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Seismic Site Improvement and Foundation Upgrade

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ABSTRACT

This paper presents an overview of techniques currently available for site improvement and foundation upgrade for structures, including buildings, against earthquake damage with the emphasis on those techniques applicable to repair or retrofit of existing structures including buildings. It is based on a review for the "NRC/IRC Guideline on Techniques for Seismic Upgrading of Building Structures" prepared by the National Research Council. Methods for improving foundations of existing structures reviewed here include conventional foundation upgrading techniques as well as soil stabilization techniques. Foundation upgrading consists of underpinning and the addition of soil anchors, piers or piles. Soil stabilization covers a variety of techniques used to strengthen the subsoil by densification, reinforcement, consolidation and drainage. Examples are given where these foundation upgrade and soil stabilization upgrade techniques are applied. The paper also discusses some recent concerns about the influence of liquefaction-induced large soil displacements on pile design and suggests potential solutions.

INTRODUCTION

Historically, few foundations on level competent ground have failed during earthquakes. Foundation failures have occurred where the underlying soils have comprised loose saturated sandy or silty soil, or very soft sensitive clays, or where foundations have been located on or near steep and marginally stable slopes

Upgrading of foundations is generally expensive because of access difficulties. The need to upgrade the foundation to resist gravity and seismic forces, however, arises in circumstances that require one or more of the following five objectives to be met (NRC 1995):

(1) to provide new foundations for vertical structural elements added in the upgrading;

(2) to enhance the bearing, uplift and lateral capacity of the existing foundation;

(3) to strengthen the connections between the foundations and vertical structural elements;

(4) to prevent potential loss of soil support (e.g., by soil stabilization); and

(5) to implement base isolation.

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Close coordination and cooperation among the owner, architect, structural and geotechnical engineers are essential to define clearly the upgrade objective such as life safety and post-earthquake functional requirement and to map out an upgrade program to achieve the objective.

FOUNDATION UPGRADE TECHNIQUES

Seismic upgrading of superstructures (Allen et al. 1995) may require upgrading of the foundations. The foundations need to accommodate increased gravity loads as well as seismic shear and overturning forces (FEMA 1992). An increase in the allowable bearing capacity, over and above those values used for static loads, is usually appropriate for short-duration seismic forces.

Existing continuous (strip) or spread footings may be subjected to excessive bearing pressure or even uplift. Techniques (see Figure 1) to alleviate these conditions include:

- underpinning the existing footing so that it is founded on competent subsoil or the footing size is increased resulting in reduced bearing pressure;
- adding soil anchors, drilled piers, or piles; and
- increasing the number of vertical-resisting elements in the superstructure.

Pile foundations may be subjected to excessive tensile and compressive loads from the combination of seismic and gravity loads. Their lateral capacity may also be inadequate for transferring the seismic base shear from the pile caps to the subsoil. The pile foundation capacity can be increased by:

- installing additional piles and enlarging the existing pile cap; and
- introducing tie beams between pile caps to assist in redistributing the loading.

Mat foundations may occasionally have inadequate moment capacity to resist the combined gravity and overturning forces. This deficiency may be corrected by providing a locally thickened reinforced concrete section such as inverted column capitals.

To prevent foundation damage due to seismic shear the passive resistance of the founding soil can be mobilized by introducing perimeter and internal tie beams or shear keys which extend into the underlying soil. These can also be used for tying footings together and redistributing forces. Alternatively, anchors, drilled piers or raked piles can also be used.

For buildings constructed on steep hills, the free-standing columns and piers should be designed to resist earthquake loads, and foundations should rest on stable ground. Piles with adequate lateral capacity should be used for buildings over water along bay shores and river banks.

Foundation uplift may not usually be a problem, but if it is, the uplift capacity of an existing foundation may be increased by adding dead weight, soil anchors, drilled piers, or piles. The ability to do this may depend on access and available headroom in the interior of the building. An alternative is to provide additional vertical resisting elements or modify the structural frame to distribute the overturning forces to other vertical members, or to tie adjacent footings together with a reinforced concrete beam so as to mobilize the resistance of the adjacent footings.

