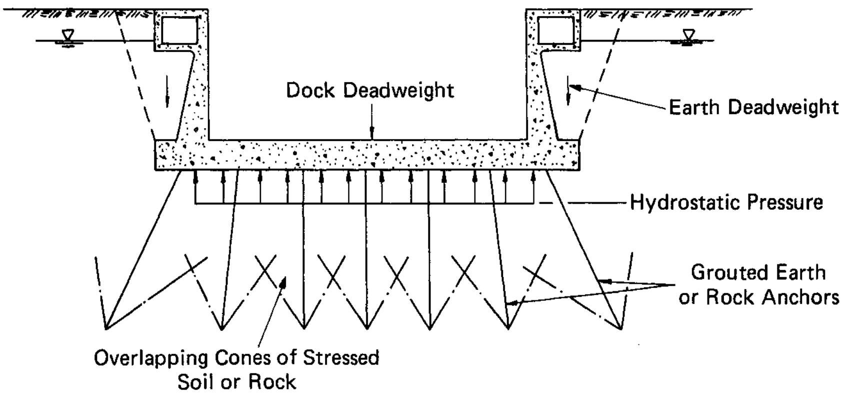


Figure 8-29. Basin dry dock with grouted tiedown anchors.

ding, and degree of weathering of the rock. Half angles of the cone typically range from 30° to 45°, but may be less, depending on bedding angles (19) (see Fig. 8-31). In any case, where anchors are closely spaced, an allowance must be made for overlapping of the cones. When calculating the soil or rock deadweight resistance, buoyant unit weights should be used. In addition to the deadweight resistance, two other modes of failure must be investigated. The bond resistance between the grout and surrounding soil or rock and

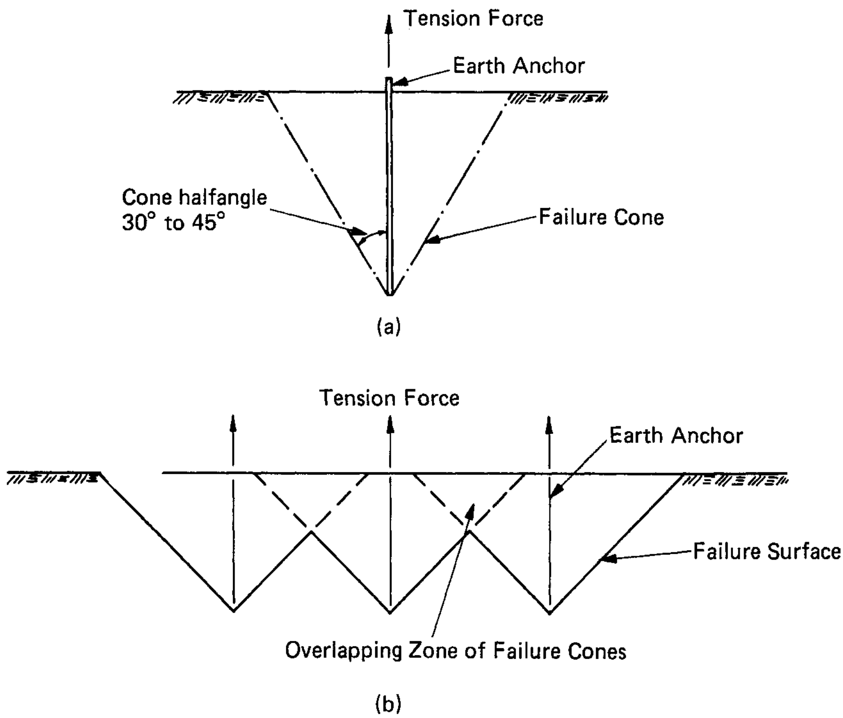
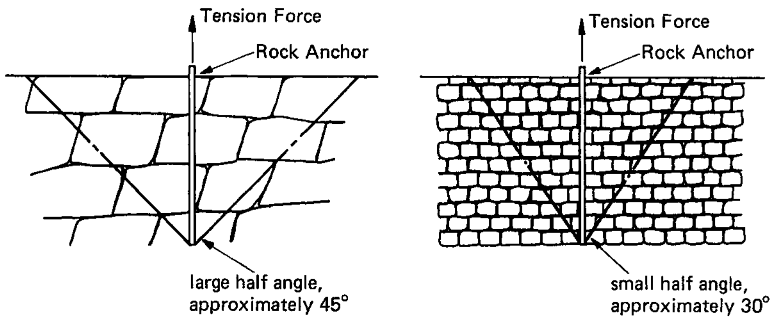


