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Comparison of Seismic Retrofitting Methods for Existing Foundations in Seismological Active Regions

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***Abstract*—**Seismic retrofitting of important structures is essential in seismological active zones. The importance is doubled when it comes to some buildings like schools, hospitals, bridges etc. because they are required to continue their serviceability even after a major earthquake. Generally, seismic retrofitting codes have paid little attention to retrofitting of foundations due to its construction complexity. In this paper different methods for seismic retrofitting of tall buildings' foundations will be discussed and evaluated. Foundations are considered in three different categories. First, foundations those are in danger of liquefaction of their underlying soil. Second, foundations located on slopes in seismological active regions. Third, foundations designed according to former design codes and may show structural defects under earthquake loads. After describing different methods used in different countries for retrofitting of the existing foundations in seismological active regions, comprehensive comparison between these methods with regard to the above mentioned categories is carried out. This paper gives some guidelines to choose the best method for seismic retrofitting of tall buildings' foundations in retrofitting projects.

***Keywords*—**Existing foundation, landslide, liquefaction, seismic retrofitting.

I. Introduction

RETROFITTING of existing foundations implies changing the structural aspects of the existing foundations and/or improving the underlying soil condition.

In the following cases seismic retrofitting of foundations is required:

1. Foundations that have been designed according to former design codes with little attention to earthquake loads, or are subjected to seismic hazards such as liquefaction or landslide. 2. In a seismic retrofitting project as a result of enlarging other structural elements such as columns, shear walls, etc.
2. Should the need arise for seismic retrofitting of the existing foundations, structural and geotechnical engineers must have in-depth knowledge of different methods used for this purpose.

American, Canadian, and Indian seismic retrofitting codes each has devoted a chapter to the issue of seismic retrofitting of existing foundations [1]-[3]. Methods which have been described in these codes are shown in Table I. Although a research report on seismic retrofitting of foundations has recently been published in New Zealand, it isn't mentioned here because this report has only focused on wooden structures [4]. There isn't any attention to seismic retrofitting of foundations in European code [5]. The Japanese seismic retrofitting code hasn't been published in English yet.

The methods for seismic retrofitting of foundations mentioned above have been developed for mitigating seismic hazards and compensating structural seismic defects of foundations. These methods will be discussed and evaluated for three categories of foundations namely: foundations in liquefiable soils, foundations on slope in seismic prone zones, and foundations with structural seismic defects.

TABLE I
Different Seismic Retrofitting Methods for Existing Foundations [1]-[3]

Country	Seismic Retrofitting Code	Seismic Retrofitting Methods for Existing Foundations
USA	Techniques for the Seismic Rehabilitation of Existing Buildings (FEMA[a] 547), 2006	**1.**Adding shallow foundation next to the existing shallow foundation **2.**Adding shallow foundation next to the existing deep foundation **3.**Adding deep foundation next to the existing shallow foundation **4.**Adding deep foundation next to the existing deep foundation **5.**Using micropiles **6.**Enlarging or replacing an existing spread footing **7.**Adding new mat foundation between existing drilled piers **8.**Adding top bars to an existing pile cap **9.**Using compaction grouting method
Canada	Guideline for Seismic Upgrading of Building Structures (NRCC[b]), 1995	**1.**Adding deep foundation next to the existing shallow foundation **2.**Underpinning an existing foundation **3.**Enlarging an existing spread footing
India	Handbook on Seismic Retrofit of Buildings, 2007	**1.**Enlarging an existing spread footing **2.**Using micropiles **3.**Underpinning an existing foundation **4.**Strengthening of existing piles **5.**Strengthening of base plates

[a] Federal Emergency Management Agency
[b] National Research Council of Canada

II. Foundations in Liquefiable Soils

When subjected to earthquake shaking, saturated loose sandy soils may suddenly change from soil (being in a soil state) to a liquid state maintaining its original density. This phenomenon is called liquefaction [6], [7].

Liquefaction greatly reduces the bearing capacity of the foundation soil. Consequently, large and different settlements, tilting, and overturning of spread footings and also large and differential settlement and tilting of piles with insufficient length may happen [7], [8]. Methods used for liquefaction

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remediation are shown in Table II. Marked methods are used for seismic retrofitting of existing foundations [8].

