CHAPTER 2: BACKGROUND ON LIQUEFACTION-INDUCED FAILURE AND GROUND IMPROVEMENT RELATIVE TO BRIDGES

2.1 Liquefaction-Induced Failure Mechanisms

Liquefaction of loose, saturated, cohesionless soils can produce several different types of ground failure depending on site conditions. These failure mechanisms include lateral spreading, loss of bearing capacity and settlement, ground oscillations, and flow failure (Youd, 1992). Any of these mechanisms can potentially cause damage to bridges due to the ground and foundation movements that occur.

2.1.1 Types of Failure Mechanisms

2.1.1.1 Lateral Spreading

Damage to many bridges due to earthquake-induced liquefaction has resulted from lateral spreading of gently sloping ground towards river channels. Lateral spreading consists of the displacement of ground down gentle slopes (i.e. - typically having inclinations less than 3 degrees according to Youd, 1992) or towards an incised channel, as a result of liquefaction of underlying soils. The displacements are usually incremental, occurring at periods during the earthquake when the strength of the liquefied material is less than needed to resist the lateral forces acting on the overlying non-liquefied soil (Kramer, 1996). The overlying soil is usually broken up in blocks which displace downslope or towards the incised channel, on top of the liquefied soil, as shown in Figure 2.1. General characteristics of lateral spreading that are manifested in the ground, as described by Youd (1993), are "… extensional deformations at the head of the feature, shear deformations along the margins, and compressed ground at the toe." Displacements can range from a few centimeters to several meters.

Since bridges are typically located at the toe of a lateral spread, they are commonly subjected to compression. Damage to the bridge is generally caused by differential lateral ground displacement. The type and magnitude of damage depend on the foundation, superstructure, substructure, and connection characteristics of the bridge.

2.1.1.2 Loss of Bearing Capacity and Settlement

Loss of bearing capacity results from the loss of soil strength associated with the increase in pore water pressures and softening of the soil occurring during partial or full liquefaction. The reduction in bearing capacity can result in excessive settlements/movements of a bridge pier or abutment whose foundation bearing pressure exceeds the reduced capacity, as shown schematically in Figure 2.2.

Excessive movements can also occur in the absence of a catastrophic or sudden ground failure, as a result of the cyclic loading of the foundation which causes it to gradually penetrate into the weakened soil. In addition, settlements can be induced due to the densification which occurs when excess pore water pressures dissipate in partially or fully liquefied soils.

Similar to a loss of bearing capacity is the loss of axial and lateral support for deep foundations extending through liquefiable soil. This loss of support can cause excessive deformations and stresses in piles or drilled shafts resulting in damage.

2.1.1.3 Ground Oscillation

Ground oscillation is a phenomenon that occurs on relatively level ground where lateral spreading does not occur. In this phenomenon, broken blocks of nonliquefied soil oscillate back and forth and up and down on top of an underlying liquefied layer during an earthquake, as shown in Figure 2.3 (Youd, 1992). A bridge supported by the surficial layer can experience severe deformations when substructure columns or walls supported by shallow foundations on the blocks undergo differential movements.

2.1.1.4 Flow Failure

Flow failure is the rapid movement of liquefied soil and overlying layers down more steeply inclined slopes (i.e. - typically greater than 3 degrees according to Youd, 1992), as illustrated in Figure 2.4. According to Youd (1992), “these failures commonly displace large masses of soil tens of meters and, in a few instances, large masses of soil have traveled tens of kilometers down long slopes at velocities ranging up to tens of kilometers per hour.” The large displacements result from the residual strength of the liquefied soil being less than necessary to resist the static gravitational forces acting on overlying nonliquefied soils during and after earthquake shaking (Kramer, 1996). Although such failures have primarily been observed to occur in offshore seabeds or tailings dams, they may be possible at a bridge site given sufficient ground slope and the proper subsurface conditions. This type of failure could cause severe damage to a bridge supported on, or even through, the liquefiable soil.

2.1.2 Implications for Bridges

Although all of the failure mechanisms mentioned above are possible at a bridge site given the proper conditions, lateral spreading and bearing capacity failure are probably more common. In order to mitigate the potential for damage to a bridge due to one or several of these mechanisms, improvement measures must be implemented to counter the development of failure and limit movements. Ground improvement methods that might be considered for this purpose are discussed below.

2.2 Remediation Using Ground Improvement

2.2.1 Improvement Categories and Methods

There are a variety of ground treatment methods available for improving the properties of liquefiable soils in order to reduce the potential for earthquake-induced liquefaction and associated damage. These methods can generally be separated into broad categories based on the primary mechanism used to achieve the improvement. The categories applicable to liquefaction mitigation at existing bridges include densification, cementation, reinforcement and containment, in-situ stress increase, and drainage. Descriptions of the principles behind the improvement mechanism associated with each category are provided in Table 2.1, along with a list of particular treatment techniques in the category that can potentially be used at existing bridges. Details concerning the specific treatment methods can be found in references on ground improvement (i.e. – Cooke and Mitchell, 1999; Andrus and Chung, 1995; Xanthakos et al., 1994; Hausmann, 1990).

2.2.2 Applicability to Different Bridge Types

The applicability of using different ground improvement methods for remediating liquefaction effects at existing highway bridges are dependent on:

- Space and geometry limitations of the bridge site affecting accessibility and working space for construction equipment,
- Subsurface conditions affecting the effectiveness of a particular method in producing the required improvement,
- Potential for construction-induced movements and vibrations of the bridge caused by the remediation method along with the likelihood of resulting damage,
- Desired post-treatment performance of the bridge,
- Potential environmental effects of improvement implementation, and
- Cost of the improvement method relative to other methods.

The potential applicability of treatment methods to some typical bridge configurations is discussed below.

2.2.2.1 Bridge Configurations Considered

There are many different types of configurations used for highway bridges. Inherent in the bridge configuration are the abutments and piers with their supporting foundations, approach embankments, span lengths and widths, and limited clearance. Site factors that influence the bridge configuration and also impact the feasibility of remediation methods include the ground surface topography and the presence of a water body, structures or other roadways.

Since it is not feasible to evaluate ground improvement relative to all of these configurations, improvement methods are discussed relative to some commonly used abutment and pier types. Abutment types considered include pile-supported stub, full-height wingwall, and floating stub abutments, as shown in Figure 2.5. Pier types considered include solid wall or multi-column, hammerhead, and single circular column piers, as shown in Figure 2.6.

Pile supported stub abutments are commonly used at the end of an approach embankment having a sloping face. The piles are typically driven through the embankment fill and several feet into underlying natural soils.

