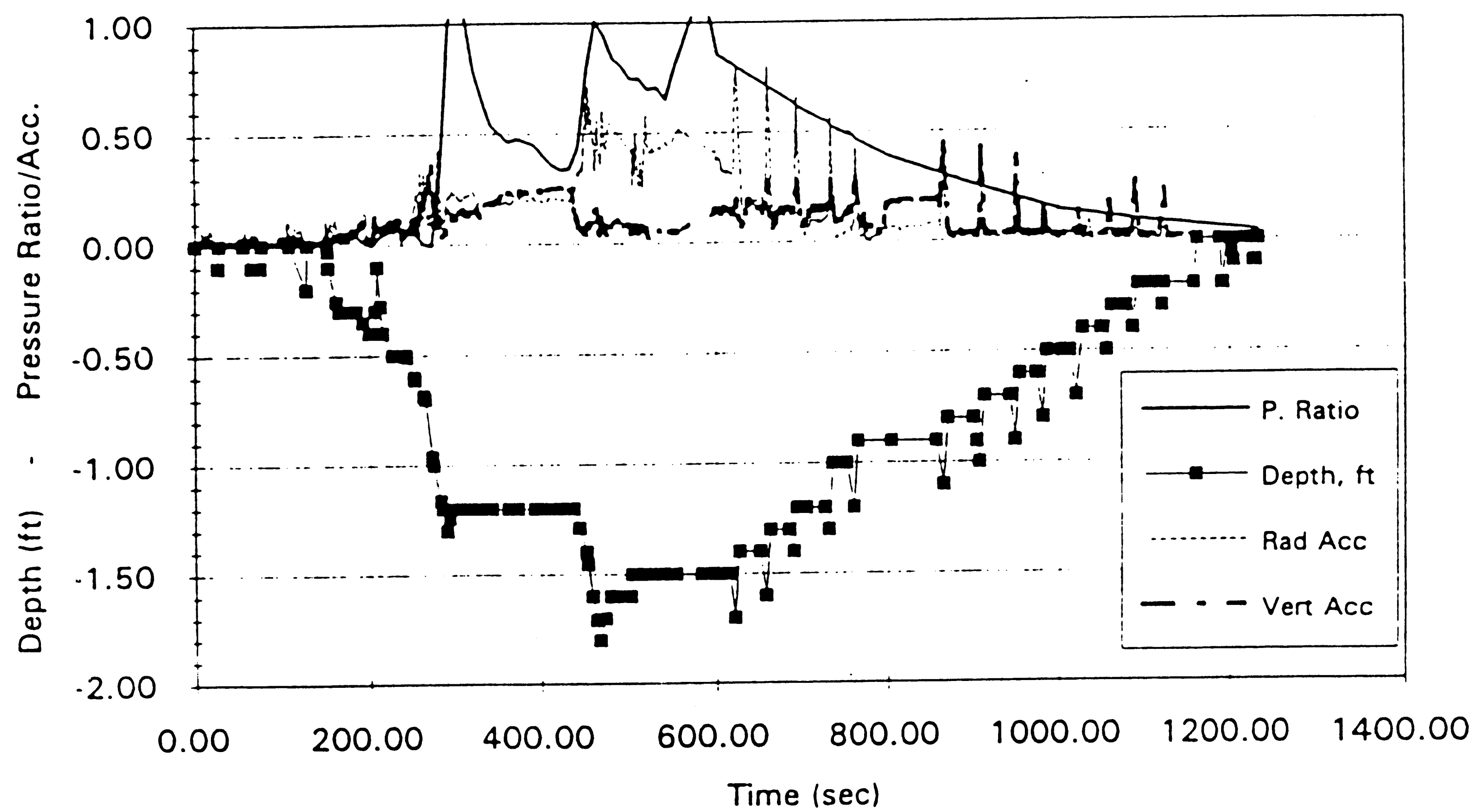


Figure 3.3 Time Histories of Vibration, Excess Pore Water Pressure, and Vibrator Depth 5 ft from Stone Column

Return to Table of Contents

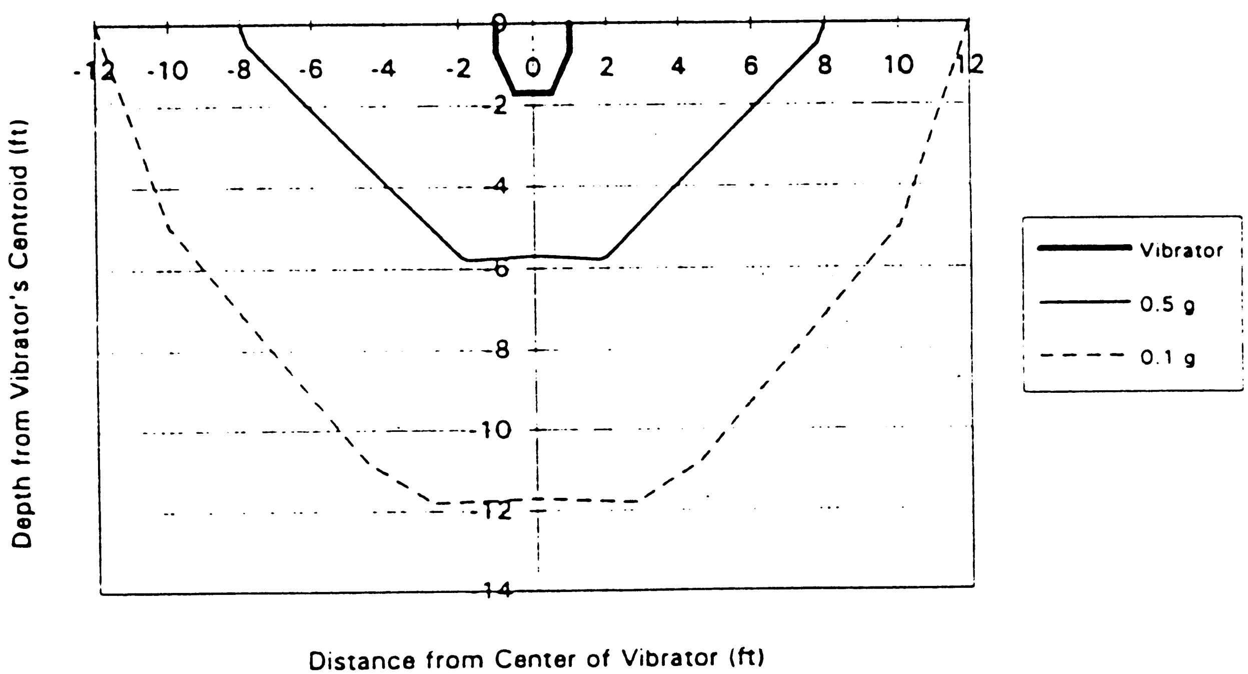
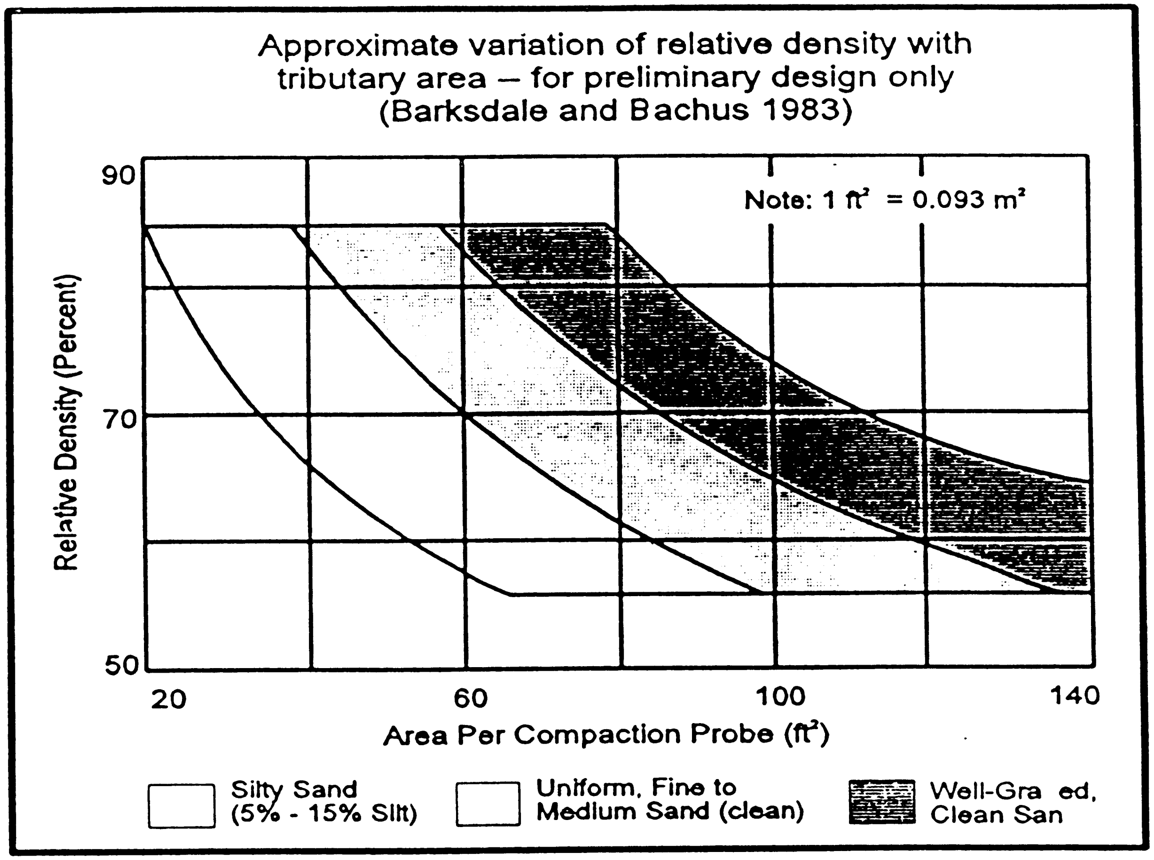


