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OBSERVATION OF GEOMATERIAL BEHAVIOR

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ABSTRACT

By focusing on the mechanical behavior of geomaterials observed by means of laboratory tests, we have attempted to survey the 50 year history of relevant studies presented in Soils and Foundations and to introduce some of the recent research outcomes. First, the developments of a variety of testing apparatuses and procedures are summarized, with a particular focus on the effects of boundary conditions and sample disturbance, local and microscopic measurements, and the observation of small strain behavior as well as large strain behavior. Second, studies on the properties of sandy soils, clayey soils, other problematic soils and cemented soils including aged soils and soft rocks, respectively, are reviewed briefly. Third, because it is a research topic that has had the attention of so many researchers for so long, and some remarkable progress has been achieved recently, studies on viscous behavior, including the dependency on the loading rate and creep deformation, are overviewed.

Key words: history, laboratory soil testing, local measurement, small strain behavior, strain localization, viscous behavior (**IGC**: D5/D6/D7)

INTRODUCTION

In order to observe and reveal the behavior of geomaterials, an extensive number of studies have been conducted by field observations, in-situ measurements, model tests and laboratory tests. In this paper, the history of relevant studies published in Soils and Foundations has been overviewed, with some recent research outcomes introduced.

First, the development of a variety of testing apparatuses and procedures are summarized. In order to do so, the following sub-topics have been selected:

1) The effects of boundary conditions and sample disturbance
2) Local and microscopic measurements
3) Small strain behavior
4) Large strain behavior.

Second, studies on the properties of different types of soils are reviewed briefly, with respect to the following sub-topics:

5) The pre-peak and peak strength properties of sandy soils
6) The liquefaction properties of sandy soils
7) The pre-peak and peak strength properties of clayey soils
8) The properties of ''problematic'' soils
9) Cemented, aged soils and soft rocks.

The last category has just one topic alone: this topic has been a topic of interest throughout the whole history of Soils and Foundations, and some researchers have made some remarkable progress in this field recently. This topic will be discussed in terms of the dependency on loading rate and creep deformation:

10) Viscous behavior

As one may easily assume, it is an extremely tough task to condense a 50 year history into the limited number of pages allocated. However, we have completed the task to the best of our knowledge and ability. The challenge was made to overview each of the above ten sub-topics.

EFFECTS OF BOUNDARY CONDITIONS AND SAMPLE DISTURBANCE

The first paper on this sub-topic that appeared in the 1960s was by Monden (1969). By employing a special apparatus equipped with a bottom load cell, as shown in Fig. 1, he evaluated the effect of side friction in one-dimensional (1-D) compression tests (or K_o-consolidation tests) on clay. He also discussed the effects of other factors, such as the trimming effect and specimen size. Recently, the issue of side friction was re-visited by Watabe et al. (2008a) who studied its effect on the long-term consolidation behavior of clays.

Another friction effect at the end platens in triaxial compression (TC) tests was first investigated by Raju et al. (1972), together with the lubrication method to reduce the friction. Later, interface friction angles for different lubrication methods were evaluated quantitatively by Tatsuoka and Haibara (1985). More recently, microscopic observation of end restraint effect on dilatant speci-

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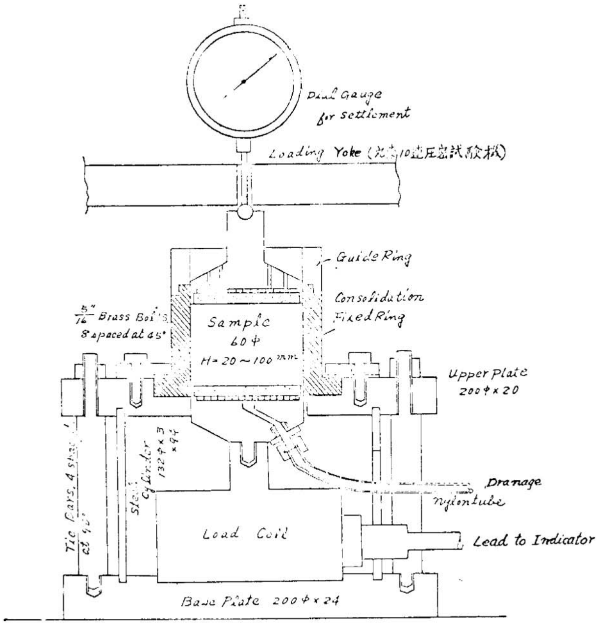

Fig. 1. Apparatus to evaluate side friction (Monden, 1969)

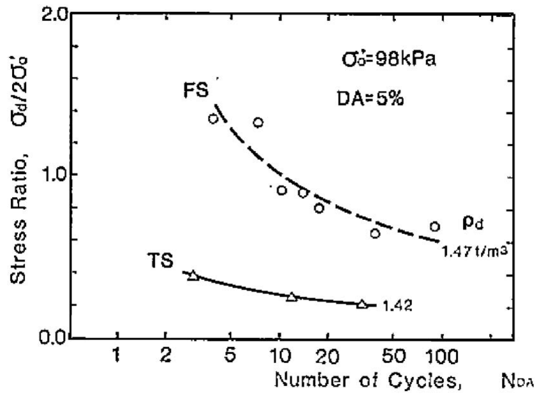

Fig. 2. Comparison of liquefaction resistance curves of samples retrieved by in-situ freezing (*FS*) and by triple-tube sampler (*TS*) (Yoshimi et al., 1978)

mens was made by Frost and Yang (2003).

It should be noted that lubrication layers at the specimen ends cause bedding error. Local measurements to reduce the effects of bedding error on strain evaluation are described in the next section. Note also that plane strain compression (*PSC*) tests with lateral confining plates with lubrication layers are also affected by the bedding error. Therefore, special *PSC* tests to actively control the position of the confining plates were performed on gravel by Maqbool and Koseki (2007) to study the effects of such lateral bedding error.

Since the membrane that covers the specimen penetrates into the local voids between soil particles depending on the magnitude of the effective confining pressure applied, its effects on the undrained behavior of soils were investigated extensively by many researchers in the late 1970s and 1980s. Among them, Tokimatsu and Nakamura (1987) proposed a simplified procedure to correct for the membrane penetration effect on the results from undrained cyclic shear tests.

Although torsional shear tests on hollow cylindrical specimens became popular in the 1980s, the non-uniformity of stress and strain distributions within the specimen was an issue to be clarified. On this issue, Sayao and Vaid (1991) numerically evaluated the influence of stress states and specimen geometry on the degrees of non-uniformity.

In testing ''undisturbed'' samples, it is important either to reduce the extent of possible sample disturbance or to correct the measured data for the effects of sample disturbance. In order to achieve the former, freezing has been frequently employed in the retrieving of sandy soil samples.

