THE COUNTERMEASURE AGAINST LIQUEFACTION OF SAND WITH CHEMICAL GROUTING FOR EXISTING FOUNDATION STRUCTURES

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ABSTRACT

In late years the earthquake scale that outbreak is assumed in the future becomes big. Therefore it becomes often that safety for the liquefaction of sand with the existing structures are not secured. In this case, as for the countermeasure of the railway structure, a scale is big, and execution characteristics and economy become the problem. As this reason, it is necessary to secure the service of the train during the construction of countermeasure. As the countermeasure against the liquefaction of sand with existing railway structures of the pile foundation, we examined applicability of the chemical grouting that an execution scale was small. The examination item is an effective injection range and degree of the injection. About the strength characteristic of the grouted sand, we carried out a laboratory soil test and grasped relationship between the strength ratio causing liquefaction and the unconfined compressive strength. In addition, we carried out the static loading test and shaking table test of the model of pile foundation and grasped relationship between an injection range and the bearing capacity of liquefied ground. The injection of a wide range was necessary conventionally, but, as a result of examination, confirmed that it was reduced the section force of the pile foundation at the time of the liquefaction by the injection only to the circumference of the pile. In addition, unconfined compressive strength of the grouted sand confirmed that there were enough effects in even low strength of the 50(kPa) degrees.

Keywords: liquefaction, countermeasure, chemical grouting, pile foundation

INTRODUCTION

In late years, an assumed earthquake is big, and that the seismic capacity of a foundation structure built so far is short is assumed. Therefore measures to increase in stability of the ground because the soft ground and the ground where liquefaction occurred increased at strength of the bearing stratum were carried out. However, it is the present conditions in the case of the railway structure that the site range that is measures possibility is limited in particular. In addition, there are many cases that execution characteristics, economy become a problem in large-scale measures method of construction by becoming measures construction while a run gender of a train is followed.

When the choice of the countermeasure is limited like a railway structure, execution is comparatively small, and the application of the solidification method of construction that an effect is expected is thought about, but an economic problem is had from measures range and the plane of improvement materials.

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Therefore, we report it about the result that examined the effective extreme setting and improvement range that bearing stratum where it is necessary can find for stability of foundation when liquefaction is assumed in particular when a solidification method of construction by the chemical grouting is applied as the seismic reinforcement method of the existing foundation structure in the railway.

![Diagram](image1.png)

**Figure 1. The image of the range of measures possibility**

EXAMINATION ABOUT INJECTION MATERIALS TO USE FOR SEISMIC REINFORCEMENT

When use chemical grouting for the seismic reinforcement of the railway structure; at the position that is near to a track is executed the work. A summary is shown in Fig. 1. Therefore, it is thought that the penetration grouting that injection materials can infiltrate the ground by comparatively low injection pressure is suitable. In this case, a characteristic of injection materials takes big influence as well as permeability of the ground. In addition, lasting measures effect is expected. Therefore, in consideration of these, we carried out examination about many conditions of injection materials when a chemical grouting of construction was applied as a countermeasure against liquefaction of sand.

A general characteristic of injection materials

The injection materials to use for chemical grouting are distributed between two kinds of suspension type and the solution type. The suspension type is represented by ultra-fine particles cement, lets the cement particle of very small particle size seep in the ground, and expects strength increase because a cement particle remains in a void between the soil particle. However, seepage deteriorates by progress of injection time, and that there is the case that it is not possible for enough penetration to ground is pointed out. In addition, there is a case to become fracture grouting if pressurization power becomes excessive. On the other hand, as for the solution type, a main material and hardening materials seep in the ground, and pore water between the soil particle is substituted for a gelatinous compaction body in what is solidified by a main material and hardening materials doing a chemical reaction. Strength increase is
expected in what the cohesion is added to in it. It is a characteristic that seepage is high generally because the solution type does not include a particle.

According to the current seismic-resistant design codes for railway structures, in the high ground of the possibility of the liquefaction, mean grain size \( (D_{50}) \) is equal to or less than 10mm, and, as for 10% diameter of soil particle \( (D_{10}) \), lower than 1mm, fine soil content \( (F_c) \) are equal to or less than 35\% \( (RTRI, 1999) \). The coefficient of permeability in the ground of such a condition is regarded as a range of about \( 10^{-1} - 10^{-3} \text{cm/sec} \). Therefore, it is thought that it is suitable to use because the coefficient of permeability of the ground where an application of the solution type is possible is a range of \( 10^{-2} - 10^{-4} \text{cm/sec} \). Relationship between kind of injection materials and range in consideration liquefaction is shown in Fig. 2.

