論文の内容の要旨

論文題目　**Damage Control of Underground RC Structures Subjected to Service and Seismic Loads**

常時および地震荷重作用下における地中RC構造の損傷制御

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Underground facilities as an integral part of the infrastructure of modern society are used nowadays for a wide range of applications, ranging from small pipelines such as those used in natural gas transmission or water transport to large underground structures including subway and highway tunnels. The underground facilities in earthquake active areas are subjected to both static and seismic loadings during earthquake. In other words, they need to satisfy the serviceability criteria which generally deal with the performance of the structure for a longtime after its construction under the surrounding sustained load as well as the seismic criteria which would occur in a short time. Therefore, the design of underground structures has to be carried out considering these two aspects in a parallel manner. Besides, the importance and cost of this kind of structures make it necessary to analyze the behavior of underground structural systems including surrounding soil media accurately.

The past inspections of underground structures have revealed a kind of contradiction in their design concept. According to the observations made on medium-size underground structures which are constructed just few years ago, large amount of cracks and leakage can occur in the elements of this type of structures which brings about the necessity of their repair and maintenance. On the other hand, fewer cracks and damage are observed in large-size underground structures, mostly subway and highway tunnels, built several years or even decades ago. Therefore, two opposing stances exist among the engineers on the design of underground structures; one suggests that their design procedure needs to be upgraded in such a manner that stronger structures would be constructed to carry longtime sustained load from surrounding media while the other argues that the current underground structures are overdesigned and the design needs to be revised.

The attitude towards the performance of underground structures from seismic point of view has also changed by time. Historically, fewer damages to the large underground structures were reported in earthquakes compared to the surface structures. This made many structural engineers believe that underground reinforced concrete structures might not be seriously damaged during earthquakes; however, followed the several severe earthquakes in recent years, the earthquake induced damages to large underground structures and the corresponding earthquake resistance design have received considerable attention.

Therefore, the need for a general and comprehensive view towards the design of underground structures by investigating their response from different aspects can be obviously felt. This is the major objective of this study which is achieved by employing a finite element program and conducting some experiments. First of all, in order to verify the accuracy of the numerical model used in the program, different analyses were performed to simulate the behavior of soil-structure interaction in a couple of experiments which were conducted by some other researchers or the author. The results show the FEM program can effectively simulate the numerical models which involve the nonlinear behavior of soil and RC structures under both static and dynamic loads. Then, the program is used to model the strong coupling effect of highly nonlinear soil and inelastic underground RC structure during a seismic excitation. Through this study, the seismic features of this type of structures under different conditions are evaluated. Furthermore, a parametric study is performed to determine the effects of sheet piling as a widely used method to suppress the uplift of

underground ducts in liquefiable soils. Finally, the long-term behavior of these structures under permanent loads was studied to investigate the serviceability and durability features of this kind of structures.

The results prove that although conventional methods of design of underground structures such as “simplified frame analysis model” or “free-field deformation method” provides good approximation for the design of underground structures in some cases, they should not be generalized to all the situations. In other words, nowadays thanks to the development of powerful tools and techniques, a numerical FEM model covering the nonlinearity of soil, RC structure and their interactions can be employed for their design as the best representation of soil-structure system. Through this study, it turns out the results of the FEM analysis sometimes could be much different from those of conventional methods. For example, when the duct is stiffer than the surrounding soil layers, the conventional methods are very conservative in the design of underground structures or when soil layers may liquefy during an earthquake, the ductility demand of underground structure based on the conventional methods is much higher than what really needed.

Liquefaction may bring about various troubles to RC underground ducts. One is the rigid-body motion like uplift and even floatation of structures. The other is the structural destruction associated with cracking and crushing of concrete and yield of reinforcing steel, which is highly related to deformation during seismic events. The simulations in this study prove that these two forms of trouble - shear deformation and the uplift - of underground structures are in relation of trade-off. Besides, it is found that if the soil is loosely deposited with high risk of liquefaction, the structural damage may be less than the case of unsaturated dry soil with the same stiffness. Finally, it should be pointed out that although installation of sheet piles as a widely0udes measure can drastically alleviate the uplift of underground RC ducts, it may cause the structure to suffer more damage due to the remained shear stiffness of the soil surrounded by the sheet piles. Hence, a rational design of sheet piling should consider both of its positive and negative effects on the underground RC structures.

The serviceability limit states needs to be paid attention for the long-term behavior of underground structures. By analyzing some numerical models, it can be concluded the design requirements of underground structures under permanent loads can be lightened by conducting more accurate analysis, considering soil-structure interaction. Furthermore, it is found the construction procedure and environmental condition are two important factors influencing the long-term behavior of underground structures and should be considered in design procedure.

Finally, it should be noted that the conventional methods widely-used for the design of underground structures in the past, have some defects in satisfying both ultimate and serviceability limit states. Also, the durability performance of a duct designed based on its elastic behavior under surrounding earth pressure lacks the sufficient accuracy and the consideration of influential factors. In the recent years, in order to reduce the constriction cost and practical problems of this kind of structures, their ultimate designs have been improved thanks to the development of powerful tools and techniques which make their analyses more reliable and available. However, it can lead to their poor durability performance which has been observed especially in small to medium-size ducts. Therefore, it is recommended that the serviceability design of underground structures needs to be elevated as well as the ultimate design by conducting more accurate and comprehensive analyses.