While additional piles may be provided for upgrading a pile foundation, the existing pile cap may not be able to distribute the loads efficiently to the new piles. In such cases it may be necessary to temporarilly support the column and replace the old pile cap with a new pile cap that includes the new piles. Deep tie beams to distribute some of the pile load to adjacent pile caps with unused capacity may be more cost effective than installing new piles.

SOIL STABILIZATION TECHNIQUES

Seismic soil failures causing building damage include: loss of soil strength due to build-up of dynamic pore pressure, liquefaction, lateral spreading of soil, excessive horizontal and vertical ground movements due to settlement of natural soil deposits or man-made fills, slope instability, or fault movements. NRC (1992) evaluation guidelines and the Canadian Foundation Engineering Manual (CGS 1993) provide guidelines for evaluation of these issues. The maintenance of slope stability in diverse geological and topographic settings is mainly a geotechnical problem and is beyond the scope of this paper.

The following describes and provides general guidance on soil stabilization techniques which may be used to prevent loss of soil support due to earthquake.

Soil stabilization techniques (see Figure 2) have been developed for many applications in geotechnical engineering, including ground improvement, foundation rehabilitation, groundwater control, excavation support and pollution control. Comprehensive state-of-the-art reports and practical applications of soil stabilization techniques are contained in ASCE (1978), Mitchell (1981), Ledbetter (1985), ASCE (1987), and ASCE (1992). The selection of the most appropriate and economical technique for a particular project depends on many factors including site and ground conditions, effects on the surrounding environment, adjacent buildings and cost. Different techniques are often combined on the same project to obtain the optimum remediation scheme. The effectiveness of the scheme can often be checked by in-situ soil testing or full-scale load testing. These techniques are continually evolving as new technology becomes available and new applications are found. The application of these techniques for existing structures and foundations, however, is often limited by the following constraints:

- limited access or headroom for construction equipment;
- limitation on vibration or physical impacts on existing structures;
- disruptions to function of the building and adjacent area; and
- field control and checking required to ensure the quality of soil improvement.

Soil stabilization techniques used for seismic upgrading of existing foundation soils perform the following basic soil improvement functions:

- densification of loose soils or strengthening of weak soils beneath existing structures and/or in adjacent areas on sloping ground;
- underpinning and strengthening the subsoil support of existing foundations;
- improvement of subsoil for the installation of new foundations; and
- drainage of subsoils to mitigate seismic pore pressure build-up.

Some techniques are more adaptable for use inside an existing building such as chemical and compaction grouting, drainage wells and minipilings. There are techniques which may involve drilling inclined holes from outside the building, such as minipiling, conventional or jet grouting. Finally, there are techniques involving equipment mainly suitable for use where space is not too restricted, such as soil mixing, vibro-compaction and vibro-replacement and compaction piles. In adopting any of these techniques, careful selection of competent and experienced specialist contractors and definition of a well-planned quality control program during construction is essential.

Chemical grouting involves injecting solutions of two or more chemicals into the soil pores to form solid precipitates or sandstone-like masses. The method relies on grout permeation and is effective in clean cohesionless soils. Compaction grouting on the other hand, injects low slump grout under high pressure to densify soils by local displacement around the injection bulb. The method can be used to reinforce the weak subsoil underneath existing footings in most subsoils. Foundation heaving, however, should be carefully controlled. Graf (1992) and Boulanger et al. (1994) described applications of compaction grouting for treating liquefiable soils for structure support.

Minipiles, also known as pinpiles or micropiles, are drilled and grouted piles with diameters less than about 300 mm. They can be installed with relatively small equipment in confined spaces not accessible to conventional piling equipment. They are used to transmit loads to competent materials and can be used to provide compression, tension or shear capacity. For a recent school seismic retrofitting project in Vancouver, a combination of vertical and inclined minipiles were installed to increase the basal shearing resistance of shear walls. A repetitive load testing program used to confirm the tension and compression capacity of a test minipile and subsequent proof-loading of 90 production minipiles is described by To and Watts (1994). Minipiles can also be used to stabilize a slope.