The effects of freezing and subsequent thawing history on *TC* test results on sands were first investigated by Yoshimi et al. (1978) in order to validate a new sampling method by in-situ freezing. This method was successfully applied to a deposit of dense clean sand by Yoshimi et al. (1984), where a remarkable difference in terms of liquefaction properties as compared to the sampling method using a triple-tube sampler was observed, as shown in Fig. 2.

Tokimatsu and Hosaka (1986) studied the effects of sampling disturbance on the cyclic shear deformation properties of clean sands, including their small strain shear moduli. They found that the extent of sample disturbance can be evaluated by comparing the small strain shear moduli measured in-situ and in the laboratory.

Later, Goto (1993) investigated the effects of the freeze-thaw history on the liquefaction properties of sands containing fines. He proposed the use of the volumetric expansion strain during freezing as an index to evaluate the extent of sample disturbance.

Not only sandy soils but also clayey soils have been studied by many researchers in terms of the effects of sample disturbance and the procedures to reduce them. For example, Watabe and Tsuchida (2001) studied the effect of sample disturbance due to stress release on clayey samples retrieved from large depths. This study can be regarded as an extension of the pioneering study on the swelling effect by Mitachi and Kitago (1976).

More recently, Shogaki (2006) proposed a procedure to evaluate in-situ undrained shear strength of clayey soils. In developing it, a series of unconfined compression (*UC*) tests on small specimens having a diameter of 15 mm and a height of 35 mm was conducted, as was described in detail by Shogaki (2007).

Further, Horng et al. (2010) investigated the effects of the geometry of sampling tubes on the quality of clayey soil samples, based on the comparisons of small strain shear moduli that were measured in-situ by seismic cone tests and in the laboratory employing bender elements. The bender element measurement will be reviewed later in the section on small strain behavior.

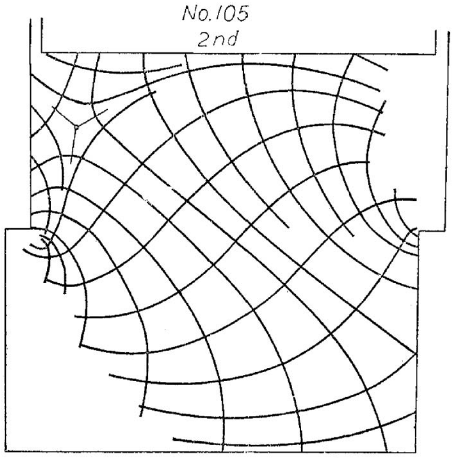

Fig. 3. Principal stress lines of glass powder in direct shear test (Wakabayashi, 1960)

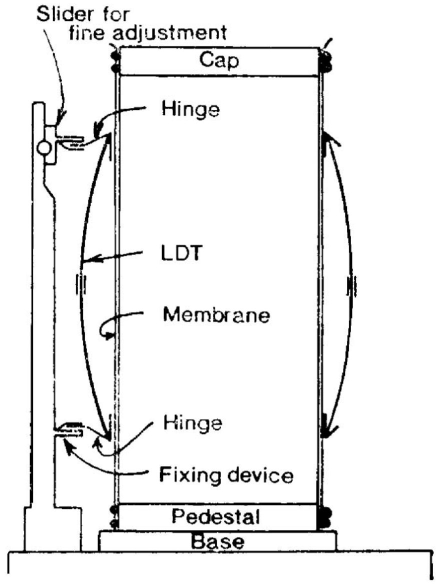

Fig. 4. Set-up of LDT using a fixing device (Goto et al., 1991)

LOCAL AND MICROSCOPIC MEASUREMENTS

The first paper on this sub-topic appeared in the very first volume of Soils and Foundations, and was authored by Wakabayashi (1960). As shown in Fig. 3, he observed the stress distribution of glass powder in direct shear (*DS*) tests with photoelastic measurements.

Later, Poellot and Yoshimi (1963) evaluated strain distribution of Kaolin clay in simple shear (*SS*) tests. The evaluation was made based on the deformations of grids drawn on the side surface of the specimen. These attempts of local measurements in the early 1960s were followed by microscopic observations conducted by Mogami and Imai (1967), who observed the shear banding behavior of metal balls in *PSC* tests.

In the 1970s, experimental studies on the anisotropy of sand fabric first began. With regard to initial or inherent anisotropy, Oda (1972) evaluated the bias of the distribution of longitudinal direction of non-spherical particles through observation of thin sections using optical microscope. Another microscopic observation was made by Matsuoka (1974a) on metal rods in *SS* and *DS* tests, who evaluated the change of the fabric induced by shear deformation.

After noticing the importance of measuring small strains accurately (e.g., Kokusho, 1980, among others), a device called local deformation transducer (LDT) was developed by Goto et al. (1991). It consists of a metal strip with strain gauges attached and a pair of hinges that fix the strip to the side surface of specimen. As shown in Fig. 4, it is capable of measuring the local deformation of specimens free from the effects of bedding error at both ends of the specimen.

LDTs were later applied to measure the locally horizontal strains of prismatic specimens (Hoque and Tatsuoka, 1998) and torsional shear strains of hollow cylindrical specimens (HongNam and Koseki, 2005).

In the last decade, new approaches that were originally developed for use in other fields were applied to the field of local and microscopic measurements in laboratory soil testing. Otani et al. (2000) conducted unconfined compression (*UC*) tests on clay with X-Ray computed tomography scanners and evaluated three dimensional changes of local density distribution during the test. Matsushima et al. (2002) employed laser-aided tomography technique in *PSC* tests on crushed glass.

In addition, other studies with microscopic measurements were also made on the microscopic particle crushing properties of sand and granular materials in 1-D compression (Nakata et al., 2001; Takei et al., 2001) and on strain localization properties of soft rocks in *PSC* tests using a digital image correlation method to analyze multiple digital photos (Bhandari and Inoue, 2005, among others).

OBSERVATION OF SMALL STRAIN BEHAVIOR

As one of the dynamic measurements to evaluate small strain behavior of soils, the resonant column (*RC*) tests were reported in Soils and Foundations by Afifi and Richart (1973). They conducted *RC* tests on sands and clays with a wide variety of grading curves.

In addition, after the pioneering work by Hashiba (1971) who introduced a high-resolution inclinometer in simple shear (*SS*) tests, the static measurement of small strain behavior became popular in the 1980s. For example, in order to perform cyclic triaxial tests over a wide strain range of the order of 10^{-6} to 10^{-3}, Kokusho (1980) developed the triaxial apparatus shown in Fig. 5. It is equipped with an inner load cell to measure the axial load that is free from the friction of the loading shaft at the bearing and a proximity transducer (or gap sensor) to evaluate the axial strain by means of measuring the vertical displacement of the top cap.

