

Utilization of Highly Expansive Polymer Injection to Mitigate Seismic Foundation Failure for Existing Structures

M. Erdemgil

SMP Engineering, Ankara, Turkey.

S. Sağlam and B. S. Bakır

Department of Civil Engineering, Middle East Technical University, Ankara, Turkey.

ABSTRACT: Seismically induced foundation failures can be triggered due to the increase of load beyond capacity or strength loss of the bearing soils. A major category of remedial measures against such mode of damage is the improvement of foundation soils. Considering the case of existing structures in the urban environment, however, applicability of a great majority of the methods included in this category are either not possible or seriously limited due to the excessive noise or vibration generated during construction. On the other hand, solidification of foundation soils through method of injection bears exceptional advantages regarding such concerns, and provides a relatively high level of effectiveness compared to the possible alternatives. Two applied cases of foundation bearing capacity improvement through utilization of commercial polymer injection are presented for existing structures in Turkey. Penetration testing was utilized before and after execution for the assessment of treatment effectiveness of the foundation soils which were liquefaction susceptible in one case and nonliquefiable rather weak fine soils in the other. On the basis of the results, the effectiveness of the method is evaluated and relevant practical aspects of implementation involved in applications in the urban environment are discussed.

1 INTRODUCTION

Foundation displacements associated with the seismically induced bearing capacity failure constitute a relatively less common form of earthquake related damage to structures. With regard to the seismic shaking, foundation failure can be triggered due to two distinct mechanisms: one, although momentarily, the forces and moments transmitted to the foundation can drastically exceed those imposed under static condition; the other, repeated loading may lead to strength loss in the underlying soil as in the case of soils susceptible to the liquefaction related phenomena. Hence, in the most general case, the adversity and possible eventual failure of the foundation is due to the reduction in capacity accompanied by the increase in demand.

Wide-spread seismically induced failures of shallow foundations occurred more recently in the city of Adapazari during 17 August 1999, Izmit (Kocaeli), Turkey earthquake (M_w 7.4). As a result, hundreds of three- to six-story reinforced concrete buildings with shallow mats were subjected to foundation displacements of various forms and levels (Fig. 1). Diverse aspects of the seismic performance of shallow mat foundations in Adapazari have been studied in detail and were reported elsewhere. A great majority of the foundation displacements were in the form of uniform settlements within 10 cm in the city. Still, however, numerous buildings had to be demolished and removed despite minor or no structural damage,

since foundation displacements exceeded the limits of serviceability. Subsequent field investigations have shown that the soils underlying part of the city where foundation failures occurred consisted of normally consolidated mixtures of fine sand, silt and clay of variable proportions with occasional susceptibility to liquefaction. Interestingly, however, a great majority of these failures took place over soils that are not liquefaction susceptible, but already rather weak (Bakir et al., 2002; Yilmaz et al., 2004; Bakir et al., 2005; Bakir et al., 2006 – a; Trifunac and Todorovska, 2006; Bakir et al., 2006 – b).

Nevertheless, whether liquefaction induced or not, extensive foundation failures that occurred in Adapazari during the 17 August earthquake attracted worldwide researcher interest and confirmed once again the need for a particular consideration of the seismic performance of foundations situated over weak or liquefiable soils in the earthquake prone areas. Eventually, the awareness with regard to this particular mode of earthquake related damage was heightened in Turkey and demand boosted for vulnerability assessment of seismic foundation response and, where necessary, implementation of remedial measures for existing structures as well as those to be built.