Full-height wingwall abutments are essentially retaining walls supported by either shallow or deep foundations. They are commonly used where space restrictions forbid a sloping face at the ends of approach embankments.

Floating stub abutments are typically used where site topography and soil conditions permit the abutments to be founded on shallow spread footings in natural soils having adequate bearing capacity.

Bridge piers are commonly supported by deep foundations due to the magnitude of loads supported and, when the pier is located in rivers or streams, concern for scour. The term pier, as used here and throughout this dissertation, refers to substructure elements constructed between the abutments for the purpose of supporting the superstructure of the bridge. Pier is not used herein to refer to deep foundation elements, such as drilled shafts, piles, or caissons.

The abutment and pier types shown in Figures 2.5 and 2.6 are typical for small (6 to 15 meter spans) to medium (15 to 60 meter spans) bridges. Since the majority of bridges in the United States fall in these categories, the evaluation of ground improvement methods presented throughout this dissertation is for bridges within this range of sizes. However, some of the results and conclusions can likely be extrapolated to large (60 to 150 meter spans) bridges.

2.2.2.2 Assessment of Applicability

Table 2.2 presents an assessment of the applicability of the ground improvement methods listed in Table 2.1 to the different abutment and pier types shown in Figures 2.5 and 2.6. In addition the table also provides brief descriptions of the principles behind each method, soil types for which it is suitable, properties of treated materials, relative costs, and pertinent comments.

The stated applicabilities given in Table 2.2 are subjective, based only on the limitations imposed by space and geometry factors and the potential for damage to the existing structure due to movements or vibrations induced by the improvement procedures. The adequacy of any method to achieve the required level of ground improvement and the improvement cost are dependent on site specific conditions; therefore these factors are not included in the assessment of the methods general applicability given in the table.

2.3 Focus of Research

The ability of various ground improvement methods to limit movements of piers and abutments to acceptable levels under earthquake loading and liquefaction are the primary focus of analyses performed for this research. These evaluations were limited to ground improvement at (1) a floating stub abutment at the crest of an approach embankment and (2) a multi-column pier supported by a spread footing foundation.

In evaluating the effectiveness of ground treatment techniques for liquefaction mitigation, the methods investigated for stub abutments and multi-column piers on shallow foundations were generally limited to those qualitatively judged to have high applicability (refer to Table 2.2). These methods included densification of the soil with compaction grouting and cementation of the soil with chemical or jet grouting. Schematics are shown in Figures 2.7 and 2.8 of potential improved ground zones formed with any one of these methods at a multi-column pier and stub abutment, respectively.

A few treatment techniques judged to have moderate applicability were also investigated as part of the research. They included mixed-in-place or jet grouted walls used for reinforcement and containment around multi-column piers and buttress fills at stub abutments used to increase effective stresses in the ground and provide additional mass. Figures 2.9 and 2.10 show schematics illustrating the use of these two improvement methods.

The actual sizes of the improved zones shown in Figures 2.7 through 2.10 are dependent in part on the particular treatment method utilized. A primary focus of the quantitative analyses performed for this dissertation was the evaluation of the impact of improvement type, size, and location on the predicted performance of abutments and piers. Information in the literature regarding this topic, as well as analytical methods that can be used for predicting the response of improved ground and supported structures within liquefiable deposits, is presented in the next chapter.

TABLE 2.1: Categories of Ground Improvement Methods for Liquefaction Mitigation at Existing Bridges

Improvement Mechanism	Principle	Potential Improvement Methods
Densification	Soil particles moved into tighter configuration increasing density	• Compaction grouting • Vibro-systems (vibratory probe, vibro-compaction, vibro-replacement)
Cementation	Soil particles bound together by filling voids with cementing material	• Particulate grouting • Chemical grouting • Jet grouting
Reinforcement and Containment	Soil mass reinforced with stiff elements used to provide additional shear resistance. When elements are overlapped and arranged to form enclosed areas, containment also provided.	• Mixed-in-place columns and walls • Jet grouting • Vibro-replacement • Root piles
In-situ stress increase	In-situ effective stresses within soil mass are increased resulting in an increase in shear resistance.	• Surcharge or buttress[2] fill • Compaction grouting[1]
Drainage	High permeability drainage elements installed to decrease drainage distance in soil mass limiting development, and providing faster dissipation, of excess pore water pressures.	• Gravel, sand, and wick drains • Vibro-replacement[1]

Notes:
1. For this specific treatment method the cited improvement mechanism is generally considered to be a secondary mechanism.
2. When used at the toe of a slope, a buttress fill also provides additional mass to resist a slope stability failure and increases the potential failure surface length.

TABLE 2.2: Summary of Ground Improvement Methods for Liquefaction Remediation at Existing Bridges

<table>
<tr><th rowspan="2">Method</th><th rowspan="2">Principle</th><th rowspan="2">Suitable Soil Types</th><th rowspan="2">Treated Soil Properties</th><th rowspan="2">Relative Costs</th><th colspan="2">Abutment Applicability*</th><th rowspan="2">Pier Applicability*</th><th rowspan="2">Comments</th></tr>
<tr><th>Stub</th><th>Full-Height Wingwall</th></tr>
<tr><td>Compaction Grout</td><td>Highly viscous grout acts as spherical hydraulic jack when pumped under high pressure resulting in densification.</td><td>Compressible soils with some fines</td><td>Increased D_r
SPT: $(N_1)_{60}$ = 25 to 30
CPT: q_{c1} = 80 to 150 tsf (Kg/cm^2)</td><td>Low material cost; high injection cost.</td><td rowspan="4">1. High. Treat anywhere between abutment and embankment toe; treat under and around abutment if excessive settlement expected.

2. High. Treat around pile groups.</td><td rowspan="4">1. Generally high. Treat under and around foundation.

2. High. Treat around pile groups.</td><td rowspan="4">High for solid wall, multi-column, and hammerhead piers. High to moderate for circular column piers.

1. Treat under and around foundation.

2. Treat around pile groups.</td><td rowspan="4">Must control heave and/or hydraulic fracture of soil.

Particulate and chemical grouting: verify size and strength of grouted soil mass.

