地震動を受ける地盤に対する埋戻し材としての流動化処理土の適用

メタデータ	言語: eng
	出版者:
	公開日: 2021-06-23
	キーワード (Ja):
	キーワード (En):
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	所属:
URL	https://doi.org/10.15118/00010398

APPLICATION OF LIQUEFIED STABILIZED SOIL AS BACKFILLING MATERIAL TO GROUND SUBJECTED TO SEISMIC MOTION

By

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A DISSERTATION SUBMITTED TO THE FACULTY OF THE MURORAN INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF ENGINEERING

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DIVISION OF CIVIL AND ENVIRONMENTAL ENGINEERING

MURORAN INSTITUTE OF TECHNOLOGY

March 2021

Acknowledgments

I would never have been able to finish my Ph.D. course without the guidance and understanding of my supervisors, assistance from lab-mates, friends, and support from my family.

First and foremost, I would like to express my sincere gratitude to my advisor Professor Yukihiro Kohata for the continuous support of my Ph.D. study and related research for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis.

Similar gratitude belongs to the members of my thesis committee: Professor Shima Kawamura and Associate Professor Noriyuki Sugata, for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives.

My sincere thanks also go to all the students in my laboratory, who are responsible for organizing seminars and many interesting activities in our laboratory. These activities helped us have a funny and friendly life in the laboratory.

Besides, I am grateful to all the staff of the Centre for International Relations, Muroran IT: Mr. Jinro Endo, Ms. Hatsuki Noda, Mr. Sangyub Baek, Ms. Mai Ikeda, and Ms. Kozue Takekawa for making my life in Hokkaido really comfortable and enjoyable. Especially thanks to Associate Professor Naoko Yamaji and Associate Professor Masatsugu Ono, who taught the Japanese language that helps me to integrate into life in Japan.

Furthermore, I also sincerely thank Associate Professor Le Anh Dung and Associate Professor Nghiem Manh Hien of the Hanoi Architectural University for offering me recommendation letters to apply for the doctor course. I also thank the Technology and Construction Management Department, Civil Engineering Faculty, and Hanoi Architectural University for creating good conditions to study at Muroran IT. Thanks are also extended to Dr. Duong Quang Hung and Dr. Nguyen Cong Giang for their introduction and recommendation to Muroran Institute of Technology and Professor Kohata before applying for a doctor course here.

Words are not enough to thank my family members for the support they have given me during this long and sometimes difficult journey. I would very much like to express my love and gratitude to my parents, my wife (Dinh Mai Huong), my son (Pham Quang Minh), and my daughter (Pham Huong Giang) for their love and support and for instilling in me the value of learning and providing me outstanding opportunities to do so throughout my life. Without their endless help, I would not be able to achieve and enjoy these successes.

Muroran, March 01, 2021

Pham Quang Vuong

Abstract

Excavated soil from the construction site is a serious problem in the big city in developing countries. Liquefied Stabilized Soil (LSS), which is an effective method of reusing excavated soil with construction works has become popular in Japan. The LSS is a kind of cement-treated soil of slurry type prepared by mixing soil, water, and cement solidification. The LSS is not only created stabilized ground without compaction but also easy to be able to fill empty space by pumping a long distance. In this study, the deformation characteristic and new advantage of LSS were investigated to promote the application of LSS in construction practice. Research works, including experiments and analyses, have been conducted. This study is summarized as follows:

(1) The effects of various factors, which are curing days, paper content, curing temperature and curing circumstance, etc., on strength and deformation property of LSS prepared at field were investigated. Two pits were excavated on the campus and then were filled with LSS mixed with fiber material amount 0 and 10 kg/m^3, respectively. After a curing time of 28 and 56 days, the specimens were prepared by trimming LSS retrieved from the model ground. A series of Consolidated-Undrained triaxial compression tests with pore water measurement (CUB test) was carried out on the specimens cured in the field ground under the conditions at an axial strain rate of 0.054 %/min and the effective confining pressure of 98 kPa. And also, the applicability of an evaluation of stiffness by the Portable FWD test (Falling Weight Deflectometer test) at a backfilling ground by LSS mixed with fiber material was investigated. Based on the test results, it was found that the curing temperature could affect the maximum deviator stress q_{max} of LSS. As for LSS with fiber material, there is independent of the q_{max} on the curing temperature when curing days increase. And the effect of curing temperature on Initial Young's modulus E_0 is smaller than that of curing days. It was considered that during the first period of the curing process of LSS mixed fiber material, the addition of the fiber material into LSS is reduced the damage degree during shear. It was found that the K-value by portable FWD can be adequately evaluated the stiffness of backfilling ground by LSS with fibered material.

(2) The effect of backfilling material on the building and ground subjected to seismic motion is analyzed by using the finite element method (FEM). A three-dimensional model of the building and ground was simulated in ABAQUS software. A reinforced concrete ten-floor building frame, 30 m high and 12 m wide with 16 columns consisting of three spans of 4 m in each direction, and one basement was selected in this simulation. The 1968 Tokachi-Oki earthquake in Hachinohe (Japan) was selected and utilized on the finite element numerical model to conduct a time-history analysis. Three case studies with three types of backfilling material: backfilling soil (sandy soil), LSS, and LSS with fiber (10 kg/m^3) were analyzed. Based on the analysis results, it was found that using LSS and LSS with fiber as a backfilling material reduce the lateral displacement and inter-story drift of building under the seismic condition. On the other hand, the application of LSS and LSS with fiber as a backfill material significantly decreases the acceleration and velocity of the ground around the building and adjacent areas. Therefore, it is considered that the LSS and LSS with fiber have an effective potential to reduce the seismic motion on the buildings and the surrounding ground. This property is a new advantage of LSS and LSS with fiber. And more, the effect of fiber material mixed with LSS was made clear in this study. LSS mixed with fiber has more advantageous than LSS.

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND OF RESEARCH

Nowadays, in developing countries with rapid economic growth, the speed of urbanization and modernization in big cities is happening strongly, this is also an inevitable trend in big cities. It was accompanied by a series of urgent social problems such as rapid population explosion, severe traffic congestion, environmental pollution, and the state of infrastructure, which does not meet society's needs, etc.

Typically Jakarta, the capital of Indonesia. According to the government's documents "Jakarta in Figures", Jakarta city has a population growth rate of about 1.9 % per year with 10.77 million people in 2020, exceeding all the government's prediction about the city's population. Jakarta has an area of 664 km^2, with a population density of 16220 people/ km^2, and become the world's ninth most densely populated metropolitan region. The population is growing too fast, leading to the demand for housing, parking, and shopping mall, etc., increase significantly. To solve the above problem, and with limited urban land area, the construction of high-rise buildings with many basements and underground facilities like underground parking is the most effective solution. The construction density of skyscrapers in Jakarta city is very high, as shown in Figure 1.1.

The quickly increasing population is also leading to an infrastructure that does not meet human movement needs. Jakarta has ranked 10th on the list of the most congested cities in the world in 2019 based on the TomTom Traffic index uploaded on the tomtom.com website. Indonesia's government recently reported that traffic congestion in Jakarta's inner city and vicinity had caused losses of up to 65 trillion rupiahs (equivalent to nearly 4.7 billion USD) per year. The frequent traffic congestion during rush hours every day, which happened on a large scale, as shown in Figure 1.2. Most of the traffic in Indonesia use private vehicles such as motorbikes and private cars, so a huge amount of emissions from vehicles contribute to environmental pollution. A report published in early 2019 by the organization Greenpeace affirms that Jakarta is the most polluted city in Southeast Asia (Figure 1.3). Throughout 2018, the ultrafine dust index ($PM_{2.5}$) in Jakarta stood at 45.3 µg (micrograms)/ m^3, four times higher than the maximum standard set by the World Health Organization (WHO) and 3 times higher than the maximum permitted level according to the national standards of Indonesia. Due to the city's urgent problem, the government has come up with optimal solutions such as expanding the transport infrastructure network, improving the transport capacity of public transport, encouraging people to use public facilities, etc. Therefore, the construction plans for the transport system were formed in 2013 to modernize the traffic. The World's longest bus rapid transit (BRT) system with a length of 230 kilometers, the Metro Jakarta Electrified Train System with 418 kilometers length consisting of 1 elevated line and 5 at ground level were built (Figure 1.4). The Indonesian government hopes these projects can solve both the traffic and the environmental problem.

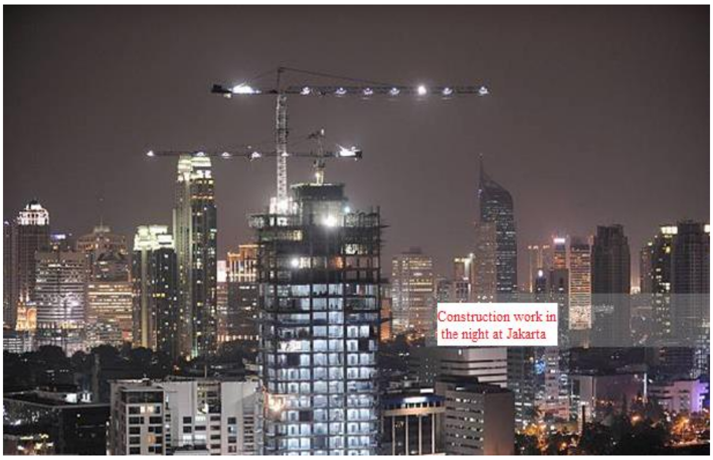

Figure 1.1 Density of high-rise buildings has significantly increased in recent years in Jakarta city

Figure 1.2 Serious traffic congestion in Jakarta city

Figure 1.3 Air pollution in Jakarta city

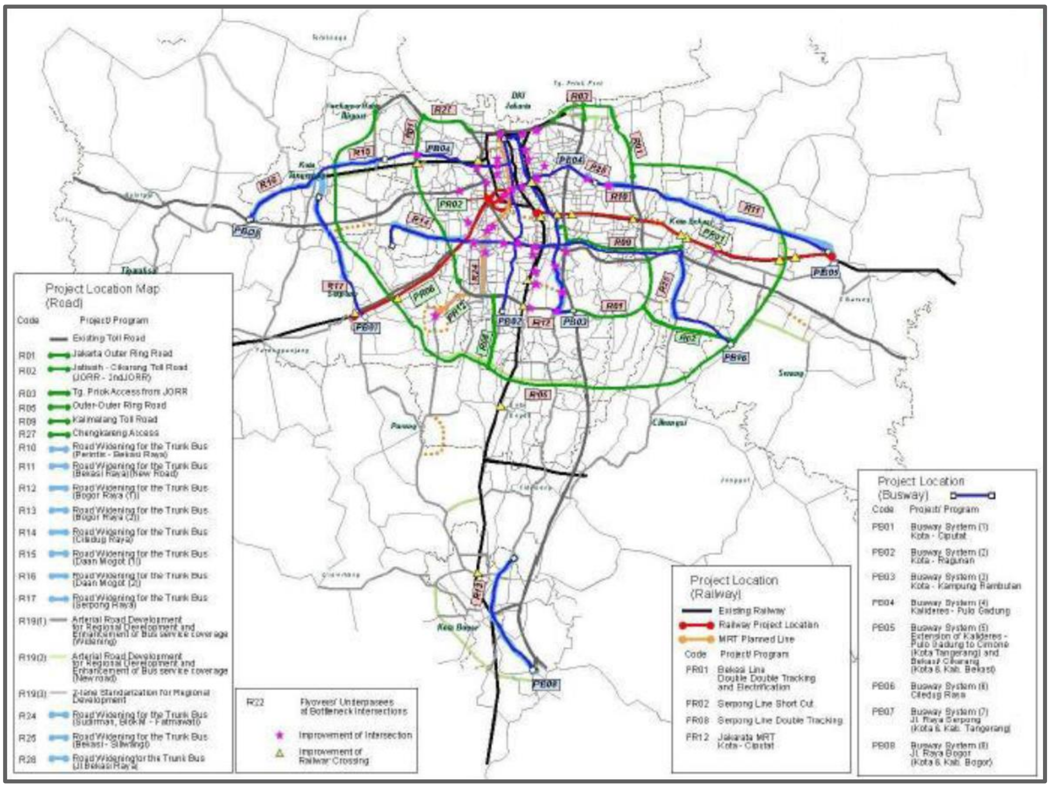

Figure 1.4 Orientation for BRT, metro and urban railway network in Jakarta city

However, it is predicted that millions of cubic meters of excavated soil will arise to be trucked from underground construction projects to disposal sites. It is the cause of environmental pollution. Besides, sand from rivers and rocks from mountains is the main material used as backfilling soil in the constructions. It is leading to increasingly depleted natural resources and serious impacts on the natural environment. On the other hand, the disposal sites are becoming increasingly scarce and overloaded in the big cities.

Therefore, the excavated soil is a serious problem in the big cities in developing countries as Jakarta. The questions are where to put the excavated soil and how to develop sustainable infrastructure, which does not only reduce the cost of construction but also does not affect the natural environment.

A long time ago, in the big cities in Japan, such as Tokyo, Kyoto, and Osaka, when the subway lines, underground constructions, and high-rise buildings were built, the Japanese government also faced this same situation in Jakarta. In Japan, the excavated soils generated from the urban construction site is often discarded as industrial waste at the dump. According to the research report: the average lifespan of landfills in Japan is estimated to be 13.6 years, 14 years in the Kinki region, and only 4.3 years in the Tokyo metropolitan area. Furthermore, it can be seen that the excavated soil has not been widely and effectively used for a long period. Therefore, how to reuse the excavated soil has become an urgent problem to be solved. To solve this problem, Japan launched a construction waste promotion plan in May 2000, and the construction recycling law was established. Since then, the reuse of excavated soil has been studied and applied in practice.

1.2. OBJECTIVE OF RESEARCH

"Liquefied Stabilized Soil" (LSS), which was mentioned by Kuno (1997), is one of the effective methods of using the excavated soil with construction works and has become popular in Japan. The LSS is a kind of cement-treated soil, which is prepared by mixing slurried soil and cement stabilizer. The LSS mixtures are not only created stabilized ground without compaction but also easy to fill empty space by pumping a long distance. However, according to previous studies, it is shown that the increase in cement content does not only increase the strength property but also the brittleness increases. Therefore, Kohata et al. proposed the LSS mixed the pulverized newspaper as fiber material to improve the brittle mechanical property and increase the ductile performance of LSS (Kohata et al., 2002). It was shown that the ductile property of LSS mixed with pulverized newspaper as a fiber material after the peak in the $q \sim \varepsilon_a$ curve was significantly improved by the reinforcement method (Kohata, 2006; Kohata et al., 2004 and 2007; Ito et al., 2011). However, it has not been explained about the influences of various factors on the strength and deformation property of LSS with fiber material prepared at field (Duong et al., 2014).

On the other hand, previous studies have shown that using LSS as a backfilling material can reduce train-induced vibration (Duong, 2015) and reduce vehicle-induced vibration (Do, 2019). It can be seen that LSS can reduce vibrations from different small or large vibration sources. However, no studies have evaluated the effect of LSS on the surrounding environment when an earthquake occurs. Especially Japan is one of the countries with the highest number of earthquakes in the world every year. According to annual statistics, earthquakes cause a lot of damage to buildings and traffic. If the application of LSS as a backfilling material can reduce the impact of earthquakes on the surrounding environment, it will be a new advantage of LSS. It will promote increased use of LSS not only in Japan but also in other countries around the world like Indonesia, Philippines, etc. For the reasons above, the main points of this research are as follows:

- The influences of various factors, which are curing days, paper content, curing temperature and curing circumstance, etc., on strength and deformation property of LSS prepared at field were investigated and discussed.
- Evaluated the effect of LSS as backfilling material on the ground and building when an earthquake occurs by the finite element method (FEM).

To clear up the above points, the following works were carried out in this research:

Firstly, two pits were excavated on the campus and then were filled with LSS mixed with fiber material amount 0 and 10 kg/ m^3, respectively. After a curing time of 28 and 56 days, the specimens were prepared by trimming LSS retrieved from the model ground. A series of Consolidated-Undrained triaxial compression tests with pore water measurement was carried out on the specimens cured in the field ground under the conditions at a constant strain rate of 0.054 %/ min and the effective confining pressure of 98 kPa. And also, the applicability of an evaluation of stiffness by the Portable Falling Weight Deflectometer (PFWD) test at a backfilling ground by LSS mixed with fiber material was investigated. Based on the test results, the influences of various factors, which are curing days, paper content, curing temperature and curing circumstance, etc., on the strength and deformation property of LSS prepared at the field are discussed.

Secondly, the effect of backfilling material on the building and ground under the earthquake is analyzed by using the finite element method (FEM). A three-dimensional model of the ground and construction was simulated in ABAQUS software. A reinforced concrete ten-floor building frame, 30 m high and 12 m wide with 16 columns consisting of three spans of 4 m in each direction, and ten slabs and one basement was selected in this simulation. The height of the floors was 3 m, and the basement floor was located at a depth of 4.5 m below the ground surface. The reinforced concrete foundation was 15x15 m square and 1 m thick, and the reinforced concrete pile of 20 m depth and 1.2 m in diameter was selected to analyze in this study. The 1968 Tokachi-Oki earthquake in Hachinohe (Japan) was selected and utilized on the finite element numerical model to conduct a time-history analysis. Three case studies with three types of backfilling material: backfilling soil, LSS, and LSS with fiber were analyzed. Base on the analysis results, the effect of backfilling material on the displacement and inter-story drift of building and acceleration and velocity of five points on the ground surface in each case were compared and investigated.

1.3. THESIS OUTLINE

APPLICATION OF LIQUEFIED STABILIZED SOIL AS BACKFILLING MATERIAL TO GROUND SUBJECTED TO SEISMIC MOTION

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CHAPTER 1
INTRODUCTION

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CHAPTER 2
OVERVIEW OF LIQUEFIED STABILIZED SOIL

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CHAPTER 3
MATERIAL AND PREPARATION METHOD OF SPECIMEN

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CHAPTER 4
APPARATUS AND TESTING PROCEDURES

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CHAPTER 5
VARIOUS FACTORS ON THE STRENGTH AND DEFORMATION PROPERTY OF LSS PREPARED AT FIELD

↓

CHAPTER 6
EVALUATION OF THE REDUCTION OF THE SEISMIC MOTION TO GROUND SUBJECTED BY USING LSS

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CHAPTER 7
CONCLUTIONS

Figure 1.5 Flow chart of this dissertation

As seen in Figure 1.5, this dissertation contains seven chapters. The introduction (CHAPTER 1) describes the general background, purpose, and objectives of the research and organization of the dissertation.

CHAPTER 2 introduces a brief overview of LSS as an effective method for the utilization of excavated soil and its applications.

CHAPTER 3 presents the materials and preparation method of the specimen at the laboratory and field applied in this study.

CHAPTER 4 shows the detailed apparatus and test procedures at the laboratory and field.

CHAPTER 5 investigates various factors on the strength and deformation property of LSS prepared at field. A series of Consolidated-Undrained triaxial compression tests with pore water measurement was carried out on the specimens cured in the field. And also, the in-situ compressive stiffness of LSS at field was evaluated by using the PFWD method.

The effect of backfilling material on the building and ground under the earthquake is analyzed by using the FEM in CHAPTER 6. A three-dimensional model of the ground and construction was simulated in ABAQUS software. Three case studies with three types of backfilling material: backfilling soil, LSS, and LSS with fiber were analyzed. Base on the analysis results, the effect of backfilling material on the building and acceleration and velocity on the ground surface in each case were compared and investigated.

Finally, the main conclusions from the research are summarized in CHAPTER 7. The ideas and future works will also be recommended.

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CHAPTER 2

OVERVIEW OF LIQUEFIED STABILIZED SOIL

2.1. INTRODUCTION

The purposes of Soil stabilization are improving the soil's strength and increasing resistance to softening by water through bonding the soil particles together, waterproofing the particles, or a combination of the two (Sherwood, 1993). The simplest stabilization processes are compaction and drainage (if water drains out of wet soil, it becomes stronger). The other process is by improving the gradation of particle size, and further improvement can be achieved by adding binders to the weak soils (Rogers et al., 1993). Several methods can accomplish soil stabilization as following.

- Mechanical stabilization: soil stabilization can be achieved through the physical process by altering native soil particles' physical nature by either induced vibration or compaction or by incorporating other physical properties such as barriers and nailing.
- Chemical stabilization: soil stabilization depends mainly on chemical reactions between stabilizer (cementitious material) and soil minerals to achieve the desired effect. Through soil stabilization, unbound materials can be stabilized with cementitious materials (cement, lime, fly ash, blast furnace slag, or a combination of these).

"Liquefied stabilized soil" is a method of using chemical stabilization. The LSS is mixed by the soil excavated from the construction project with binder and water. LSS can be used for confined spaces or excavation areas, and it can be easily placed without vibration and compaction. The advantages and applications of LSS have been shown, such as:

- **Advantages:**
    - Easy placement

- Minimum settlement
- Quick setting time
- Ability to recycle
- Low permeability
- High strength
- Protect the environment
- Faster and more convenient than conventional backfilling
- No need for a soil stockpile
- Reduce the cost of construction projects
- Reduce human resources
- Reduction of vehicle-induced vibration

- **Applications:**
  - LSS as backfilling materials for transportation and construction works
  - Backfill using a concrete pump with a large distance and big volume
  - Cavities and excavated trenches can be backfilled easily without vibration and compaction

2.2. COMPONENT OF LIQUEFIED STABILIZATION SOIL

Liquefied stabilized soil focuses on using binder materials and fiber materials in soils to improve its geotechnical properties such as compressibility, strength, permeability, flexibility, and durability. The components of liquefied stabilized soil include soils, binders (cementitious materials), and water, as shown in Figure 2.1.

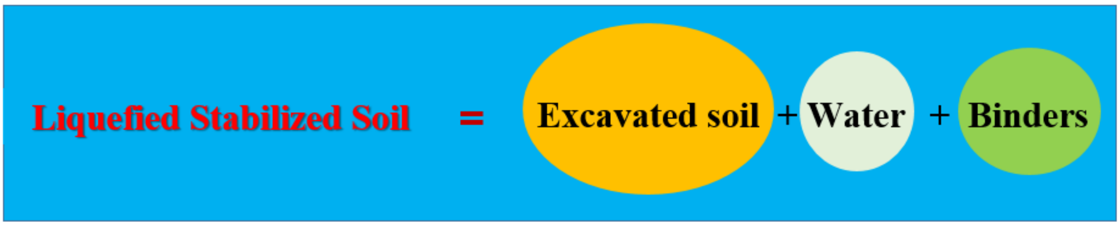

Figure 2.1 The components of Liquefied Stabilized Soil

2.2.1 Soil

Most soils in the liquefied stabilized soil method are soft soils. The stabilization has been performed to achieve desirable engineering properties. The main purpose of the liquefied stabilized method is to recycle excavated soil for backfilling processes for construction projects. Therefore, almost types of excavated soils can be used for this method. However, fine-grained materials are the easiest to stabilize due to a large surface area in their contact diameter. The excavated soils can be modified to perform mainly with the purpose of improving their usability in construction. At present, excavated soils are stabilized by binders which are selected with the type of soil. The stabilization has improved the strength of the soils and their resistance to softening.