TABLE II
METHODS USED FOR LIQUEFACTION REMEDIATION [8]

1. Soil Improvement by Compaction	**1. 1.** Using Vibro Compaction Method
	1.2. Using Dynamic Consolidation Method
	1.3. Using Sand Compaction pile Method
	1.4. Using Blasting for Soil Densification
2. Soil Improvement by Dissipating Excess Pore Water Pressure	**2.1.** Using Gravel or Rubble Drains
	2.2. Using Geosynthetics Drainage Systems
	2.3. Using Sheet Piles with Attached Drainage Pipes
3. Soil Improvement by Soil Mixing	**3.1.** Using Deep Mixing Method *
	3.2. Using Compaction Grouting Method*
4. Soil Improvement by Replacing and Displacing Soil	**4.1.** Using Vibro-Replacement Method
	4.2. Using Vibro-Displacement Method
	4.3. Using Rotocolumn Method
	4.4. Using Rammed Aggregate Pier (RAP) Method
	4.5. Using Stone Columns

As mentioned in Table II, Deep Mixing and Compaction Grouting are two methods that are applicable for the existing foundations. In compaction grouting method, grout as a mixture of water, cement, and sand is highly pressurized into loose ground and compresses the surrounding soil in lateral directions. This method is not dynamic and does not cause noise or vibration. After some time, the grout is solidified and increases the shear strength of the underlying soil to mitigate liquefaction. Fig. 1 illustrates this procedure and Fig. 2 is a schematic illustration of soil improvement under existing building by this method [9].

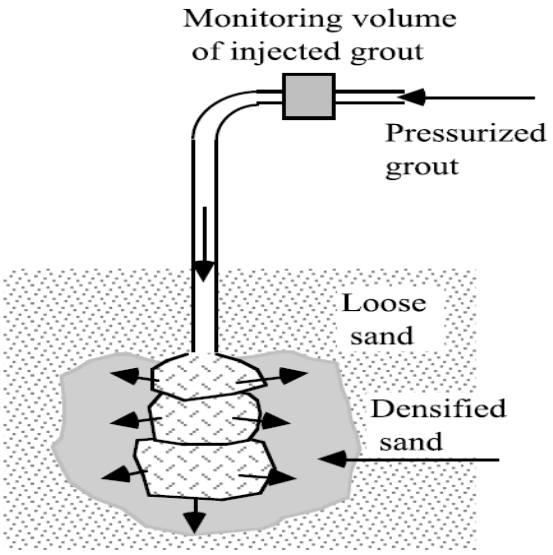

Fig. 1 Compaction Grouting Procedure [9]

In deep mixing method, impervious slurry (diaphragm) walls are constructed surrounding the existing building extended into impervious layer or bedrock. These walls are built by drilling with two or three axis augers and pouring cement-like materials in drilled places. After constructing the slurry walls, the ground water inside the area must be drained out by installation of deep walls and pumping out the water from the wells [8], [9]. This procedure is illustrated in Fig. 3. By lowering the ground water level, the possibility of liquefaction below the existing structure is diminished.

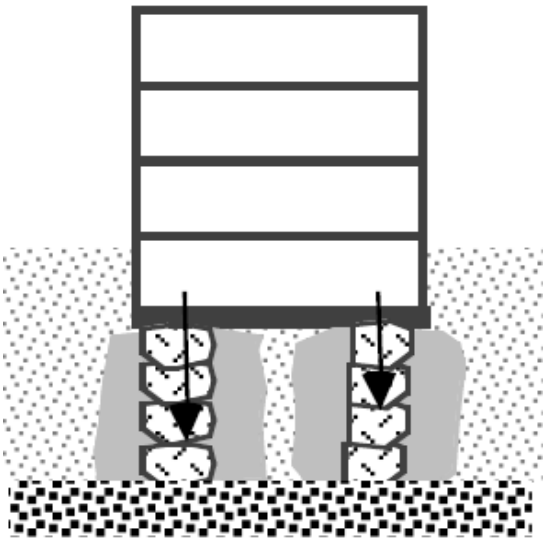

Fig. 2 Seismic Retrofitting of Existing Foundations by Compaction Grouting Method [9]