For relief or prevention of potential dynamic pore water pressure development in the subsoils, vertical gravel drains and drainage wells can be installed around and/or inside structures. If properly installed, the gravel drains can prevent liquefaction by dissipating pore pressure build-up caused by earthquake shaking. The spacing of drains depends on the permeability of subsoil. Drainage wells can also be installed with permanent dewatering to lower the groundwater table below the subsoil zone susceptible to liquefaction. A system of wells, activated by a water level monitoring system, was installed for a large methanol storage tank located on a river delta in Kitimat, British Columbia. These wells are used to maintain the groundwater table below a liquefiable subsoil layer during high river stages in the spring runoff season. This type of application could be too costly if continuous dewatering is required. In highly compressible subsoils, the potential additional settlement due to dewatering could preclude it as a practical solution. There may be other restraints to rule out lowering the groundwater level as a viable solution.

Jet grouting uses high velocity water jets to cut and lift the soil to the surface, creating a cavity into which cement slurry is injected. This technique can be used in practically all soils to form soil-cement columns or "soilcrete", and is useful for underpinning or strengthening existing foundations. A technique similar to jet grouting is soil mixing for which a large diameter auger or a series of augers penetrate and mix the soil in-situ with a controlled amount of cement slurry to form soil-cement columns. The soil mixing technique, however, requires a relatively large crane.

Vibro-compaction or vibro-floatation involves the insertion of a powerful vibrating probe into the ground to densify granular soils with less than about 20% silt and clay fines. Vibro-replacement uses a similar powerful vibrator to densify the soil at depth while simultaneously installing compacted gravel or stone columns. This technique can be used in finer soils where the stone columns act to reinforce the soil mass. Compaction piles are used to densify granular subsoils by displacement of the soil around the driven piles. Because of the size of crane involved, these techniques are mainly used for improving the subsoil condition for a new structure site, or the perimeter area around an existing structure in order to minimize the impact of liquefaction and/or lateral spreading of the subsoil. This technique was used to improve the safety of a Liquefied Natural Gas (LNG) peak shaving plant on Tilbury Island in the Fraser River delta (Wightman et al. 1987). The ground directly beneath the tank had been densified by timber compaction piles. However, the ground around the tank and beneath an earth containment berm was deemed to be susceptible to liquefaction. A seismic upgrade program was implemented which consisted of the construction of a secondary concrete containment wall founded on an annular zone of ground compacted by vibro-replacement. Egan et al. (1992) described the seismic repair program involving the use of the vibro-replacement technique at the Seventh Street Marine Terminal at the Port of Oakland, California after the 1989 Loma Prieta earthquake. The wharf distress was caused by lateral spreading and settlement of hydraulically-placed sandfill and native silty sands subsoil during the earthquake. The technique has been applied to improve the seismic resistance of the foundation soil for many new high-rise builings in Richmond, British Columbia and the new control tower and terminal building for the Vancouver international airport.

PILE FOUNDATIONS SUBJECT TO LARGE SOIL DISPLACEMENT

In recent years, the potential for pile breakage during earthquakes was confirmed by excavation around piles supporting a building damaged during the 1964 Niigata earthquake in Japan. The excavation revealed that piles appeared to have failed due to soil displacements resulting from liquefaction-induced lateral spreading. Such lateral soil displacements, as much as 1 metre in some cases, have been observed even at a relatively level or slightly sloping ground under certain subsoil conditions (Hamada et al. 1987). Therefore, prevention of collapse of a pile-supported structure due to pile breakage is an important design consideration.