In this paper, two applied cases of seismic foundation bearing capacity improvement are presented for existing structures in the urban environment in Turkey. Commercial polymer (URETEK[®]) injection was utilized for the improvement of foundation soils which were liquefaction susceptible in one case and nonliquefiable rather weak fine soils in the other. Within the course of application regarding liquefiable ground, liquefaction susceptibility is assessed through conventional approach utilizing safety factors expressed as the ratio of soil liquefaction resistance to seismic demand, both expressed on the basis of cyclic shear stress. Whereas in the case of weak fine foundation soils, bearing capacity was assessed under seismic loading condition before and after treatment and the corresponding safety factors against foundation bearing were calculated. In both cases, improvement of the target soils was interpreted through correlations of in-situ penetration testing performed before and after execution. On the basis of the results, the effectiveness of the method is evaluated and relevant practical aspects of implementation involved in urban environment are discussed.



Figure 1. Examples of bearing capacity failures of shallow foundations in Adapazari

2 REMEDIAL MEASURES TO IMPROVE BEARING CAPACITY

Remedial measures to improve foundation bearing capacity can be classified into two major categories: one is the treatment of underlying soils, and the other is to provide measures as regards the structure. The cost, performance, properties of soil, environmental effects, foundation type and structural features are comparatively important aspects to be considered during selection of the appropriate method. Methods of soil treatment, in fact, by and large improve both, soil strength and resistance against liquefaction concurrently. Structural countermeasures basically consist of application of piles or reinforced concrete elements in the foundations.

Naturally, planning and application of remedial measures are far easier and less costly for those structures to be built newly. Considering the case of existing structures, particularly in the urban environment, however, a great majority of the available methods in these two broad categories is either not applicable or seriously limited due to excessive noise or vibration generated during construction, size of equipment required or due to limitations imposed on serviceability during the period of execution. On the other hand, solidification of the foundation soils through method of injection bears exceptional advantages regarding such concerns in the urban environment, and provides a relatively high level of effectiveness compared to the possible alternatives, particularly for the existing structures. Application of the method consists of injection of specific materials (highly expansive resin in the case of applications presented here) under controlled pressures while the structural response is continuously monitored.

3 SOLIDIFICATION WITH POLYMER INJECTION

During the last 40 years various chemical grouts have been developed and utilized in the treatment of soils. The use of this technique inevitably requires knowledge of injection material and soil to be injected. The specifications of grout material, soil type, application features and the relationships among them have significant influences on the treatment efficiency (Clough et al., 1979; Christopher et al., 1989; Ata and Vipulanandan, 1999; Ozgurel and Vipulanandan, 2005).

The grain size distribution or the initial permeability dictates the groutability of soil (Ozgurel and Vipulanandan, 2005). During grouting in permeation mode, the injection pressure is a key parameter to be taken into account (Fig. 2). To avoid fracturing and heaving of the soil during the application, the injection pressure is practically limited to the effective overburden pressure. In the mode of displacement (compaction) grouting, the grout is injected in such a way as to displace the particles and consequently to compact the formation. Consequently, the effect of compaction can be observed even at the points where grout material does not reach. The injection pressures are comparatively higher with respect to those used in the permeation mode. When grouting into the soil directly beneath a foundation, the foundation pressure also becomes a parameter to be considered in selecting the appropriate application pressure. In that case, monitoring of the foundation can help controlling and adjustment of the injection pressure. Hence, the injection pressure is set on the basis of a consideration of soil permeability, overburden pressure, and the desired mode of grouting.

The commercial grout material URETEK[®], utilized in the applications presented in this paper is an inert expansive polymer. Owing to its chemical texture it can easily permeate into soils having initial permeabilities as low as 10^{-6} m/s. It can also be applied effectively in grouting modes of intrusion, and displacement, depending on the soil type and injection pressure (Fig. 2). The gelling time of URETEK[®] resin is quite short, almost immediate. One hour is sufficient to attain most of the final compressive strength. Yet, the final strength of the resin is achieved after an approximate setting time of 24 hours. The observations and the laboratory tests demonstrate that once the injected resin is hardened no remarkable reaction takes place with the surrounding natural materials or materials used in the construction industry (URETEK, 2007).

