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New liquefaction countermeasure based on pore water replacement

Nouvelle mesure contre la liquéfaction par remplacement de l'eau interstitielle

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ABSTRACT
A newly developed countermeasure against liquefaction is presented. To improve the liquefaction resistance, the pore water is replaced with a silica gel substance by using a unique injection technique. In this paper, the principle of countermeasure, the fundamental mechanical properties of treated sand, theory and practice of injection technique and the application of this method in the last five years in Japan are described.

RÉSUMÉ
Pour améliorer la résistance a la liquéfaction sous un édifice, équipé contre les secousses sismiques, aucune mesure efficace n a été trouvée en raison du coût élevé La méthode de jointure perméable présentée propose le remplacement de l'eau présente dans le sable, par un gel silicone.

1 INTRODUCTION

After the Great Hanshin Earthquake in 1995, most of the design standards against earthquakes have been revised. These new standards have increased, as a consequence, the number of old facilities in which countermeasures against liquefaction had to be taken into account. However, quite limited effective countermeasures were adoptable to improve the liquefaction resistance of soil layer beneath the existing structure. Thus, a new type of countermeasure called herein the "Permeable Grouting Method (PGM)" has been developed (Hayashi et al., 1995). In the paper, 1) the principle of countermeasure, 2) fundamental properties of treated sand, 3) theory of injection technique of chemicals and verification with the field experiment, and 4) examples of application of PGM, are presented.

2 OUTLINE OF PERMEABLE GROUTING METHOD

The principle of current liquefaction countermeasures associated with the pore water treatment can be generally classified into two; 1) the dissipation of pore water pressure and 2) the lowering of ground water table. The PGM, however, prevents the liquefaction of ground during earthquakes by replacing the pore water in sand with a silica gel substance. In that sense, the principle of PGM can be said to be the "replacement of pore water". Application of the PGM is similar to the traditional chemical injection method, except that in addition to solidifying the soil particles, the silica gel chemical used in the injection process forces to replace the pore water out of the soil void. (See Fig. 1) In order for the process of chemical diffusion to work effectively, the new method must 1) enable intensive permeable grouting by injection, 2) secure sufficiently long permeating distances within cost acceptable parameters, 3) clearly define the characteristics of pore water to increase the effectiveness of injection process, and 4) establish appropriate design and application protocols. Owing to these unique characteristics, the PGM is significantly different from the conventional chemical grouting method, although on the surface of it they may appear to be the same(Hayashi & Kusumoto, 2002).