A concrete-filled steel-pipe pile offers a high degree of survivability under such circumstances. The pile is to be driven into dense strata below the seat of liquefaction to achieve the required bearing and uplift resistance. The diameter of the pipe pile and the thickness of the steel pipe are selected to provide the capacity for carrying the vertical pile load through the liquefied zone without buckling. Even if the steel shell should crack at the location of the two plastic hinges, the crushed yet laterally confined concrete would be able to carry the vertical pile load. Furthermore, the uplift and shear resistance can be increased by adding a steel reinforcement cage inside the pipe piles. However, the most efficient use of reinforcing steel would involve a single, large-diameter reinforcing rod located at the centre of the pile. This design would minimize the bending strains of the steel rod as the pile undergoes the lateral as well as cyclic displacement imposed by the surrounding soil. This technique has been used for the design of an expansion to a manufacturing plant in Tilbury Industrial Park (Siu and Sy 1994), and the foundation upgrade for a power transmission tower in Pitt Meadows (Klohn Leonoff 1990) both located in the Fraser Delta, British Columbia.

SUMMARY

Techniques for conventional foundation upgrading and soil stabilization are reviewed herein. These techniques provide a range of options available for improving the seismic resistance of the subsoil and foundation for existing and new structures. Design as well as practical considerations required in applying these techniques are also outlined in the paper. Close coordination and cooperation among all parties involved from the initial conceptual stage to the final completion of the project are essential to achieve an economical and safe upgrade or new structure to meet the owner's objectives.

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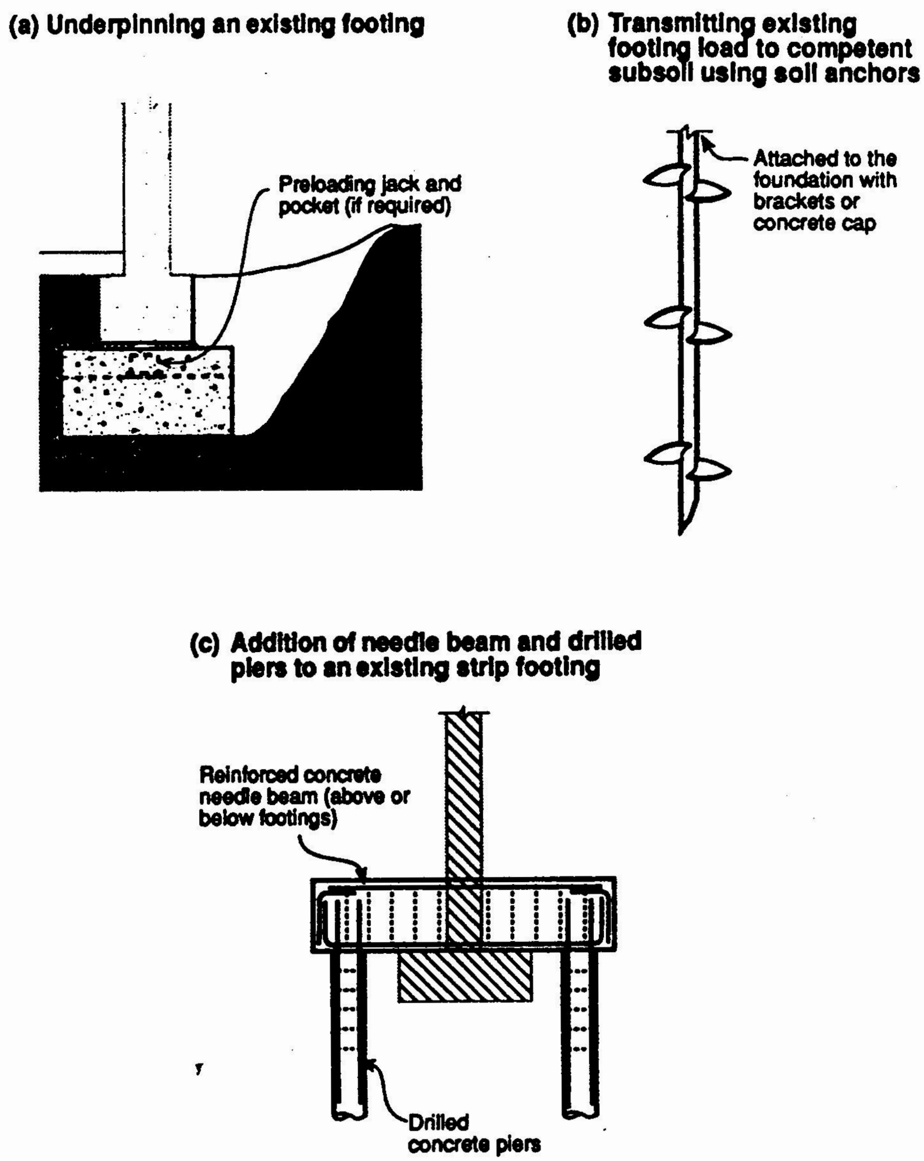

