地盤改良体の引張軟化特性を考慮した杭基礎・地中構造物の耐震補強に関する研究

A Study on Earthquake-Resistant Reinforcement of Pile Foundation and Underground Structures Regarding Tension Softening Characteristics of Ground Improvement Body

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要　旨

昨年の東北地方太平洋沖地震では数多くの尊い人命が失われ，建物や各種構造物に甚大な被害が発生した。また，東海・東南海・南海地震などのレベル 2 クラスの大地震の発生が懸念される中，旧設計基準により建設された構造物は今なお数多く存在しており，これらの構造物に対する耐震補強を含めた早急な対策が急がれている。

過去の大地震では杭基礎構造物について多くの被害が報告されており，筆者らは施工性に優れた地盤改良体を用いた新しい耐震補強工法を提案している。地中構造物についても，兵庫県南部地震の地下鉄大開駅などの被害が報告されている。また，電力施設については 2007 年新潟県中越沖地震を踏まえた耐震補強に関する検討が活発に行われており，近年では地中構造物の周辺地盤を地盤改良することによる耐震補強が検討されている。

前記の耐震補強に用いる地盤改良体の設計においては，通常は地盤改良体を弾性体としているが，レベル 2 クラスの大地震に対しては，地盤改良体のひびわれなどの損傷・破壊を考慮したより経済的で合理的な設計手法の開発が必要である。しかし，地盤改良体の破壊挙動や引張軟化特性について明確にした研究はない。

以上のような背景から，本研究では，杭基礎及び地中構造物の地盤改良体による耐震補強の確立と合理化を図ることを目的とし，主に以下の点に着目して研究を行った。

①セメント改良粘性土の引張軟化及び繰返し特性の把握
②杭基礎構造物に対する地盤改良体の破壊挙動の確認
③地中構造物に対する地盤改良体の耐震補強効果と破壊挙動の確認
④実大杭基礎・地中構造物に対する地盤改良体の耐震補強効果の評価

セメント改良粘性土については，曲げ試験などの要素試験を実施し，引張軟化特性や繰返し挙動について明確にした。また，塑性損傷モデルを用いた弾塑性 FEM による要素試験の数値解析を実施し，改良土への解析手法の適用性を確認した。

杭基礎構造物に対する地盤改良体による耐震補強については，地盤改良体の載荷試験や弾塑性 FEM による数値解析などを実施し，地盤改良体の破壊挙動を明確にした。また，地中構造物に対する地盤改良体による耐震補強については，土槽載荷試験や弾塑性 FEM による数値解析などを実施し，地盤改良体の破壊挙動や耐震補強効果を明確にした。

実大杭基礎・地中構造物に対する地盤改良体による耐震補強については，引張軟化特性を考慮した弾塑性 FEM による数値解析を用いて，補強効果を定量的に評価した。

以上より，本研究では，杭基礎構造物ならびに地中構造物に対する地盤改良体を用いた耐震補強について，地盤改良体の破壊挙動及びその補強効果を明確にし，引張軟化など地盤改良体の損傷を考慮したより合理的な設計手法を提案した。

キーワード：杭基礎，地中構造物，耐震補強，地盤改良，引張軟化

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Summary

The 2011 off the Pacific coast of Tohoku Earthquake took a heavy toll of human lives, and caused serious damages to many types of structures. Immediate anti-earthquake measures including reinforcement of ground improvement are required for the existing structures that were designed and constructed according to old design codes, because the level 2 class earthquakes, such as the Tokai, Tonankai, and Nankai Earthquakes, are predicted to occur in the near future.

Through the past big earthquakes, the occurrences of severe damages to pile foundations have been frequently reported by many researchers. The Author's research laboratory had studied the mechanism of the damages to pile foundations, and originally developed a method for directly improving ground surrounding existing pile foundations, by means of soil-cement mixing method. The method is considered to be effective to existing underground structures as well as pile foundations. As a typical damage to underground structure, Daikai Subway Station, which was severely damaged in the 1995 Hyogo-ken Nambu Earthquake, was thoroughly investigated by many researchers. And the damage to underground electric power facilities induced by the 2007 Niigata Chuetsu-oki Earthquake was investigated actively after the earthquake. As a result, the method for improving ground is considered one of the most promising measures for reinforcing existing underground structures.

The reexamination and upgrading of the design concept is necessary to apply the method for improving ground to the variety of understructures efficiently. In the current design method the improved soil-cement mass is assumed to be elastic and non-fracturing material, and the soil-cement mass, however, behaves in non-elastic manner with tension softening in damaging and cracking process during strong shakings in level 2 earthquakes. The importance of the tension softening in the design method has not been fully clarified yet.

This study focuses on the following points.

1. Understanding the non-elastic behavior of soil-cement material regarding tension softening under cyclic loading.
2. Reviewing the fracturing interactive behavior of ground improvement body and pile foundation.
3. Observing the fracturing behavior of ground improvement body surrounding underground structures in a series of model loading tests.
4. Evaluating the effect of the ground improvement on full-scale pile foundations and underground structures by means of numerical simulations.

A series of cyclic loading tests of tensile force and bending moment were carried out on cement-mixed cohesive soil specimens, and the characteristic tension softening behavior was observed. The parameters for elasto-plastic damage model, which is combined into FEM were identified by analyzing the observed behavior in the tests.

Earthquake-resistant performance of the reinforced pile foundation was observed in an model loading tests and a series of elasto-plastic FEM simulations on the model. Performance of the reinforced underground structures was observed in model loading tests in a soil container regarding the interaction between ground improvement body and underground structure. The elasto-plastic FEM simulations was also carried out on the model underground structures, and the applicability of the elasto-plastic FEM was verified.

Effect of the reinforcement with ground improvement body on pile foundations and underground structures in full-scaled condition was evaluated by means of the elasto-plastic FEM which was calibrated through the model loading tests.

In this study the characteristic fracturing behavior of ground improvement body in the process of damaging and cracking during shaking was clarified, and the effect of reinforcement of existing pile foundation and underground structure with ground improvement body was verified. The rational and economical design method for reinforcing existing pile foundation and underground structure and upgrading their earthquake resistant performance was proposed.