2.2.2 Cementitious materials

There are two kinds of binder material in the chemical stabilization method: hydraulic (primary binders) and non-hydraulic (secondary binders) materials. When in contact with water or the presence of pozzolanic minerals, these binders react with water to form cementitious composite materials. The commonly used binders are:

- Blast furnace slag
- Lime
- Cement
- Fly ash
- Pozzolana

To decide which binder will be used, the analysis has been performed based on test results and depend on the fact condition of projects.

2.2.2.1 Blast furnace slag

These are the by-product of pig iron production. The chemical compositions are similar to that of cement. However, it is not a cementitious compound by itself, but it possesses latent hydraulic properties which upon addition of lime or alkaline material the hydraulic properties can develop (Sherwood, 1993; Åhnberg et al, 2003). Depending on the cooling system, Sherwood (1993) itemized slag in three forms, namely: air-cooled slag, granulated or pelletized slag, and expanded slag.

- **Air-cooled slag:**

Hot slag after leaving the blast furnace may be slowly cooled in the open air, resulting in crystallized slag which can be crushed and used as aggregate.

- **Granulated or Pelletized slag:**

Quenching (i.e. sudden cooling with water or air) of hot slag may result in the formation of vitrified slag. The granulated blast furnace slag or Merit 5000 (commonly known in Sweden) is a result of the use of water during the quenching process, while, the use of air in the process of quenching may result in the formation of pelletized slag.

- **Expanded slag:**

Under certain conditions, steam produced during cooling of hot slag may give rise to expanded slag.

2.2.2.2 Lime

It was discovered that limestone, when burnt and combined with water, produced a material that would harden with age. The earliest documented use of lime as a construction material was approximately 4000 B.C. when it was used in Egypt for plastering the pyramids. Until approximately 1900, lime putty was used in construction applications. Limestone was burned in small kilns often built on the side of a hill to facilitate loading. Wood, coal, and coke were used as fuel. The quicklime produced from these kilns was added to water in a pit or metal trough and soaked for an extended period. The time required for soaking was dependent on the quality of the quicklime and could range from days to years. It was generally thought that the longer the quicklime was soaked, the better it would perform. The Standard Specification for Quicklime for Structural Purposes was developed in 1913.

Lime is the oldest traditional stabilizer used for soil stabilization with the lowest cost. Lime-treated soil was studied extensively in the literature. Numerous field and laboratory studies were conducted to evaluate the improvement of geotechnical properties by lime. Several types of soils, lime contents, and curing conditions and methodologies were used for this purpose. The treatment mechanism comprised hydration, cation exchange, flocculation-agglomeration of soil particles, and pozzolanic reaction to form Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H) as cementitious materials. The factors affecting lime-treated soil are lime content, curing time, curing temperature, and soil mineralogy. Soil-lime mixtures have advantages and disadvantages. Its advantages comprise increasing soil strength, reducing plasticity (increase workability), and increasing soil durability. Besides, a considerable reduction in consolidation settlement and improve compressibility characteristics were observed. Unclear behavior was noted for the permeability of soil-lime mixture when compared with the original soil. Carbonation, sulfate attack, and environmental impact are a number of the disadvantages of lime-treated soil. Some studies were conducted to provide some guidelines to reduce the deleterious effects of these cons. Magnesium oxide and hydroxide can be proposed as an alternative for lime since they possess chemical characteristics that make them eligible to overcome the mentioned cons. Moreover, a few conducted studies used magnesium-based additives to stabilize the soil was significantly improved soil strength, workability, and durability. Therefore, it needs to conduct extensive studies to determine the efficiency of this material in soil stabilization.

2.2.2.3 Cement

Cement had been known as the binding agent since the invention of soil stabilization technology in the 1960s. It may be considered as a primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil. This can be the reason why cement is used to stabilize a wide range of soils. Numerous types of cement are available in the market; these are ordinary Portland cement, blast furnace cement, sulfate resistant cement, and high alumina cement. Usually, the choice of cement depends on the type of soil to be treated and the desired final strength.

The hydration process is a process under which cement reaction takes place. The process starts when cement is mixed with water and other components for the desired application resulting in hardening phenomena. The hardening (setting) of cement will enclose soil as glue, but it will not change the structure of the soil. The hydration reaction is slow proceeding from the surface of the cement grains and the Centre of the grains may remain unhydrated. Cement hydration is a complex process with a complex series of unknown chemical reactions. However, this process can be affected by the presence of foreign matters or impurities, water-cement ratio, curing temperature, the presence of additives, and the specific surface of the mixture.

2.2.2.4 Fly ash

Fly ash is a byproduct of coal-fired electric power generation facilities. It has little cementitious properties compared to lime and cement. Most of the fly ashes belong to secondary binders. These binders cannot produce the desired effect on their own. However, in the presence of a small amount of activator, it can react chemically to form a cementitious compound that contributes to improved soft soil strength.

Fly ash has been used successfully in many projects to improve the strength characteristics of soils. Fly ash can stabilize bases or subgrades, stabilize backfill to reduce lateral earth pressures, and stabilize embankments to improve slope stability. Typically stabilized soil depths are 15 to 46 centimeters. The primary reason fly ash is used in soil stabilization applications is to improve the compressive and shearing strength of soils. The compressive strength of fly ash treated soils is dependent on:

- In-place soil properties
- Delay time
- The moisture content at the time of compaction
- Fly ash addition ratio

Class C fly ash can be used as a stand-alone material because of its self-cementitious properties. Class F fly ash can be used in soil stabilization applications with the addition of a cementitious agent (lime, lime kiln dust, CKD, and cement). The self-cementitious behavior of fly ashes is determined by ASTM D 5239. This test provides a standard method for determining the compressive strength of cubes made with fly ash and water (water/fly ash weight ratio is 0.35), tested at seven days with standard moist curing. The self-cementitious characteristics are ranked, as shown below:

- Very self-cementing> 500 psi (3,400 kPa)
- Moderately self-cementing 100 - 500 psi (700 - 3,400 kPa)
- Non self-cementing < 100 psi (700 kPa)

It should be noted that the results obtained from ASTM D 5239 only characterizes the cementitious characteristics of the fly ash-water blends and does not alone provide a basis to evaluate the potential interactions between the fly ash and soil or aggregate.

The use of fly ash in soil stabilization and soil modification may be subject to local environmental requirements about leaching and potential interaction with groundwater and adjacent watercourses.

2.2.2.5 Pozzolana

Pozzolanas are siliceous and aluminous materials, which in itself possess little or no cementitious value. However, in finely divided form and the presence of moisture, they will chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties (ASTM 595). Clay minerals such as kaolinite, montmorillonite, and mica are pozzolanic in nature. Artificial pozzolanas such as ashes are products obtained by heat treatment of natural materials containing pozzolanas such as clays, shales, and certain silicious rocks. Plants, when burnt, silica taken from soils as nutrients remain behind in the ashes contributing to the pozzolanic element. Rice husk ash and rice straw and bagasse are rich in silica and make an excellent pozzolana (Sherwood, 1993).

2.2.3 Fiber materials

Nowadays, the constructions of buildings and other civil engineering structures on weak or soft soil are highly risky because such soil is susceptible to differential settlements, poor shear strength, and low compressibility. Various soil improvement techniques have been used to enhance the engineering properties of soil. The idea of reinforcing soils using fibers is one that has been in use for a long time. Initial developments in soil reinforcement led to plant roots and straws in walls made from soil bricks to improve their mechanical properties. Soil reinforcement by fiber material is considered an effective ground improvement method because of its cost-effectiveness, easy adaptability, and reproducibility. Many previous studies apply fiber materials to reinforce the soil, such as newspaper fiber, coir fiber, papyrus fiber, polypropylene fiber, and flax fiber.

2.2.3.1 Newspaper fiber

In 2002, Kohata et al. were proposed the LSS mixed the pulverized newspaper (Figure 2.2) as fiber material to improve the brittle mechanical property and to increase the ductile performance of liquefied stabilized soil. It was shown that the ductile property of LSS mixed with pulverized newspaper as a fiber material after the peak in the $q\sim\varepsilon_a$ curve was significantly improved by the reinforcement method (Kohata 2006; Kohata et al. 2004 and 2007; Ito et al. 2011).

Figure 2.2 Fiber material was made by the newspaper

2.2.3.2 Coir fiber

Coir fibers are categorized in two ways (Khan, 2007; Gu, 2009). One distinction is based on whether they are recovered from ripe or immature coconut husks. The husks of fully ripened coconuts yield brown coir. Dark brown in color, it is used primarily in brushes, floor mats, and upholstery padding. On the other hand, white coir comes from the husks of coconuts harvested shortly before they ripen. Generally, light brown or white in color, this fiber is softer and less strong than brown coir fiber. The coir fibers were shown in Figure 2.3.

All of the published papers have generally shown that the addition of coir fiber reinforced soil significantly increases the strength and stiffness as well as ductility of soils, contributing to fiber characteristics such as tensile strength and modulus of elasticity. Direct shear tests, unconfined compression tests, flexural strength, tensile strength, and triaxial compression tests have demonstrated that the mechanical properties and shear strength are increased with the addition of coir fibers in soils. The bond strength and friction at the interface between fiber and soil grains are to be the dominant mechanism controlling the reinforcement benefit. The main factors which affect the addition between the reinforcing fibers and soil are the cohesive properties of soils and the shear resistance of the soil due to the surface form and roughness of the coir fibers. Thus, using coir fiber in the soil is an effective reinforced soil technique in the geotechnical engineering field (Anggraini, 2016).

Figure 2.3 Coir fiber

2.2.3.3 Papyrus fiber

Papyrus has a wide range distribution in swamps, streams, lakes, and wetlands. The mineral composition of papyrus differs in different parts of the plant. This variation in mineral composition is probably related to differences in the age of various portions and differences in nutrient percentage (Gaudet, 1975). The papyrus fibers were shown in Figure 2.4.

Direct shear, consolidation, and displacement tests were performed on papyrus reinforced specimens with various fiber contents. These tests' results have clearly shown a significant improvement in the failure deviator stress and shear strength parameters (c and ϕ) of the studied soil with a percent addition of 10% (the preferred percent). Moreover, this addition ratio reduced the displacement of the soil under loading. It can be concluded that papyrus fiber can be considered an appropriate soil reinforcement material (AL-Adili et al., 2012).

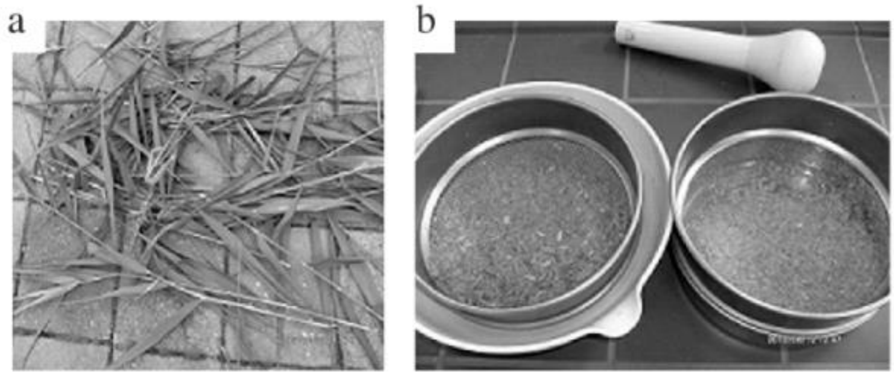

Figure 2.4 Papyrus before drying and crushing (a) and after treatment and sieving (b)

2.2.3.4 Polypropylene fiber

The polypropylene fiber, also known as polypropene or PP, is a synthetic fiber, transformed from 85% propylene and used in various applications (Figure 2.5). One of its applications is for the soil reinforcement method.

Tests were conducted on fiber-reinforced soil specimens with different polypropylene fiber contents and compacted at different water contents and dry densities. The tensile test results showed that fiber inclusion significantly increased the soil peak strength, reduced the post-peak strength, and changed the brittle tensile failure behavior to a more ductile one. Soil tensile strength increased with the increase in fiber content. The tensile strength of both reinforced and unreinforced specimens decreased with increasing water content and increased with increasing dry density. Moreover, a higher soil dry density showed a more positive effect in mobilizing fibers' reinforcement benefit. Based on the fiber/soil interfacial interaction mechanisms, the fiber reinforcement benefits on soil tensile behavior were analyzed. A linear relationship was obtained between the fiber reinforcement benefit and the fiber/soil interfacial shear strength. The desiccation test results showed that fiber inclusion significantly decreased soil cracking. The surface crack reduction ratio increased while the average crack width and length decreased with increasing fiber content, suggesting that fiber reinforcement was efficient in impeding soil tensile failure (Chao et al., 2016).

Figure 2.5 Polypropylene fiber

2.2.3.5 Flax fiber and bamboo strip

Flax (Linum usitatissimum), also known as common flax or linseed, is a member of the genus Linum in the family Linaceae. It is a food and fiber crop cultivated in cooler regions of the world. Textiles made from flax are known in Western countries as linen and are traditionally used for bed sheets, underclothes, and table linen. Its oil is known as linseed oil. In addition to referring to the plant itself, the word "flax" may refer to the fibers of the flax (Figure 2.6). Bamboos are of notable economic and cultural significance in South Asia, Southeast Asia, and East Asia, being used for building materials, as a food source, and as a versatile raw product. Bamboo, like wood, is a natural composite material with a high strength-to-weight ratio useful for structures. Fresh bamboo is also used as a pile to reinforce the ground in flooded conditions.

To study the mechanical properties of bamboo strips and flax fiber-reinforced clay, a series of tensile tests were carried out by Fang et al. (2019) to obtain the relationship between the average tensile force and deformation of flax fiber and bamboo strip; after that, triaxial shear tests were carried out under the conditions of different confining pressures. Besides, the reinforcement mechanism of the bamboo strips and flax fiber-reinforced clay is analyzed. Test results show that the bamboo strips' cohesion and internal friction angle and flax fiber-reinforced clay are improved compared with the pure clay. In flax fiber-reinforced clay, reinforced clay's cohesion is increased by 18.34%, and the friction angle is only increased by 0.39%. In bamboo strips and flax fiber-reinforced clay, the cohesion of reinforced clay is increased by 26.36%, and the friction angle is only increased by 10.24%. The addition of bamboo strips improves the shear strength of the reinforced clay and effectively improves the flax fiber-reinforced clay's deformation resistance. And it increases the internal friction angle and cohesion of the clay, although the increase in the strength is mainly reflected in the influence on the cohesion. This is an effective method for reinforced soil.

(a) (b)

Figure 2.6 Flax fiber (a) and bamboo strip (b)

2.3. HISTORICAL DEVELOPMENT

The original concept comes from the United States. Soil mixing was first developed by Intrusion-Prepakt, Inc. of Cleveland, Ohio (Liver et al., 1954) as "Intrusion Grout Mixed-in-Place Piles."

In 1961, the mixed in place was already used under license for more than 300 000 lineal meters of piles in Japan for excavated support and groundwater control. Continued until the early 1970s by Seiko Kogyo Company, to be suggested by diaphragm walls and deep mixing method (Soil-Mix Wall). Besides, Herrin and Mitchen (1961) suggested that there is no one of optimum lime content with which maximum strength of lime stabilized soils can be expected under all conditions. For a specific condition of curing tine and soil type, an optimum lime content that caused a maximum strength exists.

The development and research on deep mixing started from laboratory model tests in 1967 by the Port and Harbour Research Institute of the Japanese Ministry of Transportation. The research was continued by Okumura, Terashi, et al. through the 1970s, including 1- investigation of lime-marine reaction, and 2- develop appropriate mixing equipment. Unconfined compressive strength (UCS) of 0.1 to 1 MPa was achieved. Early equipment (Mark I-IV) used the first marine trial near Hamada Airport (10 m below the water surface). The Swedish Lime column method for treating soft clays under embankment using unslaked lime was researched (Kjeld Paus, Linden- Alimak AB, in cooperation with Swedish Geotechnical Institute, Euros AB, and BPA Byggproduction AB). And then, this follows observations by Paus on fluid lime column installation in the United States.

In the late 1960s, China reported being considering implementing the Depp lime mixing concept from Japan.

Development of Soil Mixed wall method for retaining walls, using overlap multiple augers, was started in Japan by Seiko Kogyo Co. of Osaka in 1972 to improve lateral treatment continuity and homogeneity/quality of treated soil.

The first Japanese full-scale Deep Mixing project was conducted in 1974. First applications in reclaimed soft clay at Chiba (June) and applications elsewhere in Southeast Asia follow the same year. Besides, intensive trials were conducted with Lime Columns at Ska Edeby Airport, Sweden: basic tests and assessment of drainage action (columns 15 m long and 0.5 m in diameter). In 1974, the first detailed description of the Lime Column method by Arrason et al. (Linden Alimak AB). And the first similar trial embankment using the Swedish Lime Column method in soft clay in Finland (6 m high, 8 m long; using 500-mm-diameter lime cement columns, in soft clay) in 1974.

In 1975, deep mixing's first appearance in an international forum in Bangalore, India, a Swedish paper on Lime Colum by Broms and Boman. Also, a Japanese paper on Deep Lime Mixing (DLM) by Okumura and Terashi was presented to the Swedish paper on lime columns (Broms and Boman), and a Japanese paper on DLM (Okumura and Terashi) presented at the same conference in Bangalore, India. Both countries had proceeded independently to this point. Limited technical exchanges occur thereafter. Following their research from 1973 to 1974, PHRI develops the forerunner of the Cement Deep Mixing (CDM) method using fluid cement grout and employing it for the first time in large-scale projects in soft marine soils offshore. (Originally similar methods include DCM, CMC (still in use from 1974), closely followed by DCCM, DECOM, DEMIC, etc., over the next five years). The first commercial use of the Lime Column method in Sweden for support of excavation, embankment stabilization, and shallow foundations near Stockholm (by Linden Alimak AB, as contractor and SGI as consultant/researcher) in 1975.

Public Works Institute Ministry of Construction, Japan, in conjunction with the Japanese Construction Machine Research Institute, began research on the Dry Jet Mixing (DJM) method using dry powdered cement (or less commonly, quick-lime) in 1976. It was also the same year that Soil Mixed Wall (SMW) method was used commercially for the first time in Japan by Seiko Kogyo Co.

In 1977, Cement Deep Mixing (CDM) method had been marked development. CMD method Association was established in Japan to coordinate technological development via a collaboration of industrial and research institutes and the first practical use of CMD (marine and land use). First design handbook on lime columns (Broms and Boman) published by Swedish Geotechnical Institute. China commences research into CDM, with first field application in Shanghai using its land-based equipment in 1978.

The first commercial using in Japan of Dry Jet Mixing was marked in 1980, and then it quickly superseded Deep Lime Mixing (DLM) with land-use only. Besides, DJM Association was established in Japan. In 1983, Eggestad published a state-of-the-art report in Helsinki dealing with new stabilizing agents for the Lime Column method.

In 1984, the SWING method developed in Japan, followed by various related jet-assisted (W-R-J) methods in 1986, 1988, and 1991.

The Tenox Company reported more than 1000 projects completed with the SCC method in Japan (1989), prior to major growth thereafter (9000 projects to end of 1997, with a $100 to 200 million/year revenue in Japan and elsewhere in Southeast Asia). In 1990, Dr. Terashi, involved in the development of DLM, CDM, and DJM since 1970 at Port and Harbor Research Institute, Japan, gives November lectures in Finland. Introduces more than 30 binders commercially available in Japan, some of which contain slag and gypsum as well as cement. Possibly leads to the development of "secret reagents" in Nordic Countries thereafter.

Low Displacement Jet Column Method (LDis) was developed in Japan in 1991. In the same year, the Bulgarian Academy of Sciences reports local soil-cement research results, and the Geotechnical Department of City of Helsinki, Finland, and contractor YIT introduce block stabilization of very soft clays to depths of 5 m using a variety of different binders.

In the early 1990s, the First marine application of CDM at Tiajin Port, China: designed by Japanese consultants (OCDI) and constructed by a Japanese contractor with his equipment (Takenaka Doboku).

In 1991, the Chinese Government (First Navigational Engineering Bureau of Ministry of Communications) built the first offshore CDM equipment "fleet," using Japanese technology used for the first time (1993) at Yantai Port. (Reportedly the first wholly Chinese Design-Build DMM project.). And Jet and Churning System Management (JACSMAN) developed by Fudo Company and Chemical Grout Company in Japan.

DJM Association Research Institute published updated Design and Construction Manuals (in Japanese) in 1993. In the same year, CDM Association claims 23.6 million m3 of soil treated since 1977. And SMW claims 4000 projects completed worldwide since 1976, comprising 12.5 million m2 (7 million m3). According to a Japan report, from 1977 to 1995, more than 26 million m3 of CDM treatment reported and about 15 million m3 of DJM treatment.

In 1997, the SMW method was used for massive ground treatment projects at Fort Point Channel, Boston, MA (largest DMM project to date in North America), and other adjacent projects. Input at the design stage to U.S. consultants by Dr. Terashi (Japan).

From 1998 to around the year 2000, a variety of numerical modeling work has been performed on the interaction of soil-cement columns in soft clays, for example, Kerin and Karstunen (2009), Chai et al. (2010) and Abushara et al. (2009). Their studies have focused on settlement reduction from "T" shaped columns, "cross" shaped columns, and "multi-columns" supported embankment loading.

Historical development of LSS in Kohata's laboratory

Kohata et al., (2002) were proposed the LSS mixed the pulverized newspaper as fiber material in order to improve the brittle mechanical property and to increase the ductile performance of LSS. It was shown that the ductile property of LSS mixed with pulverized newspaper as a fiber material after the peak in the $q \sim \varepsilon_a$ curve was significantly improved by the reinforcement method (Kohata 2006; Kohata et al. 2004 and 2007; Ito et al. 2011).

In 2010, Nguyen et al., performed experiments with both LSS using NSF-Clay (NSF-Clay is fine powder clay bought in the Japanese market) and Vinh Phuc-Clay (excavated soil spread in Hanoi area) as original material. The relationship between deviator stress q ($=\sigma_1-\sigma_3$) and axial strain ε_a from Consolidated–Undrained triaxial compression tests under confining pressure σ'_c = 98 kPa of Vinh Phuc-Clay LSS and NSF-Clay mixed by fibered material content of 0, 10, 20 kg/m^3 at 56 days, respectively was established. The tests were performed under an axial strain rate of 0.054 %/ min. The results of the research indicated that the physical behaviors of both LSS tend to be similar.

The previous research in 2015 investigated the time-dependency on shear deformation characteristics of LSS using NSF-clay mixed by fiber material contents of 0, 20 kg/m^3. On the other hand, the target density of slurry of 1.280 g/cm^3 was selected. A series of Undrained triaxial compression tests under confining pressure σ'_c = 98 kPa had been performed with four different conditions of axial strain rate (Duong, 2015). The specimens had been cured under indoor and outdoor conditions. The research results indicated that: Firstly, the maximum deviator stress, qmax in $q \sim \varepsilon_a$ curve of LSS mixed with fibered material indicates similar value independently of curing days. However, in the case of LSS without fibered material, there is a tendency to increase the initial stiffness as increasing of curing days; Secondly, the range of indicating E_{tan}/E_0 value of 1.0 tends to be larger on LSS mixed with fibered material. This is due to the reinforcing effect of the fibered material in LSS; Thirdly, the rigidity during loading before the peak in $q \sim \varepsilon_a$ relationship increases temporarily in a large strain level after a creep stage and a change of strain rate independently of curing day; Finally, a procedure for predicting train-induced vibration from railway tunnels in conformity with the condition of Vietnam has been established as an example for Hanoi metro line. The vibration propagation from the tunnel into the ground surface was analyzed by the two-dimensional element method (2-

D FEM). The established procedure was then used to evaluate train-induced vibration as using LSS for backfilling ground of cut and cover tunnel. The results have shown that the LSS could reduce train-induced vibration from the tunnel.