Figure 8-30. Cone of influence for grouted earth anchors: (a) single anchor; (b) overlapping cones for multiple anchors.



(a) Massive Bedrock Formation (b) Thinly Bedded, Highly Fractured Bedrock

Figure 8-31. Influence of rock fracturing and bedding on grouted anchor cone of influence.

the bond resistance between the anchor rod and grout must be checked. The length of the anchor is determined by whichever mode of failure proves to be critical.

Because of the cyclic buoyancy nature of a graving dock operation, care must be taken in the design of the anchors. Prestressing forces must be greater than the buoyancy loading from dewatering in order to maintain contact pressure between the ground and the dock. Although the mechanisms are not well understood, repeated loading reduces anchor capacity (77). Bember and Kupferman (119) suggest a factor of safety of 2.5 for ultimate static load compared to the peak cyclic load. More extensive information on the design of tension anchors is provided in references (77) and (78).

Tension piles can provide resistance to uplift and are advantageous when a pile foundation already must transfer loads across a weak or compressible layer. The calculation of anchor pile resistance (tension piles) is discussed in the previous section. Where closely spaced piles are used, single pile as well as group action must be checked to determine limiting values.

As an alternative to designing the dock to resist hydrostatic pressures and buoyancy forces, a pumped pressure-relieving subdrain system may be installed. Hydrostatic pressures on both the floors and walls may be relieved by such a system. A pumped system located above cohesive soils, however, can lead to consolidation of the layer and settlement of the dock.

8.9 SITE IMPROVEMENT—METHODS AND MATERIALS

Site improvement or ground modification can be an important phase in the development of waterfront sites. Several methods and materials can be used to densify loose soils, reduce postconstruction settlements, and increase stability. Some of these methods also can be employed to densify backfill materials, to increase soil strength and friction angle, and to reduce the possibility of liquefaction potential during earthquakes (120–124). In addition, there are several relatively new products, as well as products whose applications are new to geotechnical and marine engineering, that can assist the engineer in the design of waterfront structures.

VIBRO-COMPACTION AND VIBRO-REPLACEMENT

Vibro-compaction and vibro-replacement are two commonly used methods for the improvement of deep, soft, or loose soils (48, 125, 126). Vibro-compaction is performed by using a probe that vibrates as well as uses water jets to penetrate into loose granular soils as it is lowered by a crane. When the appropriate depth is reached, the forward water jets are turned off, and the equipment is extracted. Granular backfill material is continually fed into the void left by the probe, and the vibration compacts the backfill as well as the surrounding material (see Figs. 8-32 and 8-33). The operation leaves a column of densely compacted material approximately 7 to 9 feet in diameter.

Vibro-replacement, or the use of stone columns, is a variation on the vibro-compaction technique used for in situ stabilization of cohesive soils or densification of loose cohesionless materials (48–50, 127–130). Stone columns are composed of coarse gravel or crushed stone that is compacted as it is placed. A vibrating probe is used to open the hole for the column, and the stone is either dumped in from the surface or placed directly at the probe tip through a chute. Each load of stone then is compacted by the weight and vibration of the probe as the backfill material is pushed laterally into the surrounding soils. The column diameter depends on existing subsurface conditions.

