Soil Improvement Techniques for Mitigation of Seismic Hazards - An Overview

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SOIL IMPROVEMENT TECHNIQUES FOR MITIGATION OF SEISMIC HAZARDS - AN OVERVIEW

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ABSTRACT

If seismic hazards are deemed to be unacceptably high because of poor soil conditions, it is often possible to achieve improved seismic performance through the use of one or more soil improvement techniques. Poor performance is the result of inadequate strength, low stiffness, or insufficient drainage. Many improvement techniques have been evolved over the years, mostly through trial and error, aimed at improving at least one of these properties. When selecting one or more mitigation methods, it is important to consider the effectiveness of the improvement approach for the particular situation at hand, cost, environmental consequences, regulatory requirements, and technical feasibility. Also, careful assessment of the degree of ground improvement achieved is essential. The subject of soil improvement is quite extensive and a number of excellent sources and case studies are available in the literature. The aim of this paper is to highlight the most promising soil improvement techniques that are most commonly used for mitigation of seismic-hazard.

INTRODUCTION

Where a seismic hazard has been identified, soil improvement techniques are commonly used at sites to eliminate or reduce the hazard to an acceptable level. These techniques may include any one or a combination of the following actions: (1) avoidance of the hazard through zoning restrictions or relocation of facilities to safer sites; (2) strengthening of the structure to withstand the effects of hazard; (3) strengthening of the ground to prevent hazard and damaging ground deformations; and (4) evaluation and acceptance of the risk where hazard to life and limb is minimal. All of these measures have been used effectively to reduce damage. For strengthening of the ground to prevent hazard and damaging ground deformations various improvement techniques have been evolved over the years, mostly through trial and error, aimed at improving inadequate strength, low stiffness, or insufficient drainage properties of soil or at least one of these. When selecting one or more mitigation methods, it is important to consider the effectiveness of the improvement approach for the particular situation at hand, cost, environmental consequences, regulatory requirements, and technical feasibility. Also, careful assessment of the degree of ground improvement achieved is essential. The subject of soil improvement is quite extensive and a number of excellent sources and case studies are available in the literature (Hausmann, 1990; Broms, 1991: Mosely, 1993; Hryciw, 1995; Mitchell et al., 1995; Kramer, 1996; Schaefer, 1997).

During earthquakes, other factors can also contribute to unacceptable performance. In particular, the buildup of excess pore water pressure can lead to very large deformations. Consequently, commonly used techniques for mitigation of seismic hazards often involve reducing the tendency of the soil to generate positive excess pore water pressure during earthquake shaking as well as increasing the strength and stiffness of the soil.

Advances in soil improvement technology have generally resulted from the initiative and imagination of contractors. Research and explanatory theories have followed, rather than led, implementation; for some widely used techniques, proven theories have yet to be developed. In such cases, indirect or empirical evidence must be relied upon and the study of case histories is particularly important. This paper does not attempt to discuss all available soil improvement techniques, instead, it presents the most promising techniques that are most commonly used for mitigation of seismic-hazard.

SOIL IMPROVEMENT TECHNIQUES

The main goal of most soil improvement techniques used at sites to eliminate or reduce the hazard to an acceptable level. At present a wide variety of soil improvement techniques are available for mitigation of seismic hazards. The costs of these methods vary widely, and the conditions under which they can be used are influenced by the nature and proximity of structures and constructed facilities. On the basis of the mechanisms by which they improve the engineering properties of the soil, the most common of these can be divided into following categories:

i. Excavation and replacement techniques
ii. Densification techniques
iii. Reinforcement techniques
iv. Grouting and mixing techniques
v. Drainage techniques

EXCAVATION AND REPLACEMENT TECHNIQUES

This technique involves the excavation of the potentially liquefiable soils. This soil may then be re-compacted as an engineered fill to a higher density so that the soil will have less potential to liquefy. Alternatively, the native soils may be improved with some additives and then properly compacted as an engineered fill. Another solution would be to waste the excavated material and replace it completely with properly compacted import material that would be non-liquefiable.