![Figure 2. Relationship between kind of injection materials and range in consideration liquefaction](image)

**Examination about the durability**

It was thought that applicability of injection materials of the solution type was high on the ground where possibility of the liquefaction was pointed out as had shown in a foregoing paragraph. But, in the injection materials of the water glass system that was a representative of the solution type, a problem of durability by the cause was pointed out leaching. However, in late years injection materials pro-non-alkali are developed, and examination for such a problem advances. The main material of the non-alkali silica sol mixed a large quantity of sulfuric acid with water glass, and was neutralized; was manufactured. Therefore, sodium ion becoming the problem is removed. It was thought that the mechanism of the aging deterioration of injection materials was caused by the eluviation of the chemical materials by the ground water. Therefore we suggested a test method to let deterioration of injection materials advance for an index in the speed of the ground water. The examination sets up a specimen in flowing water and lets it deteriorate. By a suggested examination, a secular variation of unconfined compressive strength, coefficient of permeability and the silica density of non-alkali silica sol was arranged. By the examination that a specimen of relative density 60\% was used for, the unconfined compressive strength that passed for 800 days was 70\% of the initial value. Improvement of the durability was expected about the solution type by this test result. In addition, it was suggested about the relevance with decrease of unconfined compressive strength and the decrease of the silica density. Relationship between unconfined compressive strength, silica density and progress days is shown in Fig. 3.

In addition, the RTRI develops a PVA system polymer water solution as injection materials of the macromolecule system. In this polymer water solution, that there was hardly a thing washed away was
measured in the pH domain of the general ground by an experiment like the above which polymer gel was used for. It is confirmed that the stability is extremely high, and it is confirmed that there is not a problem about the durability (Tateyama, et al., 2002). The problem of the durability due to leaching is solved to some extent by these reports, and it is thought that the constancy as the countermeasure against liquefaction is secured.

Examination about a liquefaction strength characteristic

By the enforcement of the countermeasure against liquefaction by the grouting, what is set how much strength is necessary for the improvement soil that chemical was grouted becomes a problem. The liquefaction strength characteristic of the improvement soil that grouted various injection materials is investigated by a laboratory soil test, and a result is shown in Fig. 4.

![Figure 3. Relationship between unconfined compressive strength, silica density and progress days](image)

![Figure 4. A liquefaction strength characteristic of the solution type improvement soil](image)

According to this figure, it followed that the polymer improvement soil by the PVA density 3% solution could expect strength increase of around 2.5 times in comparison with non-improvement soil. In this case,
the pore water pressure of the improvement soil is under 1.0. It was suggested that the cohesion by injection materials was developed. As for the non-alkali silica sol of silica density 3%, liquefaction strength doubles about two. In this case, the pore water pressure ratio of the improvement soil is under 1.0. The strain increase does not have the distortion, and that the strain grows big slowly is reported (Yamazaki et al., 1998). This was the same, and it was suggested that the cohesion was developed.

In addition, as a result of investigation of the improvement soil which grouted injection materials, unconfined compressive strength and relations with the liquefaction strength ratio are shown in Fig. 5. According to this figure, necessary unconfined compressive strength is 50 - 100kN/m²degree so that liquefaction strength of the original ground increases to around two or three times. This comparatively understands that it is low strength. Therefore, strength of improvement soil is set to get the liquefaction strength ratio that liquefaction resistance factor of the ground to intend for becomes the targeted value.

![Figure 5. Relationship between the strength ratio causing liquefaction and the unconfined compressive strength](image)

**EFFECTIVE INJECTION RANGE**

When chemical grouting is applied as seismic reinforcement, the stability of the structure is nominated for a factor to decide an injection range. In other words, an effective injection range is a limited range influencing the stability of the structure, and it is a range decided by strength of bearing stratum of a structure. The range to contribute to for the stability of the structure is only neighborhood of the structures. Therefore, the place separated from a structure is not an object of the grouting. However, it is necessary to decide the last range in consideration of the influence that behavior of neighboring non-improvement ground gives to the grouted ground.

When liquefaction occurs, as for the pile foundation that is used a lot as foundations of viaduct of the soft ground coefficient of horizontal subgrade reaction decreases. Therefore, excessive transformation occurs from the deep position. In this case, it is necessary for the coefficient of horizontal subgrade reaction to be secured to reduce transformation.

