

The Methods of Remediation of Existing Underground Structure Against Liquefaction

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SUMMARY:

The underground structure contain lifelines, underground station, urban tunnelling and tanks are vital structures that object less damage compare to surface structure during an earthquake because of confinement in earth. Underground structures built in areas subject to earthquake activity must withstand both seismic and static loading. Because of surrounding this structure by ground, the behaviour of under ground structure is so dependent on medium. The saturated sand and loss soil are medium that have high potential of liquefaction. In this study at first in general introduced the different remediation methods against liquefaction and then explain some example of these methods and case study that observe damage in underground structures and facilities and the method of rehabilitation of theses structures.

Keywords: Underground structure, seismic, liquefaction, Remediation methods, case study

1. INTRODUCTION

One of the major factors of underground damage in earthquakes is horizontal ground displacement caused by liquefaction of loose granular soils, as illustrated in the case studies for many past earthquakes in the United States and Japan (O'Rourke and Hamada, 1992; Hamada and O'Rourke, 1992). Other important factors of underground structure damage caused by liquefaction of granular soils include local subsidence associated with densification of the soil and ejection of the water and soil, and flotation of buried structures that have a unit weight less than the unit weight of the surrounding liquefied soil. For example, horizontal ground displacement damaged many pipelines, bridges, roads, and buildings during the 1906 San Francisco, California, earthquake. Broken water lines made fighting fires after the earthquake impossible, and much of San Francisco burned. During the 1989 Loma Prieta earthquake, liquefaction, horizontal ground movement, major pipeline damage, and fires occurred at virtually the same locations in San Francisco. Of the 160 breaks in the Municipal Water Supply System of San Francisco in 1989, 123 were in the Marina where significant liquefaction and ground deformation had occurred (O'Rourke and Pease, 1992). Most recently, soil liquefaction during the January 17, 1995 Hanshin-Awaji (Kobe), Japan, earthquake completely destroyed Kobe port, which is primarily made of three man-made islands. Soil liquefaction caused numerous breaks in Kobe City and its surrounding area's water and gas supply systems, resulting in a number of fires and the total loss of water supply for fighting fires and for domestic use. Many transportation systems were also disrupted as the result of liquefaction (Chung et al., 1995). Ground improvement may be the most economical solution for these types of systems, and for all types of systems in areas where large ground displacement is anticipated.

There are different remediations methods against liquefaction which are described in general form in this paper. In other part, these remediation methods are specialized for underground structures. Based on these methods some case studies which are used this methods are introduced. In Fig. 1 and Fig. 2 two cases which are damaged during an earthquake by liquefaction are shown.



Figure 1. Uplifted sewage manhole during the 2004 Niigataken-chuetsu earthquake



Figure 2. Uplifted sewage tank during 1964 Niigata earthquake

2. GENERAL REMENDATION METHODS

Remediation methods against liquefaction are classified into two categories:

- i) Those that improve the liquefiable soil to prevent liquefaction. In this category following concepts are used.
 - 1- Use material with high density or increase the density of existence material
 - 2- Use not-liquefiable grain size
 - 3- Stable the skeleton of soil
 - 4- Decrease the saturation of soil
 - 5- Immediate dissipation of increased excess pore pressure
 - 6- Reduction of shear stress by increasing confining pressure
 - 7- Reduction of shear stress by building an underground wall.

These methods are described more in Figs 3, 4, 5.