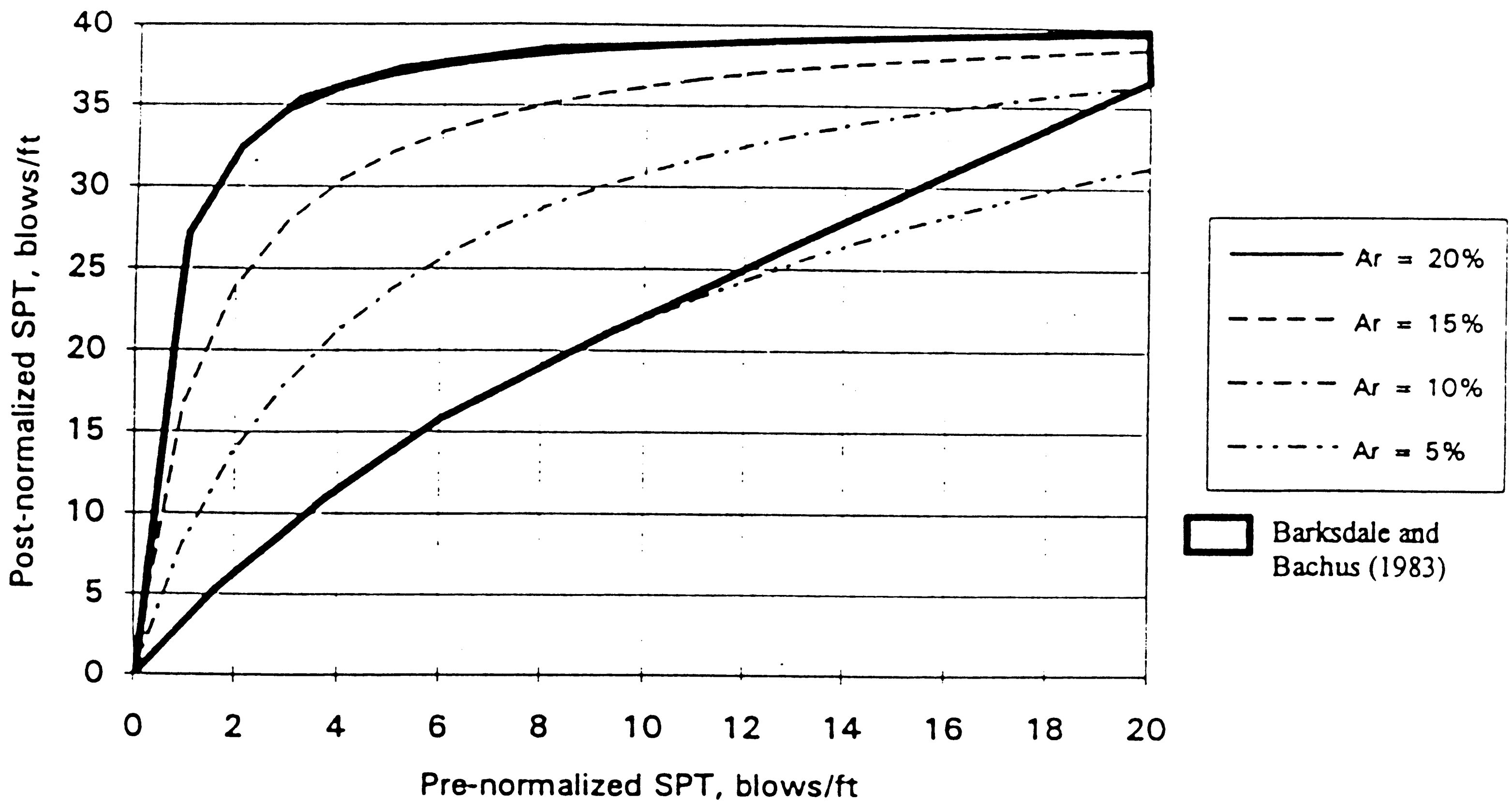
Figure 3.8 Two-Dimensional Distribution of Steady State Particle Accelerations at Monterey Site

Return to Table of Contents



Approximate Variation of Relative Density with Tributary Area (Barksdale and Bachus 1983).

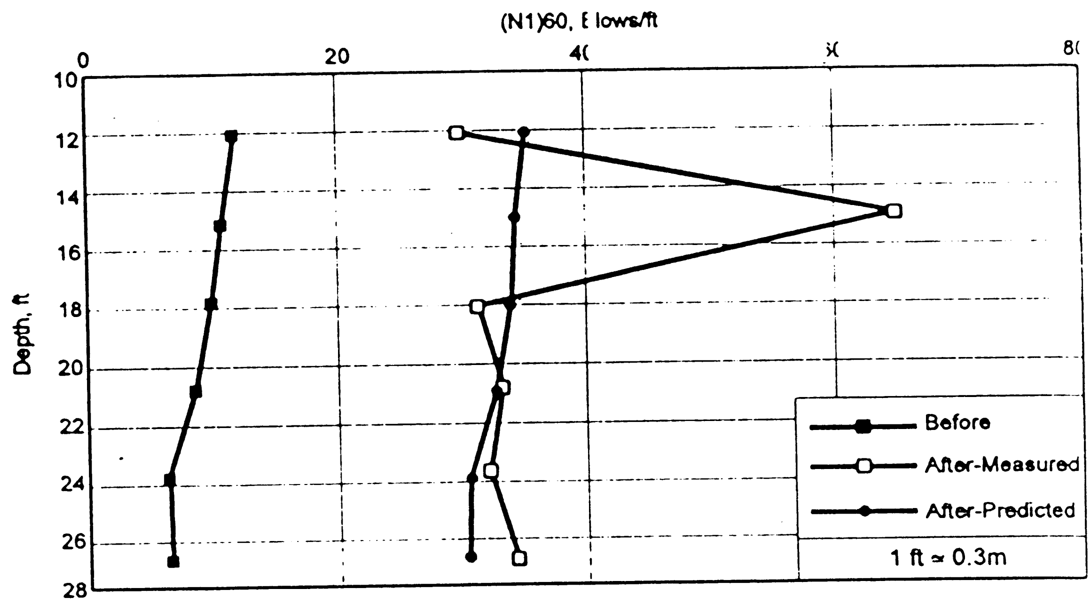
Return to Table of Contents



Comparison of Barksdale and Bachus (1983) Results and this Study

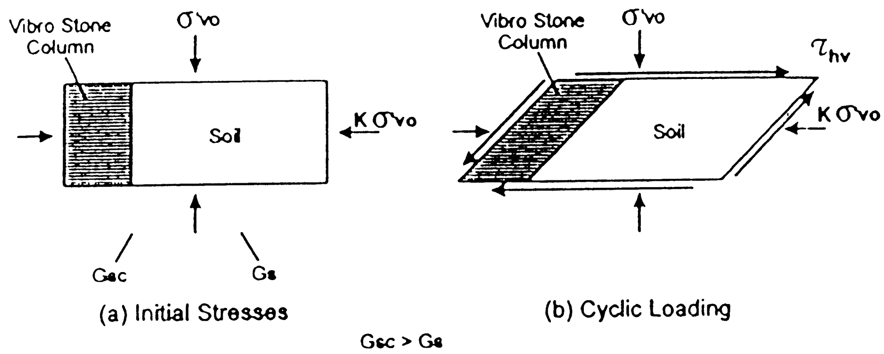
Return to Table of Contents

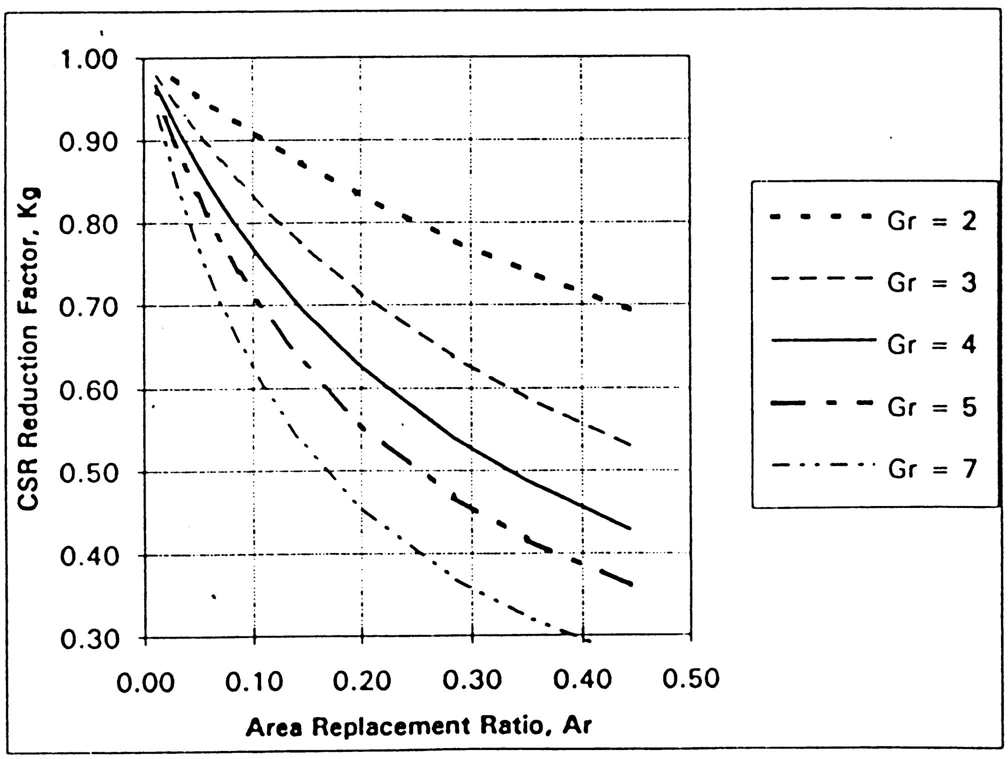
Comparison of prediction model vs measured, Ar = 12%, Berth 40,



Bent 68, Port of Oakland, CA.