By employing a triaxial apparatus similar to the one shown in Fig. 5, Tokimatsu et al. (1986) evaluated the small strain shear moduli of sands and investigated the

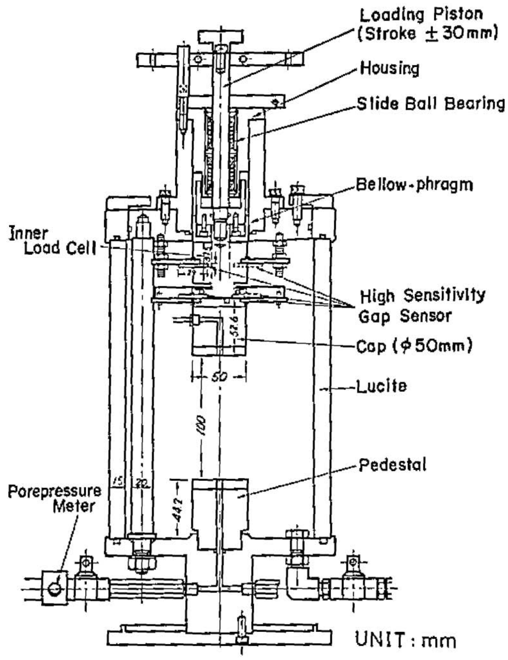

Fig. 5. Triaxial apparatus with high sensitivity gap sensor and inner load cell (Kokusho, 1980)

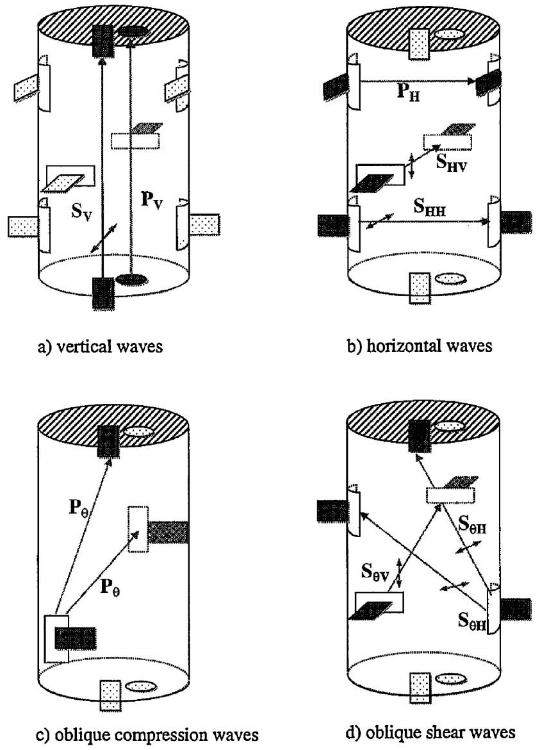

Fig. 6. Variety of bender element applications in triaxial apparatus (Fioravante, 2000)

correlation of these properties with liquefaction resistance.

With the help of the local measurement technique mentioned in the previous section, the evaluation of small normal strains not only in the vertical direction but also in the horizontal direction became possible in the 1990s. Using this technique, the anisotropy of the small strain Young's moduli of granular soils and their stress state dependency were studied by Hoque and Tatsuoka (1998) in *TC* and triaxial extension (*TE*) tests and by AnhDan and Koseki (2005) in true-triaxial tests where the three principal stresses could be controlled independently.

This technique was further applied to measure the small shear strain locally in torsional shear (*TS*) tests on hollow cylindrical specimens of sandy soil. Based on such measurement results, a modeling of quasi-elastic properties that considers the effects of inherent anisotropy and stress state-induced anisotropy was proposed by HongNam and Koseki (2005).

Another type of dynamic measurement device emerged in the 1990s. The accelerometer, which was attached on the side surface of the specimen, was developed by Nishio and Tamaoki (1990). By employing this method, Tanaka et al. (2000) conducted dynamic measurements on sands and gravels and discussed on the difference between the shear moduli evaluated with dynamic and static measurements.

Dynamic measurement techniques became more popular after the introduction of bender elements in the late 1990s. As shown in Fig. 6, they were employed in triaxial apparatus to evaluate the travel time of elastic waves not only in the vertical direction but also in the horizontal or diagonal directions (Fioravante, 2000). They could be also employed successfully in oedometer (*OD*) apparatus (Lohani et al., 2001). Factors to affect the dynamic measurements with bender elements were investigated in detail by Yamashita et al. (2009) for the purpose of establishing a standard test method.

The bender element measurement was further applied on clayey soils to formulate their small strain shear moduli (Kawaguchi and Tanaka, 2008) and to evaluate the sample quality (Horng et al., 2010).

OBSERVATION OF LARGE STRAIN BEHAVIOR

Large strain behavior, in particular the post-peak strain softening behavior, is not easy to observe accurately, since it is frequently followed by strain localization and is also affected by non-uniform deformation of specimen.

In the late 1980s, by analyzing photos of specimen surface with grid-imprinted membrane, Pradhan et al. (1988) attempted to evaluate the stress-strain relationship within a shear band formed during simple shear tests using *TS* apparatus. States B1 and B2 shown in Fig. 7 represent the local values evaluated inside and outside the shear band, respectively. The shear strain level inside the shear band at state B1 was around 40%.

Later, the effects of intermediate principal stress on the shear banding behavior of sand was studied by Lade (2003) based on true-triaxial test results and theoretical considerations. In addition, the formation of compaction bands in *OD* tests on cemented soils was investigated experimentally by Arroyo et al. (2005).

Recently, with the help of an image analysis of speci-

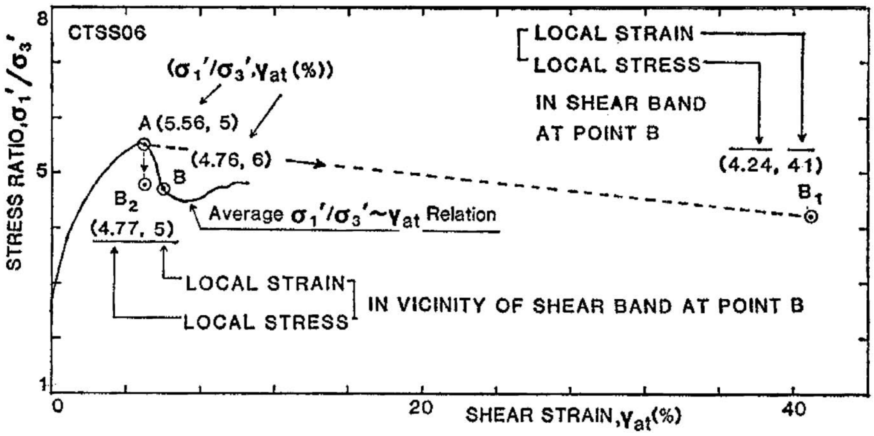

Fig. 7. Stress-strain relationship of dense Toyoura sand in simple shear tests using *TS* apparatus (Pradhan et al., 1988)