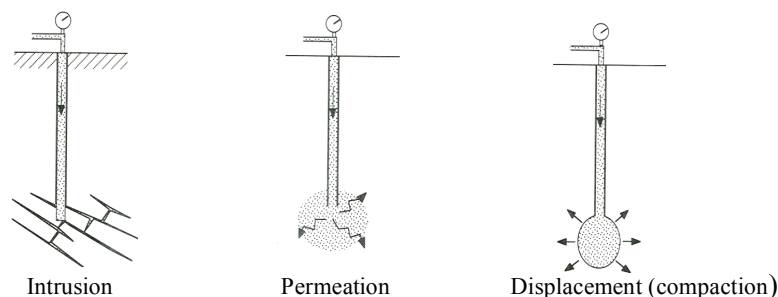


Figure 2. Modes of grouting (Hausmann, 1990)

4 APPLICATIONS

Two cases of soil treatment application to improve foundation bearing capacity through utilization of polymer injection are presented in existing structures, in Istanbul, Turkey. The first case consists of a five story residential building situated over loose sandy soils that are liquefaction susceptible in a densely inhabited district, whereas the second is a case of factory building situated over alluvial deposition of soft fine soils. Dynamic Penetration Test (DPT) is utilized due to practicality to measure soil resistance in each case before and after soil treatment, and the results are converted to equivalent Standard Penetration Test blow counts for the subsequent evaluation of the treatment effectiveness.

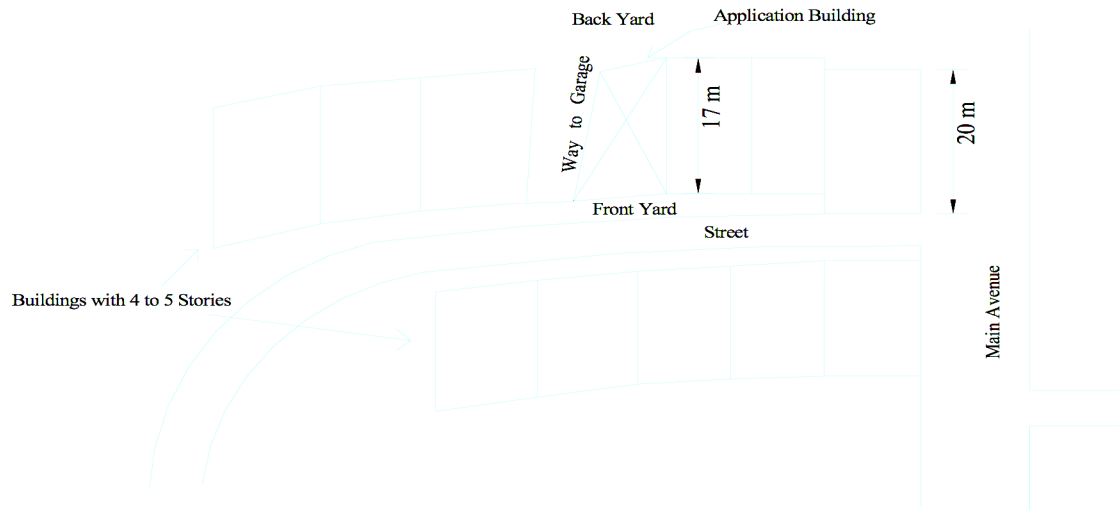


Figure 3. Location of the residential building (case I)

4.1 Case 1- Improvement of Liquefiable Soil

4.1.1 Site Conditions

The five-story building, which has a 0.8 m thick raft foundation with a depth of 2 m, stands within a block adjacent to another building on one side as shown in Figure 3. The subsurface at the site can be idealized as two layers of sand depending on the fines content and penetration resistance: a 3 m thick layer of silty to clayey sand with fines content of 15% to 25% at the surface, underlain by a silty sand with fines content varying between 15% and 40%. The field penetration resistance in terms of equivalent Standard Penetration Test (SPT) blow counts of the silty to clayey sand ranges between 10 and 25, whereas the blow counts are between 8 and 14 for the silty sand layer. Groundwater is located about 1 m below the surface. Subsurface stratification and the foundation are schematically illustrated in Figure 4.