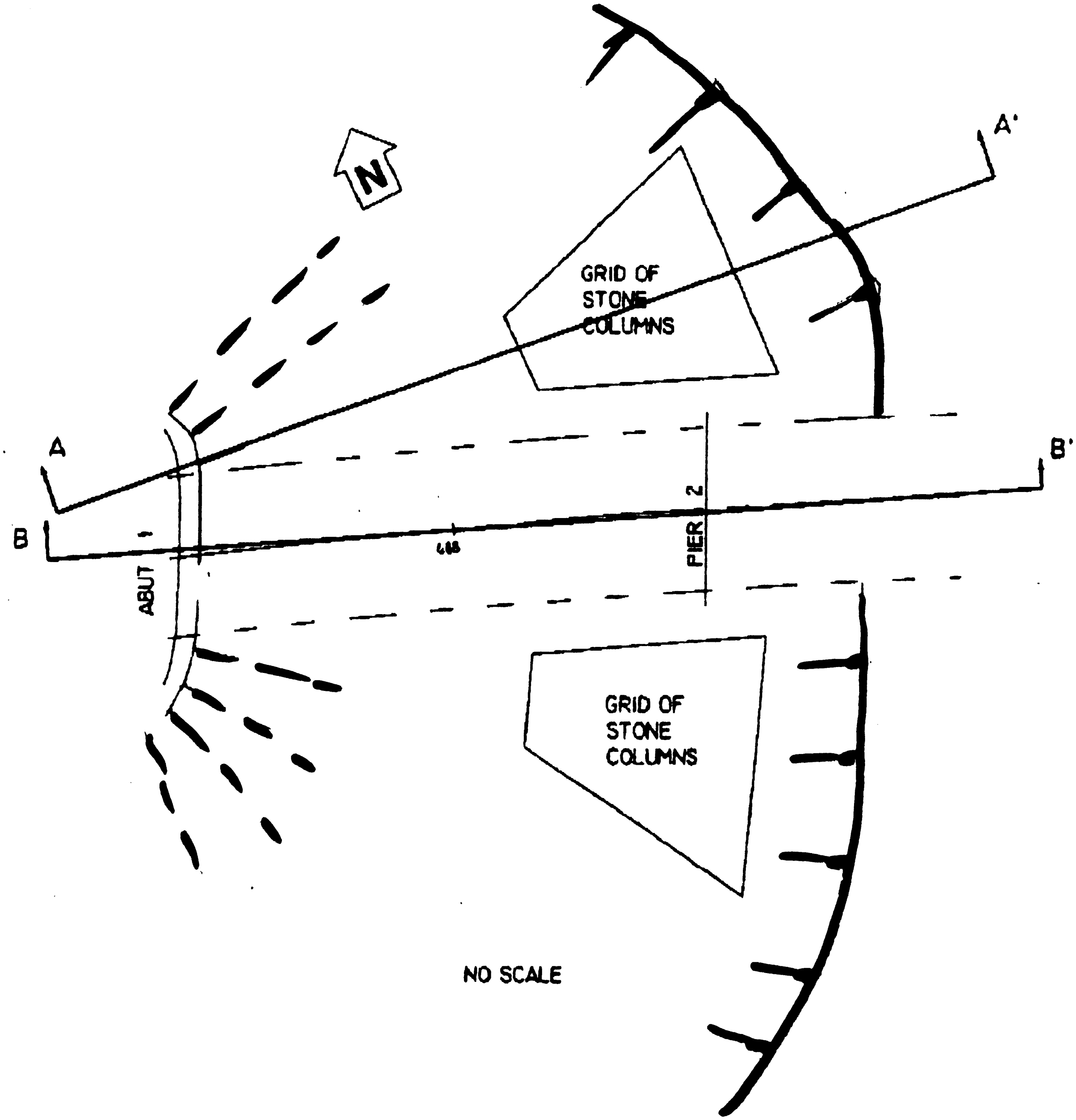
Return to Table of Contents



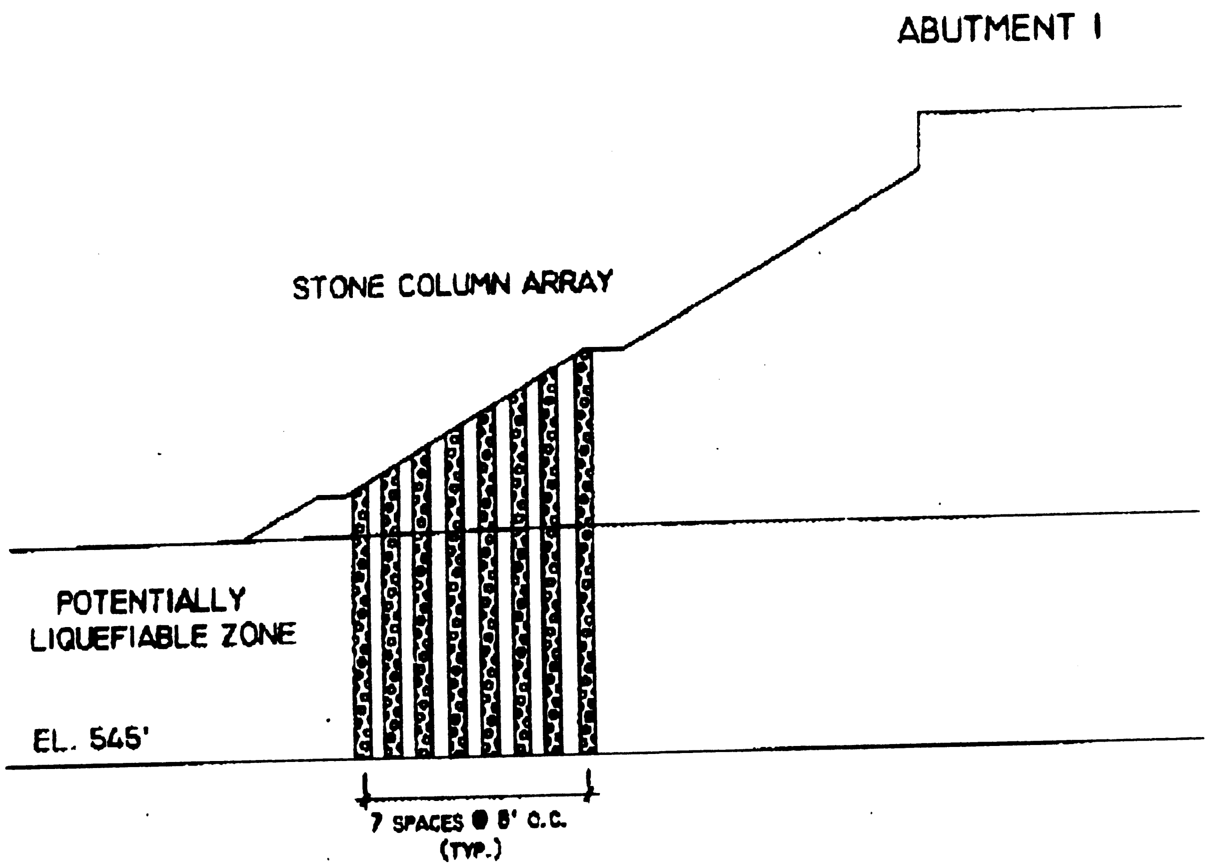


Effect of concentrated shear stresses on the CSR

Return to Table of Contents

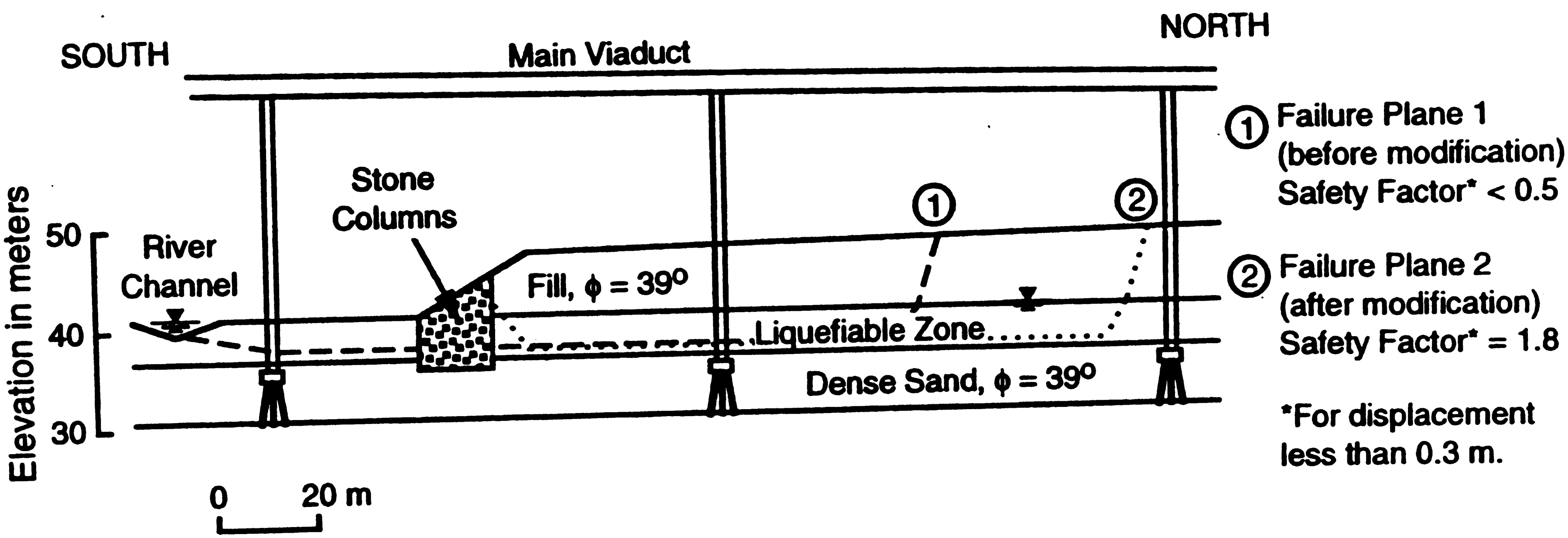


Return to Table of Contents



NO SCALE

Return to Table of Contents

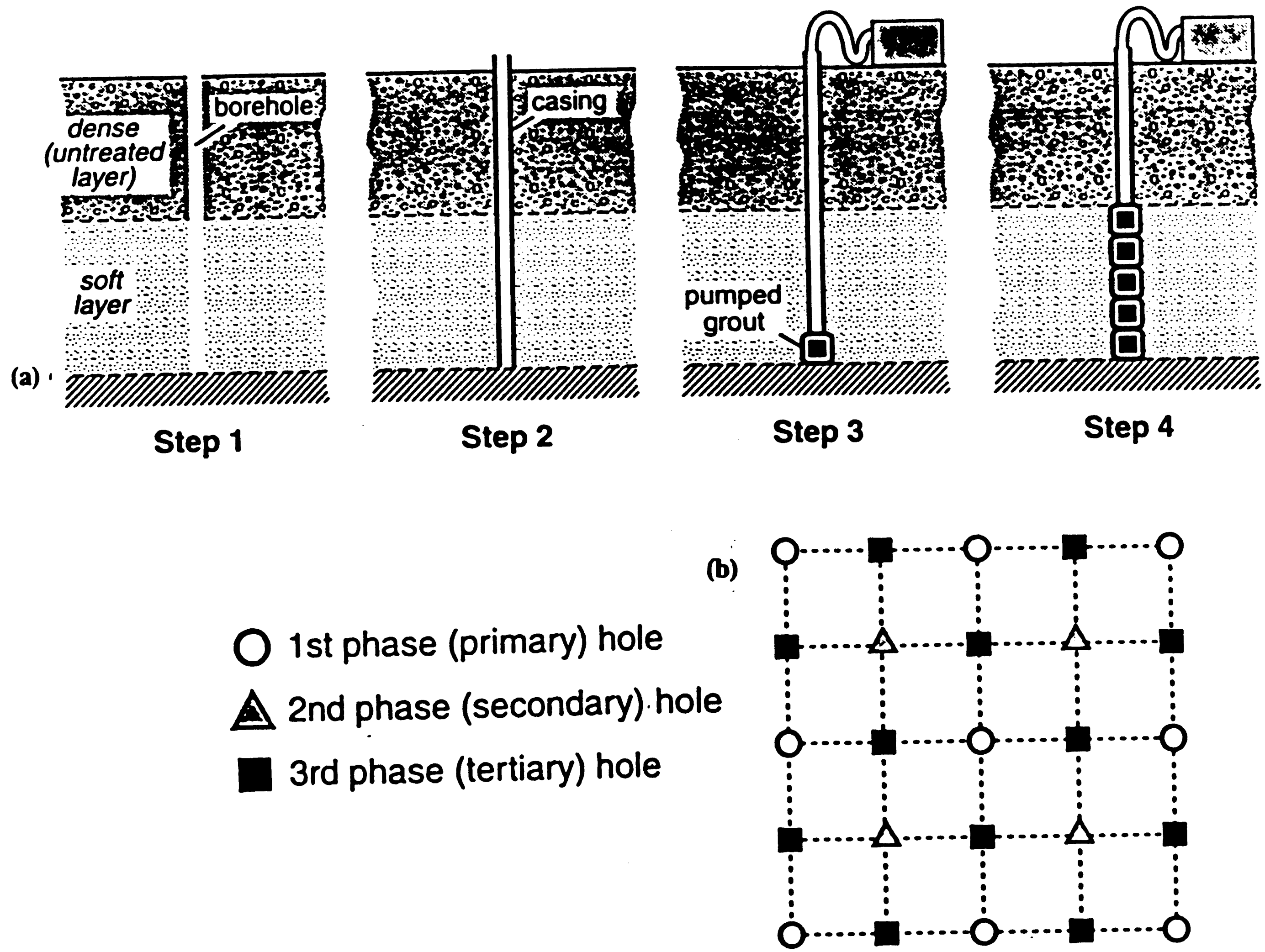


Cross Section of the I-805 Viaduct Near the San Diego River Showing the Generalized Soil and Underground Stone Column Buttress to Prevent Liquefaction-Induced Lateral Spreading (after Jackura and Abghari, 1994).