In 2019, research works including experiments and analyses had been conducted simultaneously, aiming to promote the application of LSS in the future (Do, 2019). The influence of slurry density on strength and deformation characteristics of LSS mixed with fibered material was evaluated. A series of Consolidated–Undrained triaxial compression tests with measured pore water (CUB tests) under the condition on an axial strain rate of 0.054 %/ min have been carried out for LSS mixed with fiber material amount of 0 and 10 kg/m^3 at curing time of 28 and 56 days, respectively. Based on the test results, it was found that when the slurry density is slightly decreased from the appropriate slurry density, it is considered that the maximum deviator stress (q_{max}) decreased remarkably. In addition, it was found that the local damage caused by shearing even in the LSS mixed with fiber material prepared on the low slurry density is reduced by the effect of reinforcement on the fiber material. On the other hand, the difference in triaxial shear property of LSS mixed with fiber material cured in the laboratory and at field was investigated to be carried out a series of CUB tests for both specimens of LSS mixed with fiber material amount of 0 and 10 kg/m^3 prepared by trimming LSS retrieved from a model ground by block sampling and cured in the laboratory at curing time of 28 and 56 days, respectively. Based on the test results, it was found that the q_{max} in $q \sim \varepsilon_a$ relations of LSS mixed with fiber material cured at field tends to be larger than that cured in laboratory. Besides, according to the numerical analysis results on mitigation of vehicle-induced vibration in case using LSS as backfill material by the established analysis method, it is found that the application of LSS can reduce the ground vibration.

The research in 2020 investigated the influence of reducing slurry density while preparing the LSS specimens with different cement content mixed with fibers (Yujie Cui, 2020). A series of triaxial compression tests and unconfined compression tests were conducted on LSS specimens prepared in different slurry densities of 1.216, 1.280 g/cm^3, cement contents 80, 100 kg/m^3, and the fiber contents of 0, 10kg/m^3 with different curing time of 28 and 556 days, respectively. The results showed that a slight decrease in slurry density could decrease the peak stress of LSS remarkably. Meanwhile, the change in cement content can affect peak strength and the decreasing rate of E_{tan}/ E_0 in the early loading stage. Besides, by adding fiber material, the local damage caused by shearing and the brittleness were improved.

2.4 APPLICATIONS OF LIQUEFIED STABILIZED SOIL IN CONSTRUCTION

In the 1990s, Kuno et al. presented one of the LSS method applications, filling a cavity under the pavement of an urban road (Figure 2.7). The cavity is inferred mainly because the submerged backfilled sand in the ground is washed out little by little to a nearby open space, for example, sewage pipes, and thus, a cavity is created grown. This application is thought to be possible of decreasing time and cost comparing to a conventional method. Thus, two kinds of field performance tests were conducted to verify the method's capability and applicability and acquire necessary field data for future maintenance works. The first field performance test used an on-site plant and a stabilized soil of low strength and relatively high flow condition, while the second test uses a remote plant and stabilized soils of high strength and low flow condition. The tests were evaluated in terms of adequate mix proportion, working system, working time, filling outcome, occupation of road, quality control test, and so on. Through two sequential field performance tests, it is confirmed that the method possesses the good capability of filling cavities under the pavement and makes it possible to decrease time and cost.

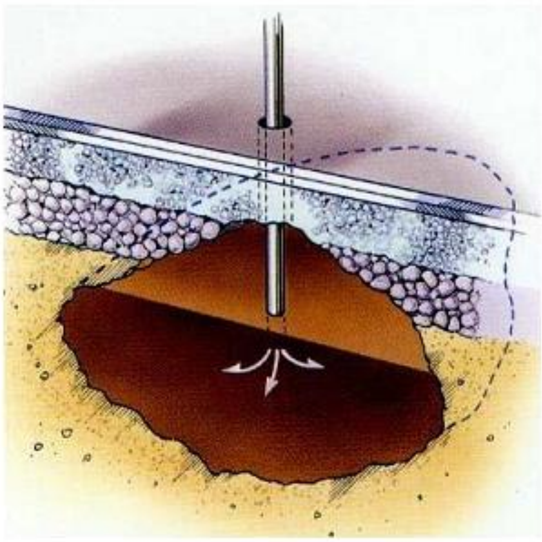

Figure 2.7 Use of LSS for filling the cavity under the road surface

Murata (2011) reported that LSS consists of the slurry made of on-site soil, water, cement, and sand of clay as appropriate LSS is used for backfill at the upper part of a cut and cover tunnel and as an invert material of a shield tunnel (Figure 2.8 and Figure 2.9). Pit sand is usually used for backfill, but LSS is much better than the sand because it is easy to use with on-site soil, and LSS can be buried without compaction into a narrow space. The lower part of the shield tunnel is usually buried by low-strength concrete (unconfined compressive strength: about 10 MN/m^2). However, from the environmental point of view, LSS, which can reuse on-site soil, is now often used. A mixture of LSS was designed from the results of unconfined compressive tests and repeated loading tests. Then, it was designed the unconfined compressive strength of liquefied soil should be 6 MN/m^2 for safety purposes. To hold this strength level for some on-site soil, a huge amount of cement is needed (300 ~ 400 kg/m^3 of LSS). So, a method to mix wasted fiber materials into LSS has been studied to increase the strength and ductility and decrease the total material cost. Studied have been promoted on what types of wasted fiber material are available and what rigidity level of wasted fiber material is needed.

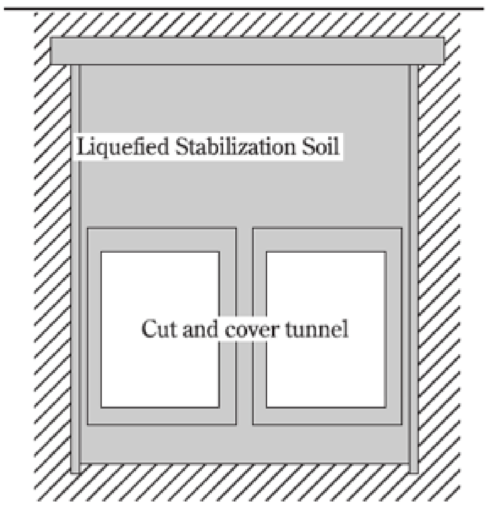

Figure 2.8 LSS used for backfill at the upper part of the cut and cover tunnel

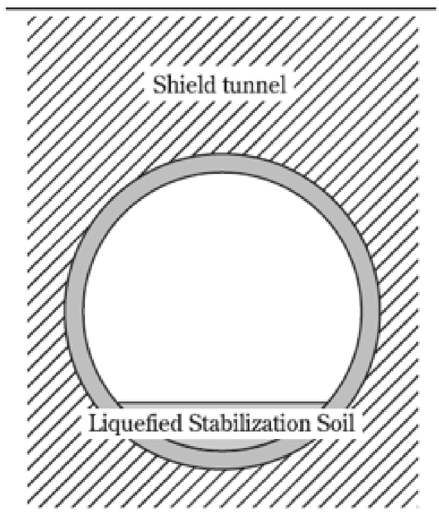

Figure 2.9 LSS used for invert material of shield tunnel

The strength and quality control method of LSS used as a building foundation is proposed by Tomoharu et al. (2005) (Figure 2.10). The research results pointed out that it is feasible for LSS to apply for the building foundation from a future perspective. Another application of LSS is for constructing fences or retaining walls. Yoshihiro et al. (2006) reported that concrete block construction is common for these structures, tens to collapse under strong earthquakes, causing a threat to traffic. In contrast, liquefied stabilized soil block construction can avoid such damage due to the greater toughness of the material. Also, soil blocks are advantageous over concrete blocks in terms of appearance. Their research has examined the effects of adding PVA fiber to LSS blocks under atmospheric conditions. Tests were carried out on the drying shrinkage properties, resistance to atmospheric exposure, and uniaxial compressive strength. It found that PVA fiber reduces the drying shrinkage, crack propagation, and compressive strength of the LSS block. The following Figure 2.11 is more examples of using LSS for various backfilling works in Japan.

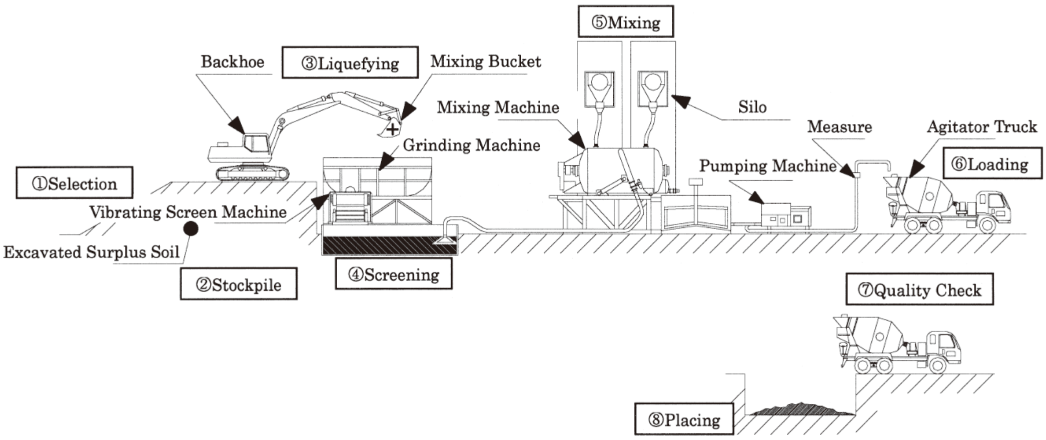

Figure 2.10 Flow of Liquefied soil stabilized method

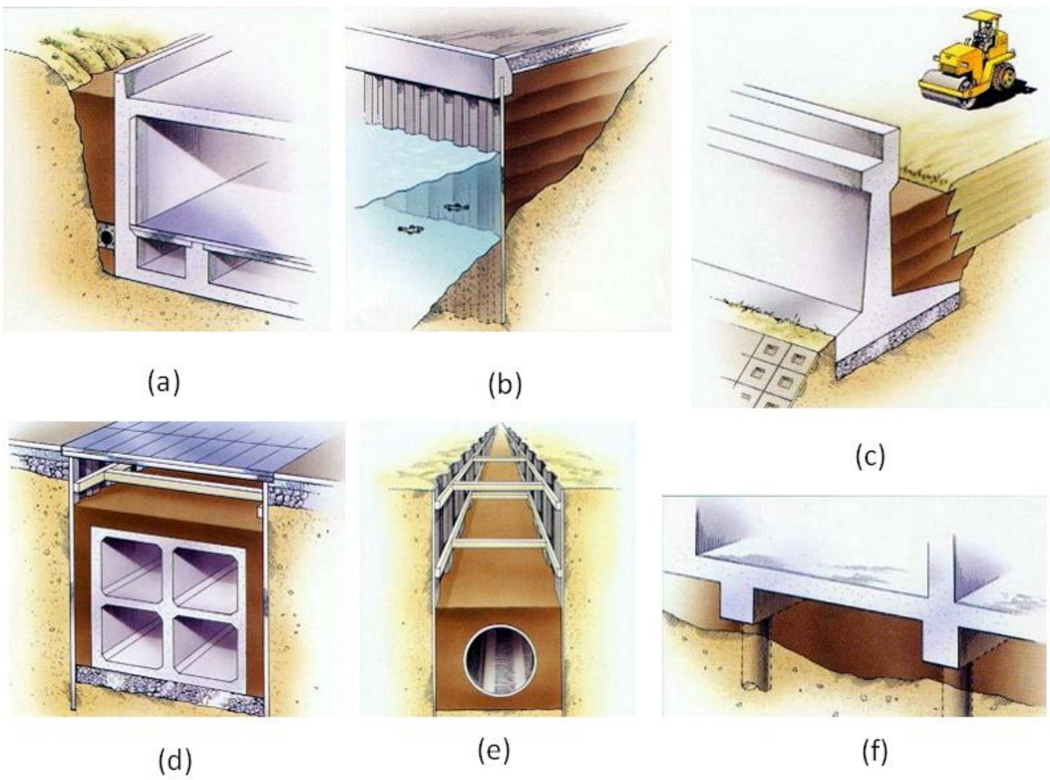

Figure 2.11 Using LSS for various backfilling works in Japan; (a): backfilling of building foundation; (b): backfilling of the underwater seawall; (c): backfilling of abutment; (d): backfilling of box culvert; (e): backfilling of the underground pipe; (f): filling of underfloor due to subsidence

Recently, most underground pipelines have been backfilled by LSS (Figure 2.11 e). Figure 2.12 shows a construction site of the pipelines using LSS. Kawabata et al. (2008) conducted a full-scale field test for a buried pipe using a steel pipe of 3500 mm-diameter and 26 mm-thickness. Five cases of backfilling methods were applied. From the test results, it was found that the stiffness of the backfilling method strongly influenced the behavior of the buried pipe. In particular, the pipe which is backfilled with LSS showed stable behavior. Moreover, Kashiwaghi et al. (2009) and Kawabata et al. (2010) have proposed a thrust restraint method using LSS. Model pit experiments using a model pipe with a diameter of 260 mm were carried out to examine the effectiveness of the LSS for the thrust restraint of buried bend. LSS was applied to the model pipe's passive area, and dry silica sand was used as backfill material. The model pipe was laterally loaded at a 1 mm/min speed after backfilling to simulate the thrust force. The lateral resistance and horizontal displacement of the model pipe were both measured. The earth pressure distributions of the passive ground were observed. The results showed that the lateral resistance of the bend in using LSS was increased. It is verified that LSS is an effective backfill material for thrust restraint. Other experimental research results showed that the bending stiffness in case using LSS with geosynthetics was increased (Kawabata et al., 2009). Besides, passive resistance was considerably increased in the case of using LSS with geogrid (Kawabata et al., 2008).

Figure 2.12 Backfilling of LSS

Another method is the pipe-line soil treatment system (Figure 2.13). For stabilization of dredged mud, pipe-line soil mixing methods are getting popularized in

Japan. The pipe-line treatment system has developed as a kind of pipe-line soil mixing method. The system is called "Kanro Mixer" installed on the way of dredging pipe-line and feeder devices for mixing materials. The system can be utilized for not only the consolidation of mud but also making the foam mixed soil, producing grainy soil, and so on (Miki et al., 2005).

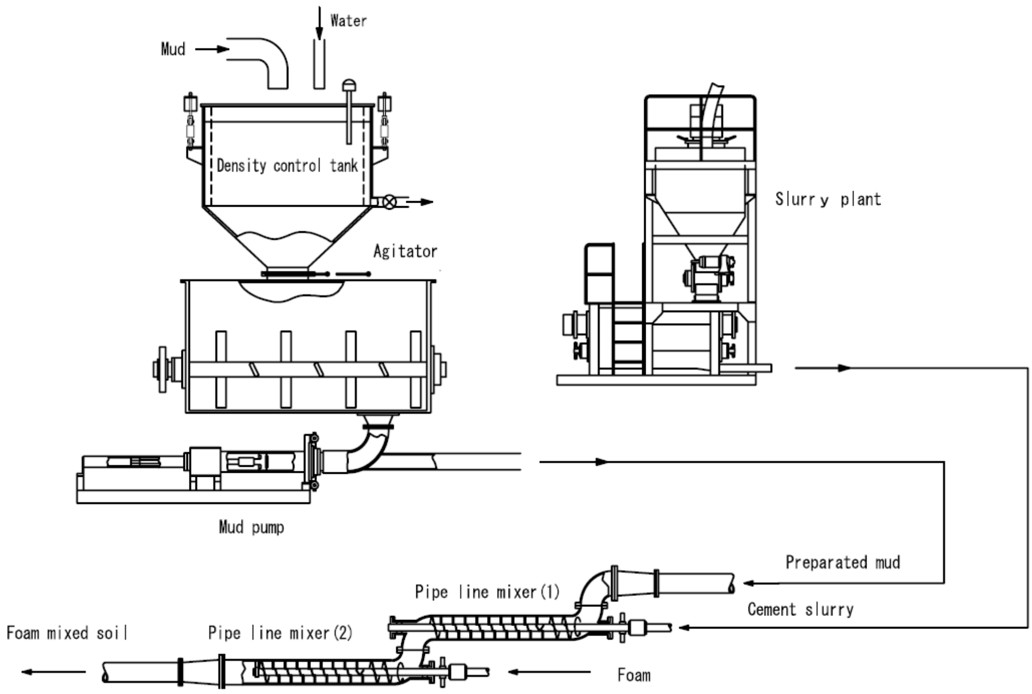

Figure 2.13 Production system for foam mixed lightweight soil

Backfill as a seep-proof structure: To protect the dredgings or waste soils from leaking through the rubble mound, it is necessary to place protection inside the wharf. It was found that dredged soft soil after being treated with cement was a rational alternative for this protection at a depth of 20 to 40 m (Tang et al., 2001). As shown in Figures 2.14 and 2.15, it was decided to place the cement-treated soil inside the wharf, with a layer thickness greater than 1.0 m and a slope about 1:3.

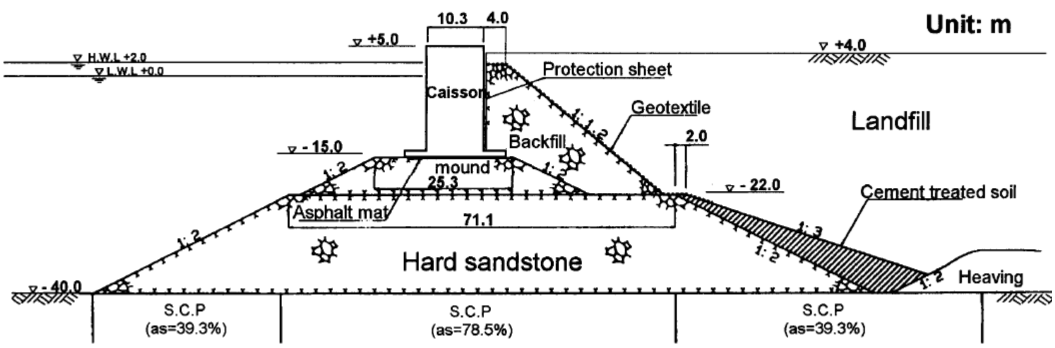

Figure 2.14 Cement treated soil using as slope protection

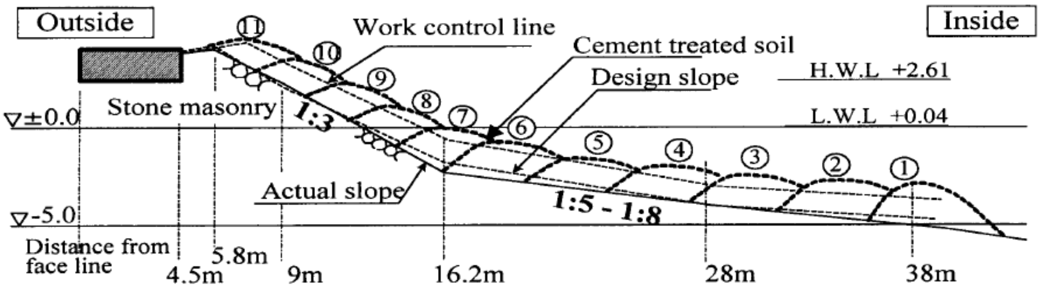

Figure 2.15 Placement of cement-treated soil along slope

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CHAPTER 3

MATERIALS AND PREPARATION METHOD OF SPECIMEN

3.1 INTRODUCTION

"Liquefied Stabilized Soil" (LSS) is one of the effective methods of using excavated soil with construction works and has become popular in Japan (Kuno, 1997). The LSS is a kind of cement-treated soil, which is prepared by mixing slurried soil and cement stabilizer. The LSS mixtures are not only created stabilized ground without compaction but also easy to fill empty space by pumping a long distance. However, according to previous studies, it is shown that the increase in cement content does not only increase the strength property but also the brittleness increases. Therefore, Kohata et al. were proposed the LSS mixed the pulverized newspaper as fiber material in order to improve the brittle mechanical property and to increase the ductile performance of LSS (Kohata et al. 2002). It was shown that the ductile property of LSS mixed with pulverized newspaper as a fiber material after the peak in the $q \sim \varepsilon_a$ curve was significantly improved by the reinforcement method (Kohata 2006; Kohata et al. 2004 and 2007; Ito et al. 2011).

In order to study the strength and deformation properties of the LSS, a series of test specimens were prepared. In this chapter, the test materials and the procedures of making the sample will be detailed.

3.2 TEST MATERIALS

The samples of LSS, which were used for the experiment in the laboratory and field, were mixed with the following ingredients: The New Snow Fine Clay, cement, fiber material, and water.

3.2.1 The New Snow Fine Clay (NSF-Clay)

In this study, the NSF-Clay (Figure 3.1) was used as a homogeneous base material, which is a commercially available cohesive soil with very clearly defined physical parameters shown in Table 3.1.

Figure 3.1 The New Snow Fine Clay

Table 3.1 Physical parameters of NSF - Clay

Physical parameters	Values
Density of particle ρ_s (g/cm^3)	2.762
Liquid limit W_L (%)	60.15
Plastic Limit W_P (%)	35.69
Plasticity Index I_P	24.46

3.2.2 Cement

In this experiment, Geoset 200 cement provided by Taiheiyo Cement Co. was chosen as the binder (Figure 3.2). GEOSET 200 is a general-purpose soil stabilizer with a minimal level of hexavalent chromium leaching. It is suited for a wide variety of purposes, including both shallow and deep stabilization of soft ground, as well as the solidification of sludge and bottom-layer soil. It delivers the required unconfined compressive strength and California bearing ratio (CBR) through the appropriate setting of additive amounts for a wide variety of soil qualities.

Figure 3.2 Geoset 200 cement

3.2.3 Pulverized newspaper

The pulverized newspaper (Figure 3.3) was used as the fiber material, which was made by the following procedure. The newspaper was cut by the office shredder into small pieces. The cut papers were mixed with water and pulverized by a food processor for cooking. The paper was untied by the hand after dried in a drying oven. It was pulverized again to smaller pieces like cotton by the food processor.

Figure 3.3 The pulverized newspaper

3.2.4 Water

The water used in the sample mixing must meet the clean water standards and be taken directly from the municipal water source. Water will be calculated at a certain percentage to produce the desired density of the LSS mixture.

3.3 MIXING METHOD

The slurry type and the adjustment slurry type are two LSS mixing methods, which are the common mixing methods for recycling excavated soil. The slurry type was chosen for this study because it prepares easier than the adjustment slurry type.

In the previous research, various mixing tests were conducted to adjust the slurry density and the amount of cement stabilizer. The bleeding rate, flow value, and unconfined compressive strength were investigated by soil tests corresponding to each parameter for each of LSS at the curing time of 28 days (Ito et al. 2011; Duong et al. 2014). Based on these tests, the standard slurry density was decided for this study, as shown in Figure 3.4.