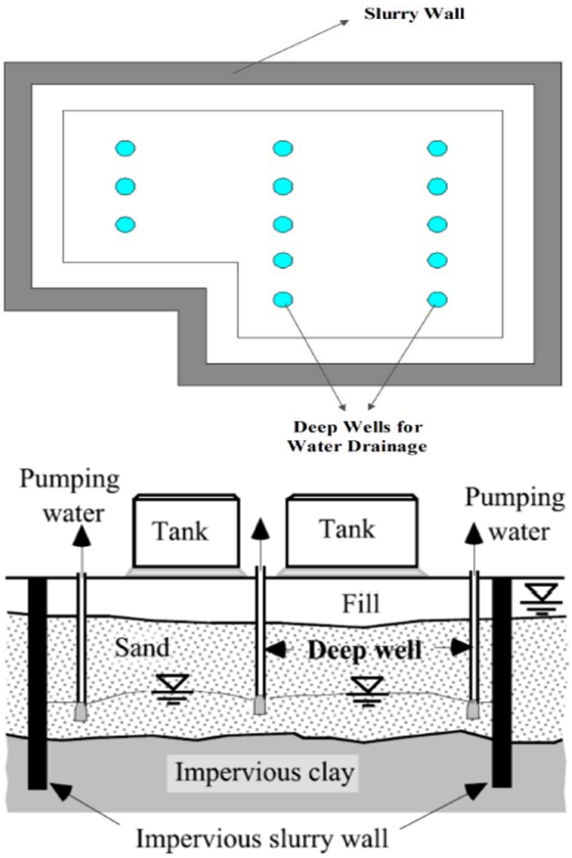

Fig. 3 Seismic Retrofitting of Existing Foundations by Deep Mixing Method

III. Foundations on Slopes in Seismic Prone Zones

A landslide is a movement of mass rock, debris, or earth down a slope. Earthquake is one of the main reasons of landslides. Landslide can affect an existing building in three ways. First, it can undermine the building and causing it to collapse (Fig. 4 A). Second, it can move building as a part of its underlying ground (Fig. 4 B). Third, it can bury the building under the sliding materials (Fig. 4 C).

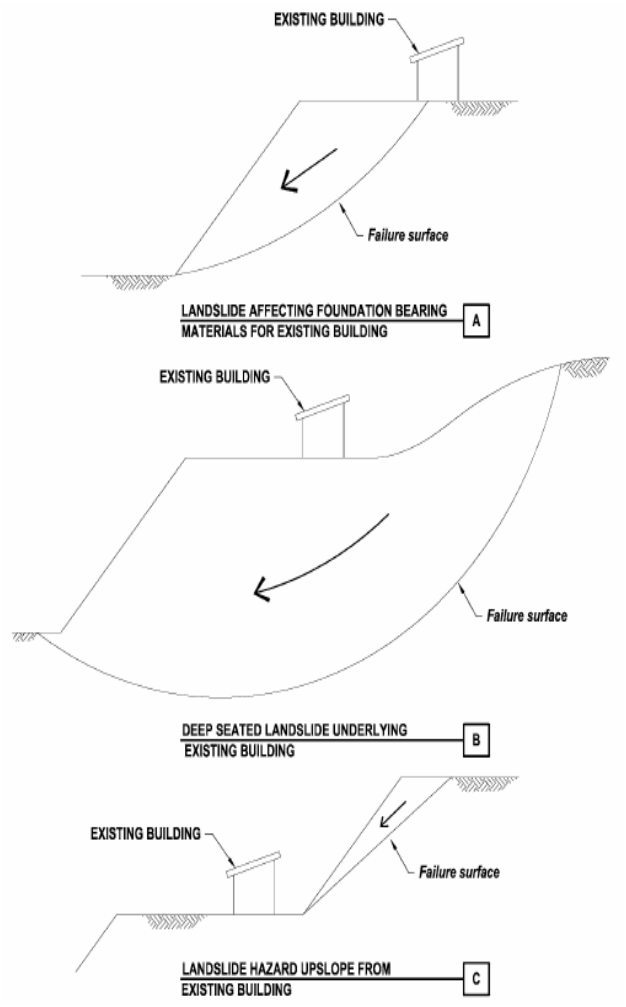

Fig. 4 Landslide Hazards [1]

Methods used for landslide prevention are shown in Table III. All these methods can be used for seismic retrofitting of existing foundations to reduce the possibility of landslides [8].

Among the methods mentioned in Table III, two more practical methods for the purpose of seismic retrofitting of tall buildings' foundations are "Soil Nailing Method" and "Using Counterberms at the Slope Toe" which are elaborated here.