Return to Table of Contents

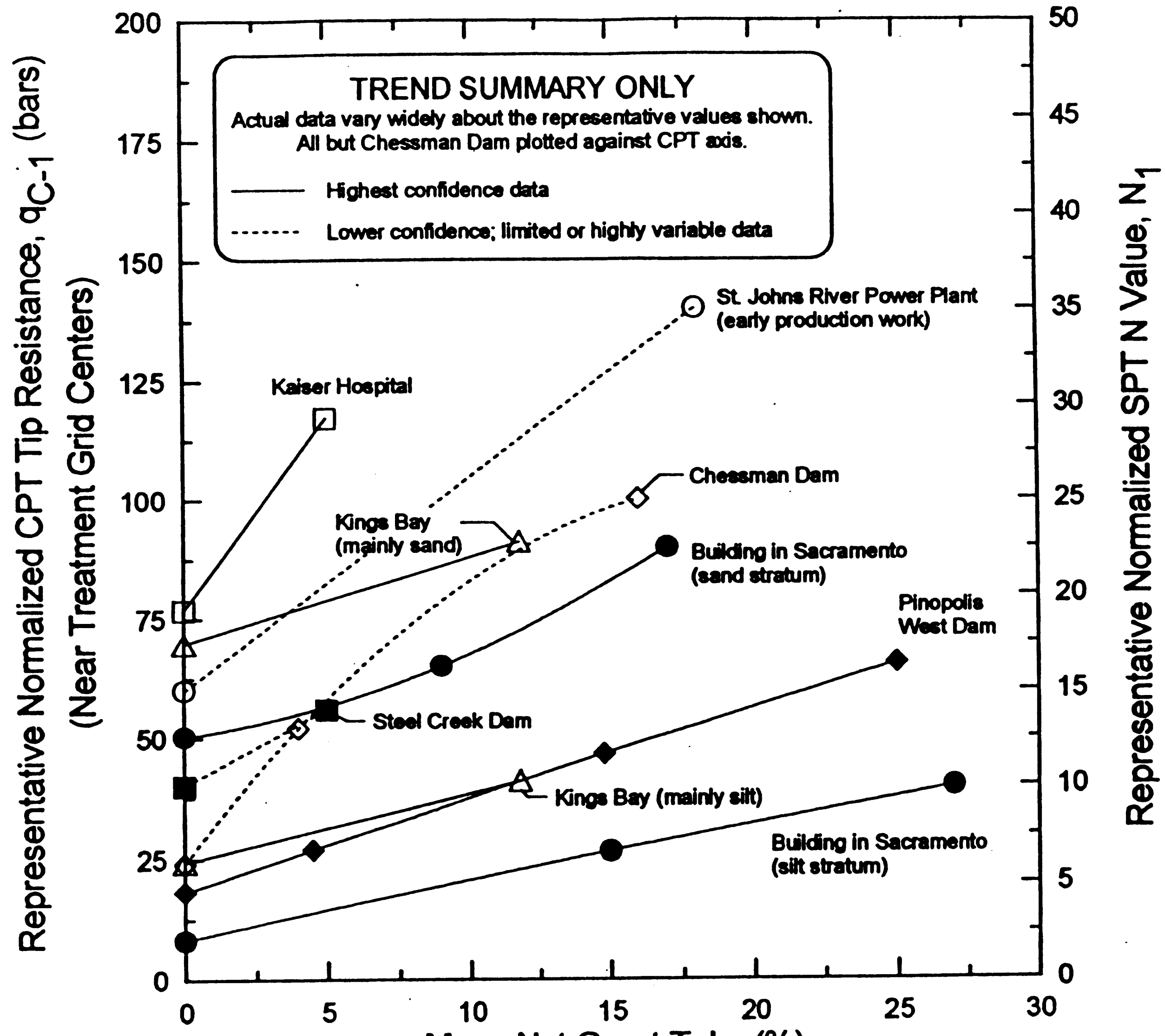
GROUND REMEDIATION—
COMPACTION GROUTING

Return to Table of Contents



Schematic of Compaction Grouting [after Gambin (1991)]: (a) Soil Cross Section and Sequences; (b) Plan View of Square Treatment Point Pattern

Return to Table of Contents



Trend Summary between Mean Values of Normalized Penetration Resistance near Treatment Grid Centers and Net Grout Take

Return to Table of Contents

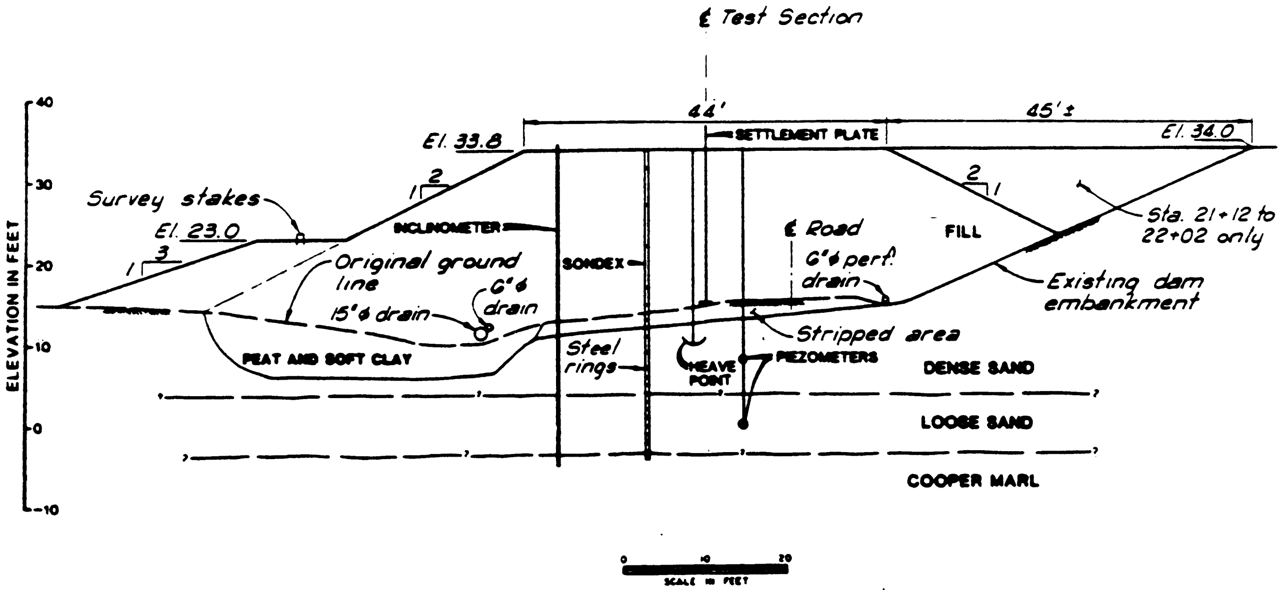
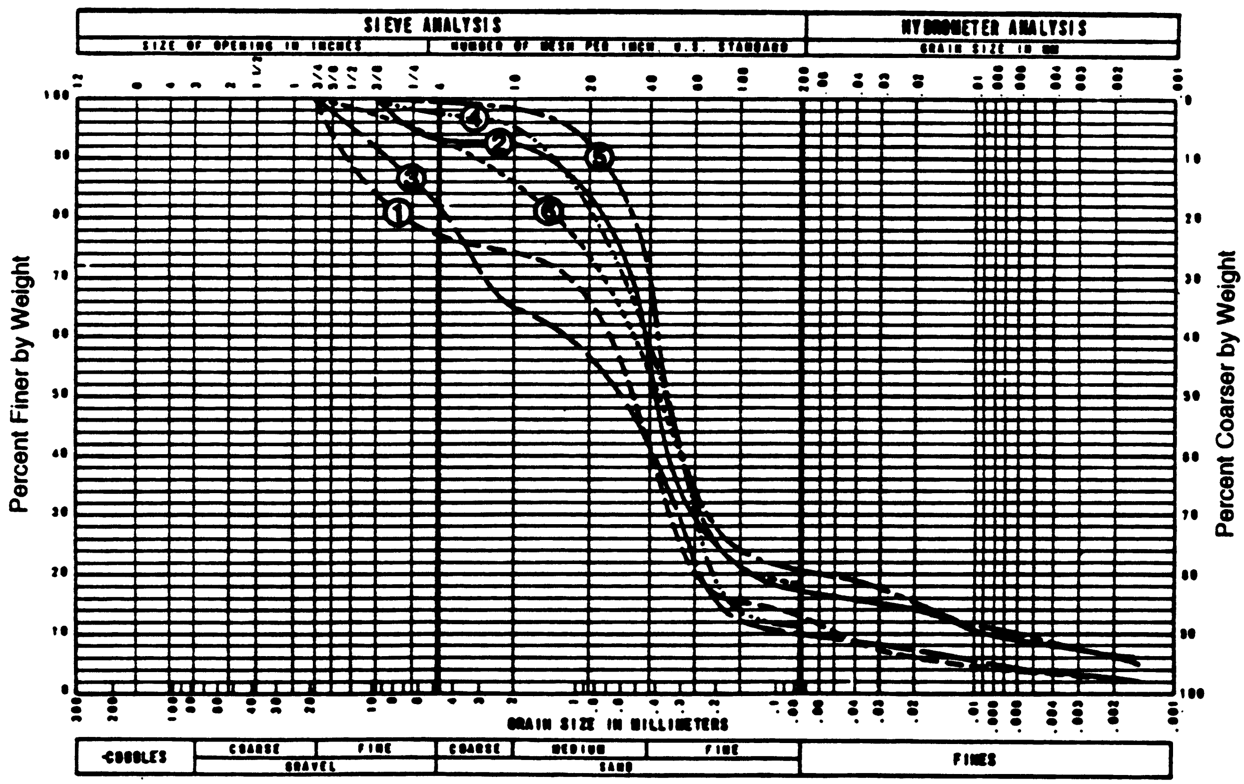
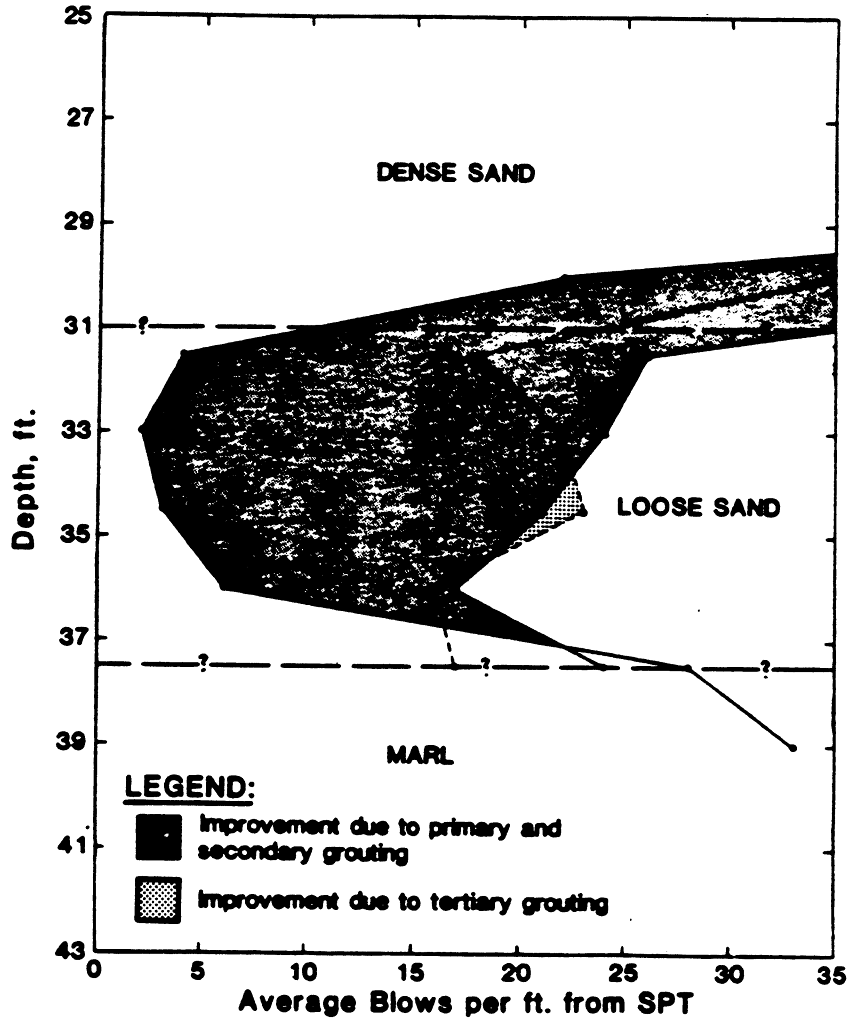