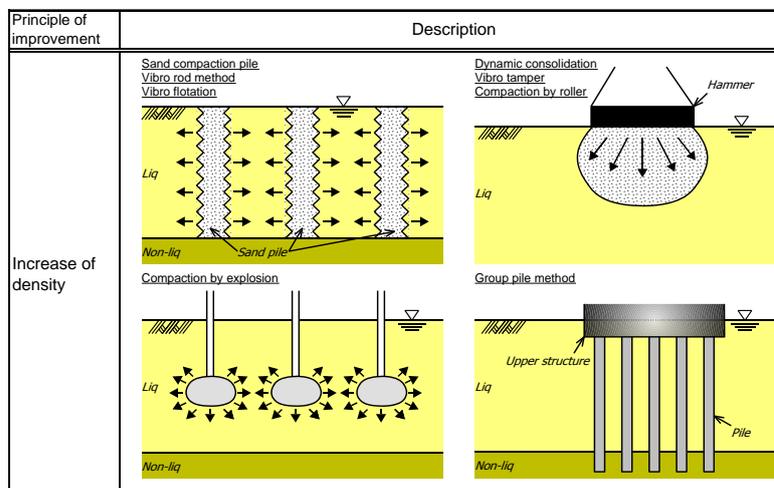


Figure 3. Method of remediation against liquefaction – Increase Density (modified from JGS, 1998)

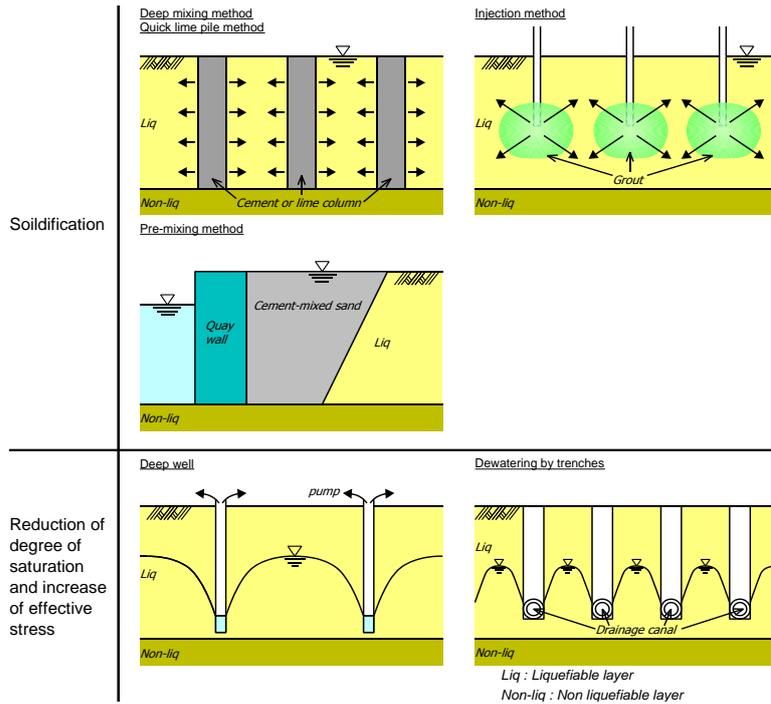


Figure 4. Method of remediation against liquefaction – Solidification and reduction of saturation (modified from JGS, 1998)