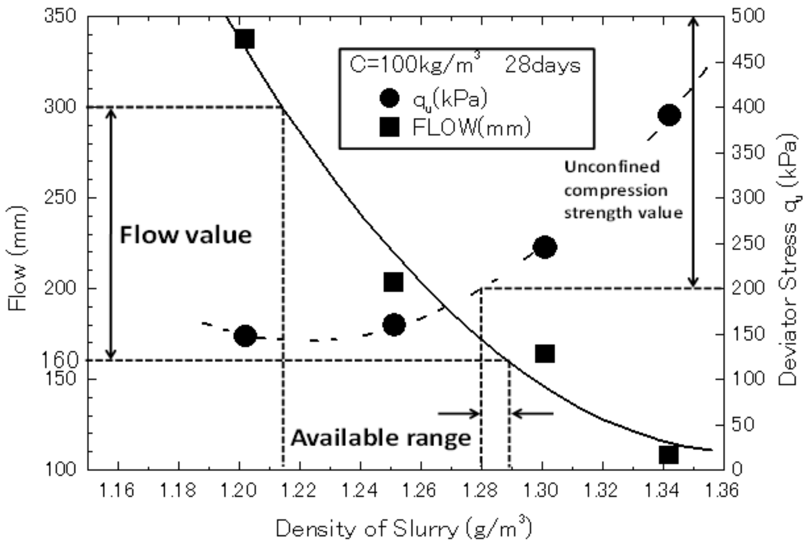

Figure 3.4 Available range of slurry density

Firstly, an appropriate amount of water was added and mixed with NSF - Clay, then the density of slurry was adjusted, after that the cement stabilizer was added and mixed. Finally, the pulverized newspaper will be put into the mixture with a calculated rate and mixed carefully. The LSS mixture is finished. The detailed steps will be shown as follows:

Step 1: Put the bucket on the scale, weigh the bucket, write down the value of the bucket, and then set the value of the scale to zero.

Figure 3.5 Bucket and electronic scale

Step 2: Based on the number of samples required, preliminary calculations of the amount of water need to mix with soil. Input water into bucket, weigh it and write down the value.

Step 3: Based on the amount of water in the bucket and the LSS mixture's density, we can calculate approximately the amount of NSF - Clay needs to mix with water. Then, adding clay into the water. When adding clay, do not put them on the wall of the bucket.

Step 4: The mixture was carefully mixed by hand mixer (Figure 3.6). After that, put the slurry into a stainless steel container of 400 cm^3 called "AE mortar container" to check its density (Figure 3.7). If there is too much difference from the target value of density, add clay or water again to adjust the density until it reached the target value of density.

Figure 3.6 NSF-Clay and water were mixed in the bucket by hand mixer

Figure 3.7 The density of the mixture was checked by AE mortar container

Step 5: After the density of slurry reached the target value, using the calculation form to show the amount of cement needs to be add.Then add cement and mix them fully with the hand mixer.

Step 6: After adding the cement, put the mixture into a sealed container for degassing (Figure 3.8). Open the main switch of negative pressure, link to the container, and open valves. Turn the negative pressure to - 98 kPa and set the time to an hour. After an hour of degassing, reduce the pressure, close the valves, and weigh the bucket (the bucket must be washed and drying at this moment and weigh).

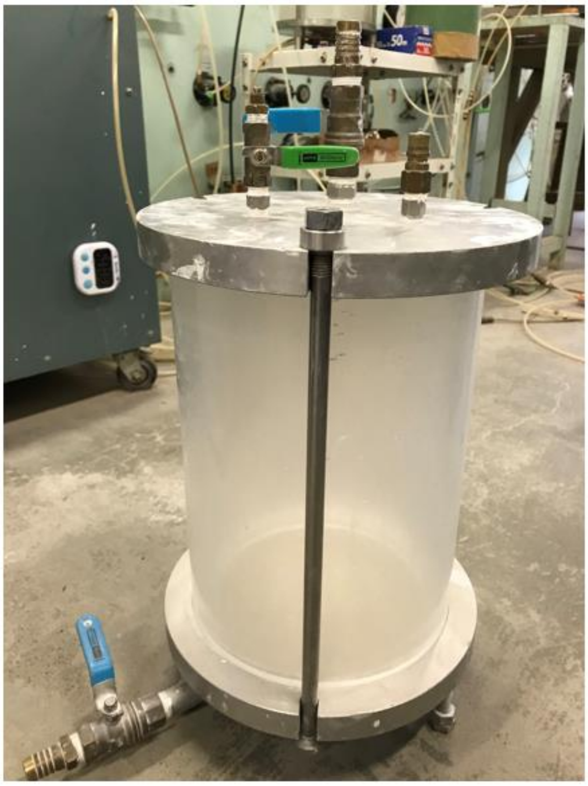

Figure 3.8 Sealed container for removing air bubbles

Step 7: Pour the measured sample material back into the bucket and weigh together.

Step 8: Based on the proportion of fiber material and volume of the mixture, we will calculate the amount of fiber to be added to the mixture. Put the fiber into the mixture and mix slowly and evenly with a hand mixer. Check the density of LSS with fiber material.

3.4 SPECIMEN PREPARATION

3.4.1 Preparation method of the specimen at laboratory

To prepare the laboratory sample, the mixture of LSS with fiber material will be filled into the plastic boxes, as shown in Figure 3.9. When half-filled, slightly shake the air bubbles at the bottom of the box to escape out. Continue to fill the other half of the box and shake for a second time. After the sample is full of mixture, cover the whole sample with thin plastic, and tie it with rubber bands. Finally, put the sample into a big container with constant temperature and humidity (Figure 3.10). After the desired number of curing days, remove the sample from the box and weigh the sample (Figure 3.11). Be careful when removing the sample to avoid the sample being chipped or cracked affect the test results.

Figure 3.9 Plastic box

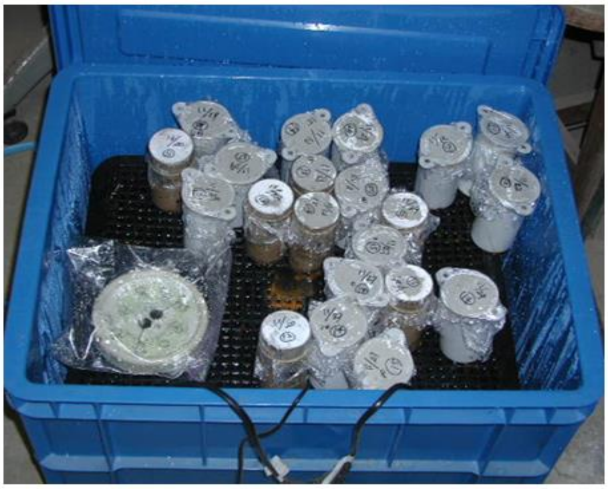

Figure 3.10 Curing specimen

Figure 3.11 The mass of the sample was checked

3.4.2 Prepared method of the specimen at field

For making samples in the field, two pits were excavated at the test field on the campus, as shown in Figure 3.12. A nonwoven geotextile filter was set to prevent the seepage of the mixture to the ground. The mixture of LSS and fiber material was filled up two pits, and the surface was covered with a polymer sheet and cured under nature condition (Figure 3.13).

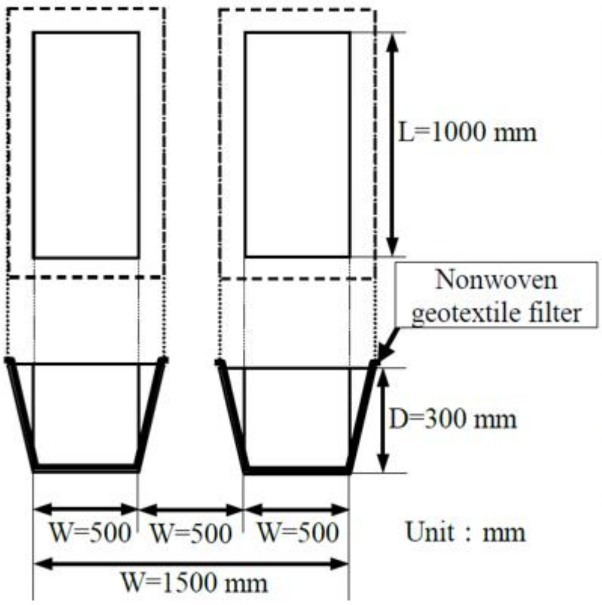

Figure 3.12 Schematic drawing of pits and specimen at the test field

Figure 3.13 Curing sample under the nature condition

To accurately determine the curing temperature of the sample under natural conditions, a temperature sensor has been installed in the excavation hole in the field of the campus, as shown in Figure 3.14. The temperature in the sample will be measured for hours, and the data will be transmitted to the data receiver. After a calculated curing time, the samples prepared by trimming LSS retrieved from the test field were subjected to CUB tests, as shown in Figure 3.15. In parallel, the model ground was subjected to portable Falling Weight Deflectometer (PFWD) tests.

Figure 3.14 Temperature sensor installed in the excavation hole

Figure 3.15 The samples prepared by trimming LSS retrieved from the test field

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CHAPTER 4

APPARATUS AND TESTING PROCEDURES

4.1 INTRODUCTION

In order to study the strength and deformation properties of the LSS, a series of tests at laboratory and field were performed. In this chapter, the apparatus and testing procedures will be detailed.

4.2 APPARATUS AND TESTING PROCEDURE

4.2.1 Experiment at laboratory

4.2.1.1 Triaxial apparatus

A triaxial shear test is a common method to measure many deformable solids' mechanical properties, especially soil (e.g., sand, clay) and rock, and other granular materials or powders. There are several variations on the test (Bardet J. P, 1997; Head K. H et al., 1998; Holtz R. D et al., 1981; Price D. G et al., 2009).

In a triaxial shear test, stress is applied to a sample of the material being tested in a way which results in stresses along one axis being different from the stresses in perpendicular directions. This is typically achieved by placing the sample between two parallel platens, which apply stress in one (usually vertical) direction, and applying fluid pressure to the specimen to apply stress in the perpendicular directions. (Testing apparatus which allows the application of different levels of stress in each of three orthogonal directions are discussed below, under "True Triaxial test.")

The application of different compressive stresses in the test apparatus causes shear stress to develop in the sample; the loads can be increased, and deflections monitored until failure of the sample. During the test, the surrounding fluid is pressurized, and the stress on the platens is increased until the material in the cylinder fails and forms sliding regions within itself, known as shear bands. The geometry of the shearing in a triaxial test typically causes the sample to become shorter while bulging out along the sides. The platen's stress is then reduced, and the water pressure pushes the sides back in, causing the sample to grow taller again. This cycle is usually repeated several times while collecting stress and strain data about the sample. During the test, the pore pressures of fluids or gasses in the sample may be measured using the pore pressure apparatus.

From the triaxial test data, it is possible to extract fundamental material parameters about the sample, including its angle of shearing resistance, apparent cohesion, and dilatancy angle. These parameters are then used in computer models to predict how the material will behave in a larger-scale engineering application. An example would be to predict the soil's stability on a slope, whether the slope will collapse or whether the soil will support the shear stresses of the slope and remain in place. Triaxial tests are used along with other tests to make such engineering predictions.

During the shearing, a granular material will typically have a net gain or loss of volume. If it had originally been in a dense state, then it typically gains volume, a characteristic known as Reynolds' dilatancy. If it had originally been in a very loose state, then contraction may occur before the shearing begins or in conjunction with the shearing.

Sometimes, testing of cohesive samples is done with no confining pressure in an unconfined compression test. This requires much simpler and less expensive apparatus and sample preparation, though the applicability is limited to samples that the sides won't crumble when exposed, and the confining stress being lower than the in-situ stress gives results which may be overly conservative.

In this study, laboratory tests were carried out in triaxial undrained conditions. The effective confining pressure was controlled to be around 98 kPa with a back pressure of 196 kPa and cell pressure of 294 kPa in all cases. The specimen's axial strain was measured by a couple of Local Deformation Transducer (LDT) (Goto et al. 1991). The LDT, which was set at the diagonally opposite ends of the specimen, is avoided the effect of bedding error caused by loose layers at the top and bottom end of the sample. The top and bottom ends of LDT was pinched between two pseudo-hinged attachments fixed on the surface of the rubber membrane at the points, which were glued to the specimen to prevent slipping between the membrane and the surface of the specimen. When the value of LDT exceeds a measurable range, the axial displacement was used the value of proximity transducer (Gap sensor) and dial gauge by correcting the bedding error. In this test, a digital servo motor was used for the loading device. This motor enables to control the axial displacements with high precision and can ignore backlash when reversing the loading direction. A PC software automatically controlled the whole operation of the apparatus during a test. The drawing of the apparatus for triaxial compression tests was shown in Figure 4.1.

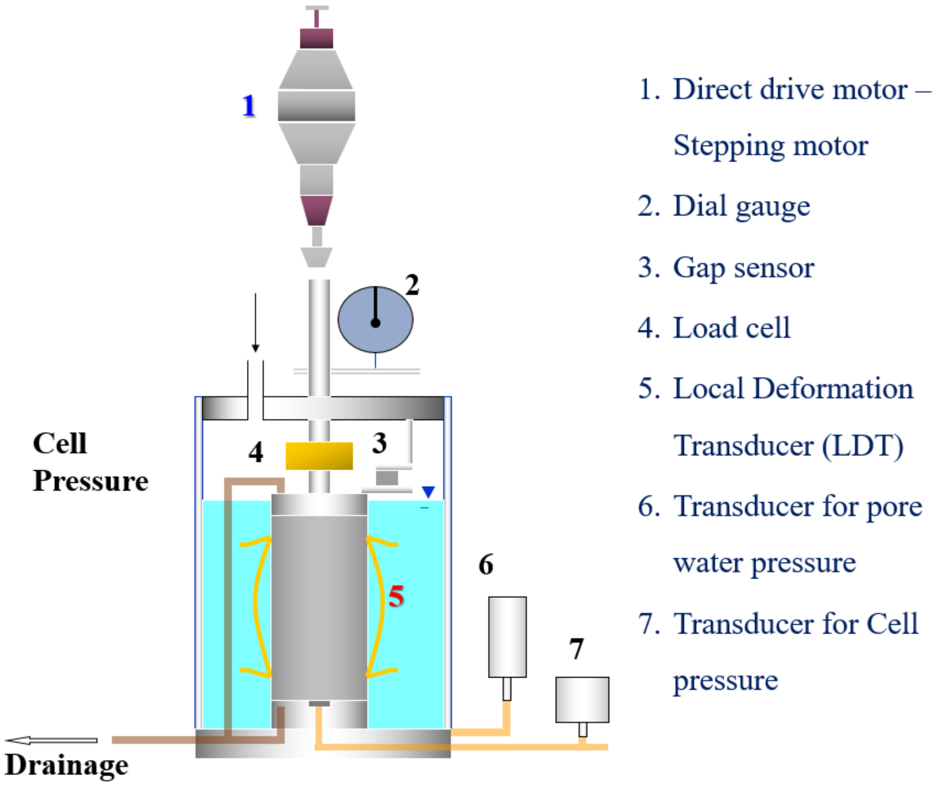

Figure 4.1 The drawing of the apparatus for triaxial compression tests

- **Direct drive motor:**

Direct drive motor enables to control the axial displacements with high precision and can ignore backlash when reversing the loading direction

- **Dial gauge:**

Dial gauge (Figure 4.2) is applied to measure the global displacement of specimen during compression test. The pointer of the gauge is touched with a metal plate fixed on the loading rod outside the cell.

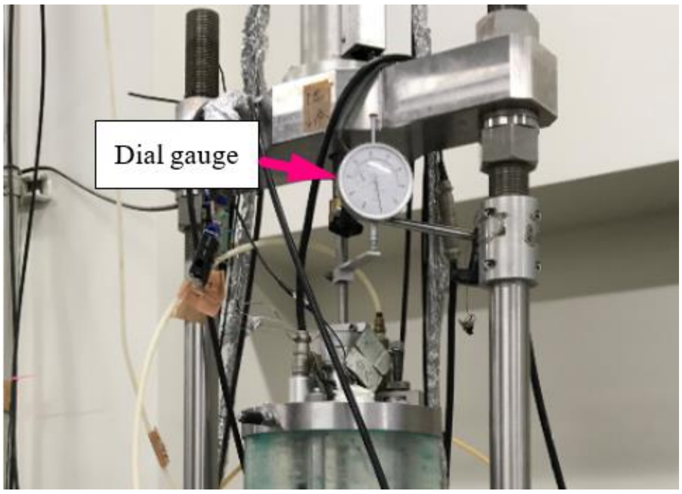

Figure 4.2 Dial gauge

- **Gap sensor (Contactless displacement transducer):**

The contactless displacement transducer (Figure 4.3) is applied as the supplement of the dial gauge to measure the global displacement of the specimen. This kind of contactless displacement transducer has much more accuracy than the dial gauge but the measuring range is limited from 0 to 2 mm generally.

Figure 4.3 Gap sensor

- **Axial load cell:**

The axial load cell can measure the axial loading applied to the specimen.

- **Local displacement transducer (LDT)**

The axial strain was measured by a local displacement transducer (LDT) (Figure 4.4) which removes the influence of bedding error and has a highly accurate measurement at the shear strain level.

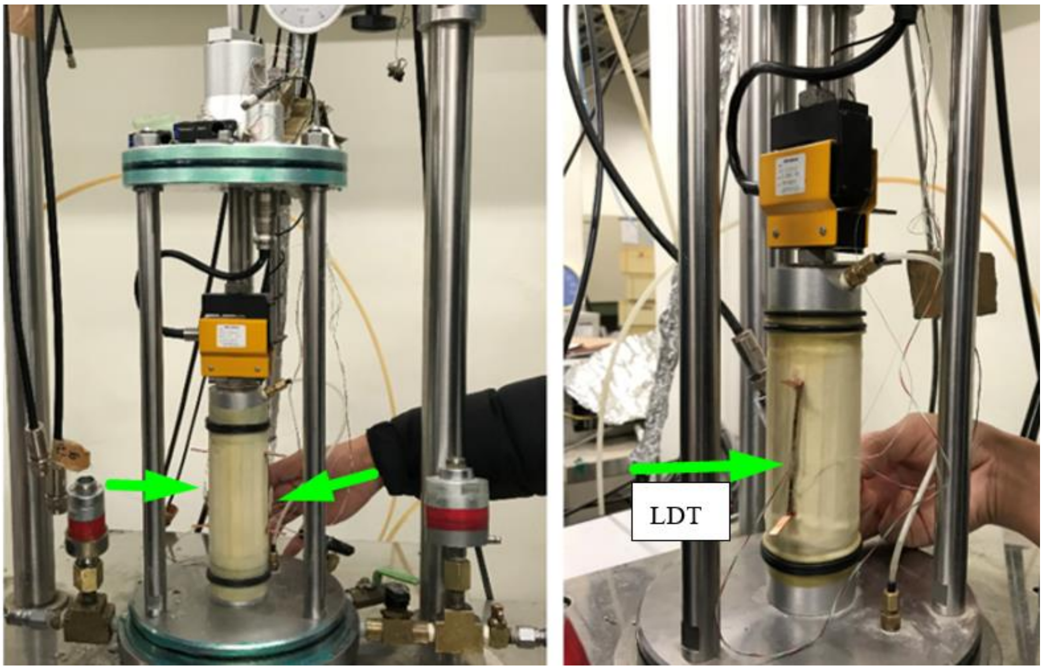

Figure 4.4 Setting LDT on the test sample

- **Transducer for pore pressure and cell pressure:**

Pore Pressure Transducer allows precision measurement of soil sample pore water pressure during triaxial and permeability testing. Cell Pressure transducer is used for the measurement of pressure, backpressure in the triaxial cell. They have to be connected to triaxial cells by the suitable De-airing block. The transducers are base on the extent metric measurement principle with strain gauges on the metal base (Figure 4.5).

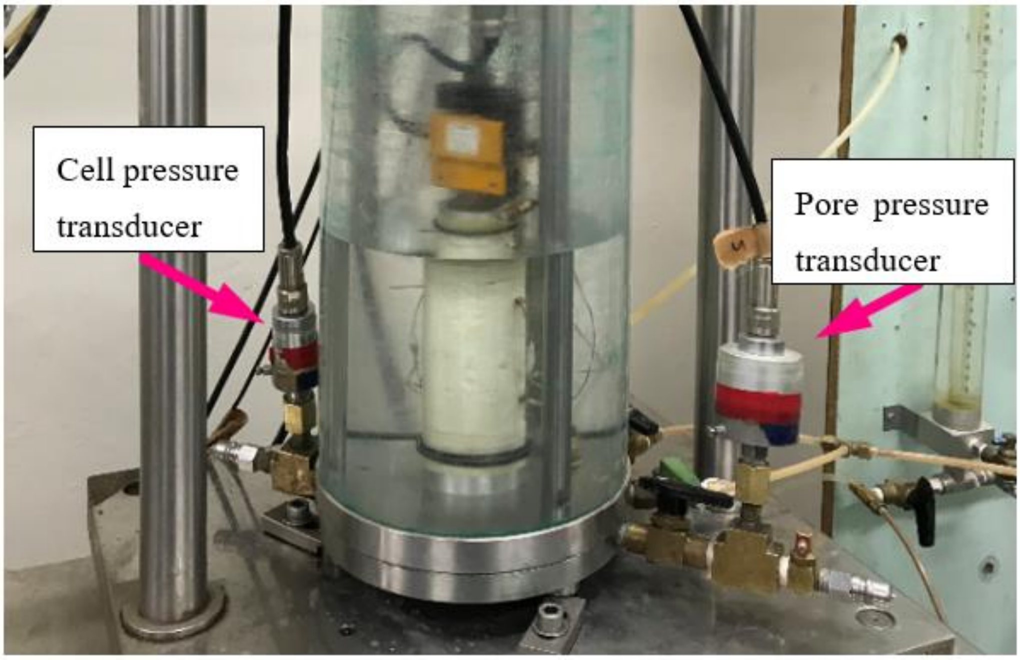

Figure 4.5 Pore pressure and cell pressure transducer

4.2.1.2 Testing procedure

The triaxial compression test procedure will be performed as follows in Fig. 4.6.