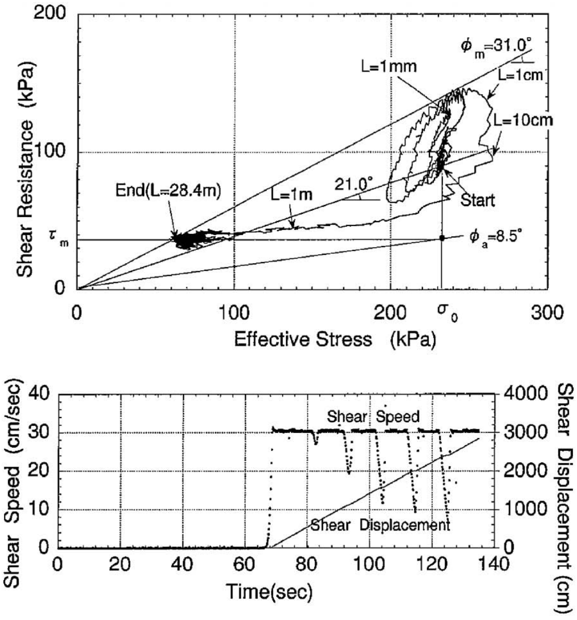

Fig. 8. Typical result from undrained cyclic ring shear test (Sassa et al., 1996)

men deformation as described in the section of local and microscopic measurements, the post-peak strain localization behavior was able to be captured more easily (e.g., Bhandari and Inoue, 2005, among others).

In the 1990s, the large strain monotonic loading behavior of sand was investigated intensively. Verdugo and Ishihara (1996) achieved the steady state of loose sands in undrained *TC* tests, which required axial loading to be continued up to an axial strain of 25% or even larger. Yamamuro and Lade (1997) investigated the undrained behavior of sands under high confining stresses in *TE* and *TC* conditions. Yoshimine et al. (1998) compared the undrained behavior of sands in *TC*, *TE* and *TS* conditions as well as a combination of these conditions. The steady state of sand in *TC* tests was further studied by Lo Presti et al. (2000) while employing local measurement of axial and radial strains.

In order to observe the behavior of liquefied sandy soils at large strain levels, several attempts have also been made. Sassa et al. (1996) conducted high-speed undrained cyclic ring shear tests up to a shear displacement of about 30 m as typically shown in Fig. 8. Kiyota et al. (2008) performed undrained cyclic *TS* tests up to a double amplitude shear strain of about 100%, while correcting for the effects of membrane force during the tests.

THE PRE-PEAK AND PEAK STRENGTH PROPERTIES OF SANDY SOILS

In the early 1970s, the properties of sands under high confining pressures in association with particle crushing were investigated by Lo and Roy (1973) by the use of *TC* tests, as shown in Fig. 9. These properties were further studied by Miura et al. (1984) employing *TE* tests as well as *TC* tests.

On the other hand, the properties of sands under extremely low confining pressures were investigated by Tatsuoka et al. (1986a) by the use of *PSC* tests, while correcting for the effect of membrane force. These properties were referred to in analyzing the behavior observed in small scale model tests conducted under normal gravity field. This issue was re-visited by Koseki et al. (2005), who performed cyclic *TS* tests on liquefaction properties under low confining stresses.

The yielding behavior of sands was first discussed in detail by Tatsuoka and Ishihara (1974a), and *TC* tests were employed in their investigation. It was further studied by Ishihara and Okada (1978), Nova and Wood (1978), Tanimoto and Tanaka (1986), Yasufuku et al. (1991), Nawir et al. (2003) among others. In particular, the anisotropic nature of yielding behavior in *TC* and *TS* tests in conjunction with the concept of multiple yielding was investigated by Chaudhary and Kuwano (2003).

The dilatancy properties of sands observed in drained monotonic and cyclic loading tests were discussed by Matsuoka (1974b) and Tatsuoka and Ishihara (1974b), respectively. The behavior during cyclic loading was further studied by Pradhan et al. (1989a) who employed *TS* tests and measured the volume change of the specimen very accurately with an electronic balance (Pradhan et al., 1989b).

The behavior of sand under more general stress states was investigated by Yamada and Ishihara (1979) using true-triaxial tests. In addition, the effects of the rotation of principal stress axes were investigated by many researchers (Miura et al., 1986; Shibuya and Hight, 1987; Nakata et al., 1998, among others) using *TS* tests. The combined effects of anisotropy and intermediate principal stress in *PSC*, *TC* and *TE* tests were systematically studied by Lam and Tatsuoka (1988), as shown in Fig. 10. Further, the effects of different sample preparation methods in *TC* and *TS* tests were revealed by Tatsuoka et al. (1986b), and the cyclic behavior of sands under plane strain compression and extension conditions was observed by Masuda et al. (1999) using a special apparatus.

In order to capture a general link between the mechanical properties of sands and their primary properties, such as the hardness and shape of grains, Miura et al. (1998) conducted *TC* tests on a wide variety of sands. By extending the test conditions, Maeda and Miura (1999a, b) investigated the effects of confining pressure and relative density, respectively, on their mechanical properties. Recently, Bahadori et al. (2008) studied the effects of non-plastic silt on the anisotropy of sand.

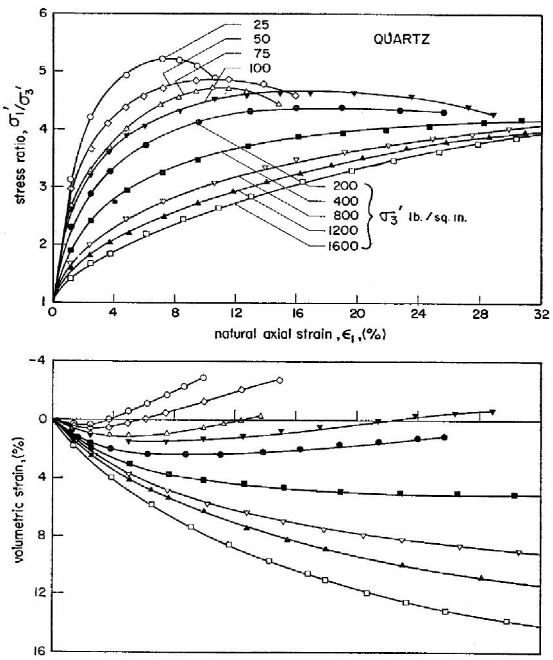

Fig. 9. Stress-strain relationships of quartz sand in *TC* tests under different confining stresses (Lo and Roy, 1973)

THE LIQUEFACTION PROPERTIES OF SANDY SOILS

The 1964 Niigata earthquake in Japan and the 1964 Alaska earthquake in USA caused severe damage to various facilities and buildings due to the liquefaction of sandy deposits. Since then, liquefaction has been one of the hot research topics.

