DYNAMIC DEFORMATION PROPERTY TESTS AT LARGE STRAINS

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SUMMARY

Dynamic deformation characteristics of soil for the earthquake response analysis under very large earthquake are investigated. Firstly, we pointed out that there is no data on the stress-strain behavior at strains between a little smaller than 1 % to several percent because this strain range lies between the target strains by dynamic deformation characteristics test and dynamic strength test. Then we conducted cyclic loading test of sand in this strain range and found that hysteresis loop does not stabilize although liquefaction does not occur. It is concluded that soil is in quasi-liquefaction state at this strain range in which deterioration of stress-strain curve occurs in each cycle of loading. The shear modulus-shear strain curve is then converted to shear stress-shear strain relationships and is found to resemble the one under monotonic loading. The comparison shows good agreement between them. Therefore, shear modulus-shear strain relation can be obtained from single monotonic loading test.

INTRODUCTION

The 1995 Hyogoken-nambu earthquake was a shocking event in the point of view of earthquake resistant design because observed and evaluated earthquake motions were much larger than the earthquake load used in the design codes or specifications. After the earthquake, Japanese Society of Civil Engineering made a propose to consider so called level 2-ground motion [JSCE, 1996], and design specifications ware, are going to be, and will be revised to consider it in Japan. Here, level 2-ground motion is a very severe ground motion caused by near fault earthquakes or huge oceanic earthquake. Fundamental idea for evaluating level 2-ground motion is to identify the fault that may cause level 2-ground motion and to compute wave propagation from the fault to the interested site. This means that dynamic response analysis is necessary in getting the design seismic motion of the structure.

Under the level 2-ground motion, soil is supposed to behave in a nonlinear manner significantly, therefore dynamic response analysis of ground should consider the nonlinear nature of soil. As shown in the followings, however, dynamic deformation characteristics test that is conducted to obtain the stress-strain relation under cyclic loading is not sufficient to grasp the behavior of soil at large strains. Moreover, there is nearly no data accumulation in the strain range from about 1% under which dynamic deformation characteristics test is applicable to several percent at which stress-strain relation has been drawn for the purpose to obtain dynamic strength or liquefaction strength. This paper gives preliminary test result how soil behaves at large strains and gives an idea to process the test result.

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DYNAMIC DEFORMATION CHARACTERISTICS TEST AND ITS LIMITATION

The nonlinear property of soil has been obtained by the dynamic deformation characteristics test [e.g., Hardin and Drnevich, 1972]. At present, the procedure defined by the Japanese Geotechnical Society [1996] is usually used in Japan and the same or similar procedure is used all over the world. Figure 1 schematically shows the process to obtain dynamic deformation characteristics in the laboratory test. Shear modulus and damping ratio are evaluated from the hysteresis loops at each stage under cyclic loading. The cyclic loading test is conducted under the undrained condition and excess porewater pressure that may generate in each stage is drained after the loading in each stage. This test procedure is called stage test in which constant shear stress amplitude loading starts at small amplitude and increased gradually. Shear stress is loaded eleven cycles in each stage. The hysteresis loop at 10 the cycles of loading is used to compute shear modulus G and damping ration h, which are expressed as functions with resect to shear strain amplitude γ.

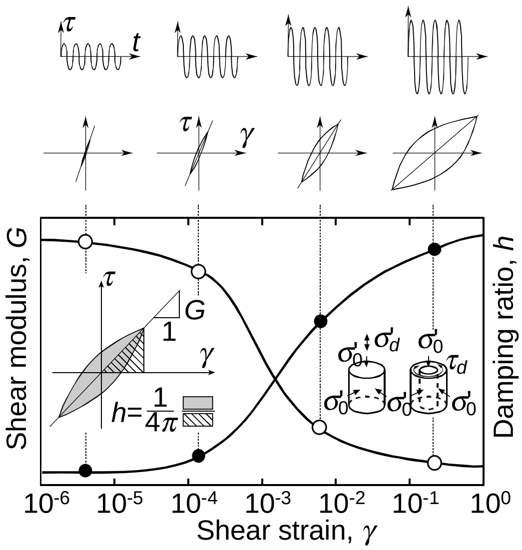
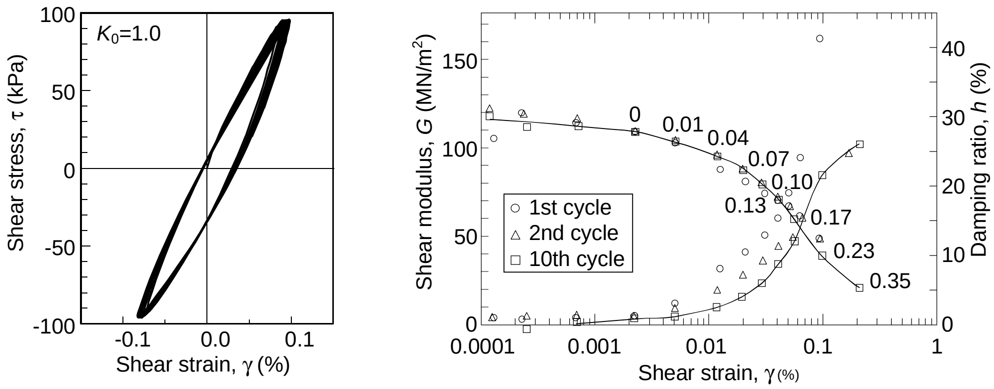