Stone columns typically are placed on a grid with a center-to-center spacing ranging from 3 to 10 feet. A series of columns can be placed under a new structure to improve bearing capacity and allow for the use of a shallow foundation, as opposed to a pile-type foundation. The use of stone columns can be less expensive than a pile foundation, and can aid in the drainage and consolidation of subsurface layers. This can be important in placing fill at sites that have underlying deposits of cohesive soils. Stone columns can also provide a conduit for excess pore water pressures to escape during earthquake events, thereby reducing the risk of liquefaction.

As mentioned in Section 8.4, vibro-replacement can be used to increase the stability of slopes (48). The strength and the friction angle of the subsurface soils are improved by

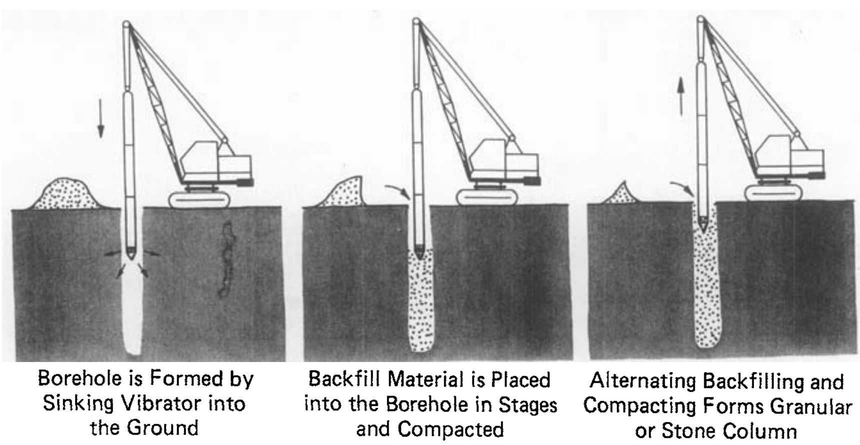


Figure 8-32. Schematic of vibro-compaction and vibro-replacement technique. (Courtesy of Hayward-Baker.)

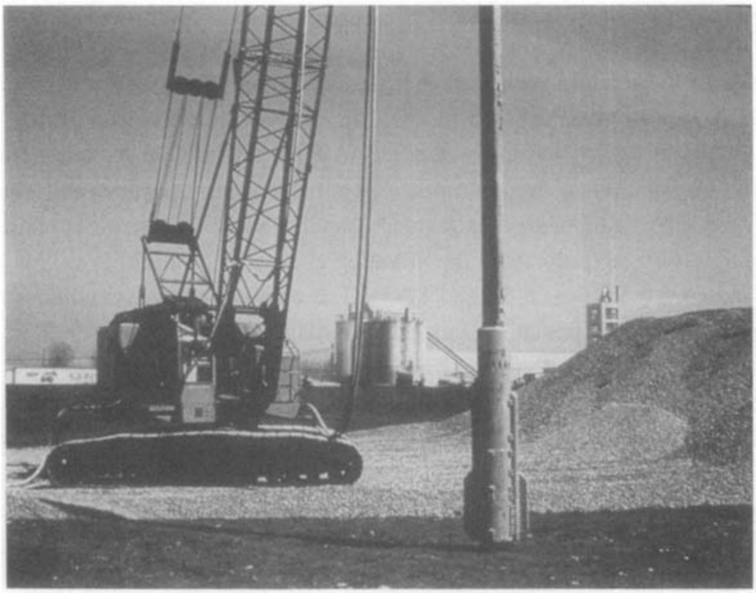


Figure 8-33. Stone column vibro-replacement equipment. (Photo courtesy of Hayward-Baker.)

the placement of stone columns. Also, the columns can penetrate through possible slip surfaces, thereby increasing factors of safety against sliding. Figure 8-34 presents a schematic of the use of stone columns to aid slope stability.