Excavation and replacement may be a cost-effective solution for sufficiently shallow deposits. Placing a structure at depth may bypass undesirable surface soils, although costs and construction difficulties increase rapidly with depth and with excavation below the water table, particularly in high-permeability soils. Surrounding deposits that have not been modified may still cause problems as lifelines and other connecting structures may be damaged during an earthquake.

DENSIFICATION TECHNIQUES

Densification can be accomplished using a variety of techniques that are aimed at increasing the density of soil, thereby resulting in improved stiffness, strength, and liquefaction resistance. The most common densification techniques are vibro-compaction, dynamic compaction, blast densification and compaction grouting. Of these techniques, the first three make use of the tendency of granular soils to densify when subjected to vibrations. As such, their effectiveness is greater for cohesion less soils such as clean sands and gravels. Just as fines tend to inhibit liquefaction during earthquakes, they tend to inhibit densification by vibration.

Vibrocompaction

Vibrocompaction is most effective for clean, loose cohesion less soils with less than about 15% silt and less than about 3% clay content. It is achieved by vibration of the head of the vibration probe as it is withdrawn. Because compaction occurs only within a short range of probe, the procedure must be repeated at regular spacing on the order of 5 to 10 ft. Of course, the spacing depends on size of the probe and the soil type. During the past few years, larger and more powerful vibrators have been introduced, which allow larger spacing's and deeper penetration (in some cases, up to 120 ft). When compaction is achieved by horizontal motion of the vibrator; it is referred to as vibroflotation. The basic equipment and the compaction process used in this method are shown in Figures 1 and 2. Vibratory techniques also exist that induce vertical vibration, such as Terra-Probe, Vibro-Wing, and Tri-Star or Y-Probe methods (Hryciw,1995). Wightman (1991) presented an overview of this technique.

Although the vibroflotation and terra-probe methods are somewhat similar, a relative comparison of the results obtained via the two methods may be more problematical than unique. Soil types, mechanical installation procedures, and equipment are influential factors in this regard. Generally, however, (1) the extraction rate for the terra-probe is higher than that for the vibroflot, and (2) more probes may be needed

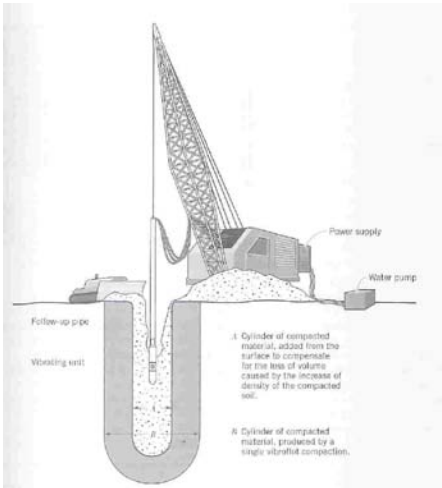


Fig. 1 Vibroflotation equipment (Brown, 1977)

for the terra-probe than for vibroflotation to achieve equivalent results (Brown et al., 1976).

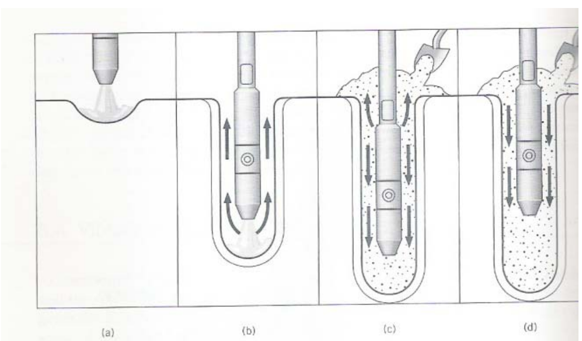
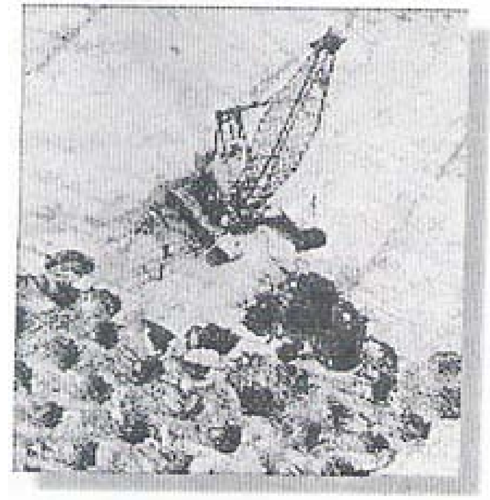