Therefore, it was suggested that chemical grouting was carried out over a wide area to show it in Fig. 6 (a). However, the range where measures are possible is usually limited in one's site. In the case of a railway, sites continue in the track direction. However, the measures site can secure only a limited range because the track right angle direction is small.
Therefore it was examined an effect when it was grouted only to the circumference of the pile to show it in Fig. 6 (b). The examination was performed in 1G condition, and it was performed by the static horizontal loading test of a pile model put on the liquefaction ground (Sawada, 2006). The summary of the experiment is shown in Fig. 7. As for the pile model used for an experiment, as for diameter 20mm, as for length 750mm, as for flexural rigidity is 28700 N/cm². Materials of the pile model are acrylic system synthetic resin materials. In addition, the strength of the grouted ground around the pile was set in consideration of the resemblance with the real grouted ground so that unconfined compressive strength became 50 - 100 kN/m²degree. The grouted ground used polymer gel, and strength and hardness were simulated. In addition, the pile tip and the base were connected. The liquefaction layer was made to 750mm in depth. Quartz sand No.6 (specific gravity 2.65, maximum void ratio 1.13, minimum void ratio 0.73, uniformity coefficients 1.62) was used and made the targeted value of the relative density for 60% by an underwater fall method. The experiment was carried out by shaking by the pettiness amplitude in the direction that went directly to the direction that did loading to a pile and generated liquefaction to reach the appointed excess pore water pressure ratio \( \Delta u/\sigma' =0.0,0.7,1.0 \). It was done loading by displacement control until the greatest displacement reached 10mm in the state that liquefaction was continued.
As an example of the result, the reduction degree of the coefficient of horizontal subgrade reaction by the grouting is shown in Fig. 8. This figure is the result that compared several kinds of injection ranges with shiftlessness. This figure is a result in the states of the liquefaction of the middle scale. It is understood that strength more than double of the ground of the shiftlessness is secured by the injection of the range of 1D (D: pile diameter) around the pile.

In addition, an example of the shaking table test result that used White Noise (0-50Hz, acceleration 400gal at the maximum) for input wave in a similar condition is shown in Fig. 9. In the case of the injection of the range of 1D around the pile, even a condition injected in only in the shallow range of the neighborhood of pile head understands what the effect that the section force of the pile is restrained can expect.

Therefore, the effect that is equal to a condition injected to the position that is deep in the condition injected only in a shallow range showing in Fig. 6 (b) is shown, and the reduction of the measures cost and improvement of execution characteristics are expected.

![Figure 8. The reduction degree of the coefficient of horizontal subgrade reaction by middle scale liquefaction](image_url)

![Figure 9. Comparison of the section force of the pile mode](image_url)
THE SUGGESTION OF THE DESIGN METHOD

Based on past examination, a design method was built. Strength of the injection materials, an injection range are decided first. However, collation does displacement and a section force by structure analysis for the real examination quantitatively and must inspect validity of the injectant strength, an improvement effect. In this case, as for the examination method of the improvement effect by the suggested medicinal solution injection, two methods are thought about. The first method relaxes reduction degree of the coefficient of horizontal subgrade reaction by the liquefaction depending on improvement degree. The second method considers the improvement ground and a pile as compound structure and evaluates the section performance of the pile. In the former, the reduction degree that considered an influence range of the coefficient of horizontal subgrade reaction to give to the displacement / section force of the pile is estimated. It is necessary to take an effect of the improvement ground in the section performance of the pile namely a non-linear characteristic by the second method. However, it is difficult soil and reinforced concrete considers it to be a compound member, and to evaluate it. Therefore, it is proper to evaluate an improvement effect by the first method when it took design into consideration. The outline of the design calculation model is shown in Fig. 10. Inverse operation k value and relations of the stability displacement of the pile head calculated than an expression of Chang to show in Eq. 1 by horizontal load and the relations of the stability displacement of a pile head provided than the loading experiment result of the model pile in 1G condition are shown in Fig. 11.

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k_h = \frac{2^{2/3}(EI)^{4/3}}{D} \left( \frac{H}{S} \right)^{4/3}
\]

in which \( k_h \) is inverse operation k value in N/mm\(^3\), \( EI \) is flexural rigidity of pile in N·mm\(^2\), \( D \) is diameter of pile in mm, \( H \) is load in N and \( S \) is horizontal displacement of pile in mm.

Figure 10. The summary of the design calculation model
According to this figure, the low lapse rate is 0.3 time by liquefaction of the middle scale degree in the injection of the 1D range. It becomes around 0.1 time by the complete liquefaction. Therefore, it can be judged by the reduction of the coefficient of horizontal subgrade reaction. If coefficient of horizontal subgrade reaction is left even at the time of complete liquefaction, reduction of a displacement / section force of a pile is expected. In addition, strength of the injection ground assumes 50kN/m$^2$ degree at compressive strength. Therefore, as for the effect of the countermeasure against liquefaction of sand of the chemical grouting, evaluation is possible by the design calculation that expressed strength / a range at the time of the injection by countermeasure against liquefaction of sand.

CONCLUSIONS

We examined an effective injection range in strength of injection materials when chemical was injected in a part of the ground of neighboring limited ranges of the pile as a countermeasure against liquefaction of sand of a pile foundation used as foundations of viaduct of the soft ground. As a result, even the injection of the limited range of the pile circumference showed that a section force was reduced. We push forward further rearranging and will examine the setting methods of an effective injection range in future. In addition, we want to suggest it about the seismic reinforcement method of the pile, which considered economy and execution characteristics.

AKNOWLEDGEMENTS

This study represents a part of the results of research carried out using a subsidy from the Ministry of Land, Infrastructure, Transport and Tourism.

REFERENCES