Figure 1: Schematic figure showing the dynamic deformation characteristics test and data processing



(a) Stress-strain loop (b) G-γ and h-γ relationships

Figure 2: Example of the result of dynamic deformation characteristics test

Figure 2 shown an example of the dynamic deformation characteristics test result. Figure 2(a) is stress-strain curve at one stage. The stress-strain curve gradually become stable, and, after 10 cycles of loading, hysteresis loop almost closes. Figure 2(b) [Yamashita, 1992] shows dynamic deformation characteristics that are frequently called G-γ and h-γ relationships. The relationship changes significantly from the 1st cycle to the second cycle, but as seen in Figure 2(a), it comes to stable state under 11 cycles of loading.

From the pioneer study by Seed and Idriss [1970] and Hardin and Drnevich [1972], efforts have been made to improve the test apparatus so as to measure small strains [e.g., Kokusho, 1980; Goto et al., 1991]. Strains close to 10^{-6} (0.0001 %) can be measured as seen in Figure 2(b) at present. The researches on dynamic deformation characteristics have been reviewed by, for example, Richart (1977), Ishihara (1982), Kokusho (1987), Woods (1991), Tatsuoka & Shibuya (1991), and Yoshida (1998b).

Looking at past results of the dynamic deformation characteristics test [JGS committee, 1994 and references above, for example], one notices that test was not conducted at strains larger than 1%. Maximum shear strain lies between 0.1 % and 1 % as shown in Figure 2 as an example. There are several reasons why dynamic deformation characteristics test was not conducted at shear strain larger than 1 %.

The result of element test should be processed so that stress-strain relationship can be reproduced. In this sense, dynamic deformation characteristic test is not sufficient, partly because the stabilization process is hardly documented and partly because shape of hysteresis loop is not described. The latter is expressed only as damping ratio. In spite of this shortage, this test has been conducted long time in the engineering practice. The reason may be related to the nonlinear dynamic response analysis of ground. Equivalent linear dynamic response analysis represented by SHAKE [Schnabel et al., 1972] has been frequently used in the engineering practice. Equivalent linear analysis requires only shear modulus and damping ratio and shape of hysteresis loop or exact stress-strain relation is not necessary. Since this method is an approximation, it is known that it is not applicable when nonlinear behavior becomes significant [Ishihara, 1982]. Looking at past dynamic response analyses, however, maximum strain lies within the range that many dynamic deformation characteristics tests were conducted. Therefore, the use of G-γ and h-γ relationships may be justified at the past. Under the very severe ground motion such as level 2-ground motion, however, soil will show more nonlinear behavior than at the past. Actually, looking at the result of the nonlinear dynamic response analyses during the 1995 Hyogoken-nambu earthquake [e.g., Suetomi and Yoshida, 1998], maximum strains exceeds 1 %. Therefore, dynamic deformation characteristics test may be better to reevaluated.

The other reason, which is the main topic of this paper, is the stabilization problem. As described before, 11 cycles of loading is to be applied in each cycles in the current dynamic deformation characteristics test. The hysteresis loop, however, does not come to stable state when amplitude becomes large as can be seen in the followings. Probably, this is the main reason why dynamic deformation characteristics test has not been conducted at trains larger than 1 %. As shown later, dilatancy effect is the cause of the unstabilization.