The pioneering papers on laboratory liquefaction tests that appeared in Soils and Foundations are Shibata et al. (1972), Ishihara and Li (1972) and Ishihara and Yasuda (1972). Shibata et al. (1972) and Ishihara and Yasuda (1972) conducted undrained cyclic triaxial tests, as typically shown in Fig. 11. Shibata et al. (1972) investigated the change of the effective stress states during liquefaction, while Ishihara and Yasuda (1972) focused on the behavior during irregular cyclic loading. On the other hand, Ishihara and Li (1972) conducted undrained cyclic *TS* tests on solid cylindrical specimens which were modified into *TS* liquefaction tests on hollow cylindrical specimens (Ishihara and Yasuda, 1975).

In the late 1970s, the effects of stress conditions and stress histories on the liquefaction properties were studied. For example, the effect of initial shear stress was studied by Yoshimi and Oh-oka (1975) employing *TS*

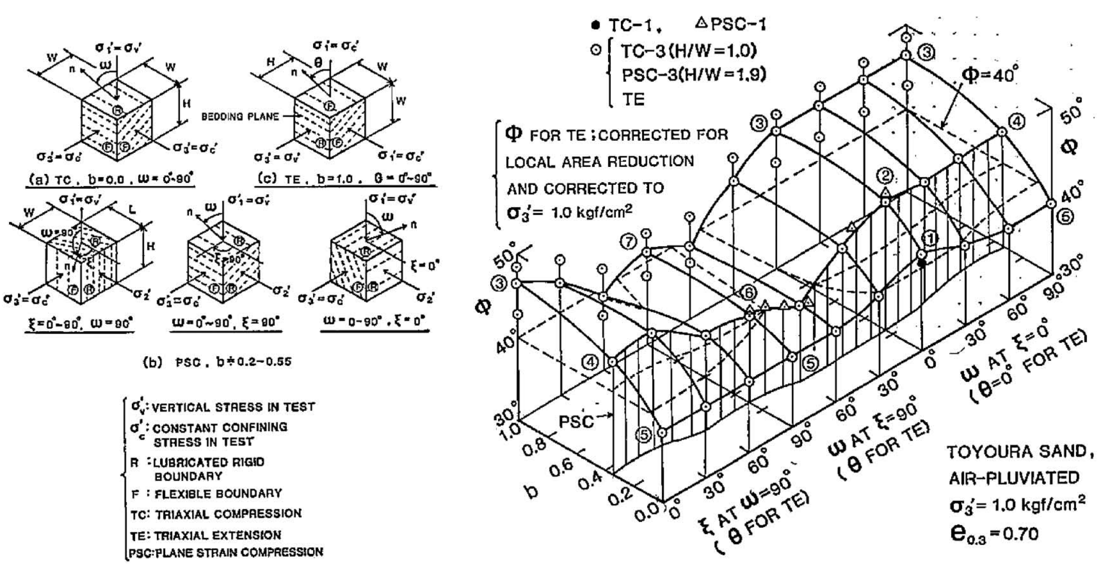

Fig. 10. Peak angles of internal friction of dense Toyoura sand in *TC*, *TE* and *PSC* tests (Lam and Tatsuoka, 1988)

tests. On this issue, extended studies were made by Vaid and Chern (1983) and Hyodo et al. (1991) using triaxial tests. Later, in order to develop a standardized test procedure to be employed in practice, factors affecting the triaxial liquefaction test results were intensively investigated by Toki et al. (1986) and Tatsuoka et al. (1986c).

In the 1980s, liquefaction behavior under principal stress axes rotation was studied by Towhata and Ishihara (1985) among others, in association with the anisotropy induced by such change of stress states. Further, following the pioneering work by Yoshimi et al. (1978) on the effectiveness of in-situ freezing sampling as mentioned in the section which dealt with sample disturbance, Hatanaka, et al. (1988) and Yoshimi et al. (1989a) evaluated the liquefaction properties of high quality gravel and sand samples, respectively, retrieved by this technique.

In the 1990s, in conjunction with the studies on the large strain monotonic loading behavior of sand as mentioned in the section on large strain behavior, a comparison between undrained cyclic and monotonic *TC* test results on loose sand was made by Hyodo et al. (1994). In addition, cyclic bi-directional *SS*, *TS* and *TC* tests combined with monotonic loading were conducted by Meneses et al. (1998).

In the last decade, the issue of liquefaction behavior of unsaturated sands initiated by Yoshimi et al. (1989b) was re-visited by Tsukamoto et al. (2002) with the help of dynamic measurements of P and S wave velocities. This issue was further studied by Okamura and Soga (2006) and Unno et al. (2008). The effect of fines on liquefaction behavior was also re-evaluated by Koseki and Ohta (2001) and Chang and Hong (2008). In addition, liquefaction properties under extremely large strain levels were investigated by Kiyota et al. (2008) as mentioned in the section dealing with large strain behavior, and the effect of anisotropy that was induced by preceding liquefaction history on the re-liquefaction behavior was studied by Yamada et al. (2010), as typically shown in Fig. 12.

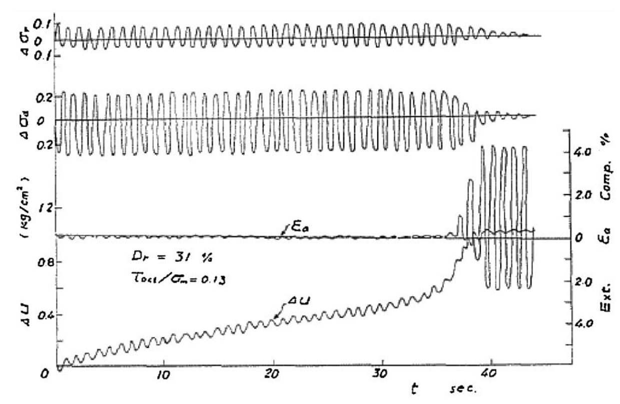

Fig. 11. Typical result from undrained cyclic triaxial test (Shibata et al., 1972)

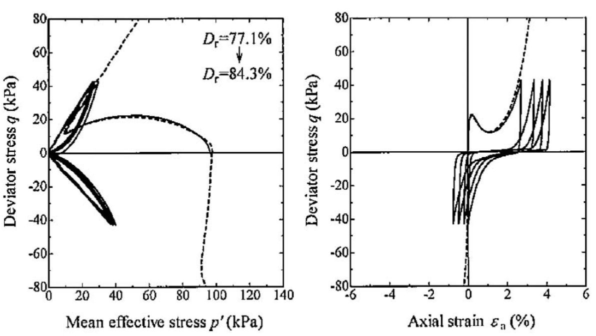

Fig. 12. Re-liquefaction behavior of specimen subjected to liquefaction history in undrained cyclic triaxial test (Yamada et al., 2010)

THE PRE-PEAK AND PEAK STRENGTH PROPERTIES OF CLAYEY SOILS

The earliest paper on clay properties that appeared in Soils and Foundations was written by Kawakami (1960), and will be described in more detail in the section entitiled ''Viscous Behaviour''. It was followed by Uchida and Matsumoto (1961), who conducted splitting tests to evaluate tensile strength of clays and compared the tensile strengths with the corresponding *UC* test results, as shown in Fig. 13.