Jet grouting: stage work to limit settlements. Evaluate potential damage to piles from jetting pressure.</td></tr>
<tr><td>Particulate Grouting</td><td>Penetration grouting: fill soil pores with cement, soil and/or clay.</td><td>Clean, medium to coarse sand and gravel</td><td>Cement grouted soil: high strength</td><td>Lowest of grouting systems</td></tr>
<tr><td>Chemical Grouting</td><td>Solutions of two or more chemicals react in soil pores to form a gel or solid precipitate.</td><td>Medium silts and coarser</td><td>Low to high strength</td><td>High to very high</td></tr>
<tr><td>Jet Grouting</td><td>High speed jets at depth excavate, inject and mix stabilizer with soil to form column or panels.</td><td>Sands, silts and clays</td><td>Solidified columns and walls</td><td>High</td></tr>
</table>

Notes: * Item No. 1 under applicability indicates applicability of improvement method for foundations over or in liquefiable soils. Item No. 2 indicates applicability for pile (or drilled shaft) foundations extending through liquefiable.

TABLE 2.2 (cont.): Summary of Ground Improvement Methods for Liquefaction Remediation at Existing Bridges

<table>
<tr><th rowspan="2">Method</th><th rowspan="2">Principle</th><th rowspan="2">Suitable Soil Types</th><th rowspan="2">Properties of Treated Soil</th><th rowspan="2">Relative Costs</th><th colspan="2">Abutment Applicability*</th><th rowspan="2">Pier Applicability*</th><th rowspan="2">Comments</th></tr>
<tr><th>Stub</th><th>Full-Height Wingwall</th></tr>
<tr><td>Vibratory Probe</td><td>Densification by vibration,liquefaction-induced settlement underwater.</td><td>Sand (< 15% passing No. 200 sieve)</td><td><u>D_r</u>: up to 80+% Ineffective in some sands.</td><td>Moderate</td><td rowspan="3">1. Moderate for lateral spreading; low for settlement. Treat at embankment toe to reduce risk of construction settlement.

2. Low. Treating around piles difficult due to access problems.</td><td rowspan="3">1. Low. Potential for excessive settlement and vibrations of bridge. Overhead clearance limitations.

2. Low. Treating around piles difficult due to access problems.</td><td rowspan="3">1. Low. Potential for excessive settlement and vibrations of bridge. Overhead clearance limitations.

2. Moderate to high. Treat around pile groups.</td><td rowspan="3">Overhead clearance limitations will restrict use. Monitor bridge for excessive vibrations. Construction in water requires special procedures.</td></tr>
<tr><td>Vibro-Compaction</td><td>Densification by vibration and compaction of backfill at depth.</td><td>Sand (<20% passing No. 200 sieve)</td><td><u>D_r</u>: up to 85+%
<u>SPT</u>: $(N_1)_{60}$ = 25 to 30
<u>CPT</u>: q_{c1} = 80 to 150 tsf (Kg/cm^2)</td><td>Moderate</td></tr>
<tr><td>Vibro-Replacement</td><td>Densely compacted gravel columns provide densification, reinforcement, and drainage.</td><td>Soft silty or clayey sands, silts, clayey silts</td><td>Increased D_r
<u>SPT</u>: $(N_1)_{60}$ = 25 to 30
<u>CPT</u>: q_{c1}= 80 to 150 tsf (Kg/cm^2)</td><td>Moderate to high</td></tr>
<tr><td>Surcharge/ Buttress Fill</td><td>Weight of surcharge increases liquefaction resistance by increasing effective stresses. Buttress fill increases stability by increasing resisting moment and extending failure surface.</td><td>Any soil surface provided it will be stable</td><td>Increase in strength</td><td>Low</td><td>1. High for slope stability; low for settlement. Place at embankment toe
2. Low. Ineffective in increasing soil stresses at piles.</td><td>1 & 2. Moderate. Place buttress fill in front of wall.</td><td>1 & 2. Moderate to low. Place surcharge around pier.</td><td>Need large area. Evaluate loads and settlement imposed on bridge.</td></tr>
</table>

Notes: * Item No.1 for foundations over or in liquefiable soils. Item No. 2 for pile (or drilled shaft) foundations extending through liquefiable soils.

TABLE 2.2 (cont.): Summary of Ground Improvement Methods for Liquefaction Remediation at Existing Bridges

Method	Principle	Suitable Soil Types	Properties of Treated Soil	Relative Costs	Abutment Applicability*		Pier Applicability*	Comments
					Stub	Full-Height Wingwall		
Mix-In-Place Walls & Columns	Lime, cement or asphalt introduced through auger or special in-place mixer.	All soft or loose soils	Solidified soil walls or columns of relatively high strength confine and/or reinforce potentially liquefiable soils	High	1. Moderate for lateral spreading; low for settlement. Install along toe of embankment. 2. Low. Hard to install around abutment pile group.	1. Moderate for lateral spreading, low for settlement. Install at toe of wall. 2. Moderate to low. Install around abut-ment pile group.	1. Moderate to low. Install completely around pier. 2. Moderate to low. Install completely around pier pile groups.	Extend to firm strata. Stage work to control construction settlements. Space limi-tations may restrict use. Construction in water requires spe-cial proce-dures.
Root Piles	Small-diameter inclusions used to carry tension, shear and compression.	All soils	Reinforced zone behaves as a coherent mass	Moderate to high	1. Moderate to low. Zone for installing piles same as described for for grouting. 2. Moderate to low. Install piles around pile groups.	1. Moderate to low. Install piles beneath and around foundation. 2. Moderate to low. Install piles around pile groups.	1. Moderate to low. Install piles beneath and around pier founda-tion. 2. Moderate to low. Install piles around pile groups.	Extend piles to firm strata. Large number of piles may be required to provide adequate reinforce-ment. Avoid damage to existing piles.

Notes: * Item No.1 for foundations over or in liquefiable soils. Item No. 2 for pile (or drilled shaft) foundations extending through liquefiable soils.

TABLE 2.2 (cont.): Summary of Ground Improvement Methods for Liquefaction Remediation at Existing Bridges

Method	Principle	Suitable Soil Types	Properties of Treated Soil	Relative Costs	Abutment Applicability*		Pier Applicability*	Comments
					Stub	Full-Height Wingwall		
Drains: **Gravel** **Sand** **Wick**	Relief of excess porewater pressure to prevent liquefaction. Intercept and dissipate excess pore water pressure plumes from adjacent liquefied soil.	Sand, silt	Improved drainage	Low to moderate	1&2. Mod-erate. Install drains around zone improved by other method(s).	1&2. Mod-erate.Install drains around zone improved by other method(s).	1&2. Mod-erate. Install drains around zone improved by other method(s).	Topography and space limitations may restrict use.

Notes: * Item No.1 for foundations over or in liquefiable soils. Item No. 2 for pile (or drilled shaft) foundations extending through liquefiable soils.