There are another tests that also intend to obtain the dynamic characteristics of soil. One of these tests is a dynamic strength test or liquefaction strength test. Stabilization of the hysteresis loop is not expected at the beginning in this test, because, this test aims to find the state where soil reaches failure state under cyclic loading. In the Japanese standard, double amplitude of 5 % axial strain under triaxial condition is frequently used as the criteria of the failure. This is equivalent to double amplitude of 7.5 % shear strain. This test is made to obtain the dynamic strength, the test data is processed to the relationship between shear strength and number of cycles causing failure, and therefore, stress-strain behavior is out of consideration in general.

Anyway, we have some data on the stress-strain behavior at very large strain range yielding failure or liquefaction and unstable behavior is assumed in this test. On the other hand, stable behavior is assumed in the dynamic deformation characteristics test. Therefore, one will notice that data between these two tests is missing in the past experience. If soil does not enter this region, it may not create problem. As discussed before, however, soil will enter this region under the level 2-ground motion. Therefore grasping the behavior of soil in this strain region, i.e., strain ranges from a little less than 1 % to several percent is important.

As a preliminary nature of this study, we examine the dynamic behavior of soil based on the conventional dynamic deformation characteristics test in large strain range.

TEST METHOD

Torsional test apparatus shown in Figure 3 is used in the dynamic deformation characteristics test. Toyoura sand is formed into hollow circular column shape with 10 cm exterior diameter, 6 cm interior diameter, and 10 cm height by air pluvial method. Relative density D_r is adjusted to be 30 %, a loose state. Initial effective confining pressure is set to be 49 kPa. Two tests is conducted under nearly the same condition.

During the test, constant shear stress amplitude is increased from small to large value. Eleven cycles of loading are applied in each stage under the undrained condition. Number of loading cycles is reduced when loading amplitude increases, because hysteresis loop does not stabilize. Excess porewater pressure that is generated in each stage is dissipated completely before moving next stage.

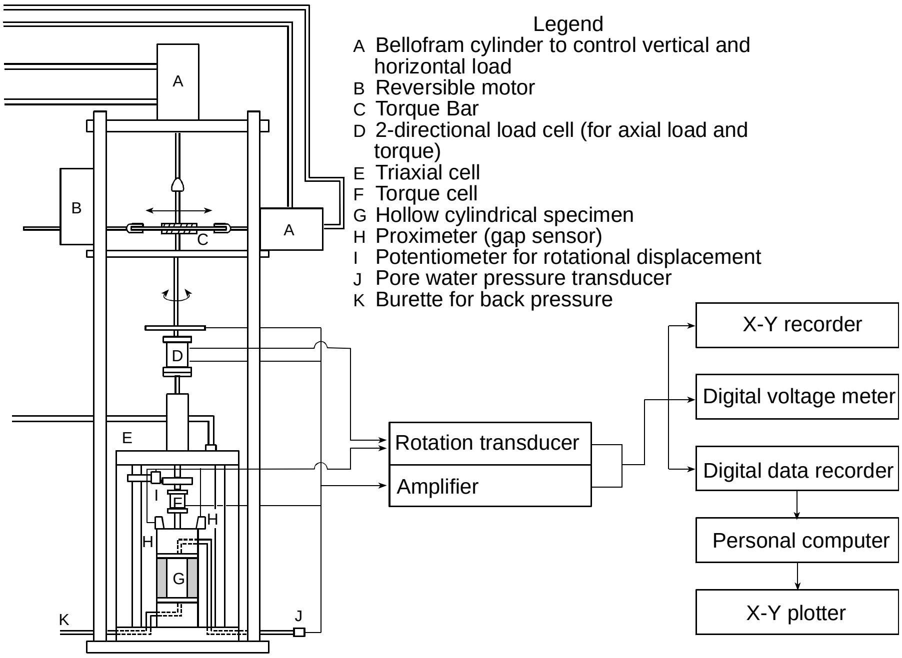


Figure 3: Test apparatus and data processing system

Shear strain is measures by three kind of sensors depending on the strain range. Gap sensor installed in the cell measures very small strains. Rotational measurement installed inside and outside the cell measures small strains and large strains, respectively. Shear modulus and damping ratio are computed from the hysteresis loop at 10th cycles of loading in the ordinary loading, but are computed from the hysteresis loop at the last loading cycle in each stage when amplitude becomes large.