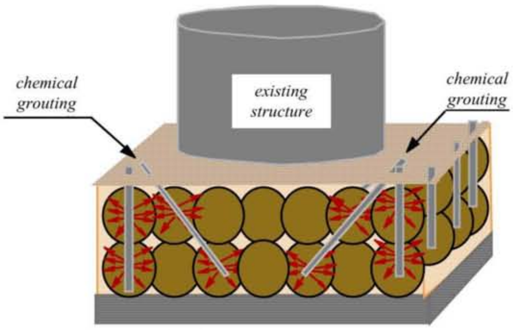


Figure. 1 Image of application

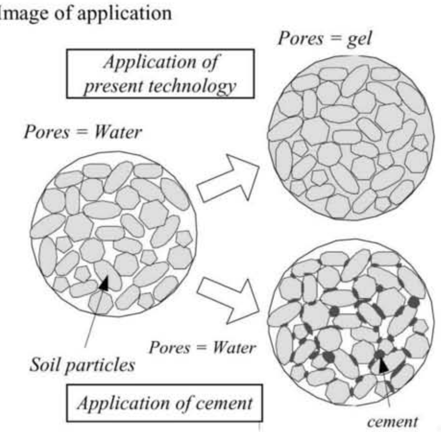


Figure. 2 Difference in vital portions for improvement

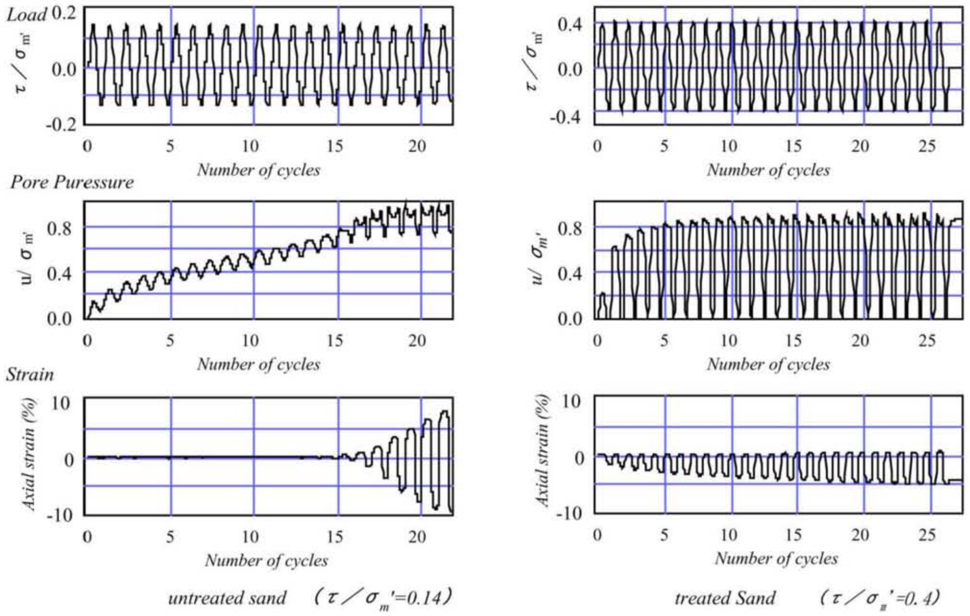


Figure.3 Comparison of cyclic triaxial test results between treated and untreated sands

Fig. 2 shows conceptual drawings clarifying the significant differences in soil structure that has been improved by using cement as a stabilizer, and by replacing pore water with a silica gel solidifier. In order to attain the complete replacement of pore water with silica gel and high level of homogeneity, the permeable grouting is critical.

The basic characteristics of treated soil, where pore water was solidified with silica gel, were investigated with the cyclic triaxial test. The substances used in this test are two forms of recently developed permanent liquid glass, activated silica and superfine particle of silica. The durability of this material was found to be very stable through the measurement of possible variation of characteristics over a period of 16 years in laboratory experiments and field tests implemented separately (Yonekura & Miwa,1993).

The laboratory test results proved that if the pore water in ground was replaced with silica gel using a chemical of appropriate concentration, even sandy soil could be improved to exhibit favorable liquefaction characteristics;

1) Fig. 3 shows the time history between pore water pressure ratio and strain in the cyclic triaxial test of untreated and treated sands. It indicates that, even when the ratio of pore water pressure (or pressure borne by the gel agent) approximates 1.0 for treated sand, no substantial strain is abruptly generated and the strain is gradually accumulated in the tensile direction of sample (Hayashi et al., 2001).

2) Fig. 4 shows the comparison of liquefaction resistance between treated and untreated sands. Liquefaction resistance in treated sand in which the double amplitude of axial strain (DA) of 5% was defined as the occurrence of liquefaction was significantly enhanced when compared with the untreated sand.

3) After the double amplitude of axial strain exceed 5%, the untreated specimen showed the behaviour as if sand particles were floating in water. However, the treated specimen did not indicate such behaviour as observed in the untreated specimen.

4) Permeability and discharging ability can be substantially reduced if the pore water in ground is replaced with silica gel.

5) As for shear strength characteristics, the internal friction angle of treateded sand was almost the same as that of untreated sand. However, the static strength increased a little due to the cohesion component added by silica gel.

6) The replacement of the pore water with silica gel did not change the rigidity of the soil skeleton, unlike the solidification of the skeleton using cement. Therefore, no significant changes were found in the rigidity between untreated and treated sands.

The above-mentioned characteristics of treated sand have the following advantages against liquefaction;

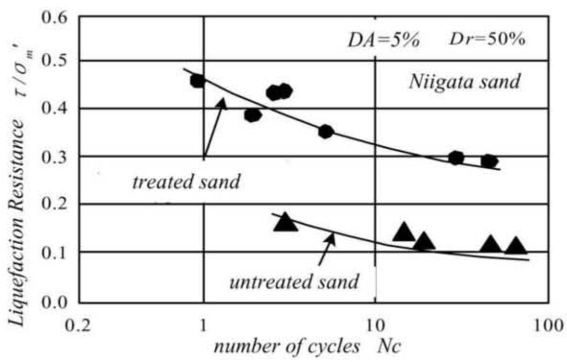


Figure. 4 Comparison of liquefaction resistance between treated and untreated sands

Item 1) suggests that no major deformation occurs, even when a large earthquake more than design level was occured.

Item 2) indicates that this method can maintain in a Level 2 vibration intensity of earthquake like the Great Hanshin Earthquake in 1995.