Fig. 2 Vibroflotation compaction process (Brown, 1977)

Dynamic Compaction

Dynamic compaction involves dropping a heavy weight from a large distance to produce a shock wave which is propagated to some depth in the ground (Fig. 3). The high energy upon impact is provided by heavy steel or concrete units (6 to 35 tons) that freefall from distances up to 100 ft or more. The energy is controlled by selection of the weight, drop height, the number of drops at each point and the spacing of the grid of drop points. The effective depth of treatment can empirically be estimated using the expression $(WH)^{0.5}$, where W is the weight to be dropped in tones and H is the drop height in meters (Slocombe, 1993). It often represents an alternative to vibrocompaction, especially for uncontrolled fills, municipal solid waste deposits, coal mine spoils, and



other loose soils. Soils with significant amounts of

Fig. 3 Dynamic compaction technique

fines (20% or more) can in some cases be densified quite effectively. The depth of improvement is related to the tamper weight and drop height but may reach up to 30 ft or more. The effectiveness of a dynamic compaction program is typically evaluated by performing SPT or CPT tests both before and after construction. In favorable conditions, the post-construction $(N_1)_{60}$ values can be 10 to 20 blows higher than those measured before construction. As this method generates substantial shock waves due to large impact forces, it cannot be used close to existing structures. A good reference on dynamic compaction is the FHWA publication by Lukas (1986), which was updated in 1996 as FHWA Geotechnical Engineering Circular No.1.

Blast Densification

Blast densification is another high-energy ground improvement technique that achieves densification by destroying existing soil structure and forcing soil grains into a tighter configuration as a result of shock waves produced by the blast. This method of densification has been used successfully on many projects, and is most effective in clean sands. Charges are placed in predrilled or jetted holes. The size of the charge must be selected carefully so that it is sufficiently large to be effective but not too intense to cause excessive vibrations that may cause damage to nearby structures. Liquefaction may develop and may have to be controlled by proper drainage means. Because of the potential of undesirable effects in surrounding areas, blast densification has not seen the same degree of use as the previous techniques. However, it has been shown effective in densifying soils to depths of approximately 130 ft (Narin van Court and Mitchell, 1995).

Compaction Grouting

A commonly used ground improvement technique is compaction grouting, which involves injection of various grouting agents into the soil. The technique consists of injecting a soil-cement grout of sufficient plasticity and friction under pressure, which displaces and densifies soil in a controlled fashion (Fig. 4).