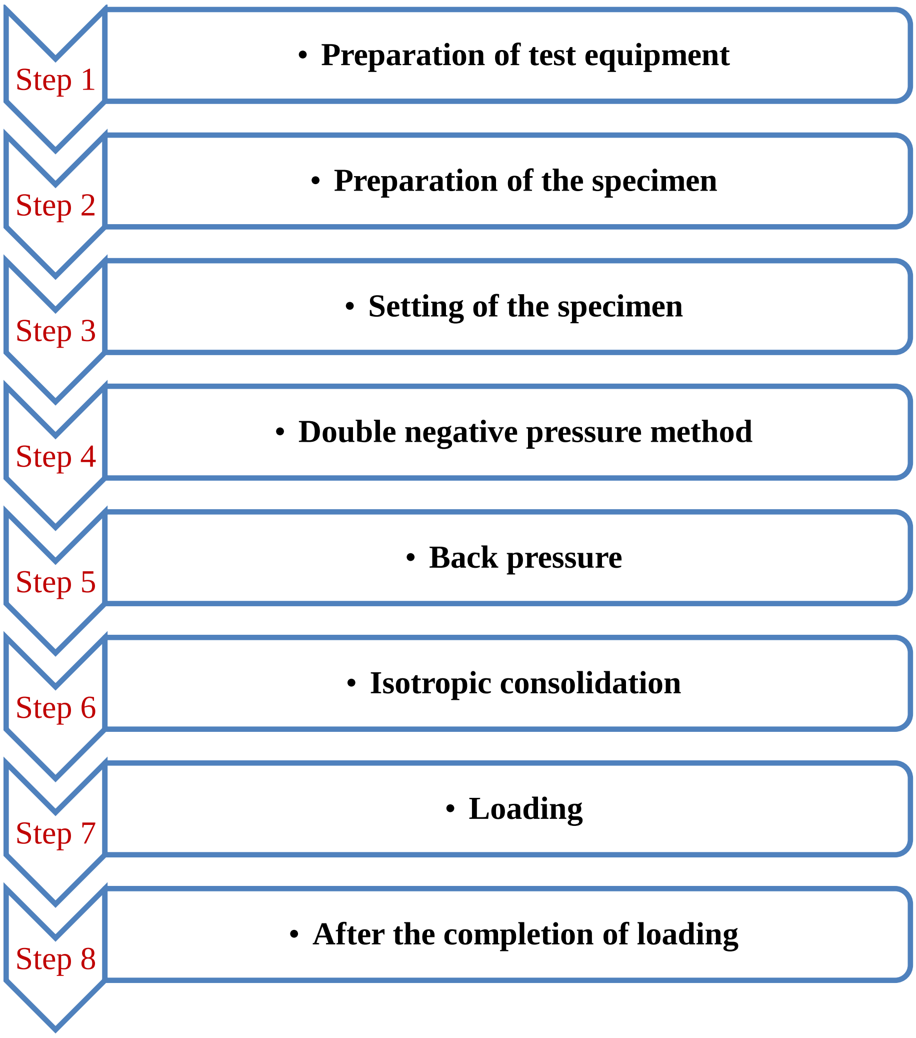

Figure 4.6 The triaxial compression test procedure

4.2.2. Experiment at field

4.2.2.1 Falling Weight Deflectometer (FWD) test

The Falling Weight Deflectometer (FWD) is an instrument that makes the weight fall freely on its loading plate to apply impact load and measures the displacement caused by the fall at the center of impact load and at the points in a radial direction from the center of impact load.

A kind of instrument that is mounted on or drawn by a vehicle used to construct concrete pavement or asphalt pavement of a runway is usually called FWD. The impact load of FWD is 49 kN to 196 kN, and it can obtain the modulus of elasticity of each pavement layer by back analysis based on the theory of multi-layer elasticity using 6 to 8 of external displacement sensors (Figure 4.7).

Figure 4.7 Falling Weight Deflectometer (FWD) apparatus

On the other hand, the small FWD is an FWD that is constructed small and easy and is applicable for hand carry. It makes the weight fall freely on the loading plate to apply impact load and measures the load and displacement caused by the fall. It was developed mainly by assessing the rigidity and bearing capacity of the subgrade easily and promptly. It can measure many points in the short term and obtain a coefficient of subgrade reaction and modulus of subgrade elasticity without using reaction facilities like a plate bearing test or CBR test. It was called Portable Falling Weight Deflectometer (PFWD) (Figure 4.8).

Figure 4.8 Portable Falling Weight Deflectometer (PFWD) apparatus

In this study, to determine the stiffness of the LSS ground, PFWD equipment was used. The basic structure of PFWD in Japan has a weight that can be lifted by hand, and the total weight of equipment is less than 30 kg. Generally, the fall height of the falling weight for the necessary impact load to occur is equal to or less than 0.7 m. The rod guides for weight falling and slide seal is furnished to decrease friction. Also, a fixable mechanism of weight falling is furnished to fix the weight stable at a specified height. The half sine-wave profile of impact load through rubber buffer shows a gradual peak, it takes 7 – 15 ms from the beginning of loading to the peak. The typical structure of PFWD is shown in Figure 4.9.

In general, the stiffness of natural/artificial ground is evaluated by the plate load test which calculates K_{30}-value with a 30 cm diameter loading plate from the relation between 1.25 mm displacement and corresponded load strength at static loading. In portable FWD tests, loading and displacement are measured and obtains $K_{P.FWD}$-value from its relation. The value evaluates the stiffness of the ground. In this study, the loading plate diameter of the apparatus was 10 cm which was different from that of the plate load test. Therefore, the loading plate diameter was corrected, and the $K_{P.FWD}$-value at 30 cm loading plate diameter was calculated as the following equation by JSCE (2002).

$$K_{P.FWD} = (P_{P.FWD.\varphi}/\delta_{P.FWD.\varphi}).(\varphi_{P.FWD}/\delta_{PLT})\ (MN/m3) \qquad (4.\ 1)$$

Where:

$P_{P.FWD.\varphi}$: loading stress at displacement $\delta_{P.FWD.\varphi}$

$\delta_{P.FWD.\varphi}$: displacement

$\varphi_{P.FWD}$: loading plate diameter of portable FWD

φ_{PLT}: loading plate diameter of plate load test (30 cm)

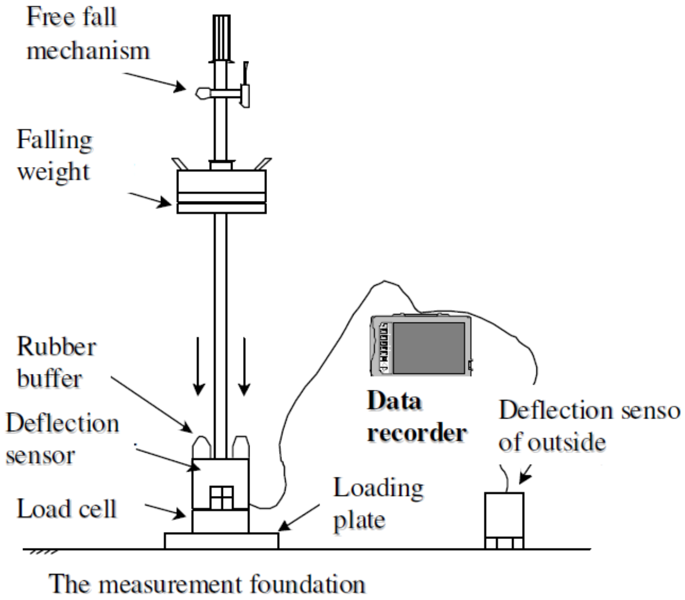

Figure 4.9 The typical structure of PFWD

Therefore, the measurement was conducted to obtain at least three different displacements including 0.417 mm (1.25 mm×φP.FWD/30 cm) in the middle, by changing weight mass and falling height. One of the displacements would be near 0.417 mm as shown in Figure 4.10.

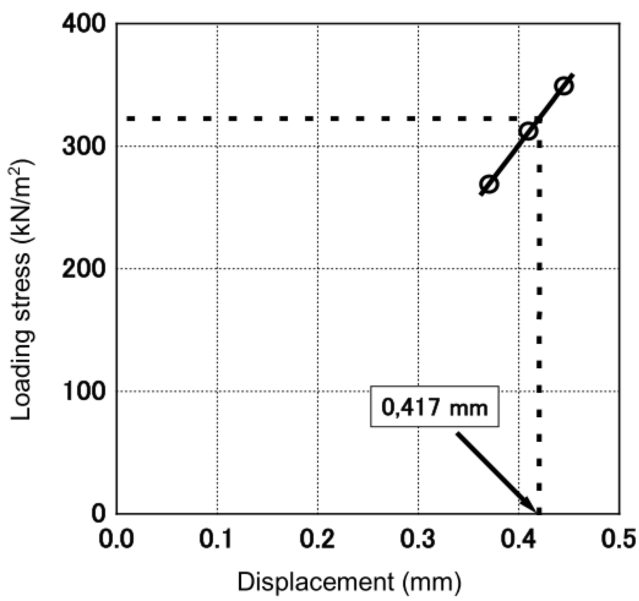

Figure 4.10 An example of displacement and loading stress at one measurement point

The number of falls at one measurement point was 5 times. The reason is the measurement result at first fall varies due to unstable contact between the loading plate and the ground. The first fall is regarded as the primary fall, so the load and displacement from the second fall are recorded as measurement data and averaged. This was repeated three times to obtain the relationship as shown in Figure 4.10. And then, the $K_{P.FWD}$-value was calculated using Equation 4.1. The model ground was subjected to the test at the designed curing time.

4.2.2.2 Testing procedure

The procedure of PFWD measurement is as follows in Figure 4.11.

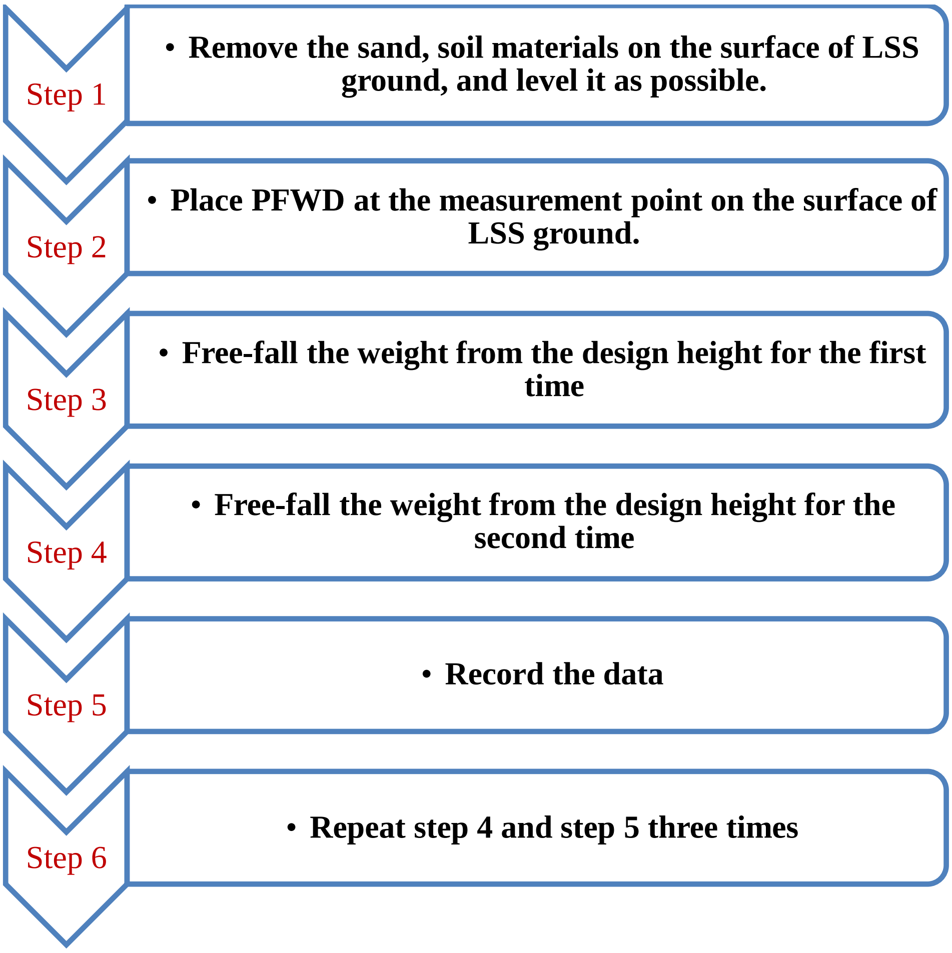

Figure 4.11 The PFWD test procedure

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CHAPTER 5

VARIOUS FACTORS ON THE STRENGTH AND DEFORMATION PROPERTY OF LIQUEFIED STABILIZED SOIL PREPARED AT FIELD

5.1 INTRODUCTION

Nowadays, the rapid urbanization and modernization in big cities in developing countries such as Jakarta, Hanoi and Ho Chi Minh, etc., is the cause of the state of infrastructure, which does not meet the needs of society. Especially, serious congestion of the traffic is happening on a large scale caused by overpopulation. With limited urban areas and solving the above problems, the construction of underground facilities like subway, underground parking, and pedestrian tunnels is the most effective solution. However, millions of cubic meters of excavated soil will arise to be trucked from underground construction projects to disposal sites. It is the cause of environmental pollution.

Besides, sand from rivers and rocks from mountains are the main material used as backfilling soil in the constructions. It is leading to increasingly depleted natural resources and serious impacts on the natural environment. According to statistics by the Ministry of Environment of Vietnam, the current demand for sand is about 600 million m^3 per year, the resources of sand will be exhausted and out of reserves about 10 years later. On the other hand, the disposal sites are becoming increasingly scarce and overloaded in the big cities. Therefore, the excavated soil is a serious problem in the big cities in Vietnam. The questions are where to put the excavated soil and how to develop sustainable infrastructure, which does not only reduce the cost of construction but also does not affect the natural environment.

A long time ago in the big cities in Japan such as Tokyo, Kyoto, and Osaka, etc., when the subway lines, underground constructions, and high-rise buildings were built, the Japanese government also faced this same situation in Vietnam. In order to solve the above problem, one of the methods was recycling the excavated soil as backfilling soil. It is mentioned by Kuno (1997) that "Liquefied Stabilized Soil" (LSS) is one of the effective methods of using the excavated soil with construction works and has become popular in Japan. The LSS is a kind of cement-treated soil, which is prepared by mixing slurried soil and cement stabilizer. The LSS mixtures are not only created stabilized ground without compaction but also easy to fill empty space by pumping a long distance. However, according to previous studies, it is shown that the increase in cement content does not only increase the strength property but also the brittleness increases. Therefore, Kohata et al. were proposed the LSS mixed the pulverized newspaper as fiber material in order to improve the brittle mechanical property and to increase the ductile performance of LSS (Kohata et al., 2002). It was shown that the ductile property of LSS mixed with pulverized newspaper as a fiber material after the peak in the $q \sim \varepsilon a$ curve was significantly improved by the reinforcement method (Kohata 2006; Kohata et al., 2004 and 2007; Ito et al., 2011). However, it has not been explained about the influences of various factors on the strength and deformation property of LSS with fiber material prepared at the field (Duong et al., 2014).

In this study, two pits were excavated on the campus and then were filled with LSS mixed with fiber material amount 0, 10 kg/m^3, respectively. After a curing time of 28 and 56 days, the specimens were prepared by trimming LSS retrieved from the model ground. A series of Consolidated-Undrained triaxial compression tests with pore water measurement was carried out on the specimens cured in the field ground under the conditions at a constant strain rate of 0.054 %/min and the effective confining pressure of 98 kPa. And also, the applicability of an evaluation of stiffness by portable FWD test at a backfilling ground by LSS mixed with fiber material was investigated. Based on the test results, the influences of various factors, which are curing days, paper content, curing temperature and curing circumstance, etc., on the strength and deformation property of LSS prepared at the field are discussed.

5.2 TEST PROCEDURE

5.2.1 Test materials

In this study, a commercially available NSF-Clay in Japan was used in the experiment. This clay is a homogeneous cohesive soil with the physical parameters shown in Table 5.1. The special cement, namely Geoset 200 of Taiheiyo Cement Co. was used as the cement stabilizer. The pulverized newspaper was used as the fiber material, which was made by the following procedure. The newspaper was cut by the office shredder into small pieces. The cut papers were mixed with water and pulverized by a food processor for cooking. The paper was untied by the hand after dried in a drying oven. It was pulverized again to smaller pieces like cotton by the food processor.

Table 5.1 Physical properties of NSF-Clay

Density of particle ρ_s (g/cm^3)	2.762
Liquid limit W_L (%)	60.15
Plastic Limit W_P (%)	35.69
Plasticity Index I_P	24.46

5.2.2 Mixing method

The slurry type and the adjustment slurry type are two LSS mixing methods, which are the common mixing methods for recycling excavated soil. The slurry type was chosen for this study because it prepares easier than the adjustment slurry type. In this method, an appropriate amount of water was added and mixed with excavated soil, then the density of slurry was adjusted, after that the cement stabilizer was added and mixed.

In the previous research, a variety of mixing tests was conducted to adjust the slurry density and the amount of cement stabilizer. The bleeding rate, flow value, and unconfined compressive strength were investigated by soil tests corresponding to each parameter for each of LSS at the curing time of 28 days (Ito et al. 2011; Duong et al., 2014). Based on these tests, the standard slurry density was decided for this study.

5.2.3 Specimen preparation

In this study, the target density of LSS was 1.280 g/cm^3, the bleeding rate was less than 1 % and the cement content was 80 kg/m^3 according to the standard mix promotion design by Ito et al. (2011). LSS slurry was made by the following procedure. NSF-CLAY and water were put into a big bucket and mixed by hand mixer. The density of the mixture was adjusted to 1.280 g/cm^3 by measuring the mass of slurry filled into a stainless steel container of 400 cm^3 called "AE mortar container".

After that, the cement content of 80 kg/m^3 was put into the mixture and mixed slowly and carefully by hand mixer. The flow test was controlled according to the JHS A313-Japan Highway Public Corporation Standard in order to measure the liquidity of LSS. The fiber material amount of 0 and 10 kg/m^3, respectively, were added with LSS slurry and mixed slowly and carefully by hand mixer.

For making samples in the field, two pits were excavated at the test field on the campus as shown in Figure 5.1. A nonwoven geotextile filter was set to prevent the seepage of the mixture to the ground. The mixture of LSS and fiber material was filled up two pits and the surface was covered with a polymer sheet and cured under nature condition. The temperature was measured hourly by a temperature sensor installed in the excavated hole in the field of the campus as shown in Figure 5.2. After a curing time of 28 and 56 days, respectively, the samples prepared by trimming LSS retrieved from the test field were subjected to CUB tests, and the conditions of specimens on the CUB test were shown in Figure 5.3. In parallel, the model ground was subjected to portable FWD tests.

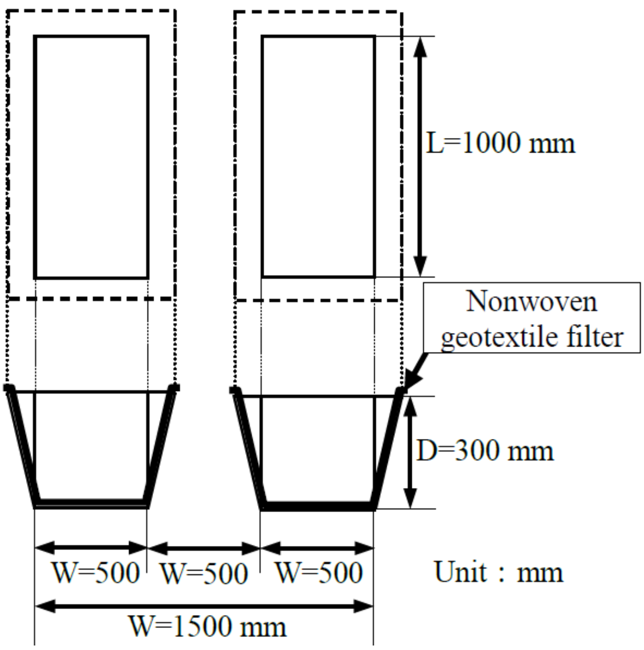

Figure 5.1 Schematic drawing of pits

Figure 5.2 Setting temperature sensor in the model ground

5.2.4 Test method and equipment

5.2.4.1 CUB test

Figure 5.3 illustrates the drawing of the apparatus for triaxial compression tests. The axial strain of the specimen was measured by a couple of Local Deformation Transducer (LDT) (Goto et al., 1991). The LDT, which was set at the diagonally opposite ends of the specimen, is avoided the effect of bedding error caused by loose layers at the top and bottom end of the sample. The top and bottom ends of LDT was pinched between two pseudo-hinged attachments fixed on the surface of the rubber membrane at the points, which were glued to the specimen to prevent slipping between the membrane and the surface of the specimen. When the value of LDT exceeds a measurable range, the axial displacement was used the value of proximity transducer (Gap sensor) and dial gauge by correcting the bedding error. In this test, a digital servo motor was used for the loading device. This motor enables to control the axial displacements with high precision and can ignore backlash when reversing the loading direction. A PC software automatically controlled the whole operation of the apparatus during a test.

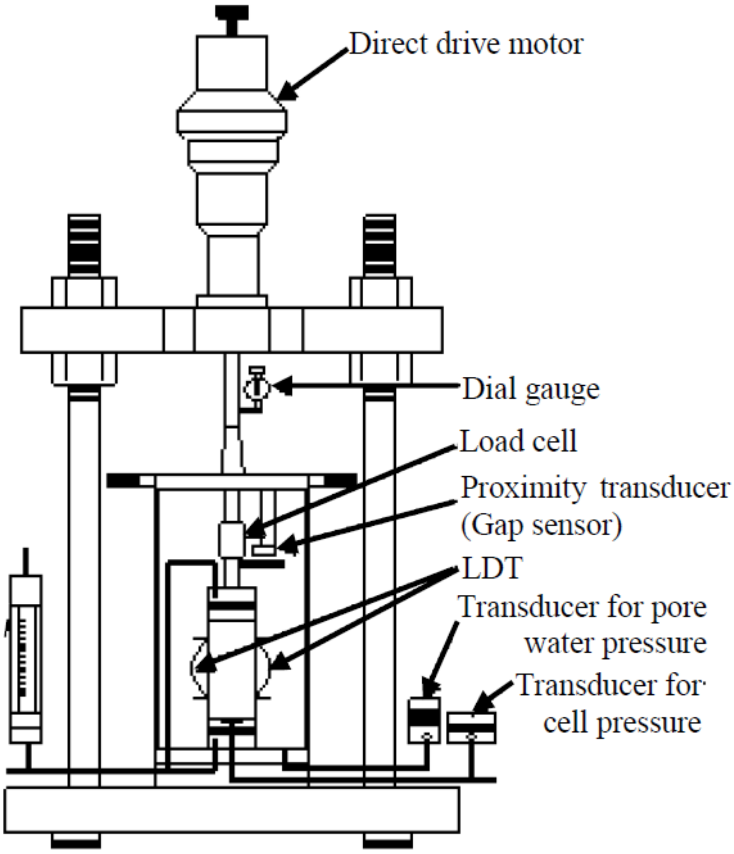

Figure 5.3 Schematic figure of the test apparatus

The LSS specimens (Pc-0, Pc-10) at curing time of 28 and 56 days were carried out by CUB tests. The specimens were saturated by using the double vacuum pressure method. The de-air water flowed through the specimen under the backpressure of 196 kPa. The isotropic consolidation was performed for 16 hours under the effective confining pressure of 98 kPa. After that, the triaxial shear was carried out under the constant strain rate, 0.054 % / min.

5.2.4.2 Portable Falling weight deflectometer (FWD) test

The schematic of a portable FWD test apparatus is shown in Figure 5.4. The apparatus consists of the weight to fall freely on its loading plate to apply impact load and the acceleration sensors to measure the displacement caused by the fall at the center of impact load and also at points in a radial direction from the center of impact load.