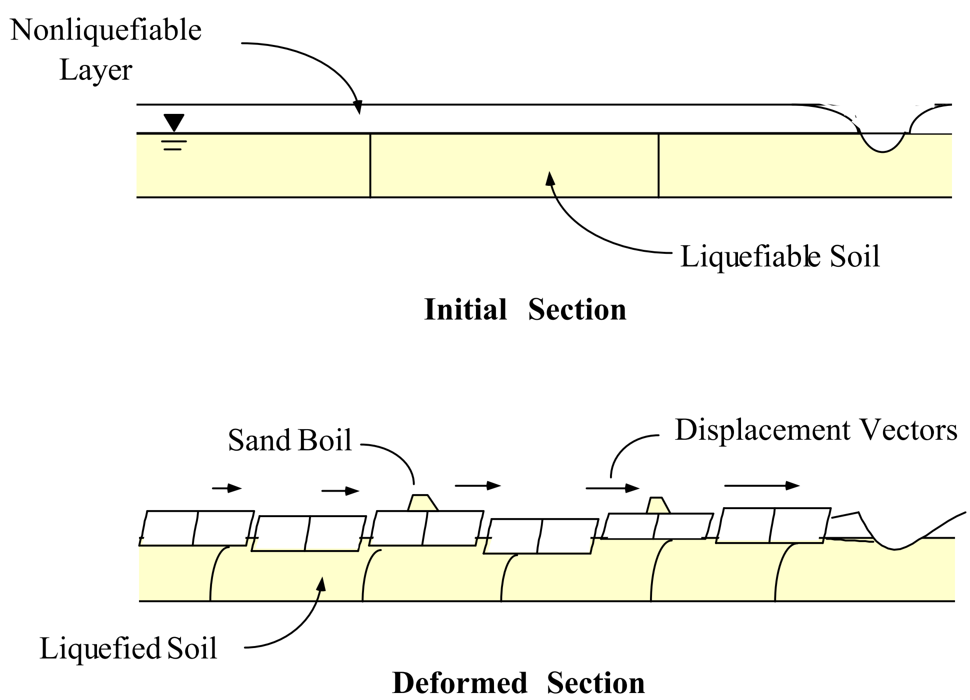


FIGURE 2.1: Lateral Spreading Mechanism (after Youd, 1984)

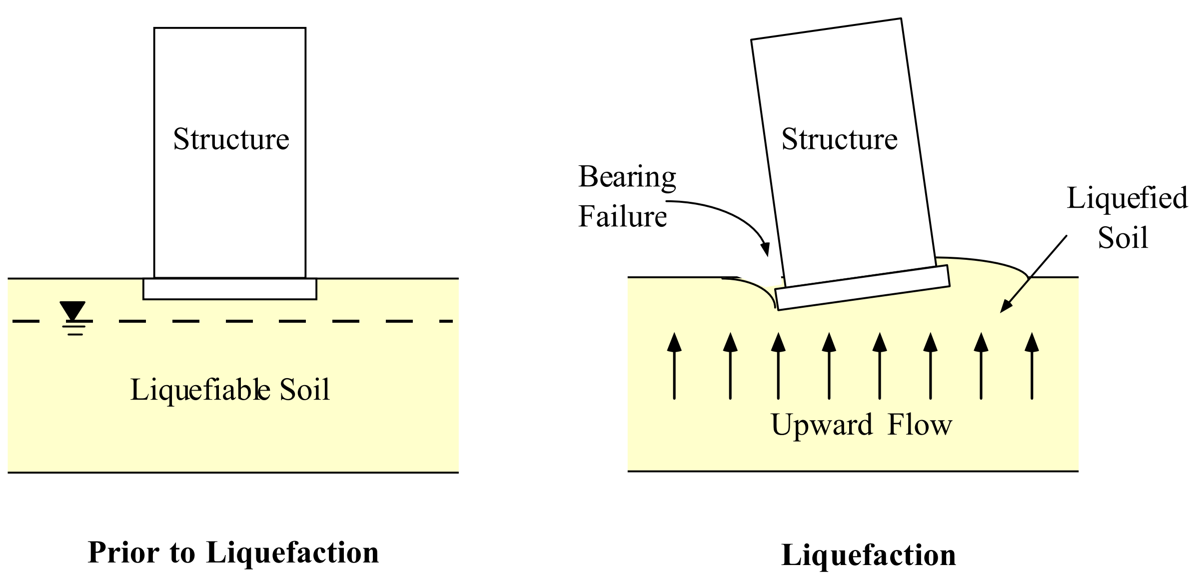


FIGURE 2.2: Bearing Capacity Failure (after Youd, 1984)

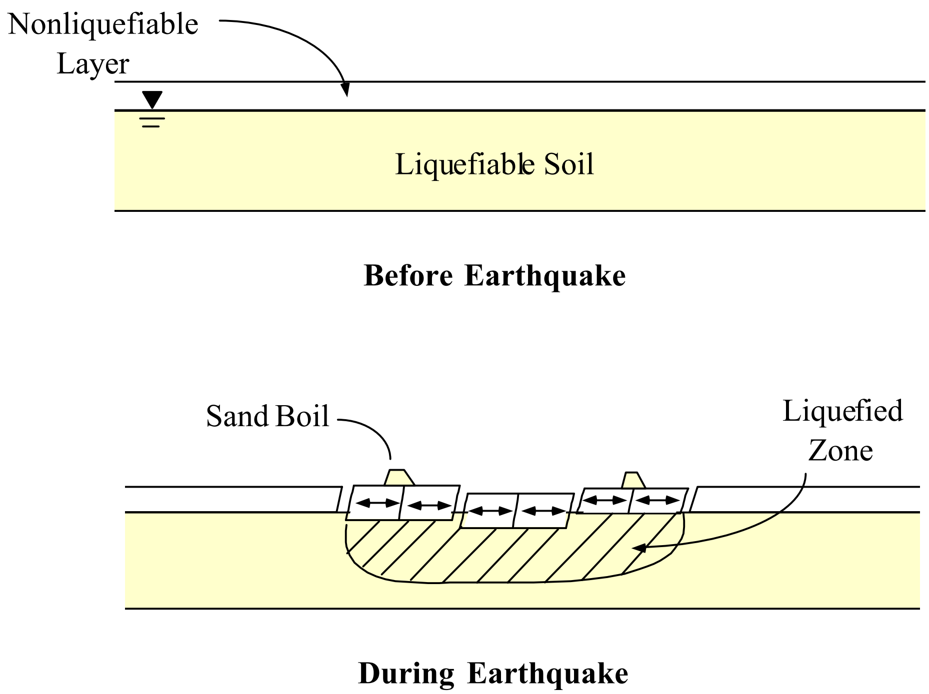


FIGURE 2.3: Ground Oscillation Phenomena (after Youd, 1984)