Item 3) means that earthquakes exceeding design level may cause substantial strain, but would not result in the damages due to the liquefaction of ground.

Item 4) indicates that in the event the surrounding ground is liquefied owing to a reduction of the permeability coefficient, the soil layer is not greatly affected by the diffusion of excess pore water pressure from the primary liquefied area, and thereby would not suffer from secondary liquefaction.

Item 5) indicates that even if the effective stress is eliminated by the diffusion of the excess pore water pressure,the strength by cohesion can be expected to work. It is also expected that the earth pressure would be reduced because of cohesion.

Item 6) indicates seismic force occurring underground would scarecely change in terms of design earthquake vibration, because deformation coefficients do not vary before and after the improvement. Since the ground is ordinarily solidified under densification or solidification methods, more seismic force tends to occur in improved ground during an earthquake, however, present technology does not allow the seismic force to grow larger.

These explanations correspond to the principle of soil improvement that forms the core of present liquefaction countermeasures. Design and application methods have been established through labolatry tests and field tests on the basis of the above-mentioned advantages and fundamental characteristics of treated sand.

3 DEVELOPMENT OF APPLICATION METHOD

The PGM includes fundamental techniques of the existing grouting/injection techniques. However, what makes this new method unique is that it also incorporates a permeable grouting phase that replaces and solidifies the pore water in soil skeleton. Conventional methods were designed as partial and temporary ground improvement attempts, whereas this method aims to create a structurally homogenous and permanent solution against the problem of liquefaction. Unlike conventional methods of chemical grouting where holes are drilled at about one-meter intervals, the new method requires two to four meter intervals, as the grouting technique have been improved so that the chemical grout can reach further distance. This method produces more homogeneous soil layer that is more resilient to the effects of earthquakes and subsequent liquefaction.

Photo 1 Improved soil excavated in a field test (Tsu-matsuzaka, Mie prefecture, 1998)

Photo 1 shows the improved soil excavated one month after the application of chemical grouting.
This observations confirmed that the improved soil had solidified in almost spherical shapes emanating from the grouting point (Hayashi et al., 2000) and that the longer permeation distance had reduced solidifying strength. Measurement of the silica content of the soil also proved that the solidifying effects of the chemicals dissipated toward the periphery of the injection area and that pore water had diluted the chemicals. Dispersion analysis was carried out to study this phenomenon of dilution.

Concentration and distribution of a silica grout injected at a point in the ground and measured at each subsequent point of injection may be represented by Equation (1) (Hayashi et al., 2004). Concerning the results of field experiment shown in Photo 1, Fig. 5 shows the relationship between the analytical solution and silica content in the sample measured in the field. The dispersion coefficient was changed to several values in back-calculations. A comparison between the two clarifies that the dispersion coefficient is found about 0.05cm^2/s in this analytical solution and then it represents the periphery shape of diluted silica grouting governed by Equation (1).

$$\frac{\partial C}{\partial t} = -V_r \frac{\partial C}{\partial r} + D \left(\frac{\partial^2 C}{\partial r^2} + \frac{2}{r} \frac{\partial C}{\partial r} \right) \quad (1)$$

Where, C: chemical concentration, D: dispersion coefficient, r: distance from the pouring point, r_0: converted radius of the permeated surface, and V_r: flow velocity at r

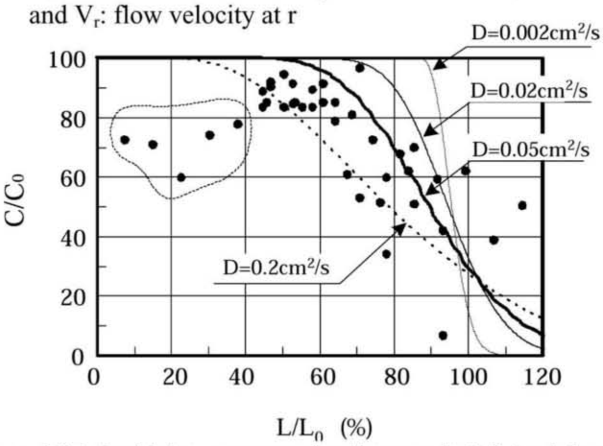
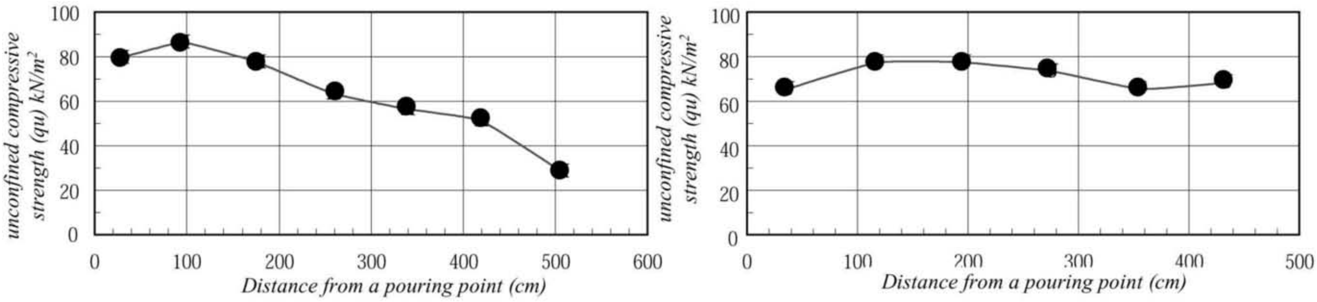