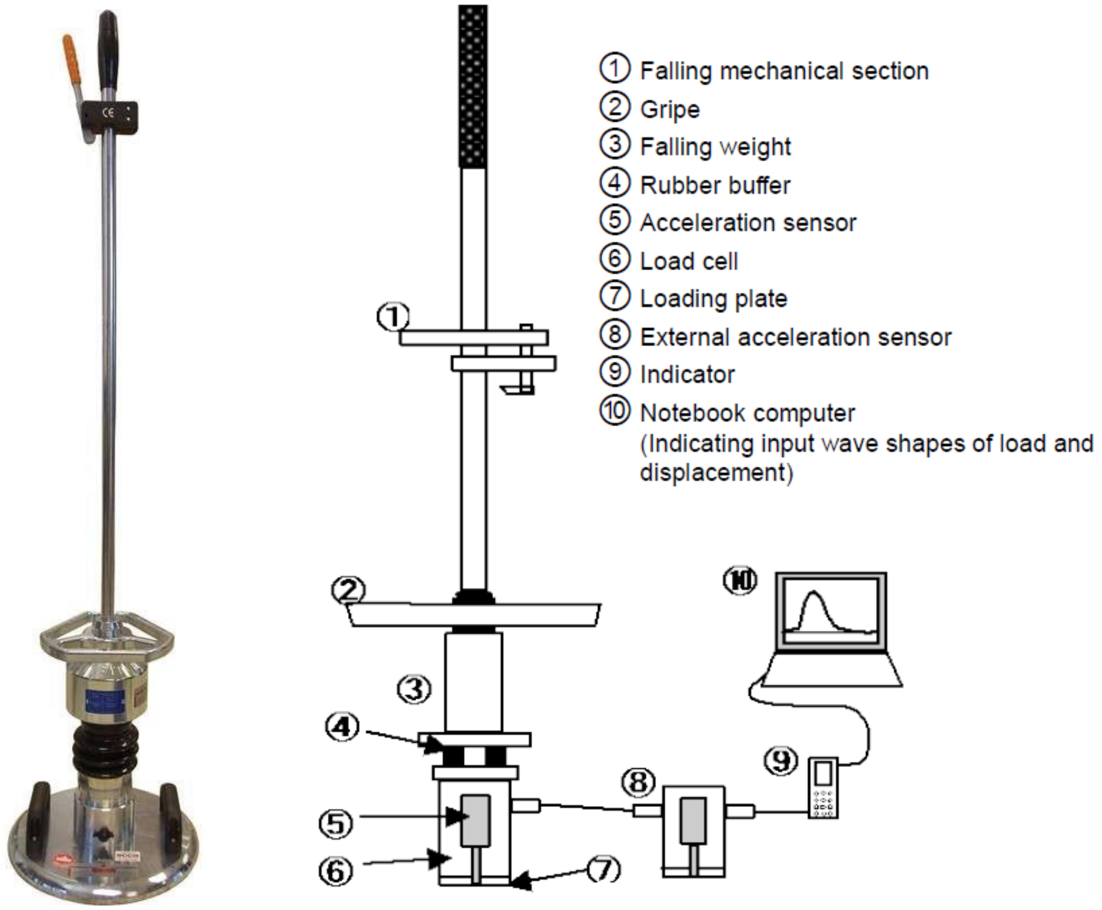

Figure 5.4 Schematic of portable FWD test apparatus

Generally, the stiffness of natural/artificial ground is evaluated by the plate loading test. From this test, the K_{30}-value with a 30 cm diameter loading plate is obtained from the relation between 1.25 mm displacement and corresponded load strength on static loading. In portable FWD tests, loading and displacement are measured and $K_{P.FWD}$-value is obtained from its relation. The value evaluates the stiffness of the ground. In this study, the loading plate diameter of the apparatus was 10 cm. Therefore, the $K_{P.FWD}$-value at 30 cm loading plate diameter was calculated as the Eq. (5.1).

$$K_{P.FWD} = (P_{P.FWD.\varphi}/\delta_{P.FWD.\varphi}).(\varphi_{P.FWD}/\delta_{PLT}) \text{ (MN/m3)} \qquad (5.1)$$

Where:

$P_{P.FWD.\varphi}$: loading stress at displacement $\delta_{P.FWD.\varphi}$

$\delta_{P.FWD.\varphi}$: displacement

$\varphi_{P.FWD}$: loading plate diameter of portable FWD

φ_{PLT}: loading plate diameter of plate load test (30 cm)

The model ground was subjected to the test at a curing time of 28 and 56 days, respectively.

5.3 TEST RESULT AND DISCUSSION

5.3.1 Relationship between deviator stress and axial strain

Figure 5.5 shows the change in the temperature of the environment during the curing period, measured hourly by a temperature sensor installed at the excavation hole in the field of the campus. It is seen that the average temperature is about 9°C from early November until about November 20. From November 20, the average temperature is about 5°C. There is a decreasing trend in temperature during the curing time. It is explained by the weather conditions of the Hokkaido area, which is changing from autumn to winter.

Figure 5.6 shows the relationship between the curing temperature (average temperature in the ground) and the maximum deviator stress q_{max}. The maximum deviator stress has been obtained from the relationship between deviator stress q ((= $\sigma_1-\sigma_3$) and axial strain ε_a, which were results of CUB test under the confining pressure σ'_c = 98 kPa of LSS mixed with fiber material of 0, 10 kg/m^3 (Pc-0, 10), respectively at 28 and 56 curing days. It is found that the q_{max} of paper content 0 kg/m^3 (Pc-0) in case of reducing the temperature in the ground from 9.1°C to 7.3°C trends to be almost constant. On the other hand, the q_{max} of Pc-10, which is the LSS mixed with fiber material of paper content 10 kg/m^3, increases as the decrease of the temperature in the ground from 9.1°C to 6.2°C. It is considered that this is due to the increase of the curing days.

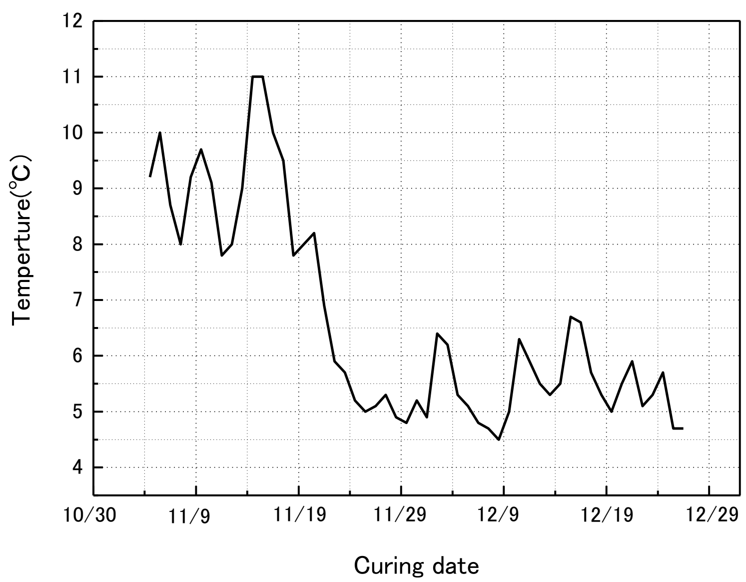

Figure 5.5 Relationship between temperature and curing date

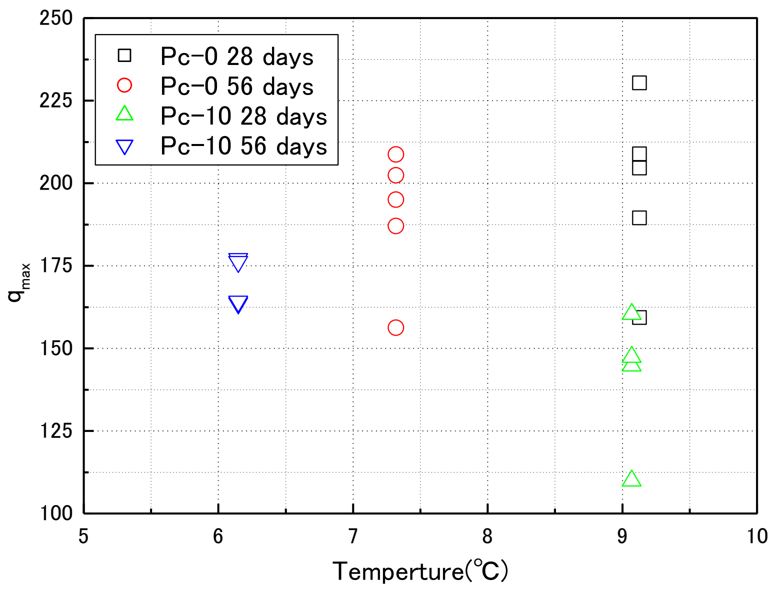

Figure 5.6 Relationship between q_{max} and temperature

The relationship between the deviator stress q and the axial strain ε_a is shown in Figure 5.7. It can be seen that the deviator stresses of Pc-0 are larger than Pc-10, but the $q\sim\varepsilon_a$ curve of Pc-0 after the peak decreases suddenly. And more, the deviator stress of Pc-0 at 28 curing days tends slightly larger than that one at 56 curing days. It can be considered due to curing conditions where the temperature and humidity at field are not constant and very different from indoor curing conditions. Or maybe the strength of the sample was influenced by the sampling disturbance. To make this point more clear, we need to conduct more field tests the next time.

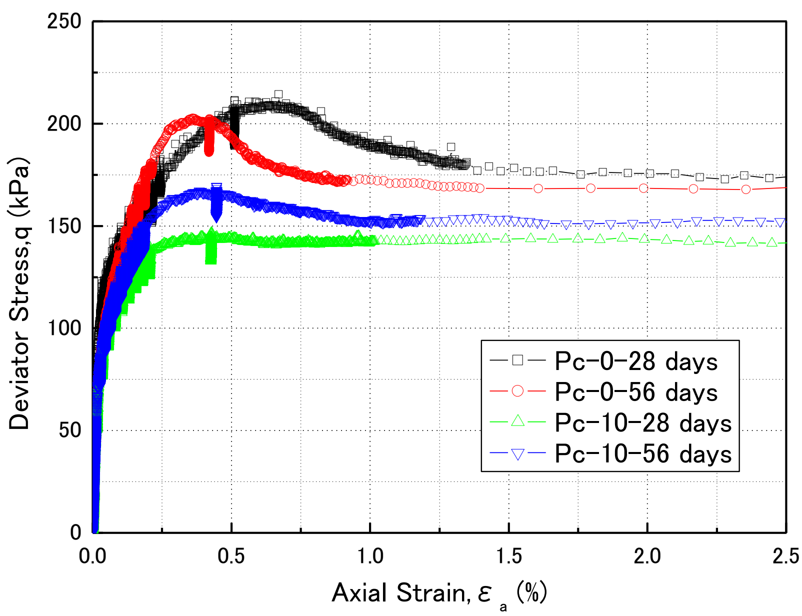

Figure 5.7 Relationship between deviator stress q and axial strain ε_a

However, in the case of Pc-10, an increasing trend of the deviator stress is seen as the curing days increase and the deviator stress after the peak does not reduce significantly for both 28, 56 curing days, respectively. It is considered that there is a reinforcement effect by adding fiber material into LSS.

Therefore, from the above results, it is seen that curing temperature could affect the deviator stress of LSS without fiber material. As for LSS with fiber material, there is an independence of the deviator stress q on the curing temperature when the curing days increases. The brittle property of LSS without fiber material has been improved by the reinforcement effect of adding fiber material as similar to the previous researches (Kohata et al., 2007; Ito et al., 2011; Duong et al., 2104). It is found that aseismic performance in the ground is improved and toughness ground will be constructed when the LSS with fiber material is used as backfilling.

5.3.2 Deformation property

5.3.2.1 Definition of Young's modulus

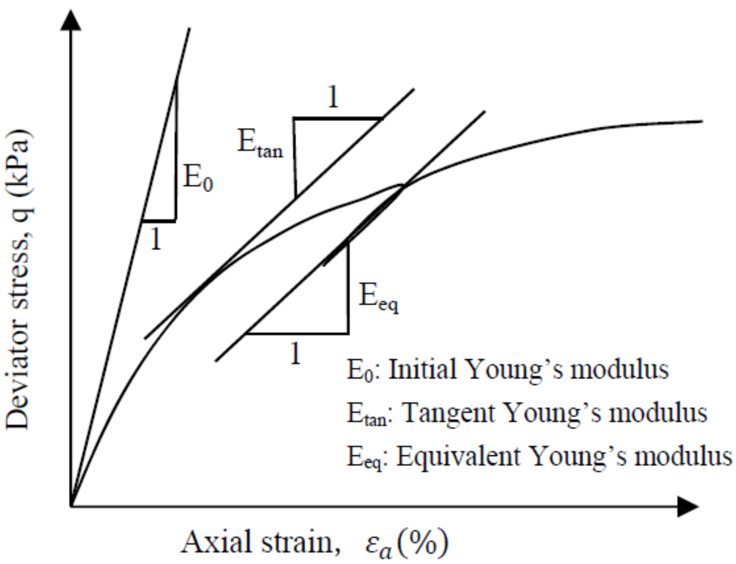

Figure 5.8 Definition of various Young's moduli

The definitions of various Young's moduli are indicated in Figure 5.8. The initial Young's modulus E_0 is defined as initial stiffness at a small strain of $\varepsilon_a = 0.002$ % or less. The tangent Young's modulus E_{tan} is defined as a tangential gradient in the q~ε_a curve, and it indicates the non-linearity of deformation property in q~ε_a relation. The equivalent Young's modulus E_{eq} is obtained from a small unloading/reloading loop during monotonic loading. Moreover, the E_{eq} in creep correction is calculated from the slope of the lower limit point and the midpoint in a line connecting the unloading point and the intersection of the q~ε_a curve in reloading. The E_{eq} indicates a changing of damage degree during shear (Kohata et al., 1997 and 1999).

5.3.2.2 Initial Young's modulus E_0

Figure 5.9 shows the influence of curing temperature on Initial Young's modulus E_0 of Pc-0, 10 respectively at 28 and 56 curing days. It is found from Figure 5.9 that E_0 values of Pc-0 at 28 and 56 curing days have almost no change. It is seen that the effect of curing temperature on E_0 values of Pc-0 is small. Moreover, the E_0 value of Pc-10 at 56 curing days is larger than E_0 value of 28 curing days. Therefore, it is considered that the effect of curing temperature is smaller than that of curing days on Initial Young's modulus E_0.

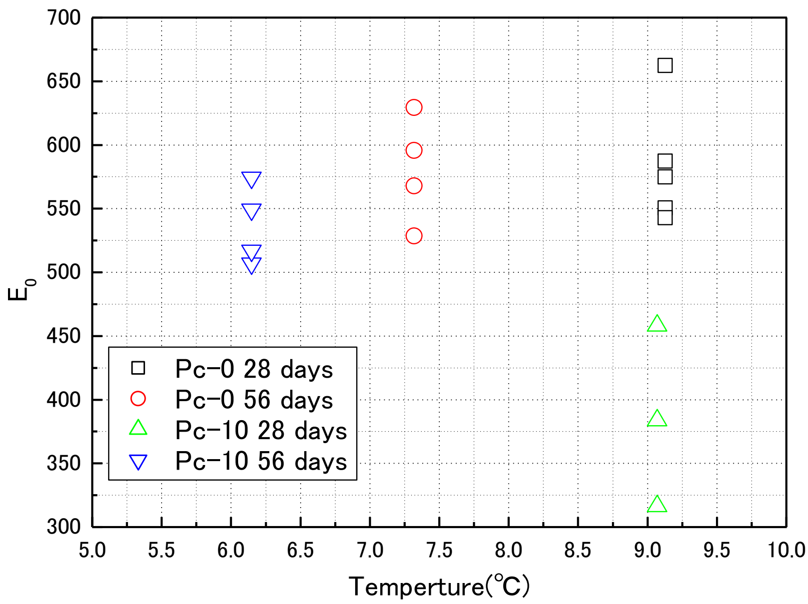

Figure 5.9 Relationship between E_0 and temperature

5.3.2.3 Tangent Young's modulus E_{tan}

The relationship between E_{tan}/E_0 and q/q_{max} of Pc-0, 10, respectively, at 28 and 56 days is shown in Figure 5.10. The values were obtained from the q~ε_a curve of the CUB test under the confining pressure of 98 kPa. In this Figure, the reduction rate of E_{tan}/E_0 shows a similar tendency in both Pc-0 and Pc-10 at 28 and 56 days, respectively. However, the reduction rate of E_{tan}/E_0 of Pc-0 is larger than Pc-10 at both 28 and 56 days.

Therefore, it is considered that the effect of adding the fiber material on LSS increases the non-linearity of deformation property in $q \sim \varepsilon_a$ relation while the curing temperature is lower.

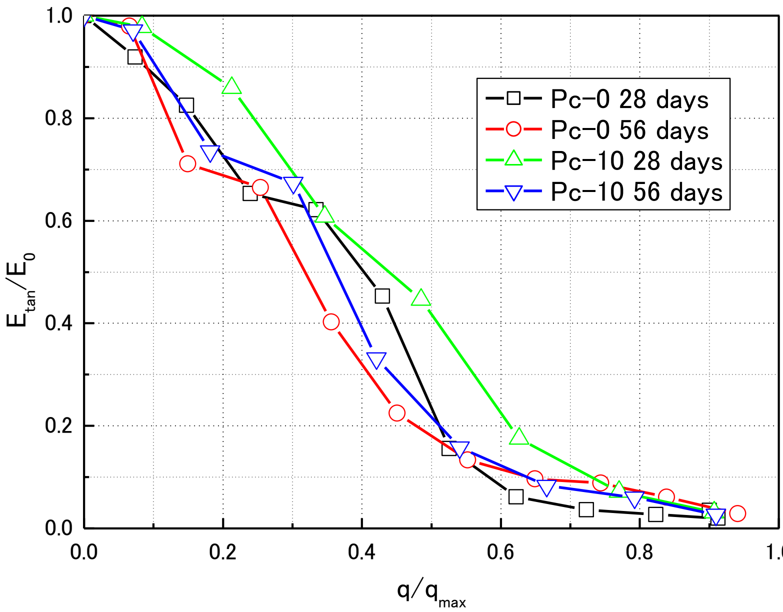

Figure 5.10 $E_{tan}/E_0 \sim q/q_{max}$ relations

5.3.2.4 Equivalent Young's modulus, E_{eq}

Figure 5.11 shows the relationship between E_{eq}/E_0 and q/q_{max} of Pc-0, 10, respectively, at 28 and 56 days. The E_{eq} values are obtained from the $q \sim \varepsilon_a$ curve of CUB tests under confining pressure 98 kPa at a small loading/reloading loop during monotonic loading. According to the previous study, Initial Young's modulus of cement-treated soil at a small strain was independent of the confining pressure. Therefore, the E_{eq}/E_0 is considered to express the degree of damage during shear. At the first period of the curing process, the soil sample is locally broken, and the collapse of soil progresses as the load value increases during shear. Finally, the specimen failures wholly as the shear band formed by the accumulation of local damages. This is explained that the cementation or microstructure between particles of soil is damaged. It caused the changes in the elasticity property of soil.

It is seen from Figure 5.11 that the reduction rate of E_{eq} / E_0 of Pc-0 is larger than Pc-10 at 28 days. For the sample of 56 days, there is no significant difference between the reduction rate of E_{eq} / E_0 of both Pc-0 and Pc-10. It is considered that during the first period of the curing process of LSS mixed fiber material, the addition of the fiber material into LSS is reduced the damage degree during shear. However, there is unclear when the curing days increases and the curing temperature drops significantly. It is probably due to the effect of the freezing and thawing process of water inside the sample under the field or the disturbance at the time of sampling (Duong et al., 2014). For this result, it considered conducting further works the next time.

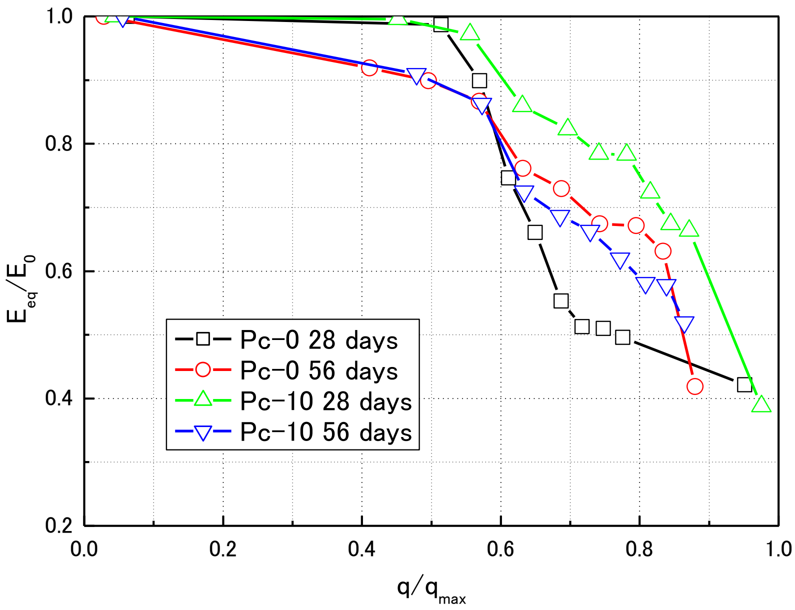

Figure 5.11 $E_{eq}/E_0 \sim q/q_{max}$ relations

5.3.3 Strain level – dependency of Young's modulus

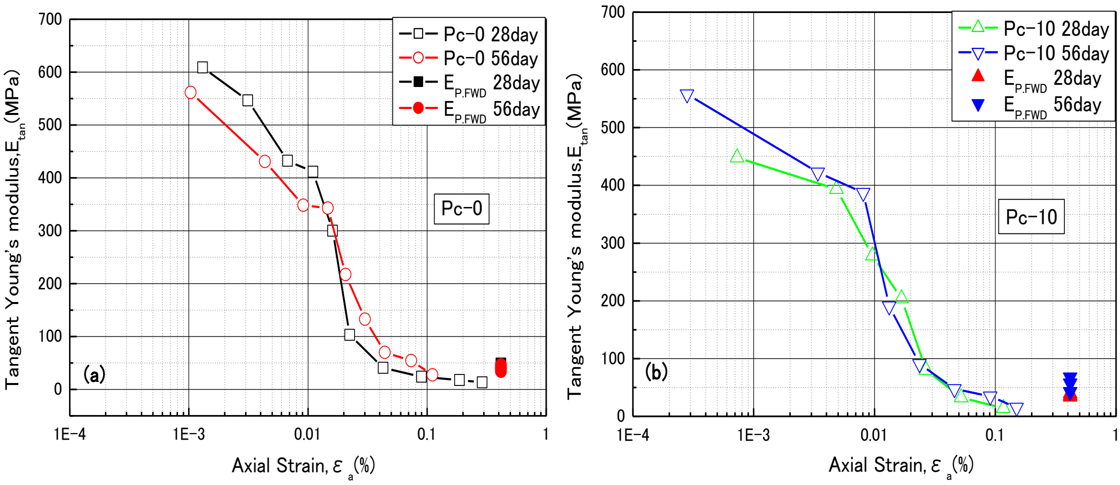

Figure 5.12 $E_{P.FWD}$ and $E_{tan} \sim \log \varepsilon_a$ relations

Figure 5.12 (a) and (b) show the strain level-dependency of tangent Young's modulus E_{tan} obtained in $q \sim \varepsilon_a$ relation from CUB tests of Pc-0 and Pc-10 at 28 and 56 days, respectively. And also, the value of $E_{P.FWD}$ in each sample is shown in this figure.

The $E_{P.FWD}$ value was calculated from the value of $K_{P.FWD}$, which was obtained by a portable FWD test performed on the surface of field ground. As shown in this figure, the values of E_{tan} and $E_{P.FWD}$ at the same strain level are approximately equal. It is found that the K-value by portable FWD can be evaluated the stiffness of backfilling ground by LSS with fibered material adequately.