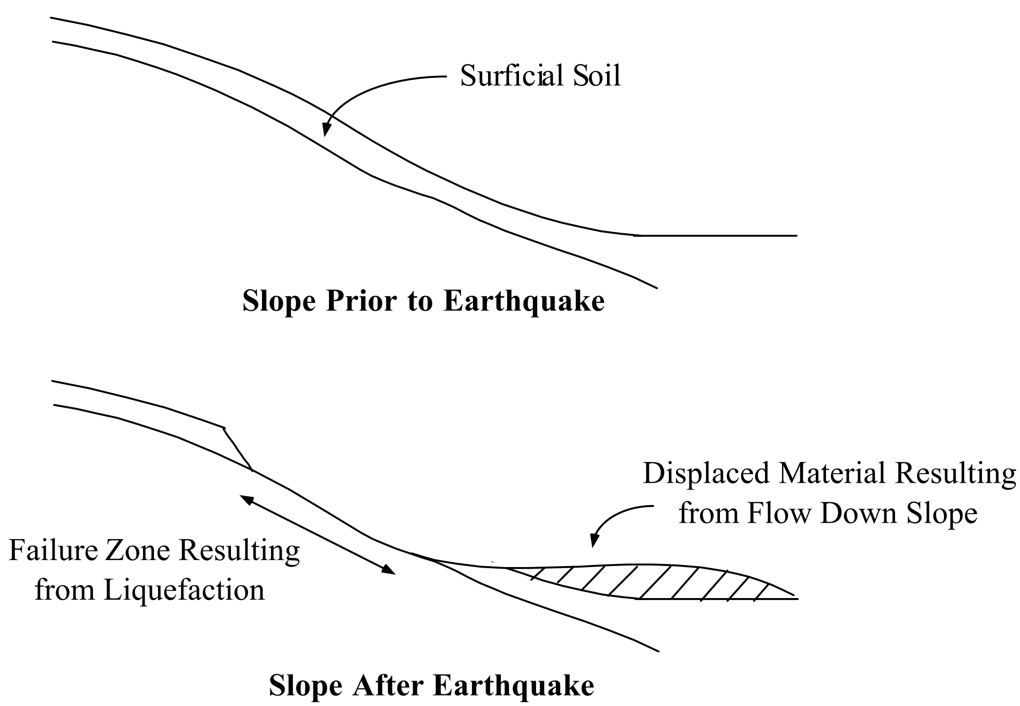


FIGURE 2.4: Flow Failure (after Youd, 1984)

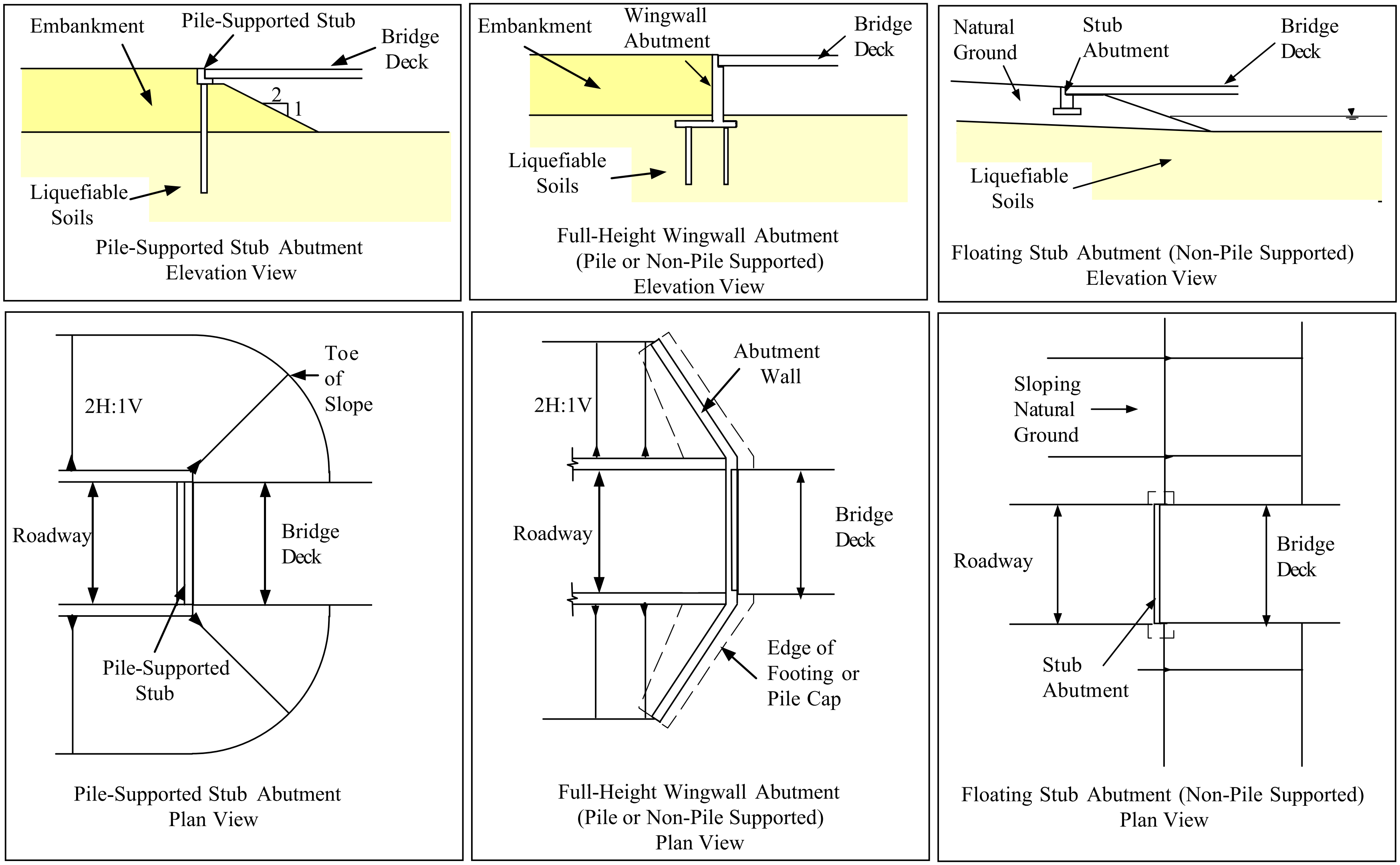


FIGURE 2.5: Some Typical Bridge Abutments (from Mitchell and Cooke, 1995)