With regard to the consolidation properties of clays, Kawakami (1964) evaluated the anisotropy in the coefficients of consolidation using *TC* tests. His research was followed by Aboshi et al. (1970) who performed consolidation tests at a constant loading rate that enabled to shorten the test period. Later, consolidation tests on very soft clays at a constant strain rate were performed by Umehara and Zen (1980), and the procedures of consolidation tests using a constant strain rate were standardized in 1993 by Japan Society of Soil Mechanics and Foundation Engineering (i.e., the former organization of Japanese Geotechnical Society).

In the late 1970s, cyclic loading tests were conducted to determine the mechanical properties of saturated clays by Ohara and Matsuda (1978). They used *SS* tests in their research, and then monotonic loading tests were performed by Mitachi and Kitago (1979), who used *TC* and *TE* tests. Among other relevant investigations, the form-

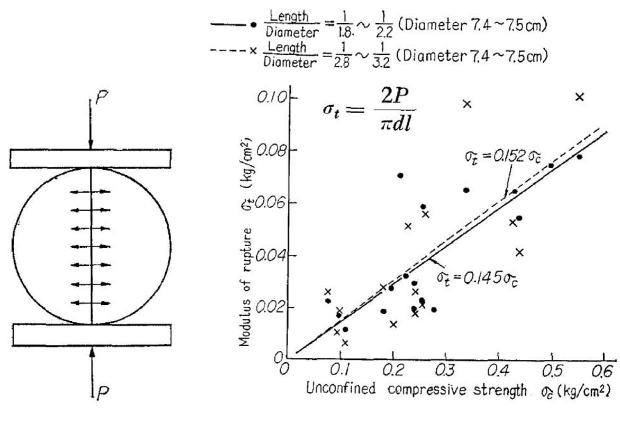

Fig. 13. Comparison of tensile strength in splitting tests and unconfined compressive strength (Uchida and Matsumoto, 1961)

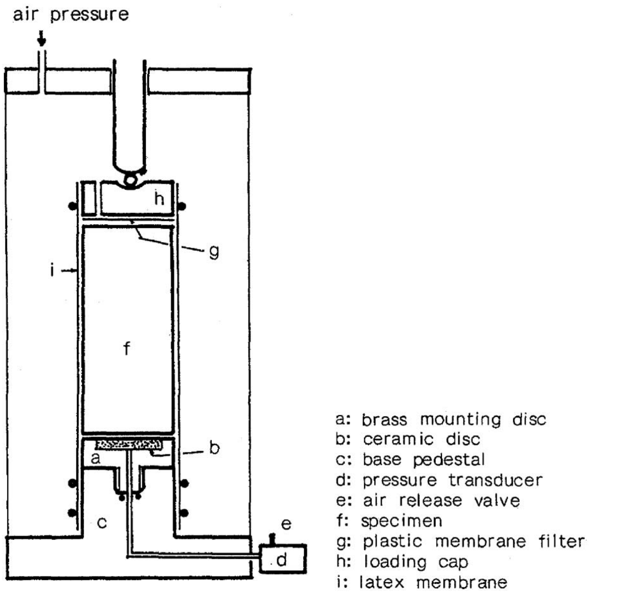

Fig. 14. Schematic illustration of *UC* test apparatus with suction measurement (Shimizu and Tabuchi, 1993)

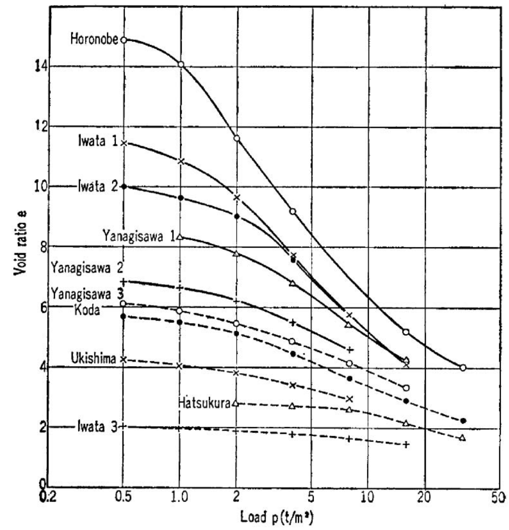

Fig. 15. Consolidation properties of various peats (Watanabe, 1964)

er study was extended into studies on cyclic deformation properties (Kokusho et al., 1982), on recompression after cyclic loading (Ohara and Matsuda, 1988; Yasuhara and Anderson, 1991) and on the difference in the cyclic loading behaviors of undisturbed and remolded samples (Hyodo et al., 1999). On the other hand, the study on monotonic loading behavior was extended into studies on the effect of anisotropy (Nakase and Kamei, 1983; Toyota et al., 2001), on the effect of intermediate principal stress in true-triaxial tests (Nakai et al., 1986) and on their combined effects in *TC* and *TS* tests (Lade and Kirkgard, 2000).

The first investigation involving the profiling of clayey ground properties at a specific site based on laboratory tests as well as in-situ tests was reported in the late 1970s (Hanzawa 1977a, b, 1979). At the same time, the effect of several sources of disturbance during sampling, transportation and trimming on the properties of clayey samples tested in the laboratory was found to be significant and investigated in detail (e.g., Kimura and Saitoh, 1982, among others). Later, in order to evaluate the stress states of clayey samples that were almost fully saturated in *UC* tests, suction measurements were made by Shimizu and Tabuchi (1993), using an improved apparatus shown in Fig. 14. It was followed by Mitachi et al. (2001), who proposed a procedure to estimate the in-situ undrained shear strength based on the *UC* test results with suction measurement. As mentioned in an earlier section, further study on the estimation procedure of in-situ undrained shear strength and its accuracy was conducted by Shogaki (2006).

THE PROPERTIES OF ''PROBLEMATIC'' SOILS

''Problematic'' soils are defined herein to be those different from the widely available clayey, sandy or gravelly soils, though they may cause geotechnical problems under certain circumstances. They include peats, organic soils, volcanic soils, decomposed soils, collapsible soils, and expansive soils.

In the first volume of Soils and Foundations, Kawakami (1960) reported on the behavior of loams (volcanic soils) as well as clays, as will be described in the section on viscous behavior. Then, Watanabe (1964) evaluated the consolidation properties of peats in *OD* tests as shown in Fig. 15. This research was followed by Uchida et al. (1968) and Haruyama (1969) who conducted *TC* tests on Masa soils (decomposed granites) and Shirasu (volcanic soils distributed in south of Kyusyu island, Japan), respectively. Further, Matsuo and Nishida (1968) evaluated the physical and chemical properties of Masa soil grains, which included the compressive strength at the grain level.