5.4 SUMMARY

To investigate the effect of various factors on the strength and deformation property of Liquefied Stabilized Soil prepared at field, the specimens prepared by trimming LSS retrieved from the model ground (field LSS) by block sampling were subjected to CUB tests. In parallel, the portable FWD tests were carried out on the backfilling ground at a curing time of 28 and 56 days.

The following conclusions were derived based on test results.

- The curing temperature could affect the deviator stress q of LSS without fiber material. As for LSS with fiber material, there is an independence of the deviator stress q on the curing temperature when curing days increases. The brittle property of LSS without fiber material has been improved by the reinforcement effect of adding fiber material. It is found that aseismic performance in the ground is improved and toughness ground will be constructed when the LSS with fiber material is using as backfilling.
- The effect of curing temperature is smaller than that of curing days on Initial Young's modulus E_0.
- The effect of adding the fiber material on LSS increases the non-linearity of deformation property in $q \sim \varepsilon_a$ relation while the curing temperature has been lower.
- During the first period of the curing process of LSS mixed fiber material, the addition of the fiber material into LSS is reduced the damage degree during shear. However, there is unclear when the number of curing days increases and the curing temperature drops significantly. For this result, it considered conducting further works the next time.
- The K-value by portable FWD can be evaluated the stiffness of backfilling ground by LSS with fibered material adequately.

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CHAPTER 6

EVALUATION OF THE REDUCTION OF THE SEISMIC MOTION TO GROUND SUBJECTED BY USING LIQUEFIED STABILIZED SOIL

6.1 INTRODUCTION

A long time ago, in the big cities in Japan such as Tokyo, Nagoya, and Osaka, etc., when the subway lines, underground constructions, and high-rise buildings were built, millions of cubic meters of soil were excavated. The soil was carried by trucks from underground construction sites to disposal sites, which was the cause of environmental pollution. With limited urban land, landfill sites were more and more scarce and led to an overload state. The questions were where to put the excavated soil and how to develop sustainable infrastructure, which did not only reduce the cost of construction but also did not affect the natural environment. To solve these problems, one of the methods was recycling the excavated soil as backfilling soil. "Liquefied Stabilized Soil" (LSS), which was reported by Kuno (1997), is one of the effective methods of using the excavated soil with construction works and has become popular in Japan. The LSS is a kind of cement-treated soil, which is prepared by mixing slurried soil and cement stabilizer. The LSS mixtures are not only created stabilized ground without compaction but also easy to fill space by pumping a long distance. However, the increase in cement content does not only increase the strength property, but also the brittleness increases. To improve the ductile performance of LSS, a reinforcement method has been created by mixing the newspaper as a fiber material into LSS. It was shown that the ductile property of LSS mixed with pulverized newspaper as a fiber material after the peak in the $q \sim \varepsilon_a$ curve was significantly improved by the reinforcement method (Kohata et al., 2002, 2004, 2006 and 2007; Duong et al., 2014). There are many previous studies on the influence of various factors on LSS (Duong et al., 2015; Do et al., 2018 and 2019; Pham et al., 2019; Cui et al., 2020). However, there is no research on the effect of using LSS as a backfilling material on the structure and the ground when the earthquake occurs.

In this study, the effect of backfilling material on the building and the ground under the earthquake is analyzed by using the FEM method. Based on the analysis results, the influences of LSS as backfilling material on the building and the ground were discussed.

6.2 NUMERICAL SIMULATION

6.2.1 Simulation of study cases

In this study, it was assumed that a 10-story building with a basement was constructed by the open-pit method. The pit was excavated to the bottom of the basement with the size as shown in Figure 6.1. When the basement is completed, the excavation region will be filled with backfilling material. The backfilling content in each case would be Case 1: backfilling soil (sandy soil), Case 2: LSS, and Case 3 was LSS mixed with fiber material (10 kg/m^3). Subsequently, nonlinear time-domain dynamic analysis under the earthquake was conducted. From the results, the effect of backfilling material on the building under in each case was discussed. Acceleration and velocity of five points on the ground surface A, B, C, D, E with distances of 0, 3, 5.95, 10.5, 18 m, respectively from the edge of the building were compared and investigated.

6.2.2 Numerical modeling and parameter

6.2.2.1 Structural modeling

In this study, a reinforced concrete ten-floor building frame, 30 m high and 12 m wide with 16 columns consisting of three spans of 4 m in each direction, and ten slabs and one basement was selected, as shown in Figure 6.1. The height of the floors was 3 m, and the basement floor was located at a depth of 4.5 m below the ground surface. The reinforced concrete foundation was 15x15 m square, and 1 m thick, and the reinforced concrete pile of 20 m depth and 1.2 m in diameter was selected to analyze in this study. The structural sections were specified after conducting a routine design procedure regulated in the relevant building codes (British standard, 2004). SAP2000 v 22 software was utilized for the structural analysis and design of the cross-sections of columns and slabs. The parameters of the columns, floor, foundation, and pile are shown in Tables 6.1 and 6.2, respectively.

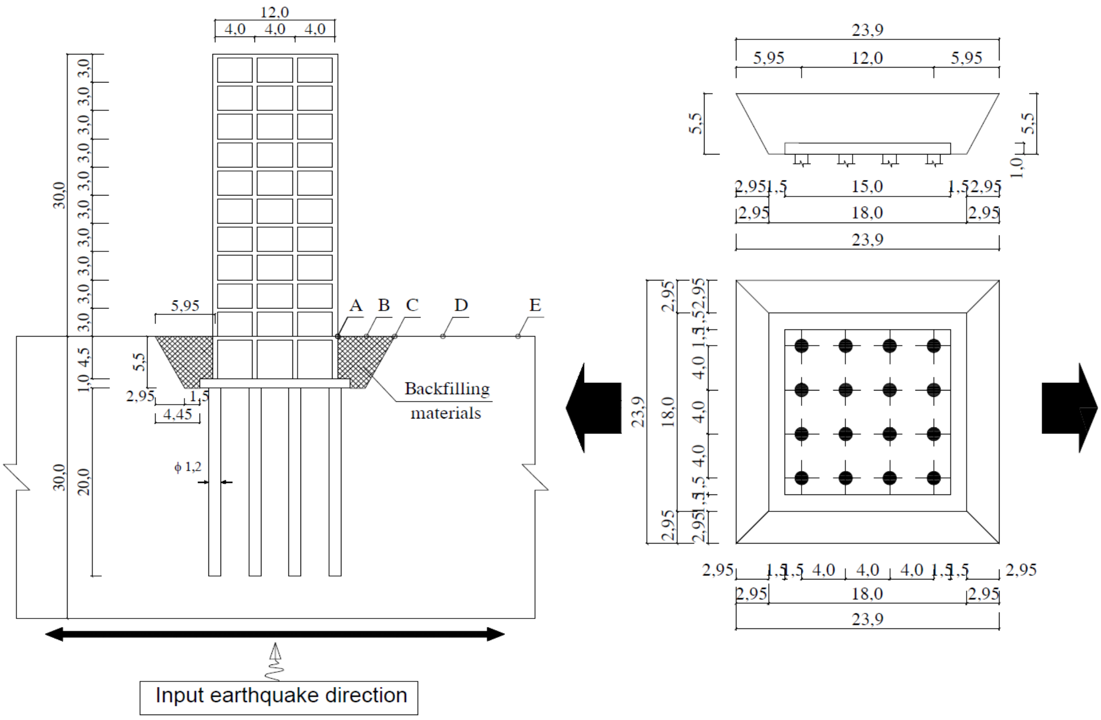


Figure 6.1 Dimension of the structure and excavation

Table 6.1 Characteristic of designed reinforced concrete column sections adopted in 3D FEM

Section Type	I_x (m^4)	I_y (m^4)	Area (m^2)	E (kN/m^2)	ν
Type I (levels 1-5 and basement)	3.64E-3	7.45E-3	0.25	2.86E7	0.2
Type II (levels 6-10)	1.50E-3	3.05E-3	0.16	2.86E7	0.2

Table 6.2 Characteristic of designed reinforced concrete floor slabs and foundations adopted in a 3D numerical model

Properties	Denote	Unit	Value
Floor slab thickness	h_s	m	0.25
Basement wall thickness	h_w	m	0.35
Foundation thickness	h_f	m	1
Density	ρ	kN/m^3	23.54
Young's modulus	E	kN/m^2	2.86E7
Poisson's ratio	ν	-	0.2

The structural elements were modeled by using an elastic-viscoelastic constitutive equation. In the time domain, material damping needs to be converted to Rayleigh damping as follows (Ryan et al., 2008).

$$[C] = \alpha\,[M] + \beta\,[K] \tag{6.1}$$

Where:

[C]: damping matrix

[M]: mass matrix

[K]: stiffness matrix

α: mass-proportional coefficient

β: stiffness-proportional coefficient

The mass-proportional (α) and stiffness-proportional (β) coefficients are calculated from selected natural frequencies and the damping ratio. The values of α and β are defined as follows (Chopra, 2011):

$$\boldsymbol{\alpha} = \xi \frac{2\omega_m\omega_n}{\omega_m+\omega_n} \tag{6.2}$$

$$\boldsymbol{\beta} = \xi \frac{2}{\omega_m+\omega_n} \tag{6.3}$$

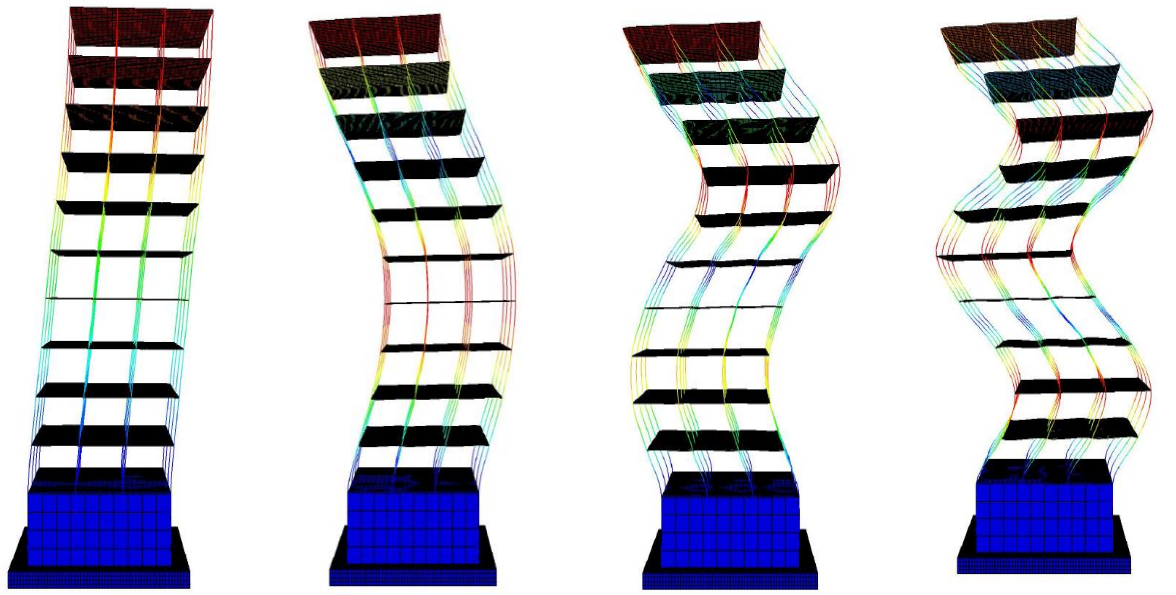
Where:

ξ: damping ratio

$\omega_m = 2\pi f_m$: angular frequency of corresponding mode m

$\omega_n = 2\pi f_n$: angular frequency of corresponding mode n

In this study, the natural frequencies of the building for the fixed base structure were simulated by SAP 2000 v22 program as shown in Figure 6.2. Base on this simulation, the first and second natural frequencies are selected to determine the values of $\omega_1 = 7.96$ (rad/s) and $\omega_2 = 22.32$ (rad/s), respectively. From Equation (6.2) and (6.3) with the material damping of 5 %, the mass-proportional and stiffness-proportional coefficients were obtained as $\alpha = 0.5868$ and $\beta = 0.0033$, respectively.



Mode 1: $f_1 = 1.267$ Hz   Mode 2: $f_2 = 3.553$ Hz   Mode 3: $f_3 = 6.267$ Hz   Mode 4: $f_4 = 8.968$ Hz

Figure 6.2 The natural frequencies of the structure

6.2.2.2 Soil modeling and characteristic of backfilling materials

The present building is constructed on 30 m deep soft clayey soil on the bedrock. From the previous research (Rayhani et al., 2008), this bedrock depth is reasonable because most of the amplification is in the first 30 m of the soil column. The properties of this soft soil were determined from actual in-situ and laboratory tests (Rahvar, 2006) with a density of 14.416 kN/m^3, a shear wave velocity of 150 m/s, and undrained shear strength of 50 kN/m^2. It was assumed that the groundwater level was equal to the level of the bedrock.

In this study, the properties of LSS and LSS with fiber (10 kg/m^3) were achieved from the laboratory tests. The relationship between deviator stress and axial strain of all samples Pc-0 (0 kg fiber/m^3) and Pc-10 (10 kg fiber/m^3) was shown in Figure 6.3. Because of the scattering of the laboratory experiments for a long time, the average parameters of LSS and LSS with fiber were used in this simulation. LSS slurry was made by the following procedure. New Snow Fine Clay (NSF-Clay) and water were put into a big bucket and mixed by hand mixer. The density of the mixture was adjusted to 12.562 kN/m^3 by measuring the mass of slurry filled into a stainless steel container of 400 cm^3 called "AE mortar container". After that, the cement content of 80 kg/m^3 was put into the mixture and mixed slowly and carefully by hand mixer. The flow test was controlled according to the JHS A313-Japan Highway Public Corporation Standard to measure the liquidity of LSS. The fiber material amount of 10 kg/m^3 were added with LSS slurry and mixed slowly and carefully by hand mixer. The damping ratio of LSS and LSS with fiber is assumed as 10 and 12 % (Duong et al., 2015; Do et al., 2019).

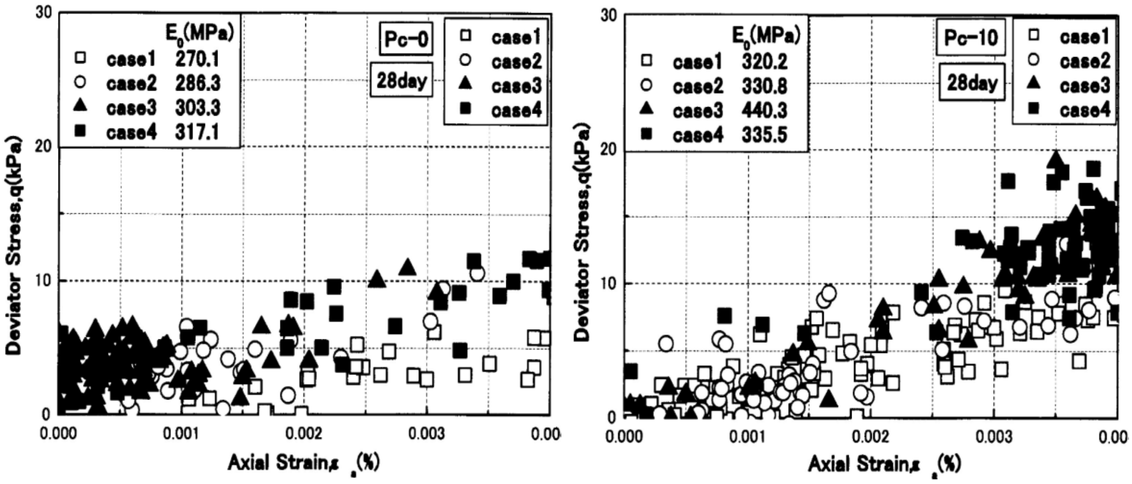


Figure 6.3 The relationship between deviator stress and axial strain of LSS and LSS with fiber.

On the other hand, characteristics of backfilling soil are considered as follows. Because of not much investigation results on the stiffness of the backfilling soil, the investigation results on backfilling soil in Daikai station, which suffered from the Southern Hyogo prefecture earthquake in 1995, were used as the backfilling soil parameters. N value and unit weight, ρ was set at 10 and 17.0 kN/m^3, respectively. Shear modulus, G = 51.531 MN/m^2, was estimated from N value by Railway Design Standard (1999). The damping ratio of backfilling soil was assumed as 4 %. The physical properties of backfilling materials are shown in Table 6.3.

Table 6.3 Parameters of backfilling materials

Material	E (kN/m^2)	ρ (kN/m^3)	V_s (m/s)	ξ (%)	ν
Backfilling soil	1.529E5	17	150	4	0.49
LSS	2.942E5	13.356	269	10	0.49
LSS with fiber	3.567E5	14.69	282.66	12	0.49

The Rayleigh damping coefficients of the soil are obtained from Equation (6.2) and (6.3). The first and second natural frequencies of the soil are selected to calculate the mass-proportional and stiffness-proportional coefficients. The values of natural frequencies of the ground are calculated as the following equation (Kramer, 1996):

$$f_n = \frac{V_s}{4H}(2n - 1) \tag{6.4}$$

Where:

n: mode number

f_n: natural frequency of the corresponding mode n

V_s: shear wave velocity of the soil deposit

H: soil deposit thickness

For multi-layer ground, the average shear wave velocity $V_{s,30}$ should be computed by the following equation (Bristish standard, Eurocode 8, 1998-2004):

$$V_{s,30} = \frac{30}{\sum_{i=1}^{N} \frac{h_i}{V_i}} \tag{6.5}$$

Where:

h_i: denote the thickness

$V_{s,30}$: average shear wave velocity (at a shear strain level of 10-5 or less) of the i-th formation or layer, in a total of N, existing in the top 30 m.

The Rayleigh damping coefficients of the soil are shown in Table 6.4.

Table 6.4 Rayleigh damping coefficients of the soil

Case	Material	h(m)	V_s(m/s)	$V_{s,30}$(m/s)	f_1	f_2	α	β
Case 1	Backfilling soil	5.5	172	153.6	1.28	3.84	0.4825	0.0025
	Soft clay soil	24.5	150				0.6031	0.0031
Case 2	LSS	5.5	269	163.24	1.36	4.08	1.282	0.00585
	Soft clay soil	24.5	150				0.641	0.00292
Case 3	LSS with fiber	5.5	282.66	164.12	1.367	4.1	1.547	0.007
	Soft clay soil	24.5	150				0.6445	0.0029

6.2.2.3 Seismic motion

In this study, the 1968 Tokachi-Oki earthquake in Hachinohe (Japan) was selected and utilized onto the finite element numerical model for conducting a time-history analysis. This earthquake has been chosen by the International Association for Structural Control and Monitoring for benchmark seismic studies (Karamodin et al., 2010). The characteristics of the earthquake ground motions were indicated in Table 6.5, and the time histories of the earthquake were shown in Figure 6.4. It was assumed that the earthquake ground motions are bedrock records.

Table 6.5 Characteristics of the adopted earthquake records

Earthquake	Country	Year	PGA (g)	M_w (R)	Duration (s)	Hypocentral distance (km)
Tokachi-Oki	Japan	1968	0.229	7.5	36	14.1

Note: PGA: peak ground acceleration; M_w: moment magnitude scale

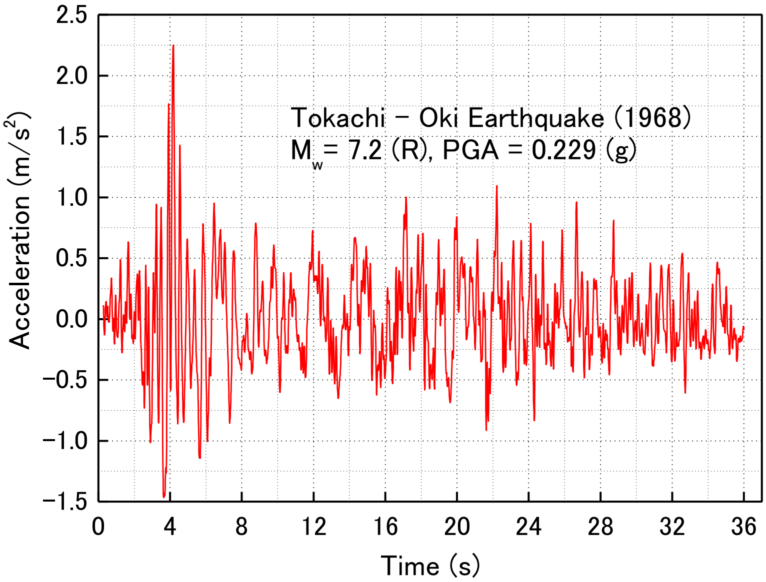


Figure 6.4 The time histories of the 1968 Tokachi-Oki earthquake in Hachinohe city in Japan

6.2.2.4 Numerical modeling in the ABAQUS program

In this study, the effect of backfilling material on the building and the ground under the earthquake is analyzed by using ABAQUS 2020, a FEM analysis program. Both linear and nonlinear analyses are provided in ABAQUS to evaluate the interaction between the building and the ground.

Beam elements (B33: 2 - node linear beam element in space) in ABAQUS are used for simulation of the columns. The floor slabs and basement walls were simulated by the shell elements (S4R: 4-node, quadrilateral, stress/displacement shell element with reduced integration), whereas the foundation and pile elements were modeled by solid elements (C3D6: 3D, 6-node linear triangular prism elements). Besides, the soil medium was modeled by using C3D8R elements (3D, 8- node linear brick, reduced integration, hourglass control elements), and C3D6 elements. The free-field soil columns were simulated by CIN3D8 elements with 3D, 8- node linear one-way infinite brick, but they have defined orientations, unlike the other numerical elements. A summary of all element types used in the FEM in this study is presented in Figure 6.5. The mesh of the structure and soil medium is shown in Figure 6.6 consists of 80135 elements and 109805 nodes. Because this model is huge (approximately 98.2 gigabytes for a single case), the very fast computer at the Muroran Institute of Technology, Hokkaido, Japan, was used to conduct this time history analysis, and even then, it took approximately 3 days (72 hours) to run a single case under the applied earthquake motion. The results of the 3D finite-element numerical simulation are discussed in the following sections.