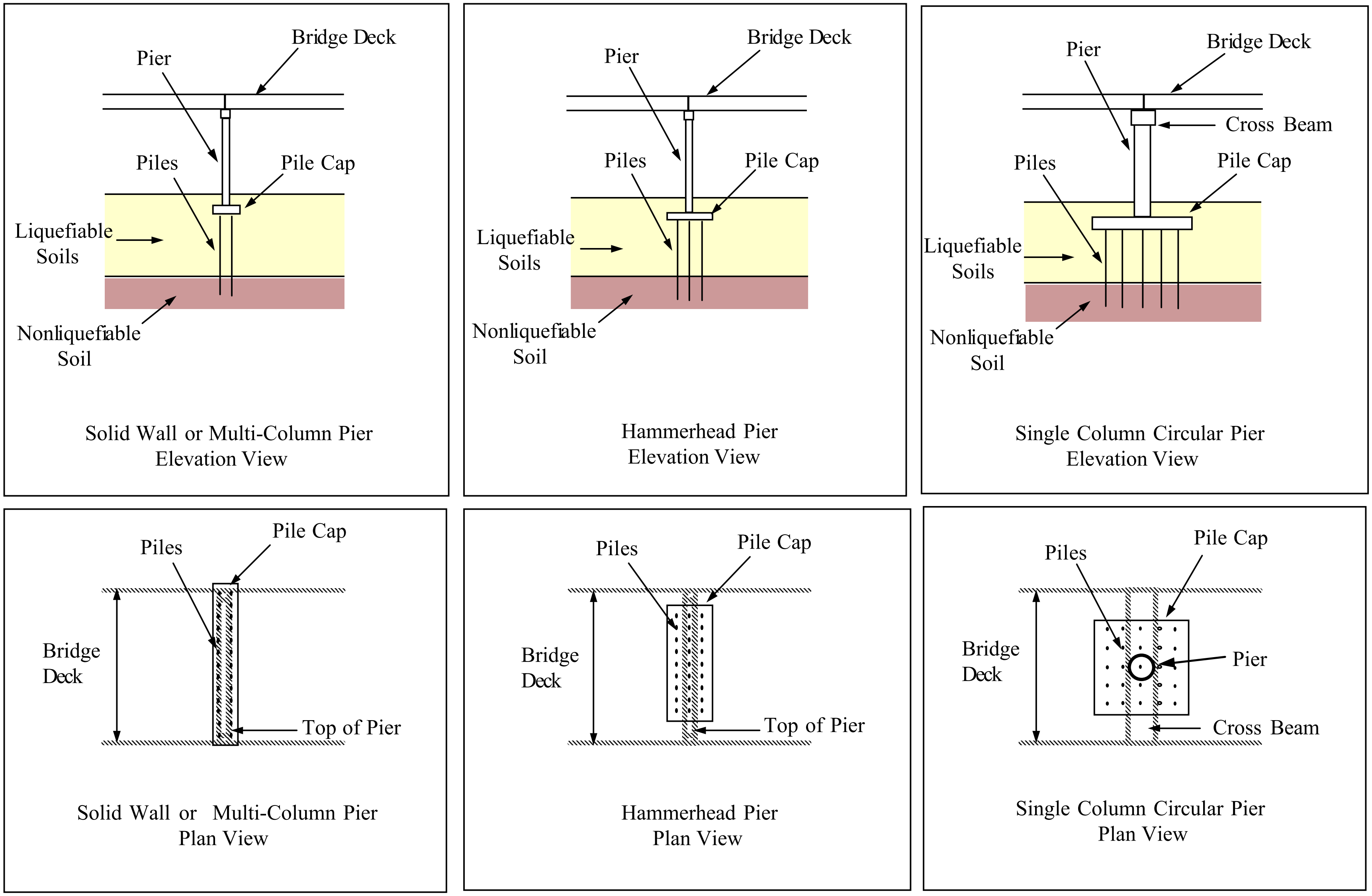


FIGURE 2.6: Some Typical Bridge Piers (from Mitchell and Cooke, 1995)