Fig. 2.2 - Typical Cross Section of Pilot Study Area at the Downstream Toe of the Pinopolis West Dam (Salley et al., 1987). (1 ft = 0.3 m.)



Grain-size Distribution Curves of Split-Barrel Samples Taken from the Loose Sand at the Pinopolis West Dam (Salley et al., 1987).

Return to Table of Contents

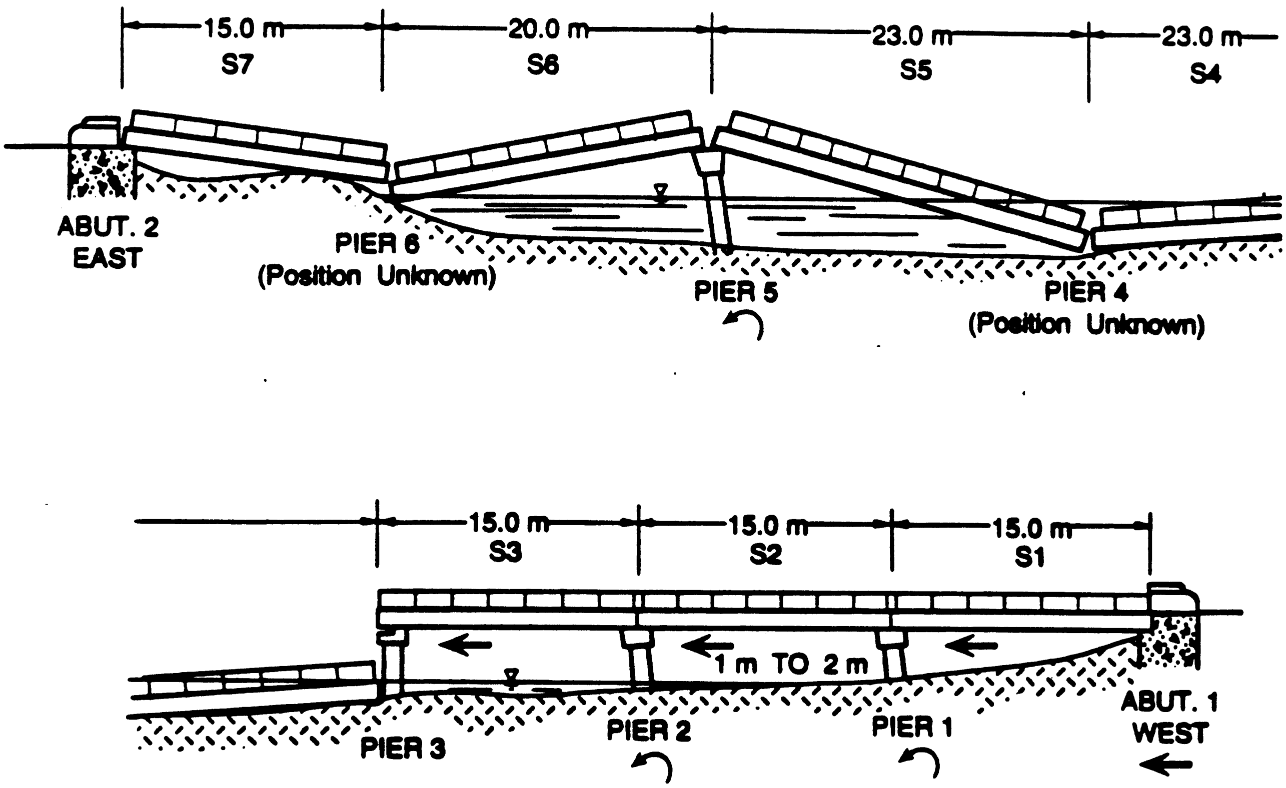


2.4 Average Corrected SPT Blow Count from Pilot Study Site Treated by Compaction Grouting at the Pinopolis West Dam (Salley et al., 1987). Before and After SPT Profiles are Plotted with the Improvement Shaded. (1 ft = 0.3 m.)

Return to Table of Contents

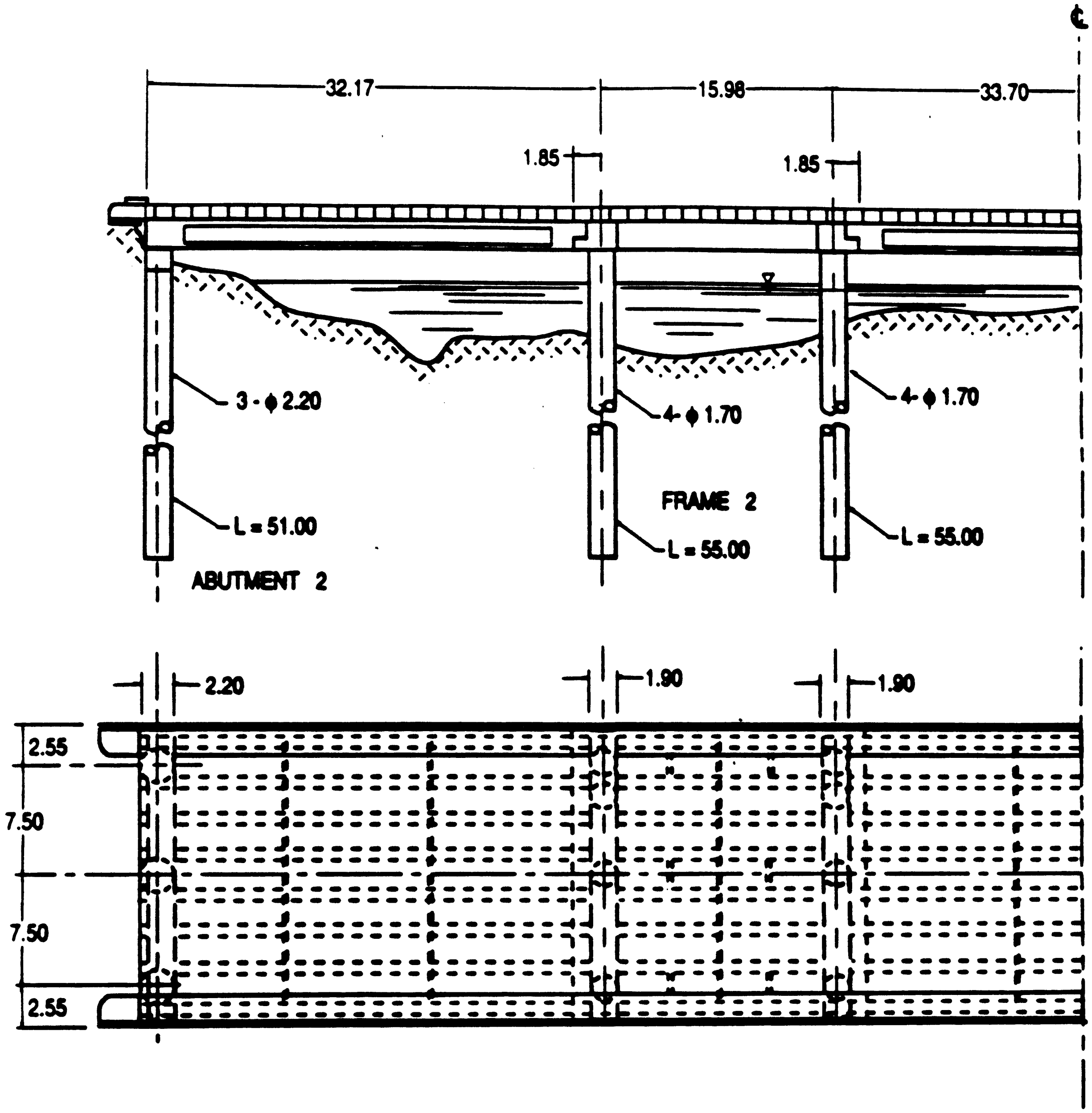
PILE FOUNDATION RETROFIT—LATERAL SPREAD DISPLACEMENT DEMAND

Return to Table of Contents



Sketch of Magsaysay Bridge showing earthquake damage.

Return to Table of Contents



Sketch showing structural details of the new Magsaysay Bridge.