The Marmara Sea branch of the North Anatolian Fault, which is capable of producing earthquakes of magnitude greater than 7, lies only about 15 km south of the building site, where the peak ground acceleration corresponding to a return period of 225 years is assessed as 0.35g. Hence, liquefaction appears to be quite likely for the loose sandy surface soils existing at the site.

In practical applications the seismic soil liquefaction assessment involves, in broad terms, contrasting of the seismic demand anticipated to act over a soil mass to the available resistance of the soil against liquefaction. This necessitates the seismic demand and the soil resistance to be expressed in terms of a common basis on which the statement regarding possibility of liquefaction can be established. As of today, the most widely used reference for the common basis is the cyclic shear stress, and the general approach has been known as the “cyclic stress approach”. Here, in the course of the application, the earthquake loading is characterized in terms of uniform stress cycles (Seed et al.,1975), and the soil

resistance is characterized in terms of cyclic shear stress required to initiate liquefaction based on the relationship provided by Seed et al. (1985).

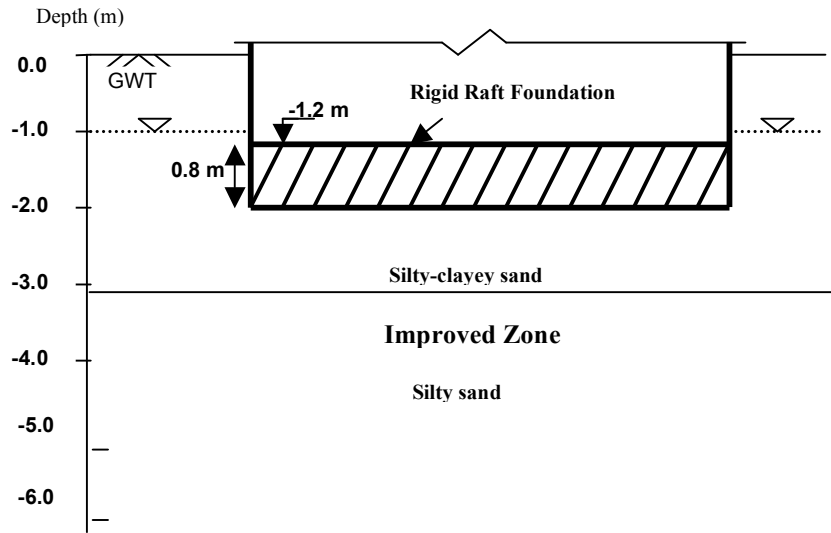


Figure 4. Cross-sectional view of subsoil stratification and foundation (case I)

4.1.2 Application, Results and Implications

Foundation soils are improved within a depth of about 4 m below the mat foundation through systematic injection on the plan of the building with application pressures reaching 6 bars at greater depths. The building is continuously monitored against any possible foundation displacements during injection process.

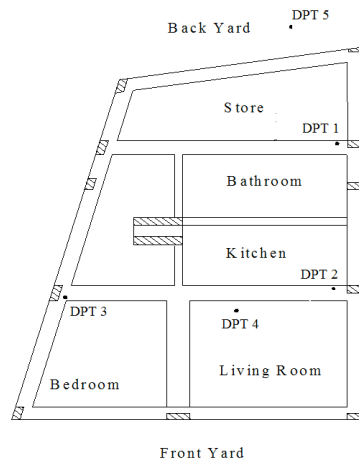


Figure 5. Plan view of the building with DPT application points (case I)

Effectiveness of the soil treatment is assessed based on the DPT tests realized at five different locations of the building (Fig. 5). Results from three of these (DPT1, DPT3 and DPT4) are processed and reported here. Figure 6a, b, and c represent respectively the pre- and post-execution variations of the equivalent corrected SPT blow counts, the corresponding cyclic stress required to initiate liquefaction and the factors of safety with soil depth beneath foundation for the three penetration tests. In calculations, earthquake

magnitude (M_w) and peak ground acceleration are presumed to be 7.0 and 0.35g, respectively.