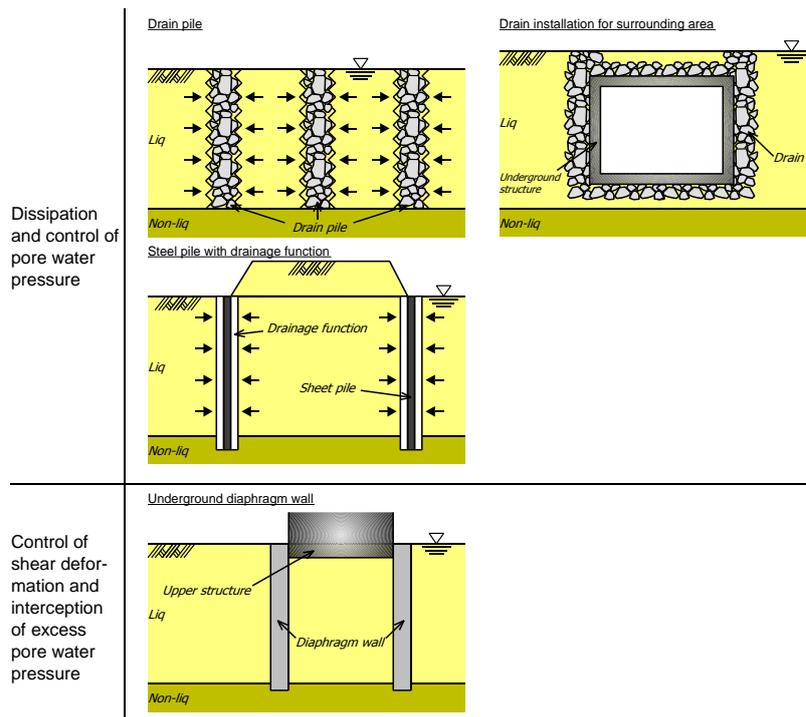


Figure 5. Method of remediation against liquefaction – Dissipation of pore pressure and reduction of shear stress (modified from JGS, 1998)

- ii) Those that strengthen structures to prevent their collapse if the ground should be liquefied. These methods and details which related with this category are described more in Fig. 6

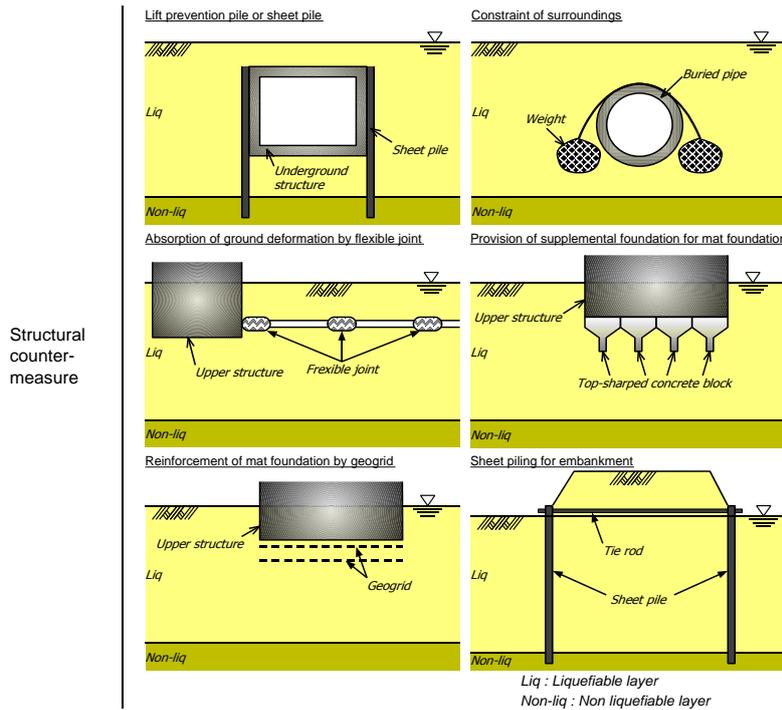


Figure 6. Method of remediation against liquefaction – strengthen structures (modified from JGS, 1998)

In Fig. 7 and Fig. 8, the methods of remediation which are mostly used for buried pipeline are shown. Underpinning, compaction grout column, jet grouting, soil cement wall and drain pile are common method which shown.

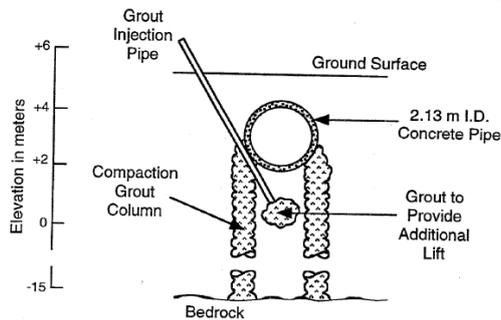


Figure 7. Underpinning and leveling settled pipe by compaction grouting (after Scherer and Weiner, 1993)