RAMMED AGGREGATE PIERS

Rammed aggregate piers are a ground improvement method commonly used to reinforce soft or loose soils (131–135). The rammed aggregate elements are installed by drilling 24-inch to 36-inch diameter holes with an excavator-mounted auger and ramming thin lifts of well-graded aggregate within the holes to form very stiff, high-density aggregate piers

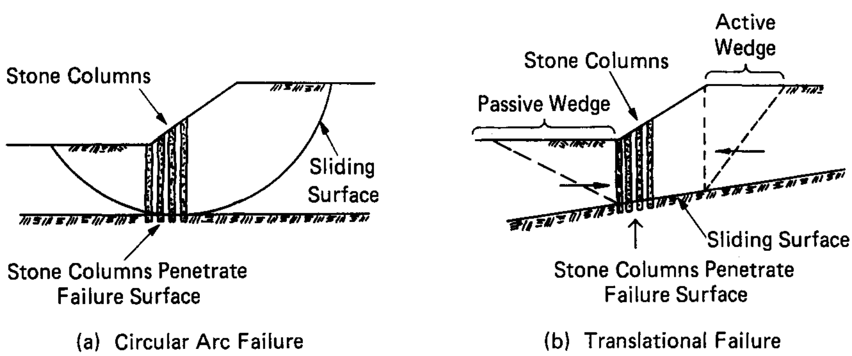


Figure 8-34. Use of stone columns or rammed aggregate piers to increase slope stability. [After Dobson (48).]

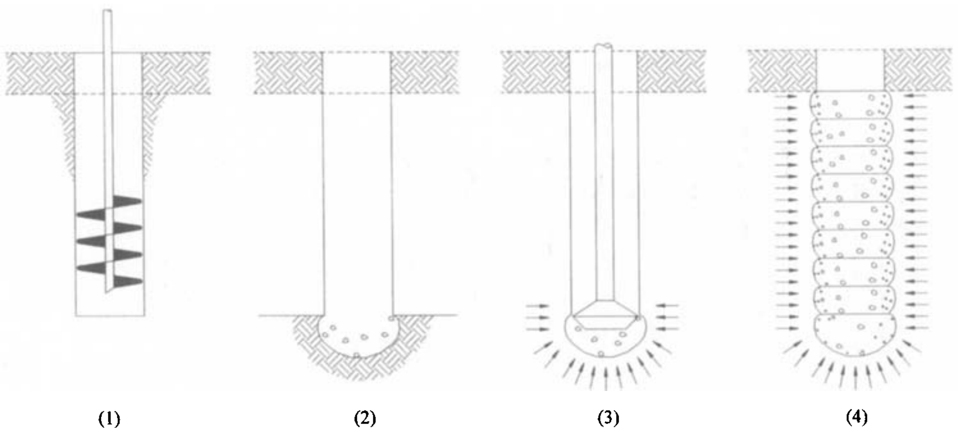


Figure 8-35. Rammed aggregate pier soil reinforcement construction process. (Courtesy of Geopier Foundation Company.)

as shown in Fig. 8-35. The drilled holes typically extend from 10 to 30 feet below grade. The first lift of aggregate forms a bulb below the bottoms of the piers, thereby prestressing and prestraining the soils to a depth equal to at least one pier diameter below drill depths. Subsequent lifts are typically about 12 inches in thickness. Ramming takes place with a high-energy beveled tamper that both densifies the aggregate and forces the aggregate laterally into the sidewalls of the hole. This action increases the lateral stress in the surrounding soil, thereby further stiffening the stabilized composite soil mass. The construction process is shown in Fig. 8-36.

The augured holes are generally drilled uncased in cohesive soils. In granular soils, temporary casing may be required to keep the hole from collapsing as the pier is constructed.

Figure 8-36. Rammed aggregate pier installation. (Photo courtesy of Geopier Foundation Company.)

The temporary casing is of particular importance when working below the water table in granular soils. In such cases, open graded stone aggregate is used and the ramming takes place below the water table.