Figure 6 clearly indicates significant improvements following the execution. As a general trend, the treatment was particularly effective in all test locations within a depth of about 2 m below the foundation. The SPT blow counts increased 2- to three-folds on the average within 4 m of the foundation with the corresponding liquefaction resistance values exceeding the imposed demand at all levels and factors of safety against liquefaction increasing from below 1 to values between 1 and 2.

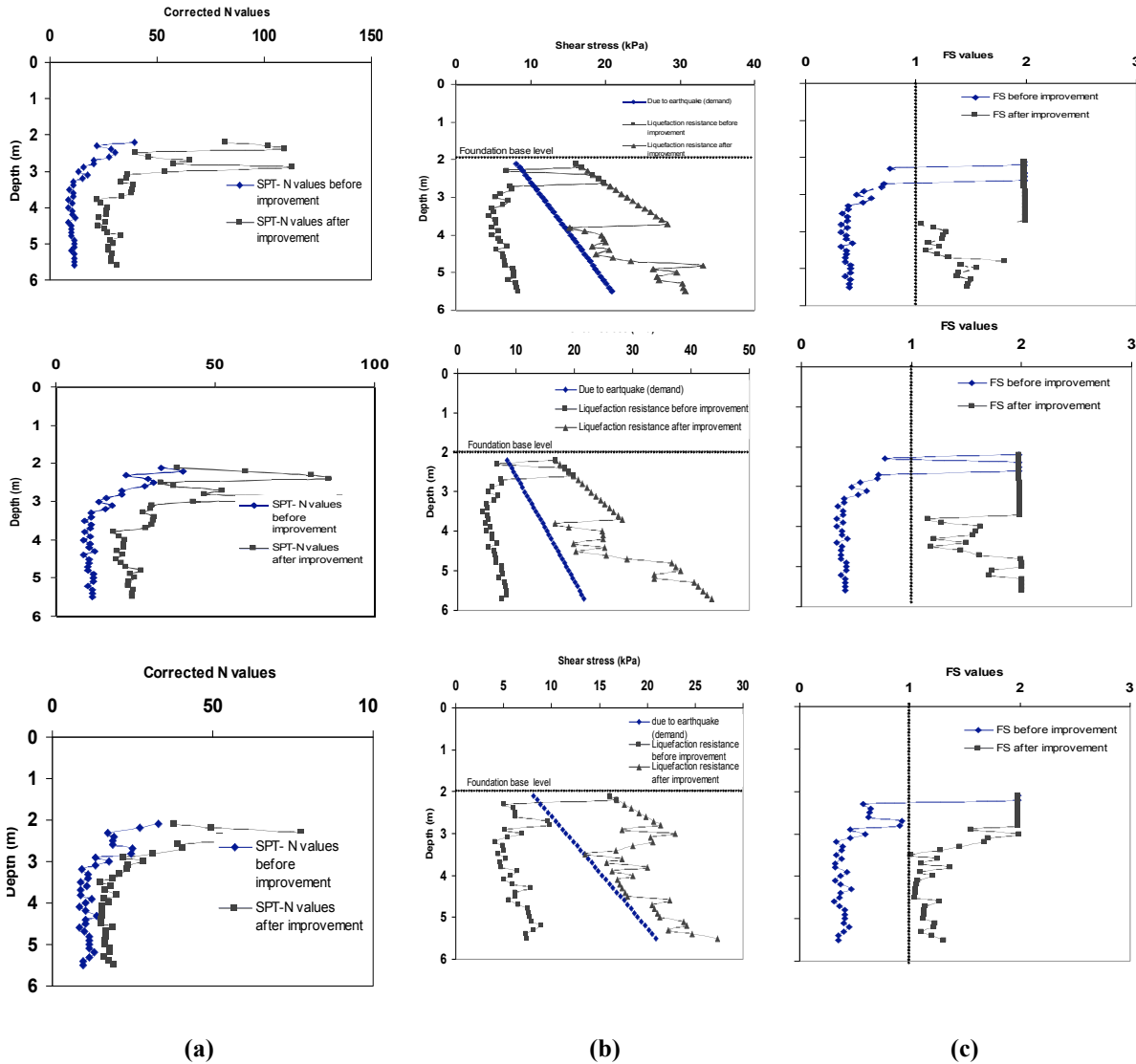


Figure 6. Pre- and post-treatment variations of (a) equivalent SPT-N values, (b) cyclic stresses required to initiate liquefaction, and (c) factors of safety against liquefaction (case I)

4.2 Case 2 – Improvement of Weak Alluvial Soils

4.2.1 Subsurface Conditions

The second case consists of a unit of an industrial plant situated in the flood plain of a stream. The reinforce concrete structure is supported by individual footings of various sizes. Ground water is located about 1 m below the surface. Investigation boreholes drilled at the site revealed existence of saturated fine alluvial deposits that are generally identified as silty clays at the surface. This layer is underlain by a medium dense silty sand at a depth of about 3 m. The subsurface soil conditions are depicted in Figure 7.