In the 1970s, Yamanouchi and Yasuhara (1975) investigated secondary compression of organic soils in *OD* and *TC* tests. In addition, Haruyama (1977) made extended studies using *TC* tests on the properties of reconstituted Shirasu samples of various densities.

In the 1980s, Ishihara et al. (1980) and Hatanaka et al. (1985) conducted cyclic triaxial liquefaction tests on tailings materials and in-situ frozen alluvial volcanic soil samples, respectively. In addition, Haruyama and Kitamura (1984) evaluated the properties of undisturbed Shirasu samples in *TC* tests. Further, Yamaguchi et al. (1985) performed *TC* and *TE* tests on peats, focusing on the effects of several factors such as confining pressure, stress path, amount of organic matter and anisotropy.

In the 1990s, Moroto (1991) conducted compaction and *UC* tests on loam and pumice. Yamaguchi et al. (1992) evaluated the change in pore size distribution of remolded peat subjected to shear history in *TC* tests. Sridharan et al. (1992) compared the behavior of remolded and undisturbed residual soils in *OD* tests. Feda et al. (1995) conducted 1-D compression tests on reconstituted loess, while employing conventional *TC* and true-triaxial

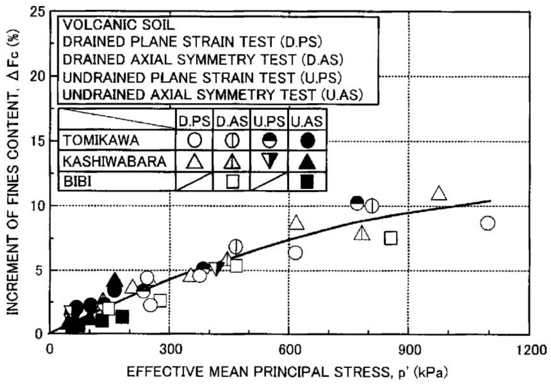

Fig. 16. Increment of fines content caused by particle crushing of volcanic soils (Miura et al., 2003)

apparatuses.

In the last decade, Miura et al. (2003) performed *TC* and *PSC* tests on crushable volcanic soils and evaluated strength anisotropy, liquefaction resistance, cyclic deformation properties and their particle crushing behavior, which is shown in Fig. 16. Agustian and Goto (2008) investigated the properties of scoria in *TC* tests at low confining stress. Karam et al. (2009) conducted cyclic *TC* tests on a natural loess to reveal its resistance against railway loads.

CEMENTED, AGED SOILS AND SOFT ROCKS

Here the term ''aged soils'' refers to soils that were subjected to positive or negative time effects with physical or chemical changes. The positive time effects include the diagenesis process, while the negative time effects include weathering processes. Since the former process tends to enhance the formation of cementation between soil particles, artificially-cemented soils and natural soft rocks are also categorized into this sub-topic.

In the 1960s, with regard to the properties of soft rocks, Nakano (1967) investigated the effect of weathering on the behavior of mudstone in swelling and *UC* tests. In the same year, Yoshinaka (1967) reported his results from a series of *TC* tests on several kinds of mudstones and sandstones, while applying a maximum confining stress of about 5 to 8 MPa, as is shown in Fig. 17. In addition, on the properties of artificially-cemented soils, Matsuo and Nishida (1969) studied the strength characteristics of cement-mixed decomposed granite in *UC* tests.

With the exception of papers dealing with aged clays (Murakami, 1979; Hanzawa, 1983; Yasuhara and Ue, 1983; Mitachi and Fujiwara, 1987, among others), it was not until the 1990s that research on this sub-topic began to reappear in Soils and Foundations. The studies on aged clay were followed by Tsuchida et al. (1991) who attempted to accelerate the positive time effects by consolidating specimens under high temperature. Further, Tanaka et al. (2004) compared the consolidation properties between young and aged clays based on results from *OD* tests as well as in-situ measurements.

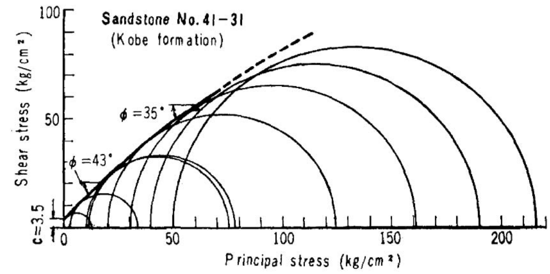

Fig. 17. Mohr's circles for peak stress states observed in consolidated undrained *TC* tests on sandstone (Yoshinaka, 1967)

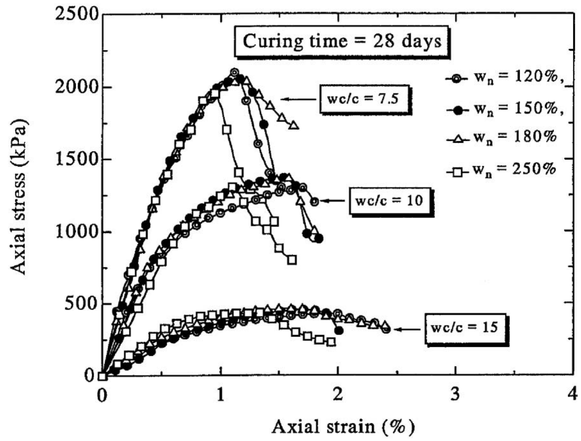

Fig. 18. *UC* test results on cement-treated clays with different initial water and cement contents (Miura et al., 2001)

On the properties of soft rocks, Maekawa and Miyakita (1991) re-visited the effect of weathering by performing *UC* and splitting tests on mudstone with drying and wetting histories. Then, Hayano et al. (2001) investigated the effect of strain rates in *TC* tests. Further, Shibata et al. (2007) studied creep properties in *UC* tests under high temperature.

On properties of artificially-cemented soils, Kamon et al. (1999) conducted *UC*, bending and *TC* tests on lime-treated decomposed granite soil. Miura et al. (2001) performed *OD* and *TC* tests on cement-treated clay at high water contents, as is shown in Fig. 18. Tang et al. (2001) summarized the properties of cement-treated dredged soils that were re-used in practice. More recently, Kasama et al. (2006) studied the effects of cementation on the properties of cement-treated soils in isotropic consolidation and undrained *TC* tests. Namikawa and Koseki (2007) compared the results from splitting, direct tension and bending tests on cement-treated sand, focusing on its tensile properties.