The result of rammed aggregate pier installation is a significant strengthening and stiffening of subsurface soils that then support high-bearing-capacity footings and control settlement. Rammed aggregate elements are installed beneath shallow footings or in grid patterns for support of floor slabs or area fills. The rammed aggregate pier system is designed to reinforce the soil where the stresses are highest immediately beneath the foundations. As a result, overall foundation settlements are controlled by significantly reducing compression of the highly stressed near-surface soils.

Rammed aggregate pier soil reinforcing elements are typically used to provide support of shallow foundations and floor slabs for ancillary structures in the backlands of marine facilities. With the rapid installation process averaging 40 to 60 elements per day, rammed aggregate pier elements can provide both cost and time savings compared to deep foundations. Rammed aggregate piers can also be used to increase the stability of slopes, as shown in Fig. 8-34.

VIBRATING PROBE COMPACTION

The vibrating probe compaction technique uses a specially fabricated, open-end, large-diameter pipe pile that is vibrated into loose sand and gravel (136, 137). Vibrations are delivered to the pile by a vibratory pile-driving hammer and cause a densification of loose materials as the pile is placed and extracted. Raising and lowering of the vibrating pile can take place several times at each location until the desired density is obtained (see Fig. 8-37). Reference (138) describes a comparison of the vibro-compaction and vibrating probe techniques based on full-scale field tests. The project consisted of the densification of hydraulically placed backfill for the construction of a graving dry dock.

DEEP DYNAMIC COMPACTION

Deep dynamic compaction is a landslide method that is used to compact loose granular materials (139–141). The method consists of raising and dropping a large mass, usually a concrete or steel block, onto the ground surface. The induced vibrations cause densification of the subsurface material. Different energies are easily obtained by increasing or decreasing either the mass of the falling block or the free fall-height (see Fig. 8-38).

As in the vibratory methods described above, an in situ test program is performed in the field and checked with the SPT or cone penetration test to determine the grid spacing, mass of the block, free fall height, and number of blows required at each location. A particular advantage of deep dynamic compaction is that it can be used in areas that have been filled with heavy boulders or rock fill, a situation that precludes the use of most other methods. Unfortunately, testing of compaction performance in this type of material is difficult to impossible, although measurement of the average total settlement will give an indication of the void ratio reduction. Deep dynamic compaction produces relatively large vibrations, compared to other vibratory methods, which can cause problems with nearby facilities.

Figure 8-37. Vibrating probe compaction used to densify loose sand in cofferdam bulkhead to eliminate possible failure due to earthquake-induced liquefaction. (Photo courtesy of Bath Iron Works Corporation.)

All of the above site improvement methods are carried out in grid-type fashion over the entire area to be compacted. The grid spacing usually is determined by field testing prior to development of the compaction program. Results are verified by performing SPT or cone penetration tests between grid locations following densification (142).

PRELOADING

An increase in site grade or additional loads due to proposed structures can result in unacceptable settlements where underlying compressible layers are present. However, this problem can be ameliorated by preloading, a method of consolidating compressible soils to a stress level greater than the stresses due to new construction loadings (143). The method generally is performed by stockpiling fill on the site until the underlying soils have

Figure 8-38. Deep dynamic compaction.

consolidated. Other preloading methods including temporarily storing bulk products such as coal, scrap steel, or iron ore on-site, or constructing lined basins in order to flood large areas, also have been successful.

Preloading can be a time-consuming process, depending on the permeability of the soil and the thickness of the compressible stratum. A thick deposit of low-permeability soil can require an excessive time span to modify the site. The use of closely spaced vertical sand drains or wick drains can speed the process considerably, however, by providing a relatively short drainage path for pore pressure dissipation.