Based on the penetration test results, strength of the fine alluvial surface soils is subject to erratic variations on the weak side with equivalent SPT blow counts being generally well below 10 within 3 m depth range. Accordingly, the concern was seismically induced bearing failure of the plant foundations.

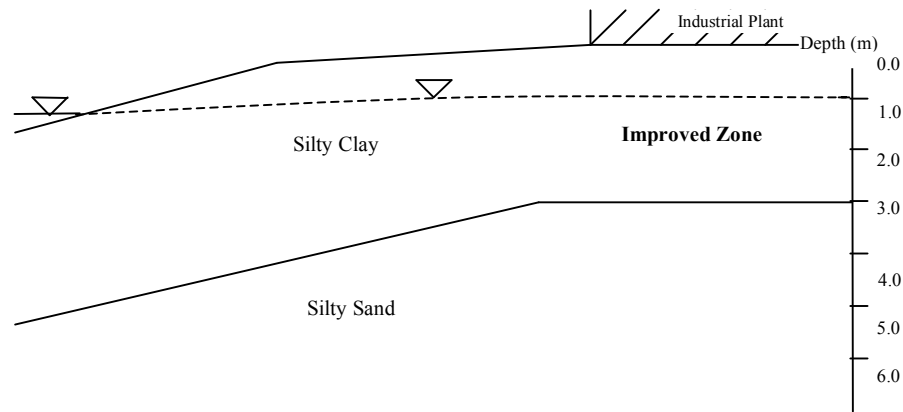


Figure 7. Subsurface conditions at the site of industrial plant (case II)

4.2.2 Application, Results and Implications

Foundation soils are treated within depths slightly exceeding 3 m through systematic injection beneath and around footings supporting the plant. Injection pressures varied between 3 and 6 bars depending on the circumstances, while the structure is continuously monitored against any possible displacements during execution.

Bearing capacity of the plant foundations which were seated at 0.75 m below surface is estimated by means of correlations through SPT blow count equivalent data based on dynamic penetration test results. The application points of dynamic penetration tests are indicated in Figure 8 on the footprint of the plant structure. Post-treatment resistance of the foundation soils is also investigated by dynamic penetration testing performed near pre-execution test points.