TABLE III
Methods Used for Landslide Prevention [8]

1. Geometrical Correction of Slopes	**1. 1.** Removing Weight from the Upper Part of the Slopes
	1.2. Flattening Slopes
	1.3. Benching of Slopes
	1.4. Using Counterberms at the Slope Toe
	1.5. Using Shear Keys
2. Water Management Measures	**2.1.** Surface Drainage
	2.2. Subsurface Drainage
	2.3. Trenches
	2.4. Cut-off Drains
	2.5. Horizontal Drains
	2.6. Wick Drains
3. Bioengineering Methods	**3.1.** Using Vegetation for Slope Stabilization
4. Reinforcement Methods	**4.1.** Soil Nailing
	4.2. Stone Columns
	4.3. Micropiles
	4.4. Anchorages and Rock Bolts
5. Mechanical Stabilization Methods	**5.1.** Using Different Types of Retaining Walls (Gravity, Cantilever, Reinforced by Geosynthetics, etc.)
6. Surface Protection of Slopes	**6.1.** Using Concrete or Masonry Blocks
	6.2. Slope Protection Using Shotcrete

Soil nailing is a method of in situ reinforcement by steel bars, metal tubes, or other metal bars. In this method, soil nailing bars installed using drilling techniques (Fig. 5 (a)). They are usually fully grouted and installed at a slight downward inclination with bars installed at regularly spaced points across the slope face as shown in Fig. 5 (b). After this, the slope is grouted as shown in Fig. 5 (c). A natural slope improved by this method is illustrated in Fig. 5 (d).

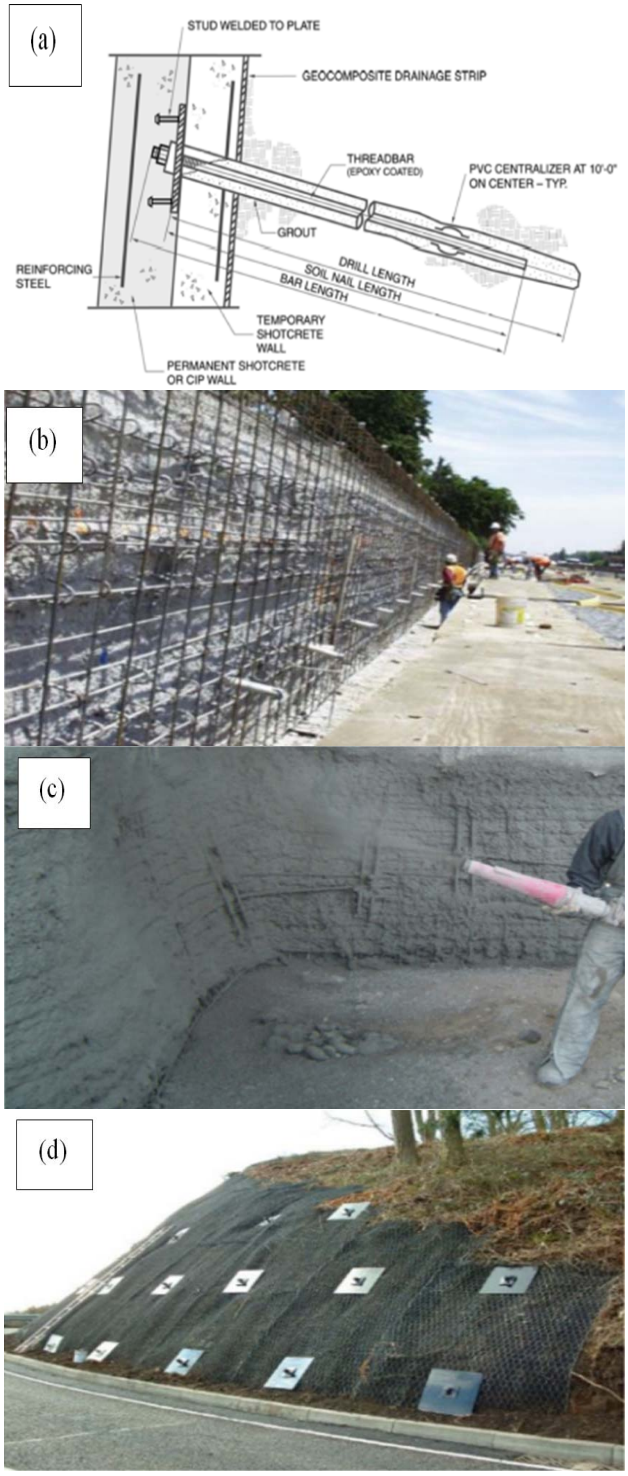

Fig. 5 Soil Nailing Method

In the second method for slope stabilization, a counterberm is used to provide weight at the toe of a slope. This method is used for increasing the shear strength below the toe and preventing soft soil at the toe from upward movement or bulge [10] (Fig. 6).