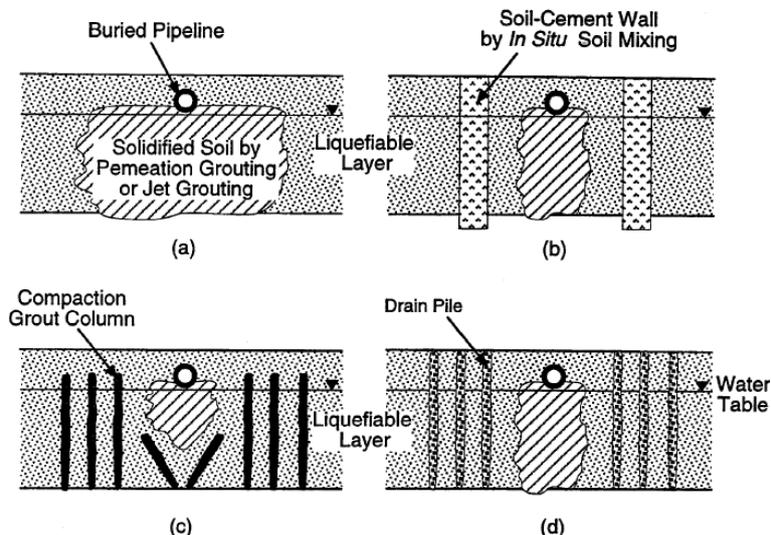


Figure 8. Liquefaction remediation near buried pipeline by combination of ground improvement techniques

For underground structure such as tunnels and metro stations, installing sheet piles can prevent uplift of these structures. These sheet piles in some cases contain also drainage system. In other cases when more restrains are needed, soil improvement under the structure is also used.

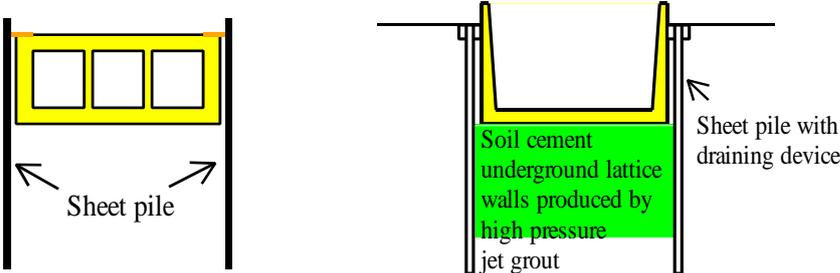


Figure 9. Remediation methods for existing underground structures

3. REVIEW OF CASE STUDIES

In this section, different case studies of underground structure which remediate against liquefaction are introduced.

3.1. The Webster Street tube

The Webster Street tube backfill along with the sand bedding fill around the bottom of the tube, consisting of loose sand with an average of SPT blowcounts of less than 10 would most likely liquefy in major earthquakes, posing severe danger that the tube would float. The plan and profile and also geological section of ground near tunnel are presented in Fig 10.