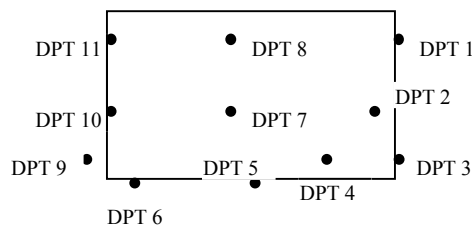


Figure 8. Penetration test points on the plan of the structure (case II)

Equivalent SPT blow counts corresponding to the pre- and post-treatment of surface soils for the tests coded DPT2 and DPT4 are illustrated in Figure 9. Based on these results, the shear strength of the silty clay layer was estimated to increase on the average about 180%, as a result of injection.

Presuming undrained conditions for the saturated clay, bearing capacities of the footings were calculated for static and seismic loading states before and after improvement. A peak ground acceleration of 0.3g was assessed for the plant site and the corresponding earthquake induced lateral forces and moments, besides increased vertical gross loads are considered to act on footings during seismic capacity calculation. The analyses results were express on the basis of factors of safety against bearing failure.

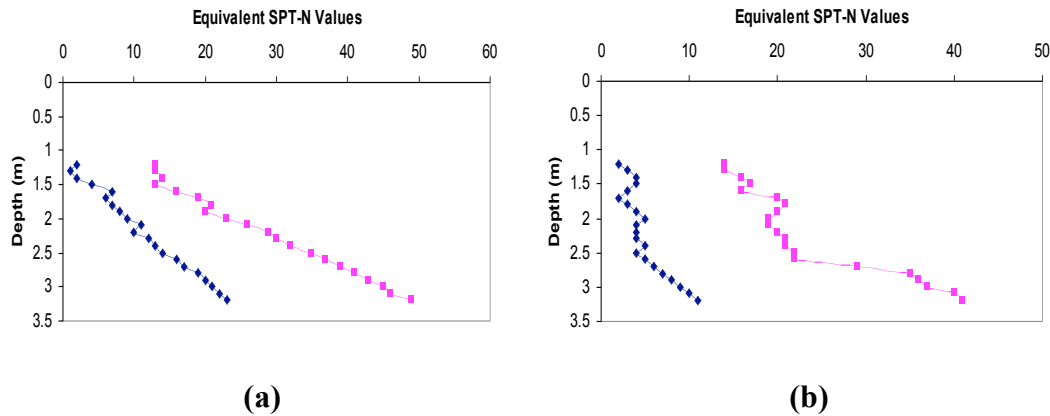


Figure 9. Pre- and post-treatment variations of equivalent SPT blow counts in (a) DPT2 and (b) DPT4 (case II)

For a typical footing, the factors of safety against bearing failure representative of the static and seismic loading states are calculated to be around 2.5 and 1.4, respectively, before treatment of the foundation soils; whereas, following the treatment, the factors of safety increased to 7 and 4.3, correspondingly. Hence, it can be stated that the footings became sufficiently safe following treatment and possibility of seismic failure has been eliminated.

5 DISCUSSION AND CONCLUSIONS

Expansive polymer injection improves soil resistance through two distinct modalities depending on the soil type and grouting mode: first, in parts of the soil through which the resin impregnates, the void space in the soil is filled by the expansive resin and a chemical bond is provided between the solid particles constituting the soil; second, due to the expansive character of the resin, injected soil tends to enlarge in volume, exerting significant pressures over the surrounding which results in increase of effective stress and reduction of voids (compaction) in the soil mass. The combined effect provides a substantial improvement of the soil strength and hence the penetration resistance.

It has been shown through presented cases of application that the expansive polymer injection can be effectively utilized for strengthening foundation soils against earthquake related damage. Based on the results of penetration testing performed to assess the quality of improvement, the method is equally efficient as a remedial measure against liquefaction in coarse grained soils as well in strengthening of the weak alluvial deposits. Also, it is to be noted that the penetration testing is a viable and practical tool for the in-situ assessment of application effectiveness.

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