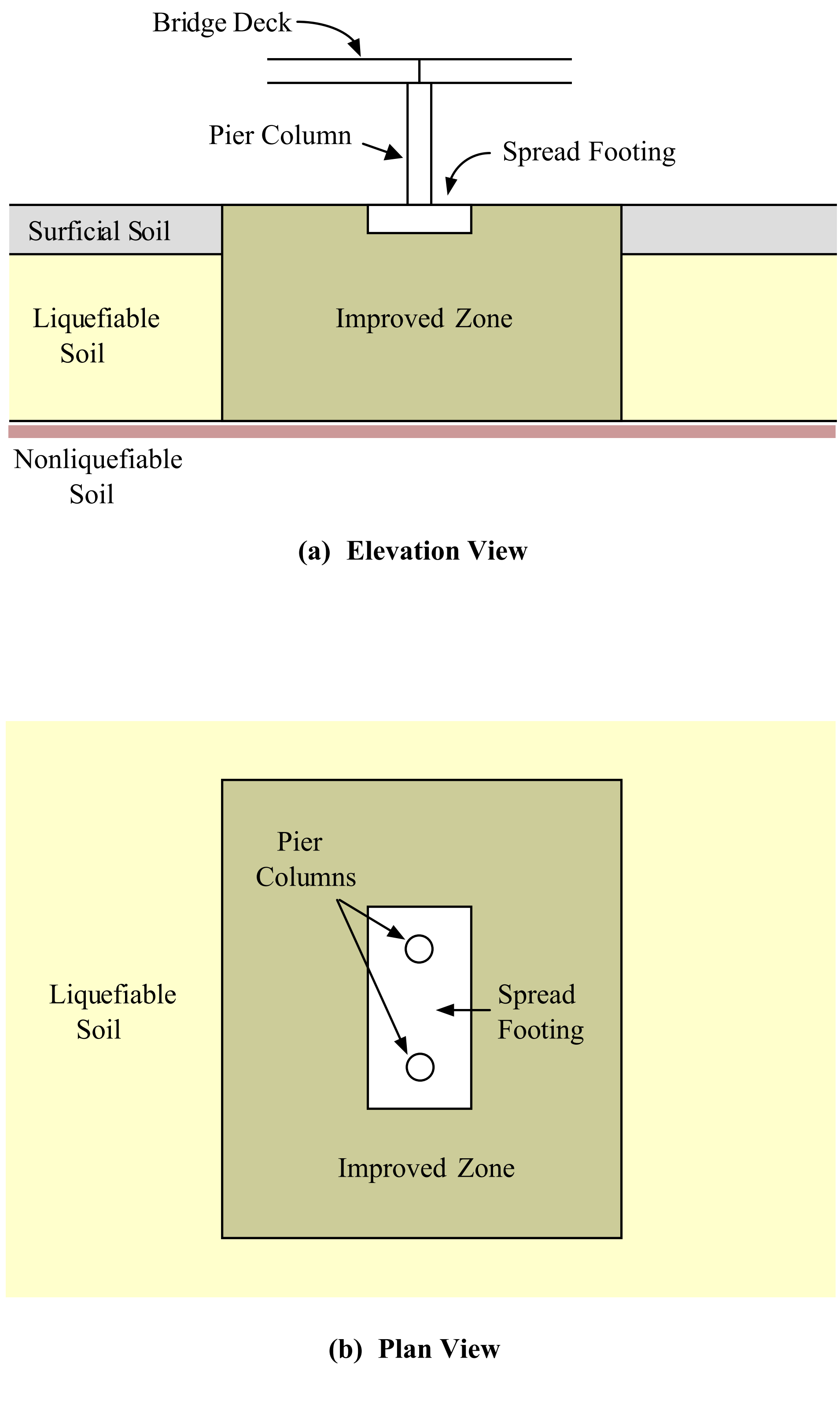
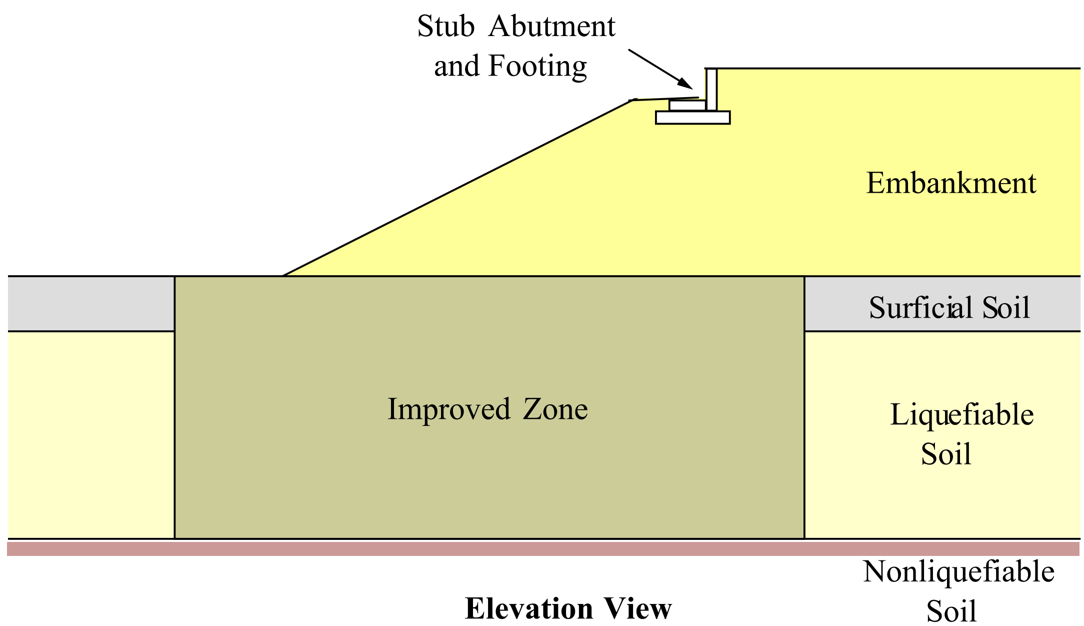
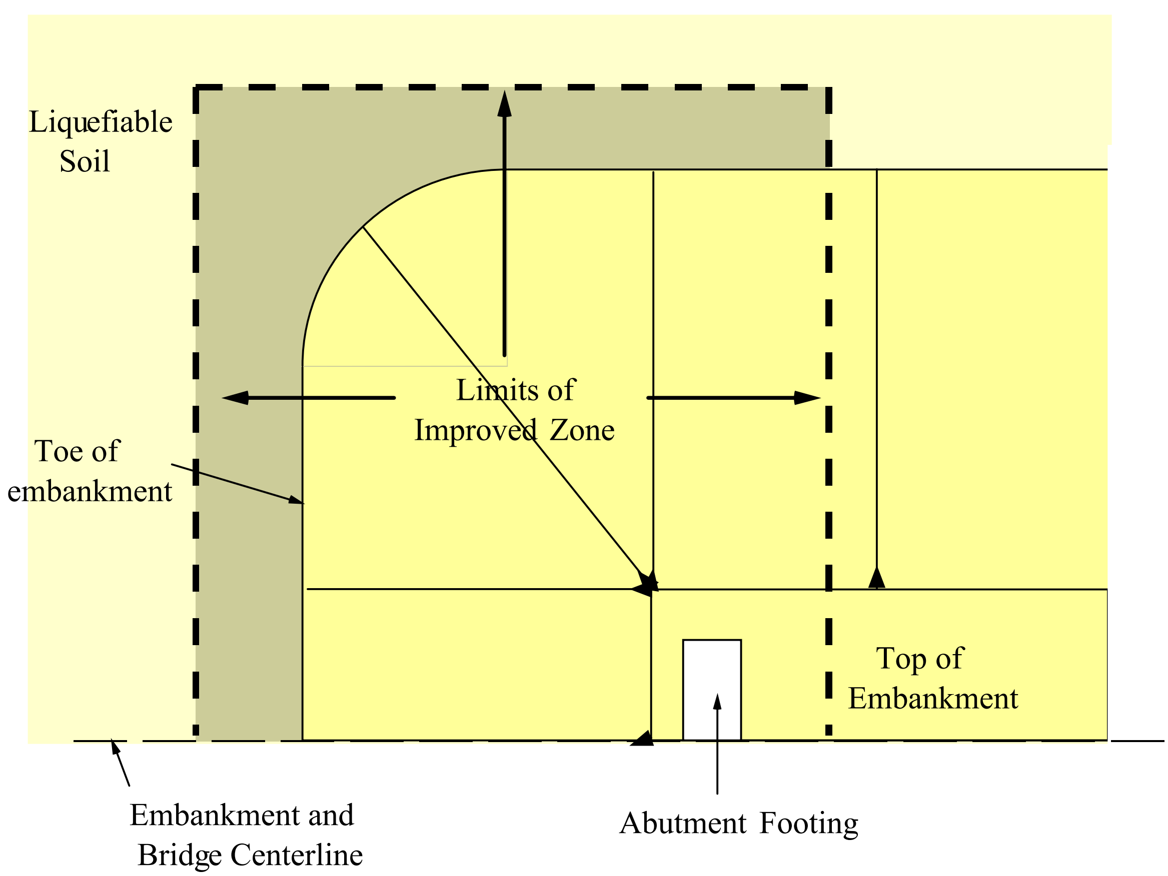