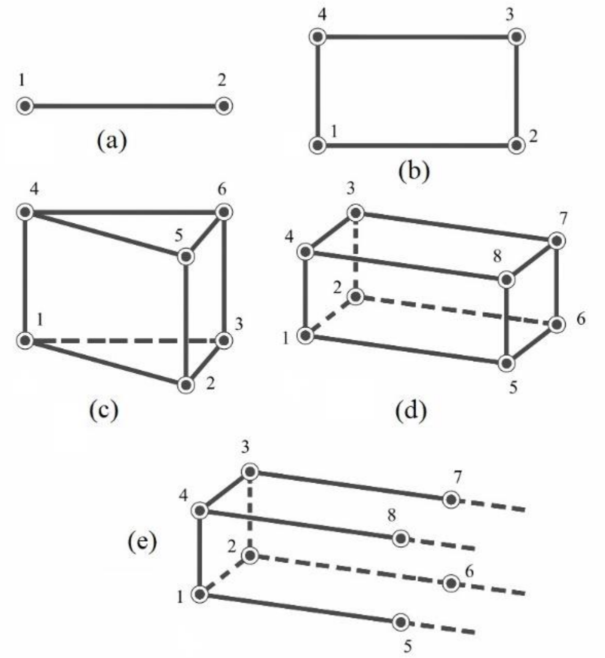


Fig. 6.5 Element types used in FEM: (a) 2-node linear beam element in space (B33); (b) 4-node, quadrilateral, stress/displacement shell element with reduced integration (S4R); (c) 3D, 6-node linear triangular prism elements (C3D6); (d) 3D, 8-node linear brick, reduced integration, hourglass control (C3D8R); (e) 3D, 8-node linear one-way infinite brick (CIN3D8)

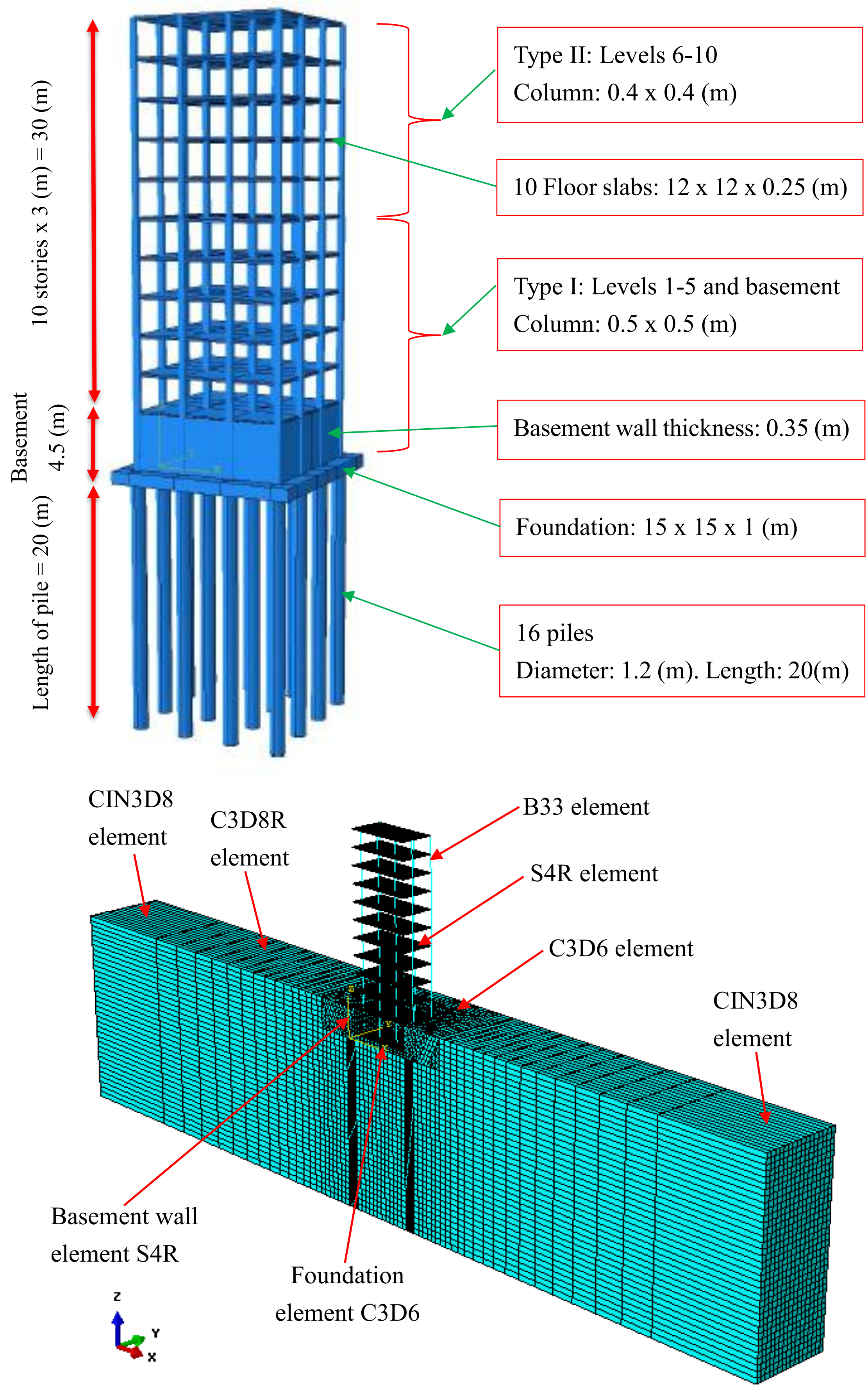


Figure 6.6 The FEM of the structure and ground in the ABAQUS software program

6.3 RESULT AND DISCUSSION

6.3.1 Maximum lateral displacement and inter-story drift

The maximum lateral displacement of the 10-story structure supported by the pile foundation under the 1968 Tokachi-Oki earthquake in each case is shown in Figure 6.7. It is found that the maximum lateral displacements of the building in Case 2 (LSS) and Case 3 (LSS mixed with fiber) have a significant reduction trend when compared with Case 1 (Backfilling soil). It is explained that this is due to the stiffnesses of LSS and LSS mixed with fiber are much larger than backfilling soil. Besides, the maximum displacement in Case 3 was a little smaller than in Case 2. It is considered that the effect of adding fiber material on LSS leads to increased stiffness and improved brittleness of LSS.

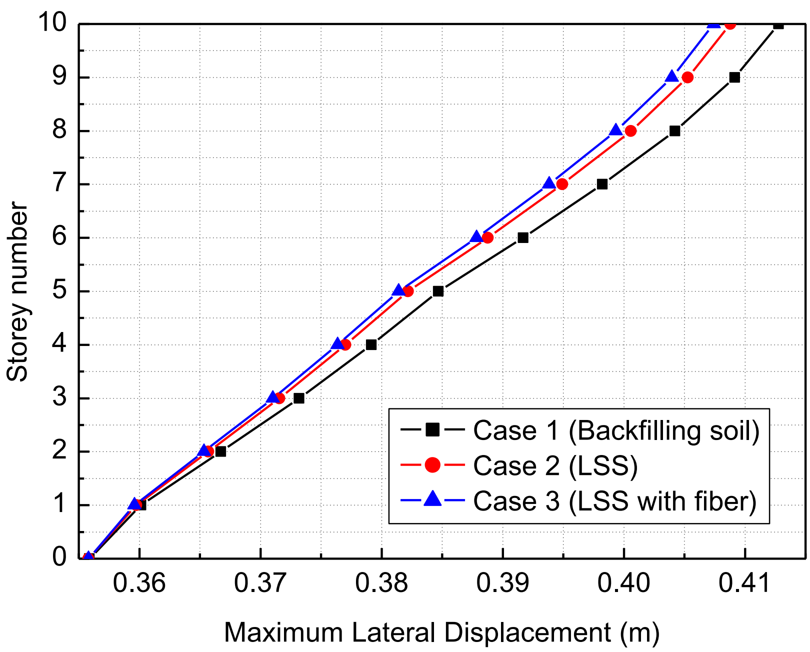


Figure 6.7 Maximum lateral displacement of the 10-story structure supported by pile foundation under the 1968 Tokachi- Oki earthquake

The maximum inter-story drifts of the building were calculated by the following equation (Standard Australia, 2007), and the results were indicated in Figure 6.8:

$$D_{rift} = \frac{d_{i+1-}\ d_i}{h} \qquad (6.6)$$

Where:

d_{i+1}: the deflection at the (i+1) level

d_i: the deflection at the (i) level

h: height of the story

Figure 6.8 shows that the inter-story drift of the building in Case 1 is the largest, followed by Case 2, and Case 3 is the smallest. It was found that when using LSS as a backfill material, the inter-story drift of the structure was reduced comparing to the backfilling soil. In particular, this figure also clearly shows the effect of fiber material, when mixed with LSS, will slightly reduce inter-story drift comparing with the case LSS without fiber.

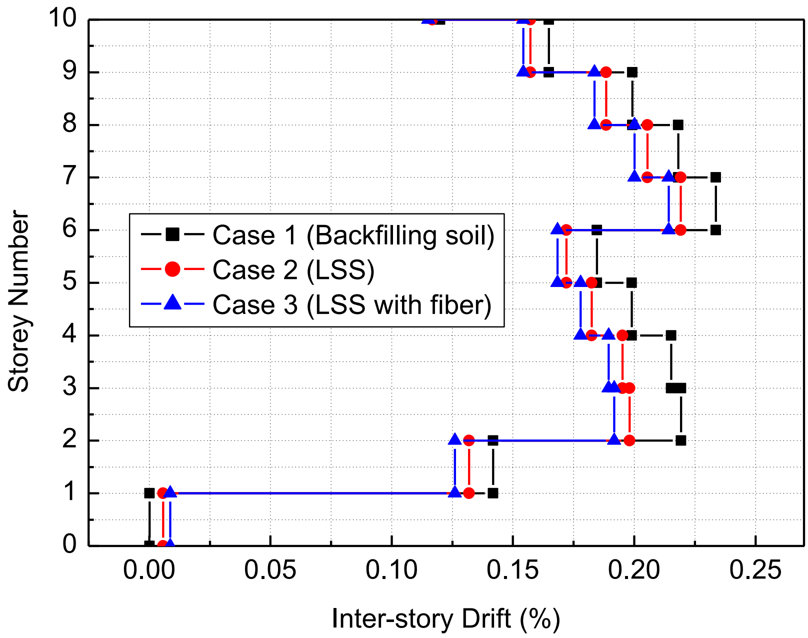


Figure 6.8 The inter-story drift of the 10-story structure supported by pile foundation under the 1968 Tokachi – Oki earthquake

Therefore, from the above results, it is seen that using LSS and LSS mixed with fiber as a backfilling material will reduce the lateral displacement and inter-story drift of building under the earthquake. Moreover, in this study, LSS mixed with fiber has a little useful than LSS without fiber.

6.3.2 Relationship between acceleration and velocity with distance

The maximum acceleration and velocity of 5 points A, B, C, D, and E in both the horizontal and vertical directions on the ground when affected by the earthquake are shown in Figure 6.9 – 6.12, respectively.

From the four figures above, we can see that the maximum acceleration and velocity values at 5 points in Case 2 is a little larger than in Case 3. Besides, there is a huge difference between Case 1 with Case 2 and Case 3. There is a significant decrease trend in maximum acceleration and velocity when using LSS with fiber as a backfilling material compared with backfilling soil. Point A is the adjacent location to the construction, has the accelerating and speed with the highest reduction rate of 32.3 %, 49.3 %, 3.2 %, and 24.8 %, respectively. It is followed by points B, C, and D that have a decreasing rate of acceleration and velocity inversely proportional to distance. In particular, from Figure 6.10 and Figure 6.12, we can see that acceleration and velocity in the vertical direction at point B has a reduction ratio slightly lower than point C. It is explained that point C is a special point, where the junction between the two types of soil is LSS and soft clayey soil. Finally, the location has the 18 meters farthest distance from the building is point E with almost no significant difference in the value of acceleration and velocity in the cases of LSS, LSS with fiber, and backfilling soil. It indicates that when using LSS with fiber and LSS as a backfill material will significantly reduce the acceleration and velocity of the ground around the building and the surrounding area when affected by the earthquake. It is considered by the fact that LSS with fiber and LSS have much higher stiffness and damping than backfilling soil.

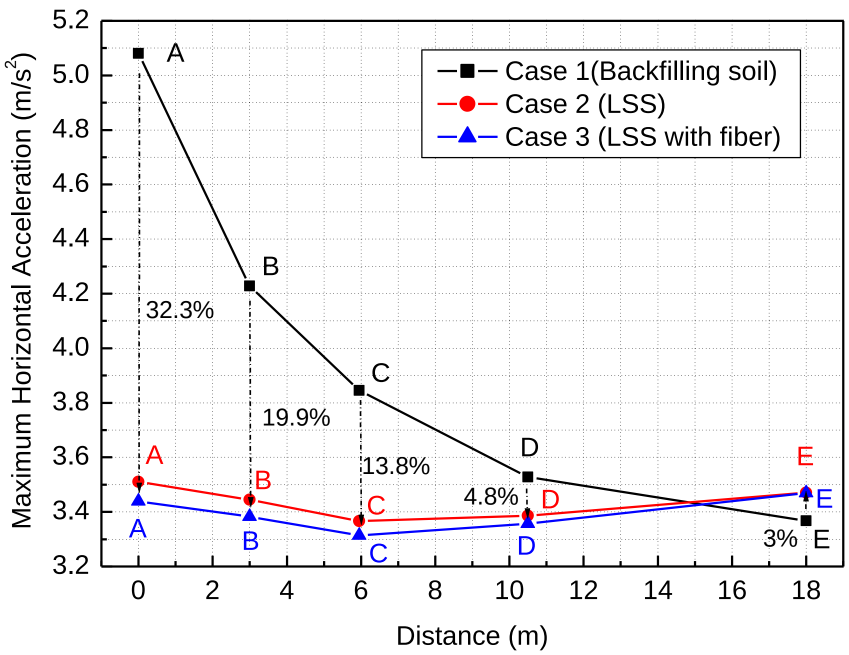


Figure 6.9 Maximum horizontal acceleration at points A, B, C, D, and E

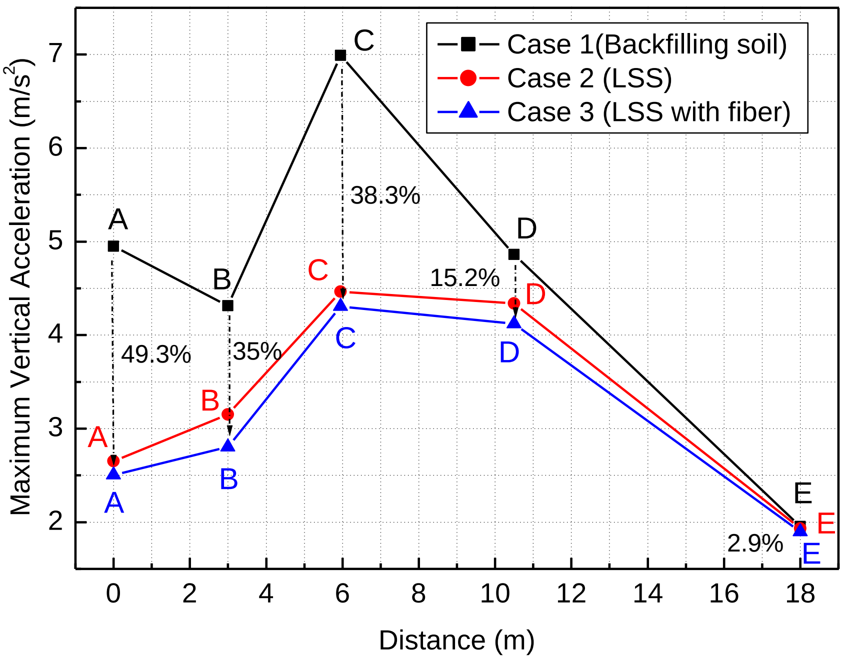


Figure 6.10 Maximum vertical acceleration at points A, B, C, D, and E

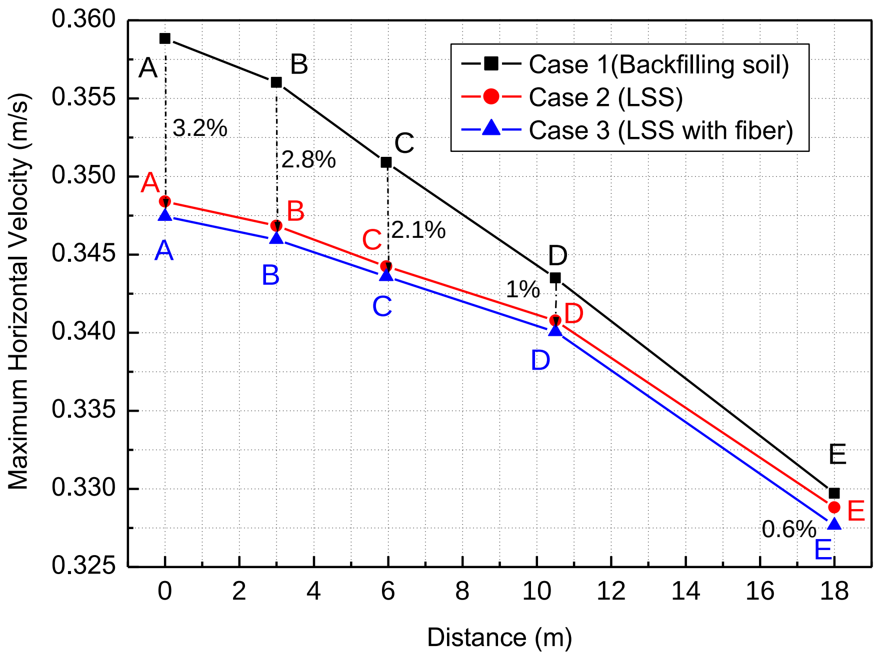


Figure 6.11 Maximum horizontal velocity at points A, B, C, D, and E

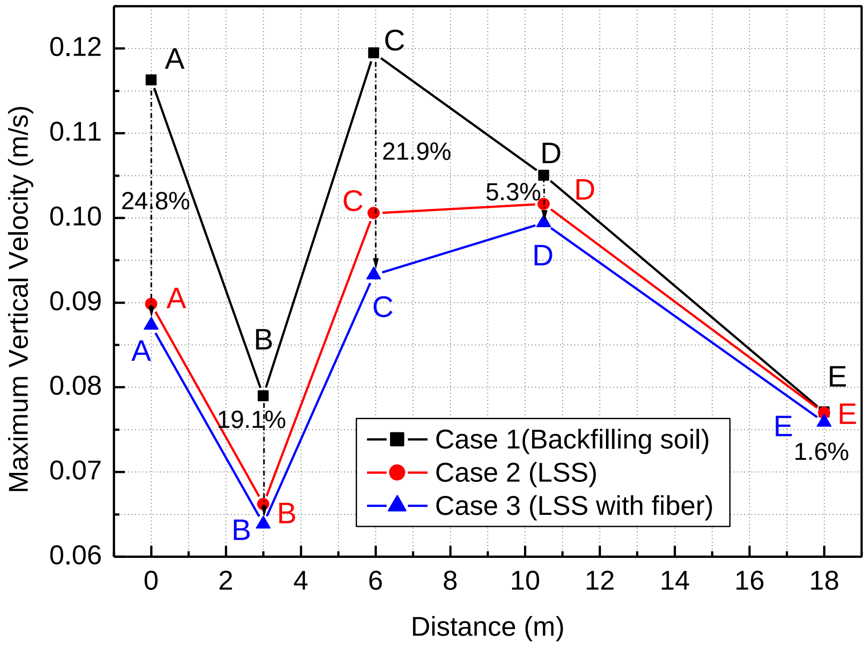


Figure 6.12 Maximum vertical velocity at points A, B, C, D, and E

Therefore, base on the above results, it is shown that the application of LSS with fiber as a backfill material will significantly reduce the acceleration and velocity of the ground around the building and adjacent areas. Furthermore, the effect of adding fiber in LSS was made more clear in this study. LSS mixed with fiber has more advantageous than LSS without fiber.

6.4 SUMMARY

To investigate the effect of using LSS as a backfilling material on the building and surrounding ground under an earthquake, the FEM of the structure and ground was simulated by the ABAQUS software program. After that, a nonlinear time-domain dynamic analysis under the earthquake was conducted. The displacement and inter-story drift of the building and acceleration and velocity of the ground corresponding to each kind of backfilling material were compared. Based on the analysis results, the following conclusions were obtained.

- Using LSS with fiber and LSS as a backfilling material will slightly reduce the lateral displacement and inter-story drift of the building under the impact of the earthquake.
- The application of LSS with fiber and LSS as a backfill material will significantly decrease the acceleration and velocity of the ground around the building and adjacent areas.

- The effect of fiber material, when mixed with LSS, was made clear in this study. LSS mixed with fiber has more advantageous than LSS.
- It is considered that the LSS and LSS with fiber have an effective potential to reduce the seismic motion on the buildings and the surrounding soil environment. This property is a new advantage of LSS and LSS with fiber.

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CHAPTER 7

CONCLUSIONS AND SUGGESTIONS

7.1 CONCLUSIONS

This research has carried out both experiments and analyses to investigate the strength, deformation property, and advantage of Liquefied Stabilized Soil (LSS) and LSS mixed with fibered material to promote its application backfilling material in underground construction projects. Firstly, various factors affect the strength and deformation property of LSS prepared at field that has been investigated by both laboratory and field testing. On the other hand, the effects of LSS as backfilling material on the building and ground environment under an earthquake were evaluated. Based on the test and analysis results, the main findings obtained as follow:

1) Various factors affect the strength and deformation property of LSS prepared at field

a) The curing temperature could affect the deviator stress q of LSS without fiber material. As for LSS with fiber material, there is an independence of the deviator stress q on the curing temperature when curing days increases. The brittle property of LSS without fiber material has been improved by the reinforcement effect of adding fiber material. It is found that aseismic performance in the ground is improved and toughness ground will be constructed when the LSS with fiber material is using as backfilling.

b) The effect of curing temperature is smaller than that of curing days on Initial Young's modulus E_0.

c) The effect of adding the fiber material on LSS increases the non-linearity of deformation property in $q \sim \varepsilon_a$ relation while the curing temperature has been lower.

d) During the first period of the curing process of LSS mixed fiber material, the addition of the fiber material into LSS is reduced the damage degree during shear. However, there is unclear when the number of curing days increases and the curing temperature drops significantly. For this result, it considered conducting further works the next time.

e) The K-value by portable FWD can be evaluated the stiffness of backfilling ground by LSS with fibered material adequately.

2) The effects of LSS as backfilling material on the building and ground environment under an earthquake

a) Using LSS with fiber and LSS as a backfilling material will slightly reduce the lateral displacement and inter-story drift of the building under the impact of the earthquake.
b) The application of LSS with fiber and LSS as a backfill material will significantly decrease the acceleration and velocity of the ground around the building and adjacent areas when the earthquake occurs.
c) The effect of fiber material, when mixed with LSS, was made clear in this study. LSS mixed with fiber has more advantageous than LSS.
d) It is considered that the LSS and LSS with fiber have an effective potential to reduce the seismic motion on the buildings and the surrounding soil environment. This property is a new advantage of LSS and LSS with fiber.

7.2 RECOMMENDATIONS

With the conclusions and findings of this research, several suggestions for future work can be given as follows:

Due to the complicated climate in Japan, summers are hot, and winters are freezing, especially in Hokkaido. Therefore, it is necessary to carry out many field tests under extreme conditions such as the test sample being cured for a long time when snowfall (temperature in the ground will increase dramatically), then the snow melts (temperature significant reduction). The strain strength and deformation property of the LSS at each time should be checked and compared. From there, the impact of the environment on LSS is investigated.

Different types of loading should be considered to apply in the triaxial compression test. For example, cyclic loadings are necessary to investigate the behavior of LSS when using as backfilling material to cover the tunnel railway.

Numerical models of LSS applications under real construction conditions and special loads should be conducted in the future to find out more advantages of LSS to promote the strong use of LSS in construction.

There is still a lot of work worthy of being done in the future to investigate the deformation property of LSS in more detail. With these efforts, we surely believe that this material could have wide utilization in the future.