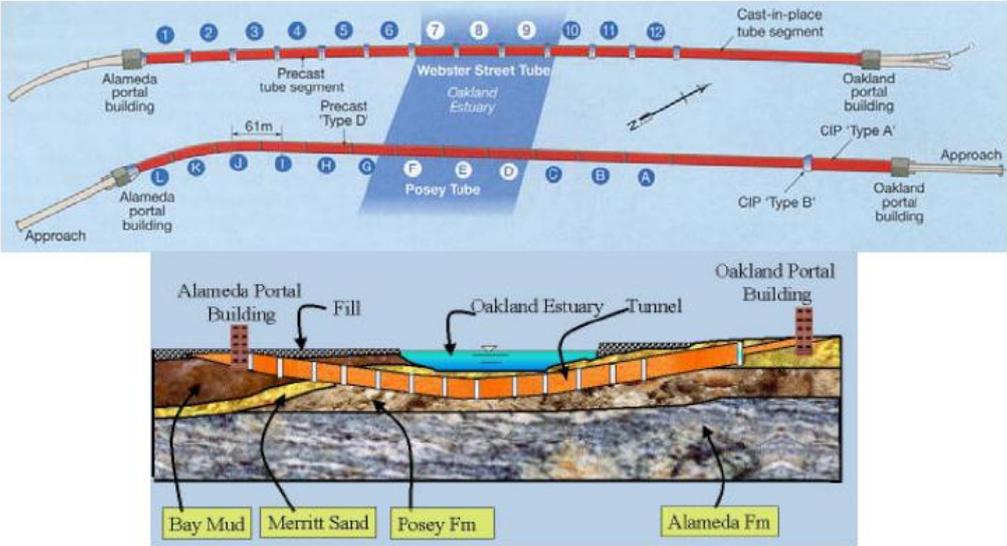


Figure 10. Plan, profile and geological section between Oakland and Alameda portal

In 1989, the Loma Prieta earthquake caused modest liquefaction damage to a bulkhead above the Alameda Landing of the Webster Street tube. Liquefaction spouts and back displacements were also seen above the adjacent Posey tube. It was estimated that the horizontal ground acceleration of about 0.2g was felt at the site and minimal damage to the tubes was noted. A number of options were considered to stabilize the loose to soft backfill surrounding the two tubes, thereby mitigating potential liquefaction and arresting flotation of the tubes. In Fig 11, the mechanism of floating of tube due to uplift pressure is shown.

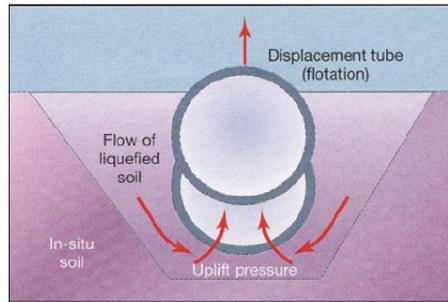


Figure 11. Potential flotation mechanism of tube in Webster Street

Two basic approaches can be adopted; one is to improve conditions of the ground such that it would not liquefy, and the other is to permit liquefaction, but to prevent flotation of the tubes by confining the liquefied material within impermeable or highly densities zones.

- Improving Soil Conditions of the Tubes

1. Densifying the sand backfill material by vibroflotation and other means may seem to be a method, but it cannot reach the loose sand bedding fill immediately below the tubes. In addition, densifying the material under the tubes would cause settlements.
2. Grouting the backfill material from the ground or the estuary could be a solution. However, great difficulty was foreseen in reaching the materials below the tubes with directional drilling.
3. Grouting from inside the tube bottom would be a difficult task in view of the tight space in the lower plenum and the possibility of drilling numerous grout holes in the tubes under 75 ft water pressure, the operation of which could exacerbate the structural integrity of the tubes, but also a single failure of the process could flood the tunnel.

- Isolation Principle

For an immersed tube tunnel to move upward in a liquefied soil mass, the liquid must be able to flow under the tube as it moves up. If this mechanism is prevented, the tube would not float, even if the soil under the tube were to liquefy. Thus was born the isolation principle. The space under the tubes can be isolated from the surrounding material by building “isolation” walls, consisting of material that would not liquefy and that would withstand differential pressure from the liquefied mass. The isolation walls can be sheet piles, but for the Webster Street Tube which is surrounded by sandy backfill, a non-liquefiable wall consisting of vertical displacement stone columns is adopted. According to Mitchell (1994), soils most suitable for densification by vibroflotation method should:

1. Be granular and free draining with $D_{10} > 0.03$ mm;
2. By the Cone Penetration Test (CPT) have: Friction ratio $< 1\%$ and Cone tip resistance greater than 50 tsf (if < 50 tsf, likely to indicate silt, clay, and organic material).
3. Have coefficient of permeability $k > 1 \times 10^{-4}$ cm per second.