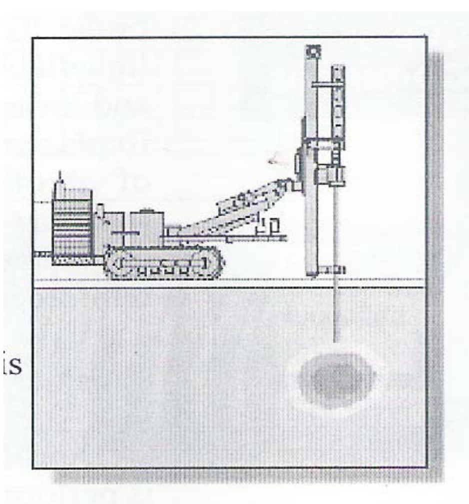


Fig. 4 Compaction grouting technique

Compaction grouting has been shown to be effective in increasing the density of poorly compacted fill, alluvium, and compressible or collapsible soil for mitigation of liquefaction potential (Graf, 1992; Boulanger and Hyden, 1995). The advantages of compaction grouting are less expense and disturbance to the structure than foundation underpinning, and it can be used to relevel the structure. The disadvantages of compaction grouting are that it is difficult to analyze the results, it is usually ineffective near slopes or for near-surface soils because of the lack of confining pressure, and there is the danger of filling underground pipes with grout (Brown and Warner 1973). Although the technique is widely used for a number of purposes, there is little in terms of a rational design methodology. Instead, the method has progressed based almost entirely on trial and error and a few empirical observations. Research is now under way to establish optimum grout characteristics, injection pressures, and effective pumping rates vs. soil characteristics (Schaefer, 1997). Advances have been made recently in terms of equipment and monitoring, and particularly in terms of evaluating the degree of improvement through seismic testing.

REINFORCEMENT TECHNIQUES

In some cases it is possible to improve the strength and stiffness of an existing soil deposit by installing discrete inclusions that reinforce the soil. These inclusions may consist of structural materials, such as steel, concrete, or timber, and geomaterials such as densified gravel. Vibrostone columns and Compaction piles are generally used as reinforcement to improve soils prone to liquefaction.

Vibrostone Columns

Vibrostone columns have been used to improve soils prone to liquefaction since the 1970s (Dobson, 1987). It can be installed in variety of ways and constructed by introducing gravel during the process of vibroflotation. Construction is accomplished by introducing a vibratory probe into the ground, which displaces the soil laterally through vibratory motion and therefore induces densification in the surrounding volume. The void that is created is backfilled with stone. The resulting column and surrounding soil provide for higher stiffness and strength. Also, the damaging effects of liquefaction are reduced because the stone columns provide a relief path for excess pore pressures to dissipate. A review of the performance of vibrostone columns for reduction of soil liquefaction is presented by Baez (1995).

Compaction Piles

Compaction piles achieve densification by displacing the soil as the piles are driven into the ground. Prestressed concrete or timber piles are generally used for this purpose and are driven in a grid pattern and left there. The seismic performance of the soil deposit is improved using compaction piles by three different mechanisms. First, the flexural strength of the piles themselves provides resistance to soil improvement (reinforcement). Second, the vibration and displacements produced by their installation cause densification. Finally, the installation process increases the lateral stresses in the soil surrounding the piles.

Because the compaction piles typically densify the soil to distances on the order of a only few pile diameters, they must be placed close together to be effective. Improvements have been noted to depths of about 60ft (Marcuson et al., 1991).

GROUTING AND MIXING TECHNIQUES

Grouting and mixing techniques improve the shear resistance of the soils by injection of particulate matter, resins, or chemicals into the voids. Common applications are permeation grouting, jet grouting and deep soil mixing.

Permeation Grouting

Permeation grouting uses low viscosity grouts that are able to penetrate into individual voids with minimal disturbance to the soil structure. The types of grouts used range from high-slump cements to various gels of very low viscosity, depending primarily on the void characteristics of the soil (Graf, 1992).

Jet Grouting

In jet grouting, a high-pressure fluid is used to erode soil in a predrilled hole and replace it with and engineered soil-grout mix to form a solid element sometimes referred to as soilcrete or grout column. The dimensions of the grouted cavities are controlled by the injection pressure, the type and operation of the injection nozzle, and the erosion susceptibility of the soil. Jet grouting is most successful in cohesionless soils and can be performed as deep as predrilled holes can be provided. This technique has been used successfully as a liquefaction countermeasure (Hayden, 1994).

Deep Soil Mixing

During the 1970s and 1980s, a new technique of soil improvement was developed in Japan. It uses rotating mixer shafts, paddles, or jets that penetrate into the ground while injecting and mixing Portland cement or some other stabilizing agent (Toth, 1993; Yang, 1994; Schafer, 1997). These techniques include deep cement mixing, soil mix walls, deep jet mixing, deep soil mixing, deep mixed method, and others. There are several kinds of mixing machines available, which are used for this technique.

The treated soil has greater stiffness and strength, reduced compressibility, and lower hydraulic conductivity and becomes effective to provide support for overlaying structures and to reduce liquefaction hazards.