Return to Table of Contents

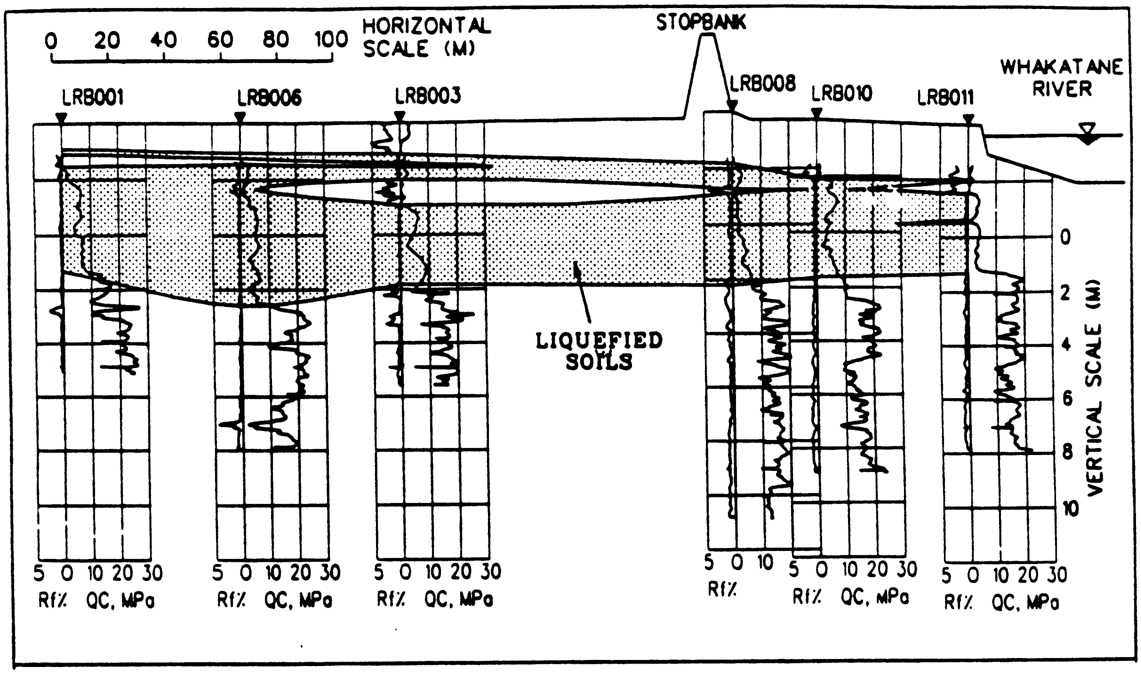


Figure 10 Cross Section AA at Landing Road Bridge showing the estimated liquefied strata. Cross Section BB is generally similar, with the loose sand layer slightly thicker.

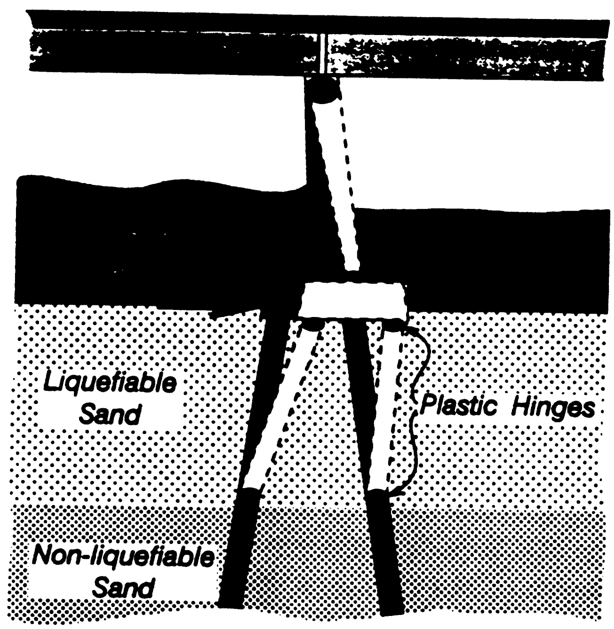
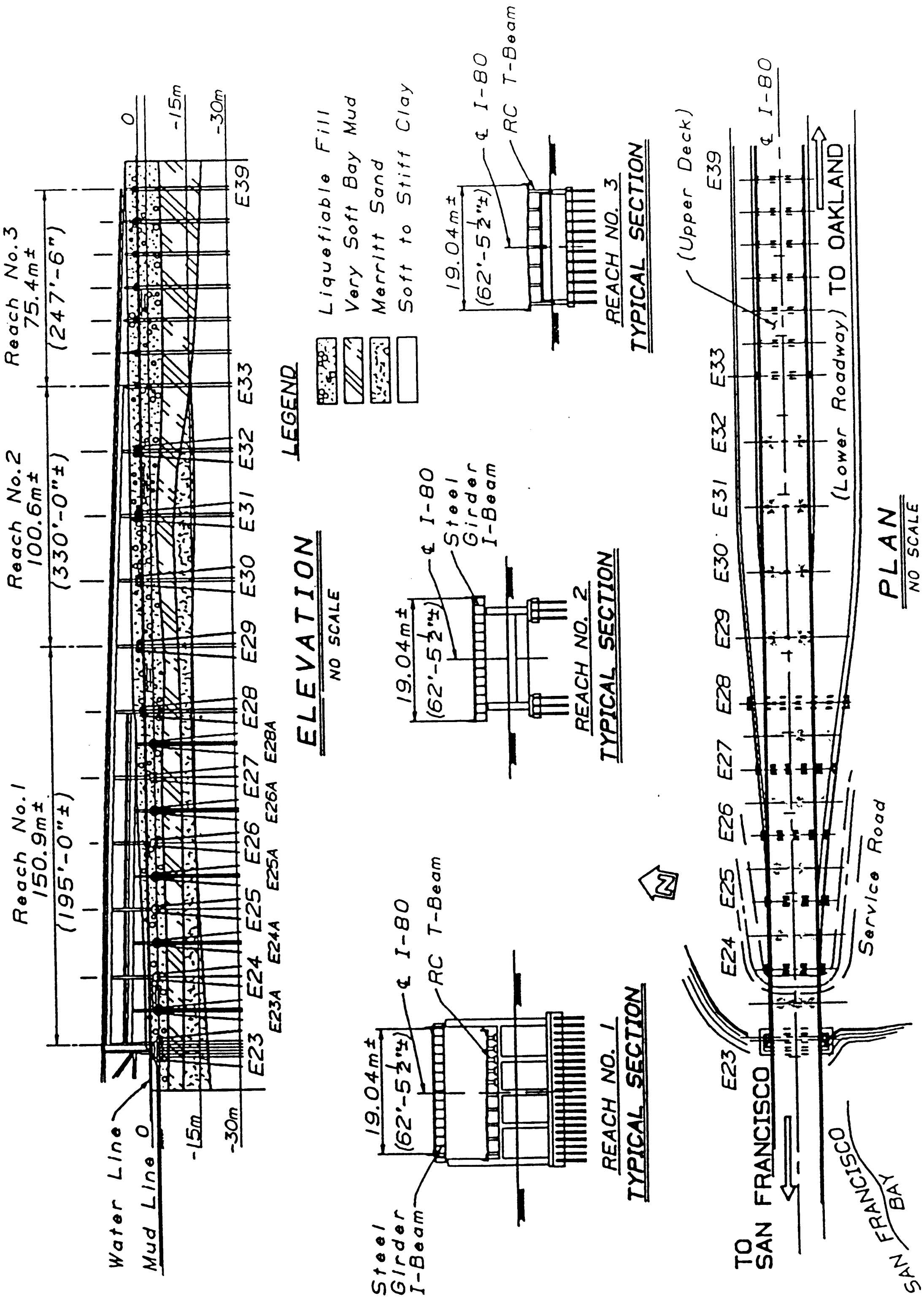


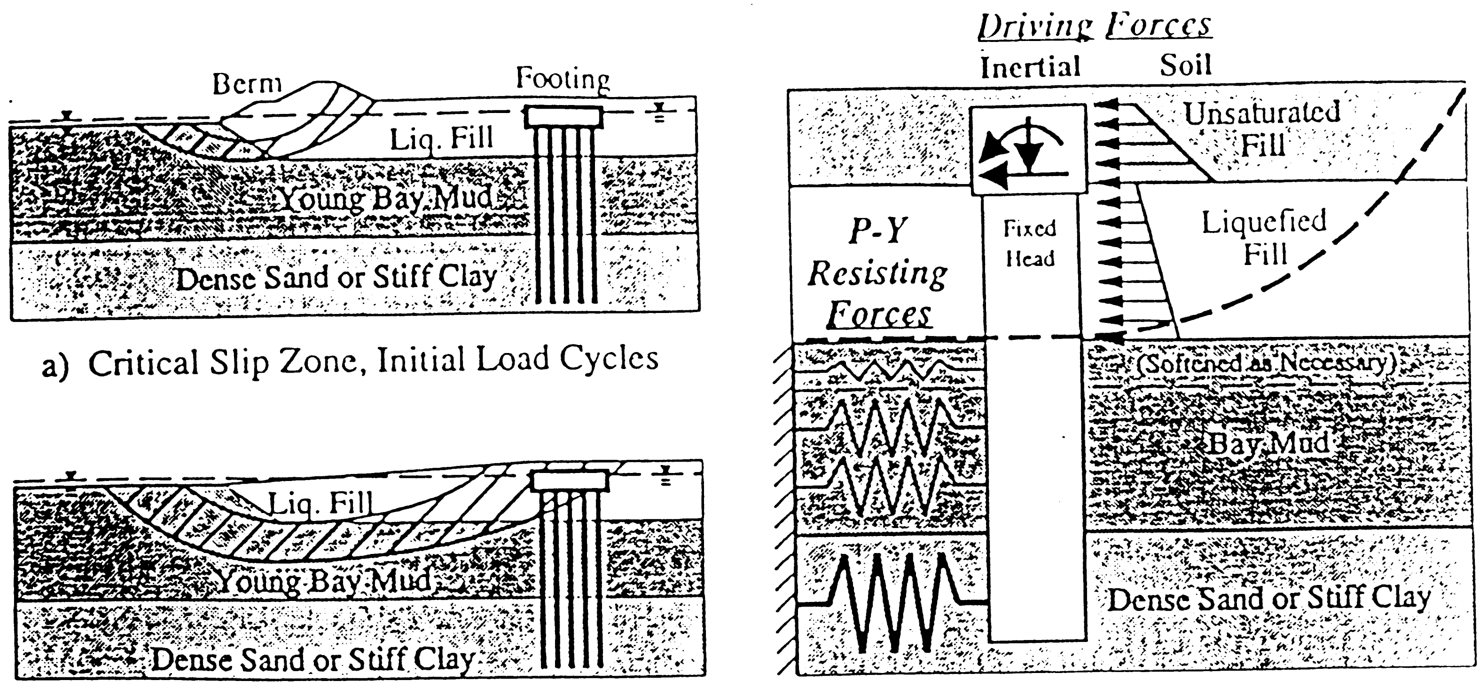
Figure 11 Substructure collapse mechanism.