In Fig12 and Fig. 13, these two approaches are presented.

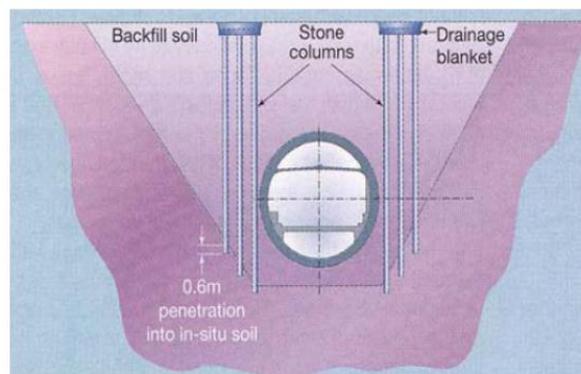


Figure 12. Improving conditions of the ground by stone columns for Webster street tunnel

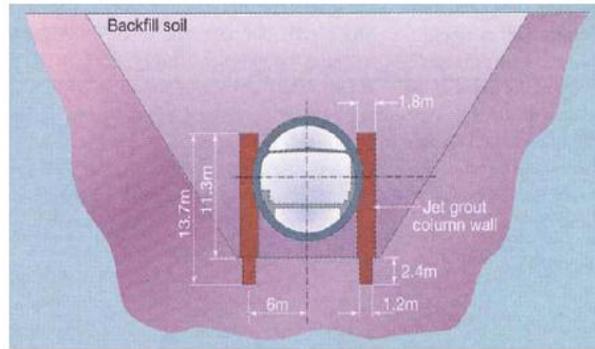


Figure 13. Jet grout walls (soilcrete) for pipe

In both methods, numerical analysis can help to predict the situation after remediation. Fig. 14 shows some example of these methods.

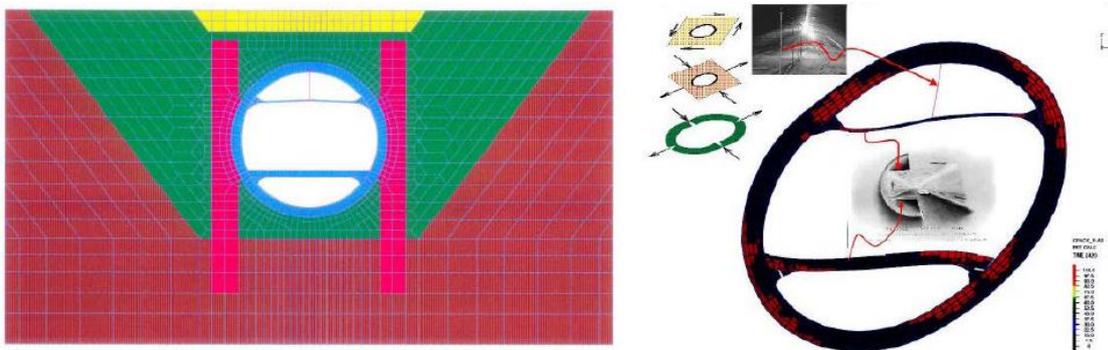


Figure 14. Two-Dimensional racking finite element mesh and Tunnel deformation and crack pattern

3.2. A multi-service tunnel (partially quoted from JGS (1998))

A multi service tunnel is also remedied by sheet piles to prevent liquefaction. This tunnel has 8 meter width which is protected with 22 meter piles. The scheme of this design and the real condition of installing of sheet pile are presented in Fig. 15.