In addition, several studies were also conducted on the properties of aged sands. Tatsuoka et al. (1988) studied the effects of long-term consolidation on the liquefaction behavior of sands, while comparing them with the effects of over-consolidation. Ismael (1999) reported results from *UC*, *TC* and *OD* tests on cemented sand in Kuwait. Recently, Kiyota et al. (2009) compared the liquefaction behavior and small strain stiffness of in-situ frozen sam-

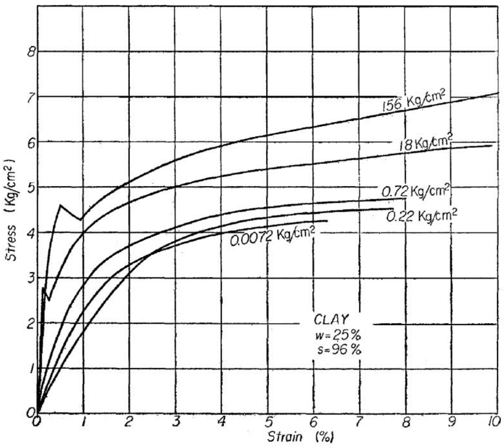

Fig. 19. Effects of loading rates in *UC* tests on clay (Kawakami, 1960) (Note: the loading rates shown in the figure are per second.)

ples with different geological ages and their reconstituted specimens with/without simulated seismic histories.

VISCOUS BEHAVIOR

Here the term ''viscous'' refers to the properties that change with different loading rates, while excluding the positive or negative time effects with physical or chemical changes that have been covered in the previous section. In addition, the creep behavior under a sustained load can be analyzed from the same perspective, since it is also accompanied by a change in the strain rate.

A pioneering study that appeared in a 1960 edition of Soils and Foundations was Kawakami's evaluation of the effects of different loading rates on compacted clay and loams in *UC* tests. The set-up employed in this research is shown in Fig. 19. Kawakami's work was followed by Akai (1963) who investigated the long-term consolidation behavior of clay in *OD* tests, including the secondary compression. Later, Akai and Yamanouchi (1968) performed axial and torsional impact loading tests on clay at high loading rates.

Further, in the 1970s, Nagaraj (1970) and Murayama et al. (1974) investigated the effects of different strain rates and stress relaxation, respectively, on clay behavior in *TC* tests. Then, Murayama et al. (1984) studied the creep behavior of sand in *TC* tests, including the creep failure.

The viscous effects were re-visited in the 1990s. By employing a special *OD* apparatus using inter-connected cells, Imai and Tang (1992) evaluated viscous properties of remolded clay during the whole processes of consolidation, including the primary one. Di Benedetto and Tatsuoka (1997) studied the effects of strain rates on the small strain behavior of various geomaterials, including gravel, sand, clay and soft rock. d'Onofrio et al. (1999) investigated the behavior of stiff clay under different strain rates in *TS* and *RC* tests.

In the last decade, quite a number of papers dealt with this sub-topic. For example, Tatsuoka et al. (2002) investigated the effects of strain rates on sand behavior by per-

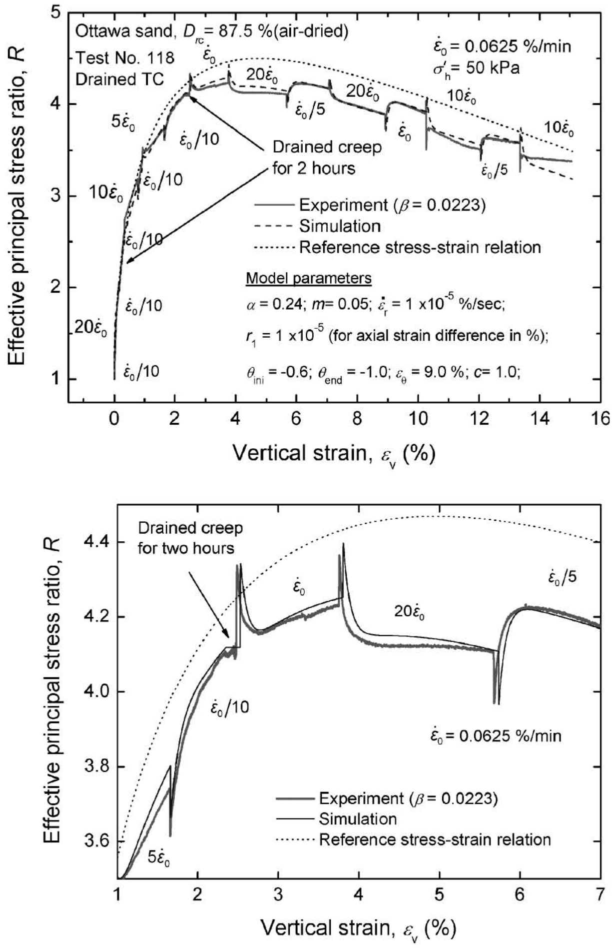

Fig. 20. Positive and negative viscosity in drained *TC* test on Ottawa sand (Enomoto et al., 2009)

forming a series of *TC* and *PSC* tests, including special tests in which the strain rate was suddenly changed during monotonic loading. Oka et al. (2003) performed similar special tests on clay. Bowman and Soga (2003) made a microscopic observation of changes in the microstructures of dense granular materials during the creep process. Vucetic and Tabata (2003) studied the behavior of clay under different strain rates in cyclic *SS* tests.

More recently, Kongsukprasert and Tatsuoka (2005) investigated the combined effects of aging and viscous behavior on the properties of cement-mixed gravel in *TC* tests. The effect of strain rate on the consolidation behavior of clay as observed by Imai and Tang (1992) was re-evaluated by Tanaka et al. (2006) and Watabe et al. (2008b) based on *OD* test results on natural clay samples. As typically shown in Fig. 20, Duttine et al. (2008) and Enomoto et al. (2009) studied the strain rate effects on granular materials with different particle characteristics in *DS* and *TC* tests, respectively. In addition, Peckley and Uchimura (2009) reported results from cyclic *TC* tests on soft rock, focusing on effects of loading period under different strain rates.

SUMMARY

This paper is an overview the 50 year history of laboratory soil testing studies on the mechanical behavior of geomaterials presented in Soils and Foundations.

A variety of testing apparatuses and procedures to accurately observe various behavior, from very small to very large strain levels, have been developed, with various efforts to reduce the effects of boundary conditions and sample disturbance, and both local and microscopic measurements have been taken as deemed necessary.

Thanks to the developments in this field, it has been possible to reveal many aspects of the properties of sandy soils, clayey soils, other problematic soils and cemented soils including aged soils and soft rocks. However, long lasting research topics like viscous behavior have only just begun to make significant progress.

NOTATIONS

DS: direct shear
OD: oedometer
PSC: plane strain compression
RC: resonant column
SS: simple shear
TC: triaxial compression
TE: triaxial extension
TS: torsional shear
UC: unconfined compression

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