Return to Table of Contents



Plan, Elevation, and Soil Profile for East Approach of SFOBB

Return to Table of Contents



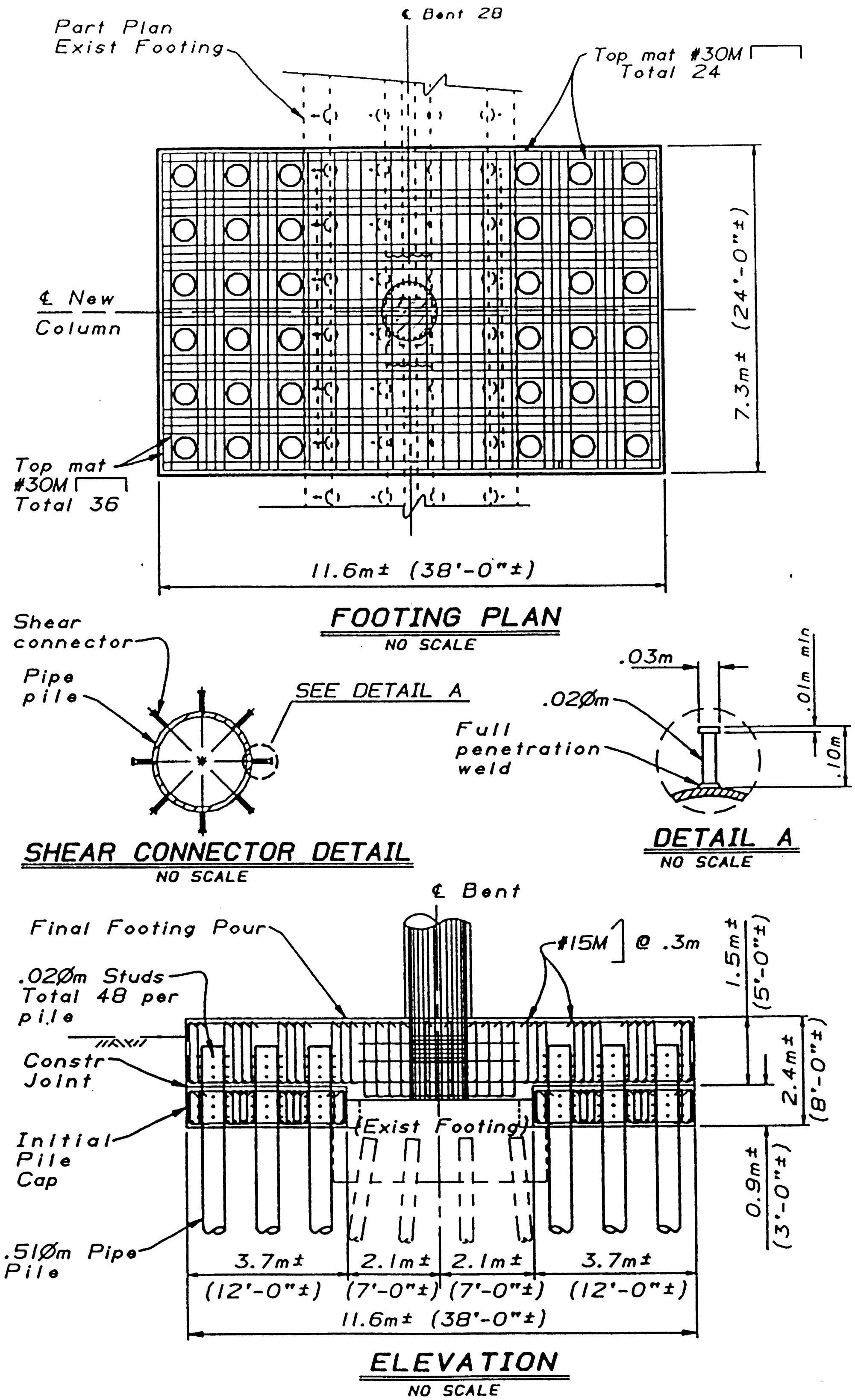
a) Critical Slip Zone, Initial Load Cycles

b) Critical Slip Zone, Final Load Cycles

c) System Considered for Foundation Analysis

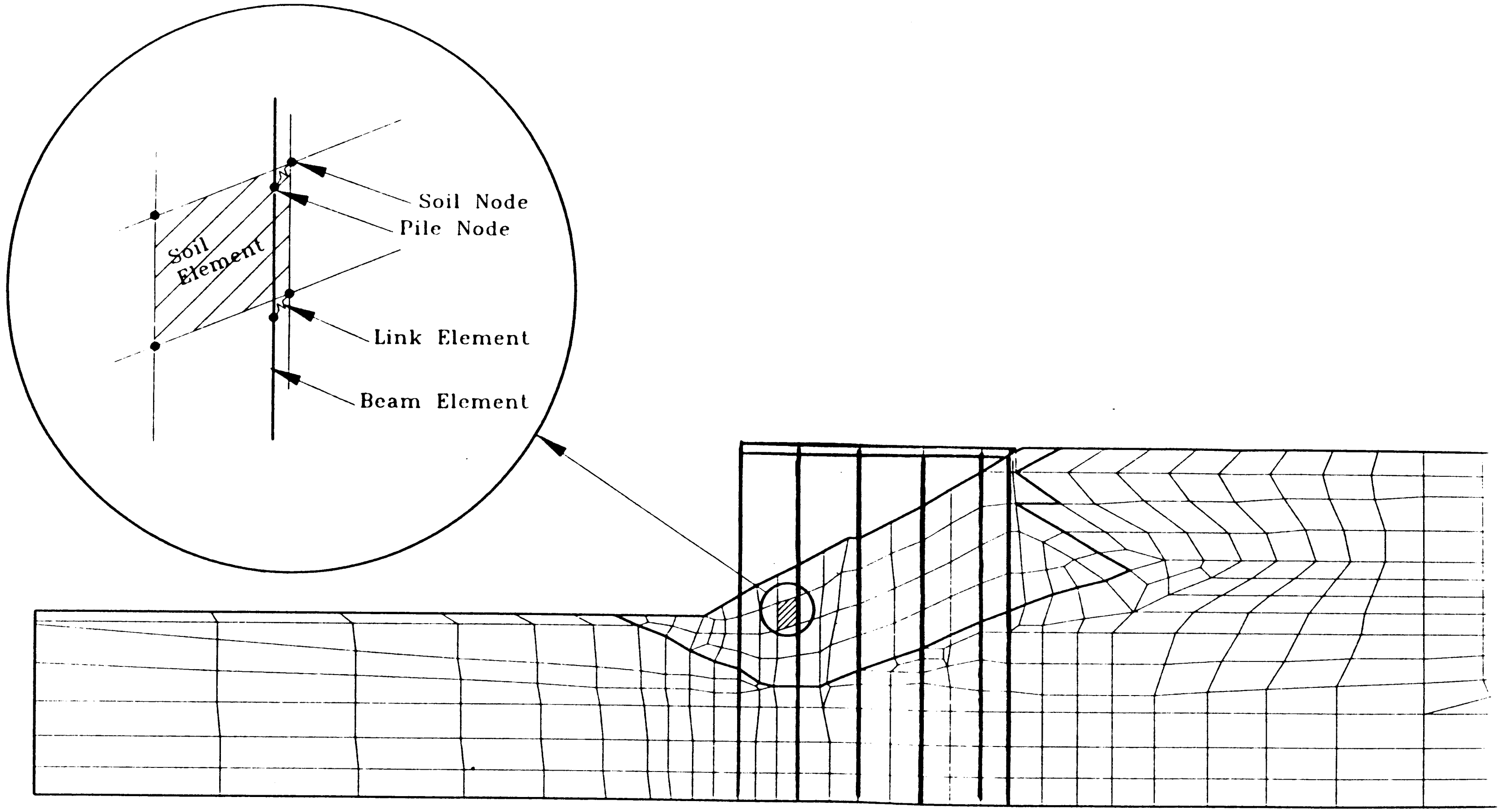
Key Elements of Geotechnical Analysis for SFOBB East Approach

Return to Table of Contents



Typical Retrofit Footing Details for the SFOBB East Approach

Return to Table of Contents

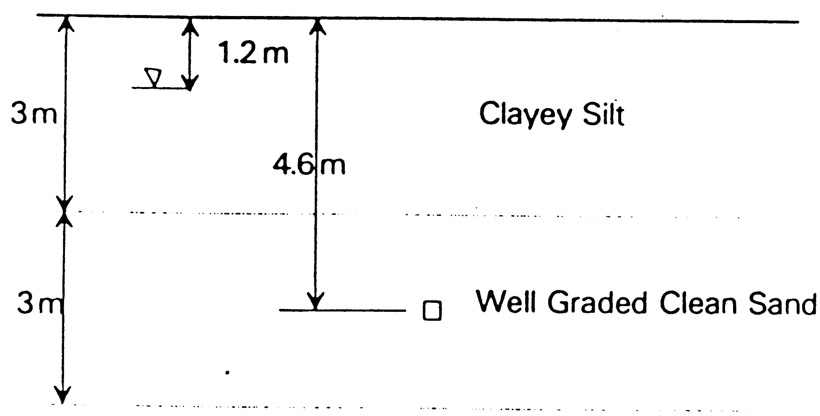


Return to Table of Contents

Design Example Problem for Earthquake Liquefaction Mitigation by Stone Columns and Vibro-Concrete columns

Suppose we have the following soil profile and parameters for a Clean Sand at a depth of 4.5 m:

Total stress, σ_o = 85.2 kPa
Effective Stress, σ'_o =52.4 kPa
Permeability, k = 1.0×10^{-3} cm/sec
Coeff. of Vol. Compressibility, m_v = 1.4×10^{-6} sf/lb = 2.9×10^{-5} KN/m^2
Corrected Penetration Resistance, $(N_1)_{60}$ = 15
Relative Density, Dr = 60%
Shear Modulus, Gs = 99.7 MPa
Depth Factor, r_d = 0.97



Earthquake parameters:

Earthquake Magnitude, Ms = 7.5
Number of Representative Cycles, N = 15
Duration, t = 40 sec
Peak Ground Acceleration, a_{max} = 0.3g

Therefore, the computed cyclic stress ratio, CSR = $\frac{\tau}{\sigma'_o} = 0.65 \frac{a_{max}}{g} \frac{\sigma_o}{\sigma'_o} r_d$ =0.31