VERTICAL WICK AND SAND DRAINS

Wick drains and sand drains are vertically installed drainage elements used to hasten consolidation of deep deposits of cohesive soils (see Fig. 8-39). Sand drains are columns of sand that are installed by driving a pipe pile fitted with a trapdoor bottom plate into the ground. The pipe is subsequently filled with sand that stays in the ground as the pipe is extracted. Wick drains are corrugated plastic strips covered with filter fabric that are pushed into the groundwater with a specially designed mandrel. Wick drains have been used exten-

Figure 8-39. Typical wickdrain installation equipment. (Photo courtesy of TerraSystems, Inc.)

sively to decrease the time required for drainage of pore water from deep deposits of cohesive materials (144–148). The vertical drains are used to accelerate consolidation of fine-grained materials and avoid a buildup of excess pore water pressure that can lead to slope stability problems. Closely spaced wick drains provide a short horizontal drainage path for pore water to travel to where it is conveyed to the surface and carried away.

In the few years that wick drains have been available, they have received wide acceptance and have almost totally replaced the use of sand drains. They are cleaner, easier, and faster to install, and are more reliable, efficient, and cost-effective than sand drains (147). It should be noted, however, that in certain situations the filter fabric can become smeared with fine-grained soils that reduce the effectiveness of the method.

LIGHTWEIGHT FILL

Lightweight aggregate, commonly used in the production of lightweight concrete, currently is being used as a geotechnical backfill material. Its high strength-to-weight ratio can be used to solve stability, settlement, and high lateral earth pressure problems associated with many waterfront structures.

Rotary-kiln-produced expanded shale aggregate has a number of important properties that make its use as a lightweight backfill material viable. The angle of internal friction is in the range of 40° to 45°, and compacted dry unit weights below 65 pounds per cubic foot are possible (149). Individual particles have fairly high abrasion resistance and do not exhibit appreciable breakdown in the field. The material also can be supplied in a number of standard gradations. Though lightweight fill is more expensive than granular backfill material, it can lead to an economical solution by allowing the use of lighter structural members for new construction. Lightweight backfill also may be used to relieve lateral earth pressures on existing distressed structures. Not only has lightweight aggregate been used successfully for numerous small rehabilitation projects, its use on large-scale projects also has proved economical (65).

Low-density cellular concrete recently has been used to reduce loads on existing waterfront structures (150). The material is aerated prior to being pumped in a slurry consistency, and resultant unit weights are on the order of 36 pounds per cubic foot.

REINFORCED EARTH

Reinforced earth is another relatively new concept in foundation engineering. Originally developed for a vertical retaining wall system (51, 52), it has proved useful in many other foundation applications. Reinforced earth retaining walls are built with individual interlocking members attached to a series of rows of reinforcing strips or geosynthetic grids. The strips or grids reinforce the soil by acting as a series of tension members, reducing lateral earth pressure to such an extent that only lightweight face panels or blocks are required to prevent the loss of fill.

The use of reinforced earth in the marine environment has been reasonably successful (51, 151, 152) (see Fig. 8-40). Construction can be somewhat difficult, however, because of the nature of the environment, especially where deep water or large tidal fluctuations exist. The use of filter fabrics or face unit sealants usually is required to prevent migration of fines from the backfill. Concerns about the corrosion of metal reinforcing strips have been addressed with coatings and the recent use of geosynthetic grids.

The concept of soil reinforcement also can be applied to the design of embankments and fills over soft ground. The reinforcing material allows the use of steeper slopes and reduces the possibility of stability failure.

FABRICS AND FILTER MATERIALS

The use of fabrics in geotechnical engineering has boomed in recent years. Numerous types of fabrics are being used for filters, impermeable barriers, reinforced earth, wick drains, drainage mats, and erosion control.

In waterfront engineering, the use of fabrics has been mainly for filters and erosion control. Normally, filters for granular soils used in coastal structures are made up of graded layers of gravel and stone (53). Materials in the proper gradation are often of limited availability or costly, and proper placement is often time-consuming and difficult to control. Woven plastic fabrics have been used successfully in a number of coastal structures to alleviate filter problems and preclude the possibility of structural failures due to leaching and erosion of construction materials (58 and 59).