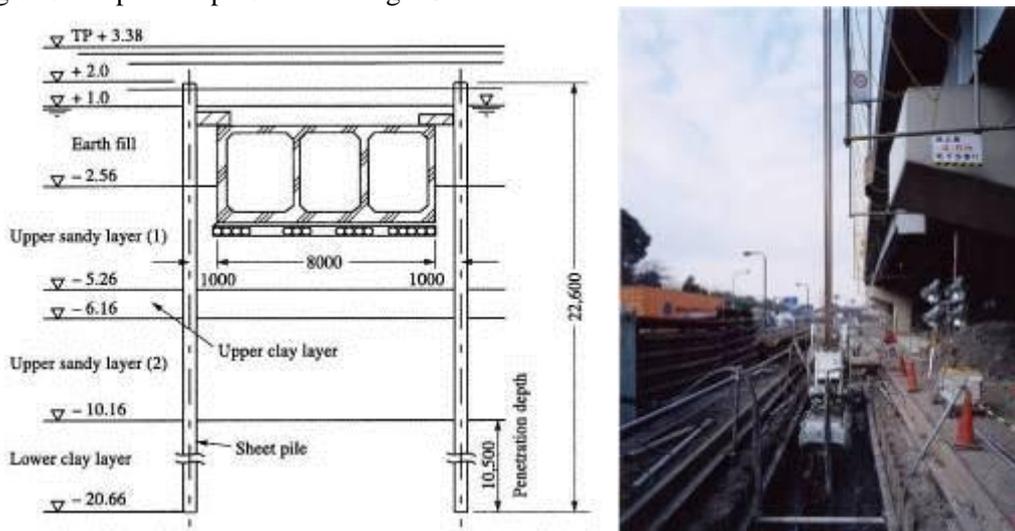


Figure 15. Sheet piles were driven besides the tunnel to prevent liquefaction-induced uplift in multi service tunnel

3.3. A subway station in Tokyo (partially quoted from Yokota et al. (2001))

Three position of metro in Tokyo are Treated to liquefaction-induced uplift. In these segments the ground under tunnel is improved by pressure jet grouting through the floor of tunnel to make soil cement underground lattice.

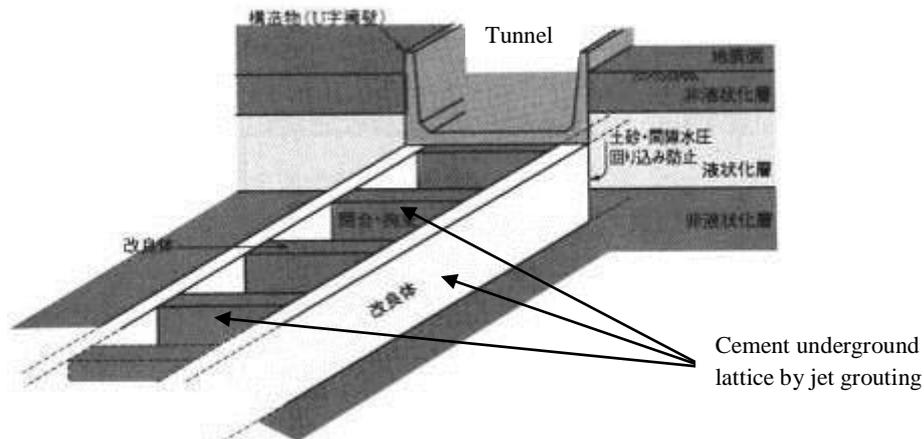


Figure 16. The method of remediation in metro of Tokyo

3.4. Tunnel Construction Beneath Rail Line, Switzerland

A new underpass was to be constructed beneath a busy rail line that separates the town of Fluelen from Lake Uri (Steiner et al., 1992). The upper 3 m of soil below the railroad embankment consisted of gravel and cobble fill. The fill was underlain by wood and stone rubble, remnants of a former boat landing facility. Below the rubble, fluvial and lacustrine deposits were interfingered ranging from silt to gravel. These natural soils were characterized by SPT blow counts between 1 and 10. The ground water table was located close to the surface and was in direct contact with the lake. Two cut-off walls were needed to make dewatering effective and prevent excessive settlement beneath the tracks.