Return to Table of Contents

Summary of Results from Design Example of Liquefaction Mitigation

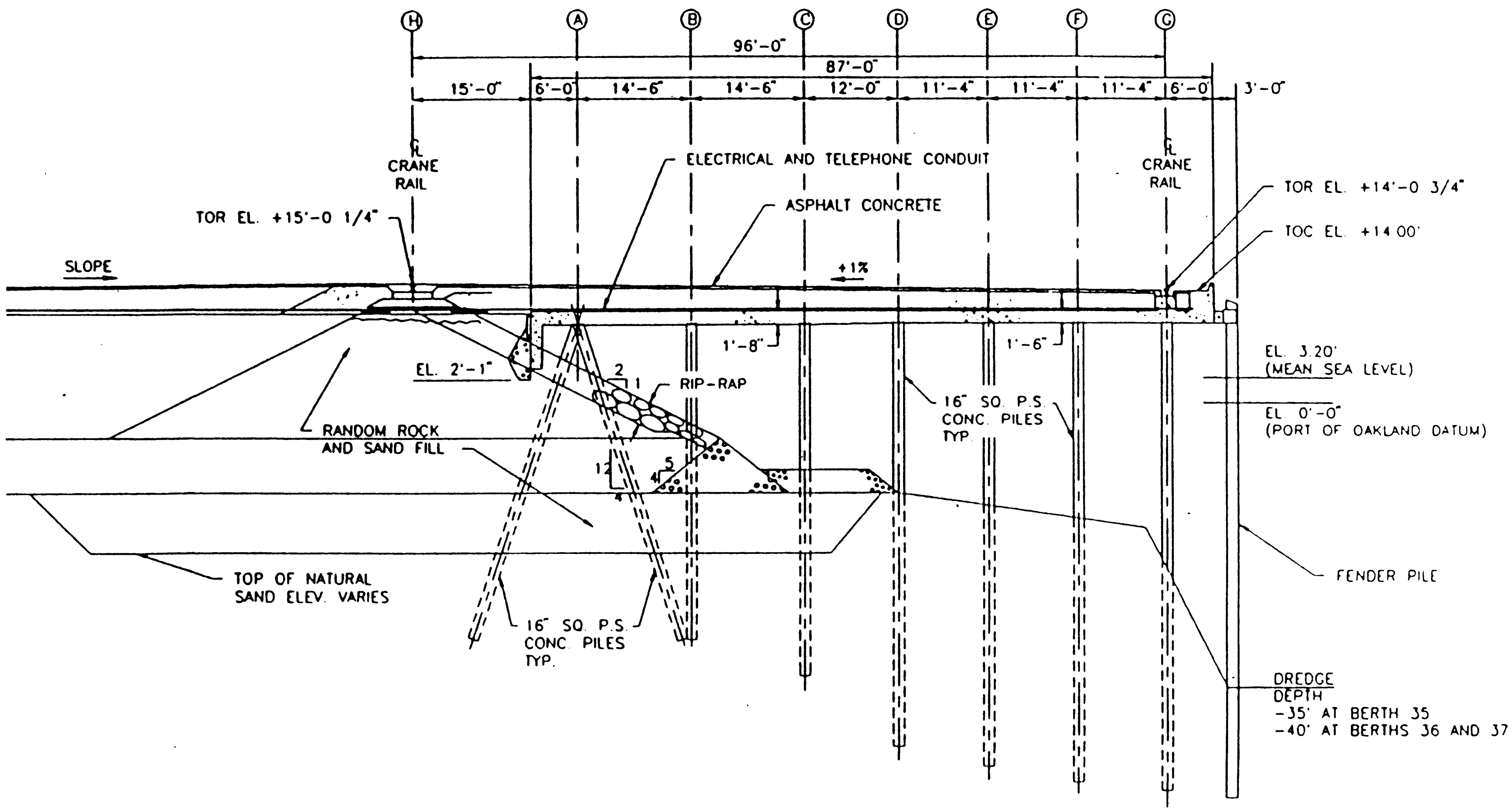
Well graded sand:

	Spacing (meters)	
Criterion	**Stone Column d = 0.76 m**	**Vibro-Concrete Column d = 0.65 m**
Densification	2.7 m	2.3 m
Drainage	1.5 m	N/A
Stress Concentration	1.0 m	1.4 m
Densification + Drainage	3.3 m	N/A
Densification + Stress Concentration	3.2 m	3.0 m
Densification + Drainage + Stress Concentration	3.4 m	N/A

Silty (35%) sand:

	Spacing (meters)	
Criterion	**Stone Column d =0.76 m**	**Vibro-Concrete Column d = 0.65 m**
Stress Concentration	2.0 m	2.8 m

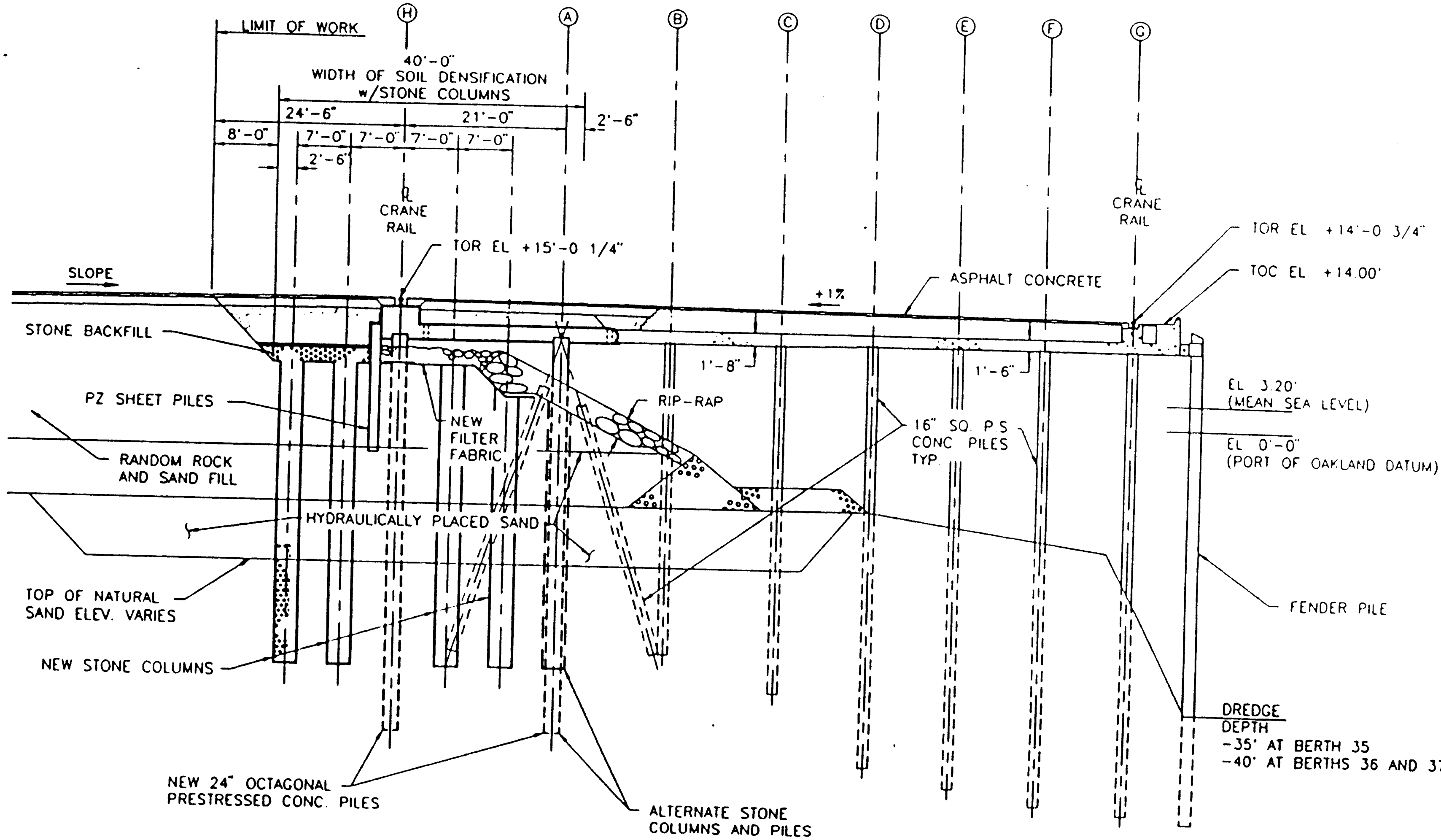
Return to Table of Contents



TYPICAL WHARF SECTION – ORIGINAL CONSTRUCTION

CASE HISTORY 8
PORT OF OAKLAND - 7TH STREET WHARF
PRE 1989 LOMA PRIETA EARTHQUAKE CROSS SECTION

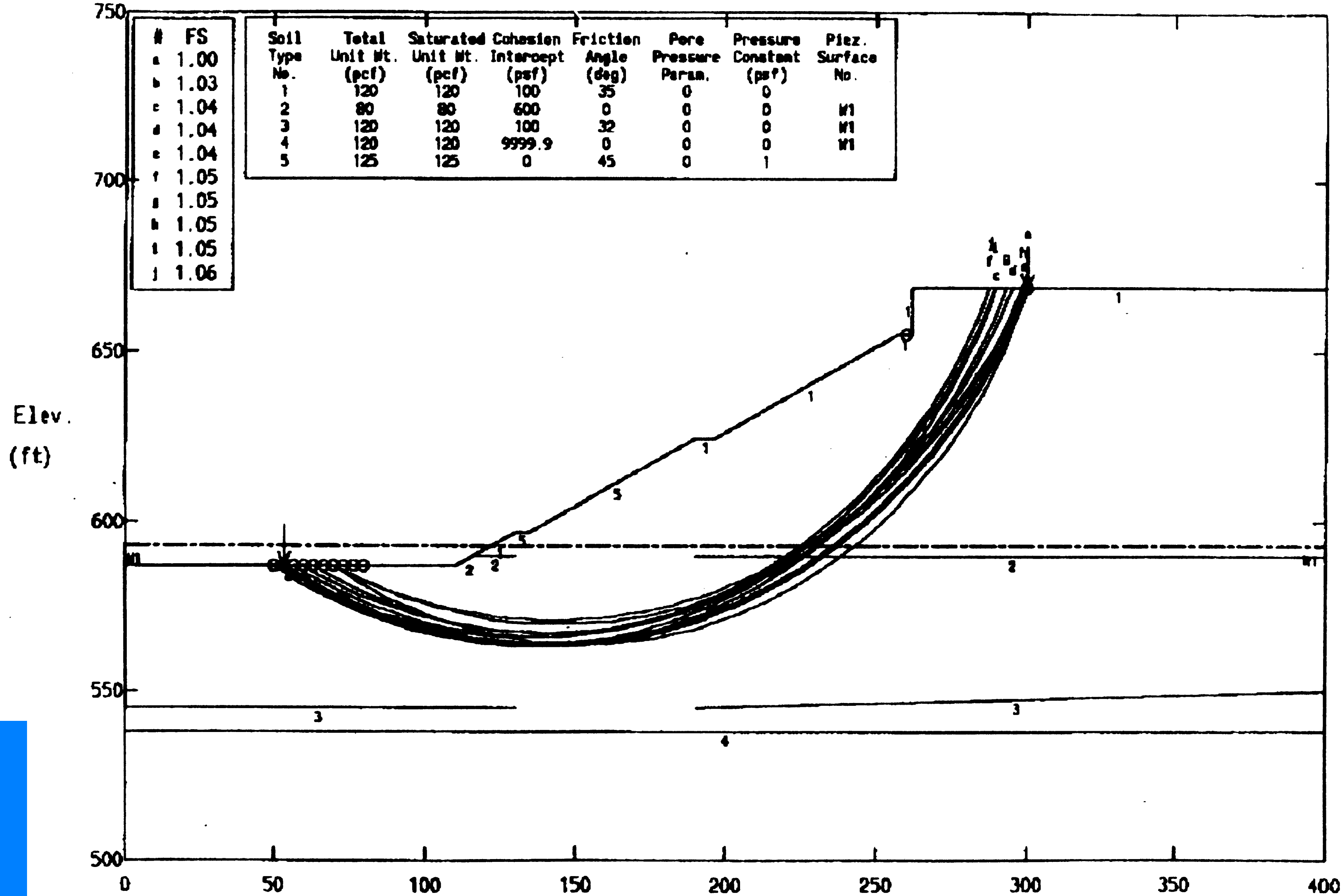
Return to Table of Contents



TYPICAL WHARF SECTION AT STONE COLUMN DRAINS

CASE HISTORY 8
PORT OF OAKLAND - 7TH STREET WHARF
1989 LOMA PRIETA EARTHQUAKE GROUND IMPROVEMENT

Return to Table of Contents



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Factors Of Safety Calculated By The Modified Bishop Method

Return to Table of Contents