Figure. 5 Relationship between permeating distance ratio (L/L_0) and chemical concentration ratio (C/C_0)



case1 a fixed chemical concentrations

case2 changing chemical concentrations in consideration of possible dilution

Figure. 6 Comparison of unconfined compressive strength after injection in one dimensional model experiment

To reduce the influences of these dilution phenomena, a methods to change the chemical concentrations in accordance with the permeating distances, or to control their concentrations at an initial stage of injection, were developed by referring to theoretical analysis results concerning dilution and dispersion. Fig.6 indicates the distribution of unconfined compressive strength in the case of injection of chemicals at a fixed concentration in the sandy soil and by changing their concentrations to compensate for dilution. It is clear in this one dimensional model experiment that the injection of the chemicals by changing their concentrations produces improved soil of higher homogeneity of strength.

Owing to the development of these application techniques, liquefaction countermeasure beneath the existing structures has been made more practical, notwithstanding the cost and difficulty of application.

4. APPLICATION OF PGM

The new method was employed for the first time in 1999, as a liquefaction countermeasure under Runway B at the Tokyo International Airport, improving the volume of 20,000 m^3 of runway substructure. So far, the PGM has been applied in approximately 40 other facilities such as quaywall, bridge foundation, docks and other important infrastructures, over a period of six years as shown in Fig.7. The reliability of PGM was demonstrated by surveys made after the completion of projects(Hayashi et al., 2003).

5. CONCLUDING REMARKS

When some countermeasures have to be taken against liquefaction of soil layer under the existing facilities, so far there exist quite limited countermeasures in terms of cost and time in practical application. Namely, in some cases, when liquefaction has seriously compromised the structural integrity of buildings or structures, complete reconstruction has been an appropriate measure, although disrupting business and traffic and occasionally causing severe economic repercussions in the locale surrounding the affected area. To cope with this problem, the PGM was developed and the development of PGM, as an alternative for the existing measures, has resulted in more cost and time effective countermeasure for dealing with liquefaction problem under the existing facilities.

Recent years, it is becoming increasingly important to improve the cost effectiveness of maintenance on large structures and buildings in order to conserve resources as well as to improve safety. It is expected that the PGM will protect the existing structures from liquefaction and enhance their longevity decades beyond the projected life spans.

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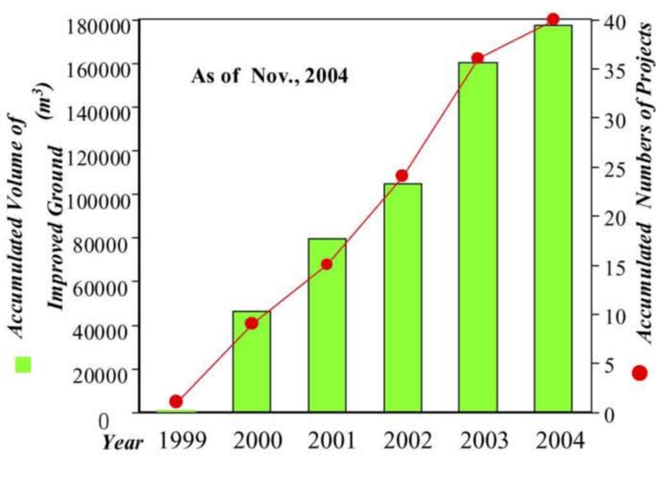

Figure.7 Number of sites and improved volume