FIGURE I CONVENTIONAL FOUNDATION UPGRADING TECHNIQUES

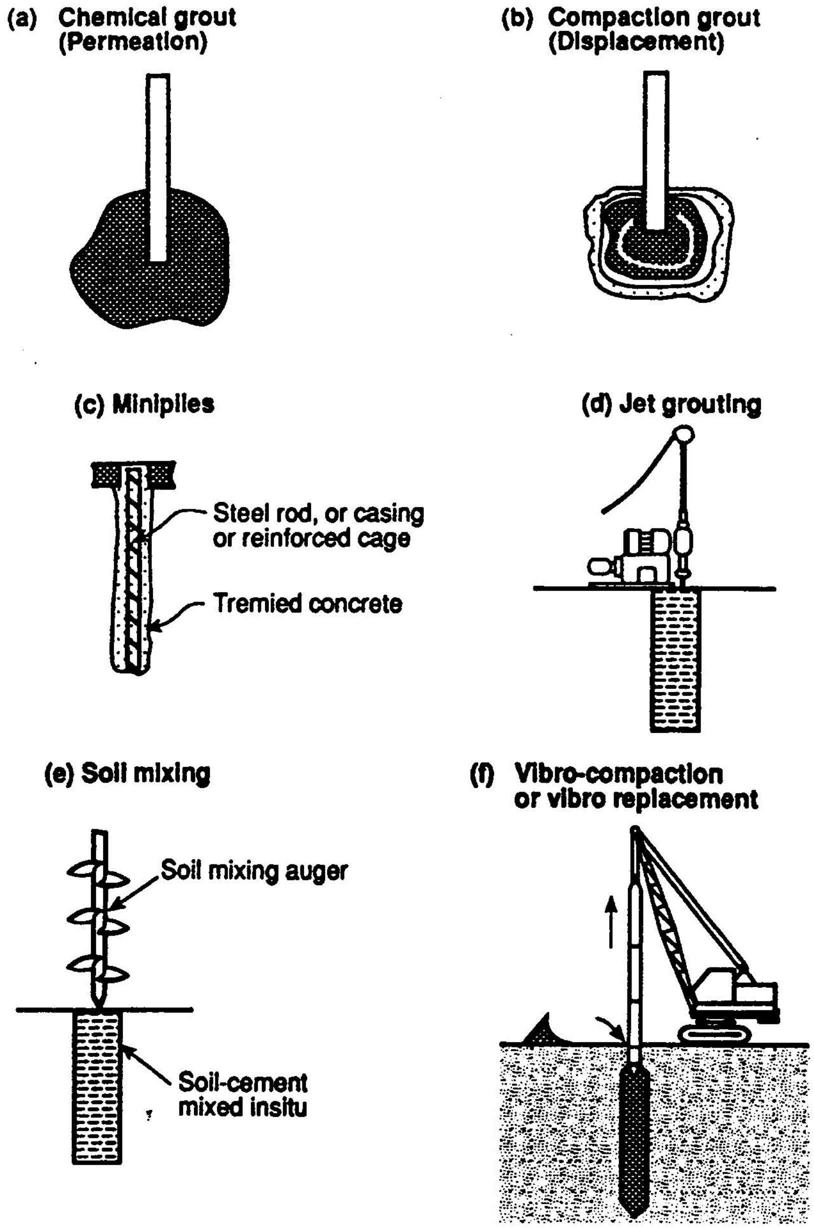

FIGURE 2 SOIL STABILIZATION TECHNIQUES