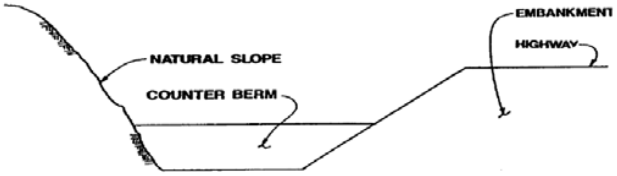

Fig. 6 Using Counterberms at the Slope Toe [10]

IV. Foundations with Structural Seismic Defects

Consideration of foundation is an integral part of the overall retrofitting strategy for the structure. Hence when other structural elements such as columns, shear walls, etc. are strengthened or enlarged in a retrofitting project, strengthening of foundations for supporting new loads is necessary.

The foundations may not have adequate strength as per the requirements of the current seismic codes. This kind of deficiency may happen in the foundations itself, or in column-footing connections. Therefore, it is essential to diagnose the deficiencies in the foundation before undertaking retrofit.

Methods used for retrofitting of existing foundations with structural seismic defects are shown in Table IV [8].

TABLE IV
Methods Used for Retrofitting of Existing Foundations with Structural Seismic Defects [8]

1. Using New Foundation Next to Existing Foundation	**1. 1.** Adding shallow foundation next to the existing shallow foundation **1.2.** Adding shallow foundation next to the existing deep foundation **1.3.** Adding deep foundation next to the existing shallow foundation **1.4.** Adding deep foundation next to the existing deep foundation
2. Retrofitting of Foundations with Connection Defects	**2.1.** Strengthening of base plates **2.2.** Strengthening of the concrete column-footing connections **2.3.** Increasing the dimensions of straps **2.**4. Adding top bars to an existing pile cap
3. Retrofitting of Foundations with Structural Defects	**3.1.** Using micropiles **3.2.** Underpinning an existing foundation **3.3.** Strengthening of the existing piles **3.4.** Using horizontal and vertical pre-stressing forces **3.5.** Strengthening the foundations by changing the type of footings **3.6.** Enlarging and replacing an existing spread footing **3.7.** Adding new mat foundation between existing drilled piers

Among the methods mentioned in Table IV, two more practical methods for the purpose of seismic retrofitting of tall buildings' foundations are "Micropiles" and "Strengthening of the Existing Piles".

A micropile is a pile with steel pipes that has a diameter of 300mm or less and a reinforcing bar in the middle of it. Pipes are installed in the pre-drilled holes. Then, grout fills up the hole around and inside of the pipes. This procedure is shown in Fig. 7 (a). Post-grouting or secondary grouting can be used to increase the bar capacity [1], [8], [11]. A foundation retrofitted by this method is illustrated in Fig. 7 (b).

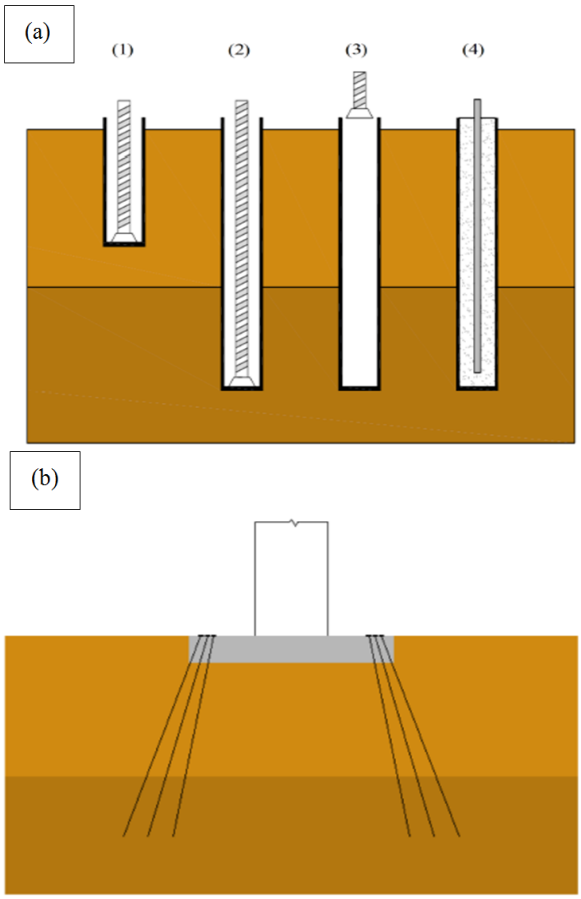

Fig. 7 Using Micropiles Method (a) Drilling, bar placement, and grouting procedure, (b) Footing retrofitted by micropiles