DRAINAGE TECHNIQUES

Liquefaction hazards can be reduced by increasing the drainage ability of the soil. If the pore water within the soil can drain freely, the build-up of excess pore water pressure will be reduced. Drainage techniques include installation of drains of gravel, sand or synthetic materials. Procedures for selecting the sizes and spacings of gravel drains have been developed by Seed and Booker (1976, 1977) for mitigation of liquefaction hazards. The use of gravel drains for suppression of excess porewater pressure requires careful attention to drain permeability and filtration behavior of the drain-soil boundary. Even though drainage techniques can mitigate liquefaction hazards by suppressing excess porewater pressure buildup, postearthquake settlement may still occur. Synthetic wick drains can be installed at various angles, in contrast to gravel, or sand drains that are usually installed vertically. Drainage techniques are often used in combination with other types of soil improvement techniques for more effective liquefaction hazard reduction. Case histories of the use of drainage techniques for mitigation of seismic hazards have been described by Ishihara et al. (1980), Aboshi et al. (1991) and Iai et al. (1994).

VERIFICATION OF IMPROVEMENT

Verification of the effectiveness of soil improvement is an important part of seismic hazard mitigation. A number of methods are evolved to verify the effectiveness of soil improvement. Whatever method of soil improvement is selected, the final step should be to check the results in the field, using laboratory or field testing techniques. Field testing techniques are popular because of the limitation of many laboratory techniques. In situ testing techniques and geophysical testing techniques are considered as field testing technique. The SPT, CPT, PMT, and DMT are used as in situ techniques, whereas cross-hole and downhole (including seismic cone) are used as geophysical techniques for verification of soil improvement effectiveness. Usually, in situ, test are performed to evaluate the liquefaction potential of a soil deposit before the improvement was attempted. With the knowledge of the existing ground characteristics, one can then specify a necessary level of improvement in terms of in situ test parameters. Performing in situ tests after improvement has been completed, allows one to decide if the degree of improvement was satisfactory. In some cases, the extent of the improvement is not reflected in in-situ test results until some time after the improvement has been completed.

SUMMARY AND CONCLUSIONS

Where a seismic hazard has been identified, soil improvement techniques are commonly used at sites to eliminate or reduce the hazard to an acceptable level. A variety of improvement techniques have been evolved over the years, mostly through trial and error, aimed at improving inadequate strength, low stiffness, or insufficient drainage properties of soil or at least one of these. The most promising techniques that are most commonly used for mitigation of seismic hazard are excavation and replacement, densification, reinforcement, grouting and mixing, and drainage techniques. The applicability and suitability of these soil improvement techniques to the particular situation and their limitations along with verification of the effectiveness of improvement are presented in this paper.

Excavation and replacement technique is one of the oldest and simplest methods of soil improvement. However, it is usually cost effective only when the required volumes are small and the excavation does need to extend below the groundwater table.

Densification is probably the most commonly used soil improvement technique for mitigation of seismic hazards. Most densification techniques use strong vibrations to densify the ground, and are effective in sandy soils. Strong vibration can be potentially damaging to structures, pipelines, and other constructed facilities, therefore cannot be used closed to existing structures.

Reinforcement techniques introduce discrete inclusions that stiffen and strengthen a soil deposit. The high stiffness and strength of the inclusions also tend to reduce the stresses imposed on the weaker material between the inclusions.

Grouting techniques involve the injection of special liquid or slurry materials to improve the soil, whereas mixing techniques consists of mixing soil with Portland cement or some other materials. The treated soil has greater strength, reduced compressibility, and lower hydraulic conductivity than the original soils.

Drainage technique minimize the buildup of porewater pressure during earthquakes by shortening the drainage paths in a soil deposit. The installation of drains generally involves some degree of densification and the drains themselves may also provide some reinforcement.

Verification of the effectiveness of soil improvement is an important part of seismic hazard mitigation. Direct or indirect measurement of stiffness, strength, or density characteristics both before and after improvement can allow reliable evaluation of soil improvement effectiveness. These characteristics may be measured by laboratory, in situ, or geophysical tests.

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