As reported by Steiner et al. (1992), jet grouting was used to construct the two cut-off walls. It was determined from a pilot study that columns with diameters of 1.5 m and 1.2 m could be constructed with the double jet system and single jet system, respectively. The double jet system, i.e. grout jet shrouded with air, was used to construct columns with dip greater than 200. The single jet system, which uses no air, was used for the flatter columns. Each wall consisted of three rows of columns. The general arrangement column for one row is shown in Fig. 3.7. The outer row was constructed first, and the central row was constructed last with the axes of columns shifted so that they were positioned between the outer and inner columns. Cores taken from two borings drilled through the final wall revealed no evidence of joints between columns. Core specimens after 28 days exhibited an unconfined compressive strength between 6 and 10 MPa. During the two months of jet grouting work, the tracks underwent 4 mm of settlement, about the same rate observed before the work started. Measured settlement during excavation of the underpass was about 3 mm.

3.5. Tunnel Construction Beneath Airport Runway, Japan

A 70-m-wide underpass for vehicles was planned beneath a functioning airport runway in Japan (Ichihashi et al., 1992). The runway had been built on top of a concrete slab supported by steel sheet piles, as depicted in Fig. 17. However, not all sheet piles extended to the bearing layer and some underpinning was necessary to support the excavation. The excavation would require dewatering, which could also cause settlement. It was determined that settlement and heave to the runway could not exceed 50 mm.

As reported by Ichihashi et al. (1992), jet grouting was used to form soil-cement piles that extend to the bearing layer, and cut-off walls to prevent lowering of the water level outside the excavation. Since the soil could be improved by jet grouting through chill holes less than 220 mm in diameter, minimal damage occurred to the runway. To prevent settlement, a steel guide casing was first installed down to the top of the zone to be grouted. The grout pipe was then lowered down through the guide casing and advanced to the final depth, 2 m into the bearing layer. A tank containing a sand pump was attached to the casing guide at the ground surface to prevent waste slurry from flowing onto the runway. A triple jet system was used. Grout injection pressures varied between 30 and 40 MPa. Air injection pressures varied between 0.6 and 0.7 MPa. The drill rod was withdrawn at a rate between 50 and 100 mm/min. During the excavation of the tunnel, measured settlement and heave of the runway surface was less than 3 mm.

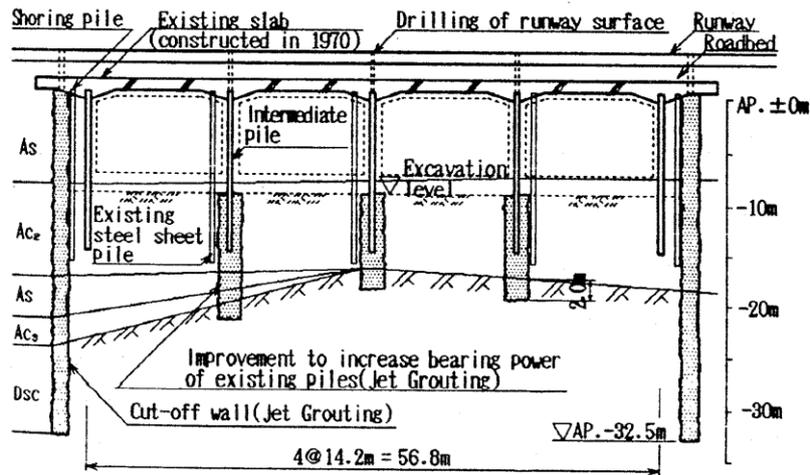


Figure 17. Excavation support seepage control by jet Grouting beneath existing airport runway (Ichihashi et al., 1992)

6. CONCLUSIONS

Remediation methods can divide in two categories; Existing structure and future structure. Remediation methods against liquefaction which can be applied to existing structures are introduced in this paper. The remediation of old structures is very important because a huge number of these structures have not been treated against liquefaction. More remediation methods for existing structures must be developed. In the design of remediation methods for existing structures, it is desired to introduce performance-based design methods.

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