FIGURE 2.7: Ground Improvement at Bridge Pier

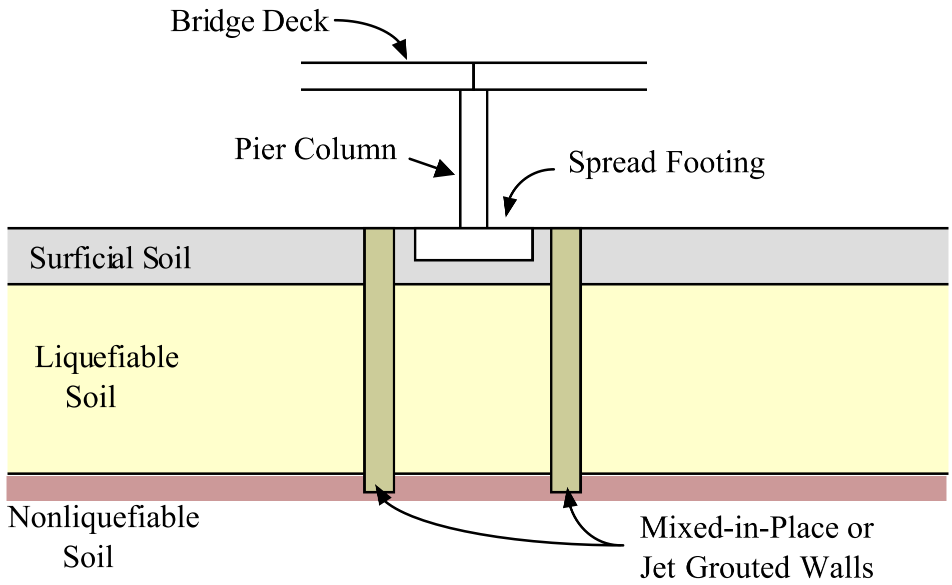


Elevation View

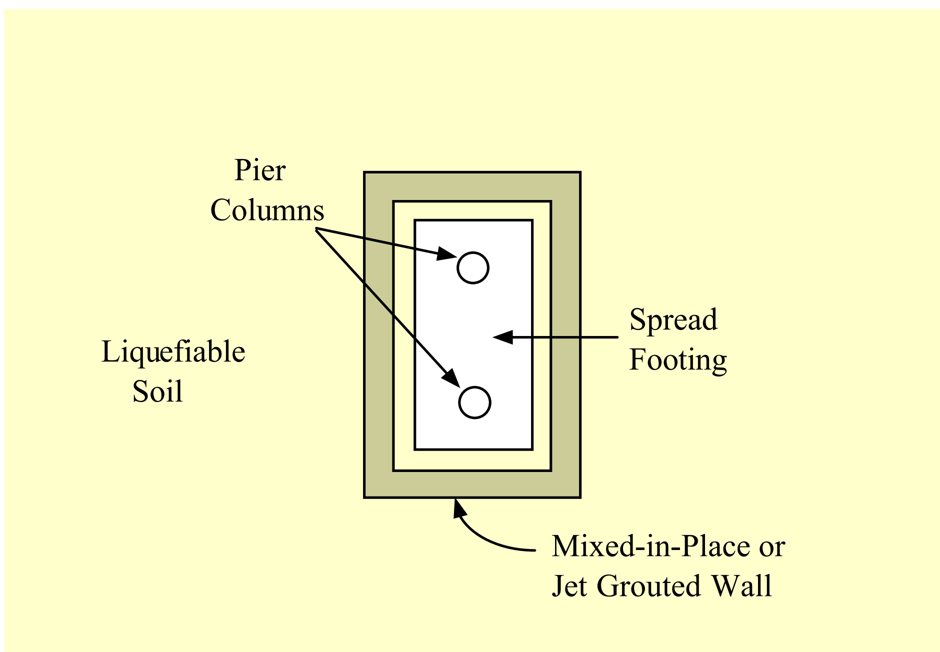


Plan View

FIGURE 2.8: Ground Improvement at Stub Abutment



(a) Elevation View



(b) Plan View

FIGURE 2.9: Mixed-in-Place or Jet Grouted Wall at Bridge Pier

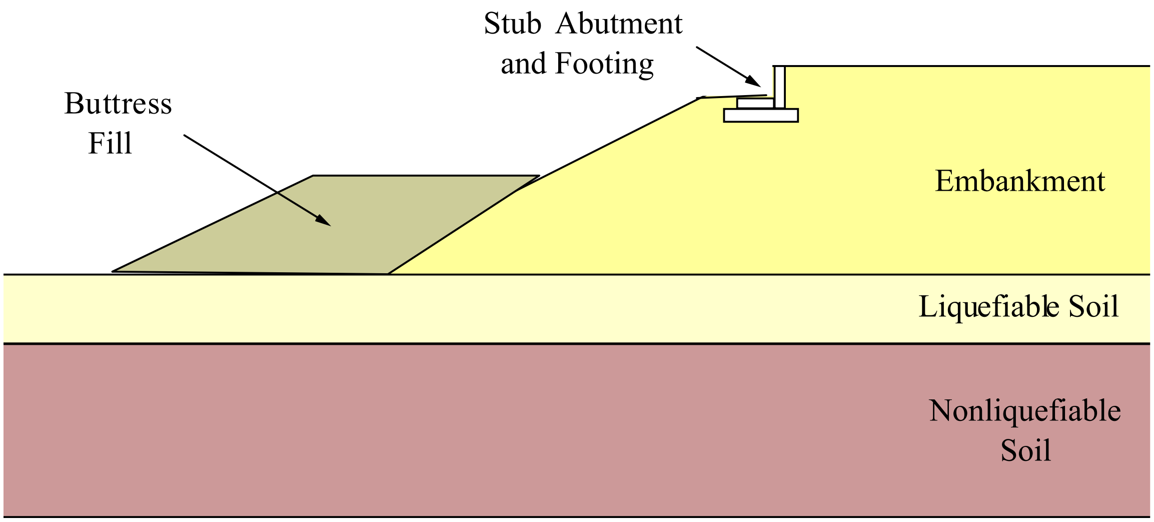


FIGURE 2.10: Buttress Fill at Stub Abutment