Table 5.1: Liquefaction Remediation Measures *(after Ferritto 1997)*

METHOD	PRINCIPLE	Most Suitable Soil Conditions Or Types	Maximum Effective Treatment Depth	Relative Costs
1) Vibratory Probe a) Terraprobe b) Vibrorods c) Vibrowing	Densification by vibration; liquefaction-induced settlement and settlement in dry soil under overburden to produce a higher density.	Saturated or dry clean sand; sand.	20 m routinely (ineffective above 3-4 m depth); > 30 m sometimes; vibrowing, 40 m.	Moderate
2) Vibro-compaction a) Vibrofloat b) Vibro-Composer system.	Densification by vibration and compaction of backfill material of sand or gravel.	Cohesionless soils with less than 20% fines.	> 20 m	Low to moderate
3) Compaction Piles	Densification by displacement of pile volume and by vibration during driving, increase in lateral effective earth pressure.	Loose sandy soil; partly saturated clayey soil; loess.	> 20 m	Moderate to high
4) Heavy tamping (dynamic compaction)	Repeated application of high-intensity impacts at surface.	Cohesionless soils best, other types can also be improved.	30 m (possibly deeper)	Low
5) Displacement (compaction grout)	Highly viscous grout acts as radial hydraulic jack when pumped in under high pressure.	All soils.	Unlimited	Low to moderate
6) Surcharge or buttress	The weight of a surcharge/buttress increases the liquefaction resistance by increasing the effective confining pressures in the foundation.	Can be placed on any soil surface.	Dependent on size of surcharge/buttress	Moderate if vertical drains are used
7) Drains a) Gravel b) Sand c) Wick d) Wells (for permanent dewatering)	Relief of excess pore water pressure to prevent liquefaction. (Wick drains have comparable permeability to sand drains). Primarily gravel drains; sand/wick may supplement gravel drain or relieve existing excess pore water pressure. Permanent dewatering with pumps.	Sand, silt, clay.	Gravel and sand > 30 m; depth limited by vibratory equipment; wick, > 45 m	Moderate to high
8) Particulate grouting	Penetration grouting-fill soil pores with soil, cement, and/or clay.	Medium to coarse sand and gravel.	Unlimited	Lowest of grout methods
9) Chemical grouting	Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate.	Medium silts and coarser.	Unlimited	High
10) Pressure injected lime	Penetration grouting – fill soil pores with lime.	Medium to coarse sand and gravel.	Unlimited	Low
11) Electrokinetic injection	Stabilizing chemical moved into and fills soil pores by electro-osmosis or colloids in to pores by electrophoresis.	Saturated sands, silts, silty clays.	Unknown	Expensive
12) Jet grouting	High-speed jets at depth excavate, inject and mix a stabilizer with soil to form columns or panels.	Sands, silts, clays.	Unknown	High
13) Mix-in-place piles and walls	Lime, cement or asphalt introduced through rotating auger or special in-place mixer.	Sands, silts, clays, all soft or loose inorganic soils.	> 20 m (60 m obtained in Japan)	High

METHOD	PRINCIPLE	Most Suitable Soil Conditions Or Types	Maximum Effective Treatment Depth	Relative Costs
14) Vibro-replacement stone and sand columns a) Grouted b) Not grouted	Hole jetted into fine-grained soil and backfilled with densely compacted gravel or sand hole formed in cohesionless soils by vibro techniques and compaction of backfilled gravel or sand. For grouted columns, voids filled with a grout.	Sands, silts, clays.	> 30 m (limited by vibratory equipment)	Moderate
15) Root piles, soil nailing	Small-diameter inclusions used to carry tension, shear and compression.	All soils.	Unknown	Moderate to high
16) Blasting	Shock waves and vibrations cause limited liquefaction, displacement, remolding and settlement to higher density.	Saturated, clean sand; partly saturated sands and silts after flooding.	> 40 m	Low

The practical applications of many of these measures have been presented in the literature *(Hryciw 1995; Stewart et al. 1997; Boulanger et al. 1997; Mitchell et al. 1998b)*. The following references are recommended for outlining the design of ground treatment schemes and for evaluating the effectiveness of soil improvement.

1. ***Vibro-compaction and related methods of densification.*** Vibro-compaction and derivatives such as sand compaction piles have been widely used around the world. Numerous case studies from Japan document the successful seismic performance of treated soils located in proximity to unimproved sites where significant liquefaction-induced ground failures were noted *(Iai et al. 1994; Yasuda et al. 1996)*.
2. ***Stone columns for densification, drainage and strengthening.*** The design of stone column applications for liquefaction mitigation has been described by Baez *(1995)*, Baez and Martin *(1992)*, Barksdale *(1987)*, and Boulanger and others *(1998b)*. Additional references that describe the utilization of stone columns around pile-supported structures are provided by Ashford and others *(1999)*, Egan and others *(1992)*, and Jackura and Abghari *(1994)*.
3. ***Compaction grouting.*** The monitored injection of very stiff grout into a loose sandy soil results in the controlled growth of a grout bulb mass that displaces the surrounding soils. This action increases lateral earth pressures and compacts the soil, thereby increasing its resistance to liquefaction. Recent case studies on the effectiveness of grouting for liquefaction applications have been described by Boulanger and others *(Boulanger and Hayden 1995; Stewart et al. 1997; Boulanger et al. 1997)*.
4. ***Deep soil-cement mixing methods.*** The in situ injection and mixing of cement into weak soils is becoming more common in the western United States. Recent applications include liquefaction mitigation and the strengthening of weak cohesive soils adjacent to embankments, levees and bridge abutments. References on the application of this method include Francis and Gorski *(1998)* and Bruce *(2000)*. Bruce describes field applications and design considerations for the use of deep soil mixing methods in liquefiable soils.