For building constructed on piles, the piles may be inadequate to resist the lateral loads calculated according to the current seismic codes. Also, the piles may be deficient just below the pile-cap, where deterioration and damage to piles are common.

The strengthening of piles can be done by digging down in segments to expose the piles to a level where the defects are visible (Fig. 8 (a)), exposing the cover to an extent such that the damages and corrosion are removed and providing a base cap at the bottom level to ensure continuity of additional reinforcement for the piles (Fig. 8 (b)), providing additional reinforcement and concrete jacket around the piles based on the forces from the analysis of the building (Fig. 8 (c)), backfilling the foundation with cohesionless soils (Fig. 8 (d)) and completing the flooring [3].

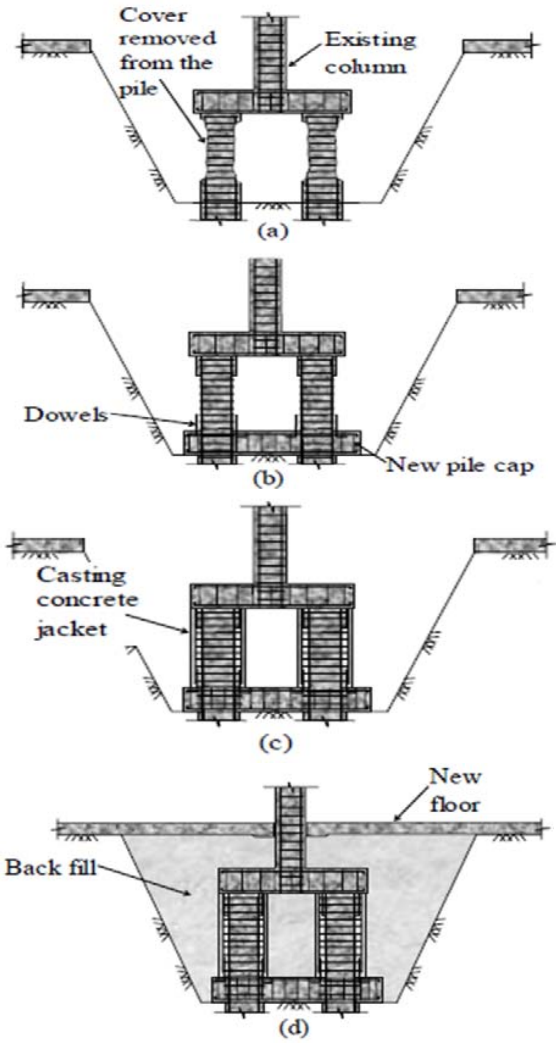

Fig. 8 Strengthening of the Existing Piles [3]

V. Conclusion

A builder has several options for selecting the material and construction of the building, such as masonry, timber, concrete or steel. However, in many cases, there is little choice with regard to the site (location) of the building. The site may have liquefaction or landslide susceptible soils. In these cases, soil improvement must be considered as a part of seismic retrofitting project. After studying seismic retrofitting codes of a number of countries and comparing them with the code of USA, it was found that in the American seismic retrofitting code, only “Using Compaction Grouting Method” is described [1]. It is suggested that methods used for mitigating liquefaction in seismic retrofitting projects such as “Deep Mixing Method” and also methods used for landslide prevention presented in Table III, be added to the American seismic retrofitting code.

Consideration of the foundations as a part of overall seismic retrofitting of a building requires structural retrofitting of the existing foundations. Methods used for retrofitting of the

existing foundations with structural defects were shown in Table IV. It is suggested that the following methods be added to the American seismic retrofitting code:

1. Strengthening of base plates
2. Strengthening of the concrete column-footing connections
3. Increasing dimensions of straps
4. Underpinning an existing foundation
5. Strengthening of the existing piles
6. Using horizontal and vertical pre-stressing forces
7. Strengthening the foundations by changing the type of footings.

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