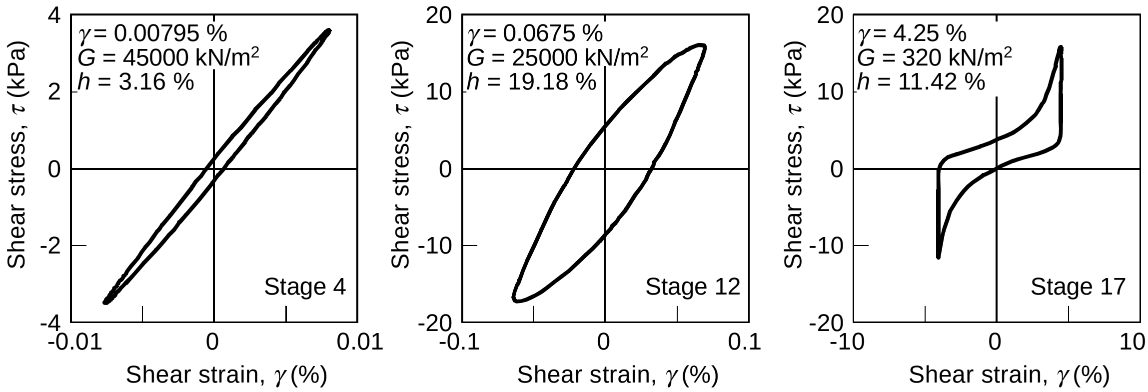
TEST RESULT

Figure 4 shows examples of the hysteresis loop at small, medium and large strain range. Hysteresis loop is very slender and damping is very small at small strains. Reduction of shear modulus is clearly observed in the hysteresis loop at medium strains. Excess porewater pressure is, however, hardly observed and hysteresis loop yields stable under cyclic loading. Damping ratio is about 20 %, which is rather large value. The result up to here coincide with the result done by other organizations [JGS committee, 1994].

Excess porewater pressure begins to generate when loading amplitude increases. In other words, soils enters quasi-liquefaction state [Yoshida, 1998a], i.e., the state that stress-strain behavior is affected by the excess porewater generation but liquefaction does not occur. In this state, degrading behavior is observed in the stress-strain curve as seen in Figure 5. Hysteresis loop does not stabilize any more at this stage, therefore ordinary loading program, i.e., 11 cycles of loading, becomes difficult to conduct. Figure 4(c) shows typical stress-strain loop at this stage. Shape of hysteresis loop is now far from the spindle shape that is seen in the conventional dynamic deformation characteristics test as seen in Figure 4(a),(b). If damping ratio is computed following the conventional procedure, damping ratio decreases as shear strain amplitude increase unlike the behavior at small and medium strains.

The G/G_0-γ and h-γ relationships obtained by two series of test are shown in Figure 6. Here G_0 denotes maximum shear modulus at each test, e_0 denotes initial void ratio, and σ'_c denotes initial effective mean stress. Maximum shear modulus (shear modulus at strains about 1×10^{-5} or 0.001 %) is 50.0 and 50.6 MN/m^2 in two cases. Shear modulus begins to reduce largely at about 1×10^{-4} (0.01 %) shear strain and it becomes a half of initial value at strain of about 5×10^{-4} (0.05 %).

Shear modulus reduces to 1/100 or less when soils enters quasi-liquefaction state at strain of about 2×10^{-2} (2 %). It gradually decreases after the subsequent loading. On the other hand, damping ratio reaches peak value at 1×10^{-3} (0.1 %) strain. Then it begins to decrease, and finally it becomes 10 % or less at several percents shear strain.



(a) Small strain (b) Medium strain (c) Large strain

Figure 4: Hysteresis loops at small, medium and large strains

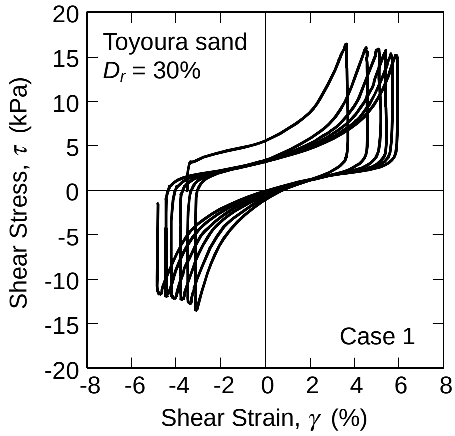


Figure 5: Degradation of stress-strain curve due to excess porewater pressure generation

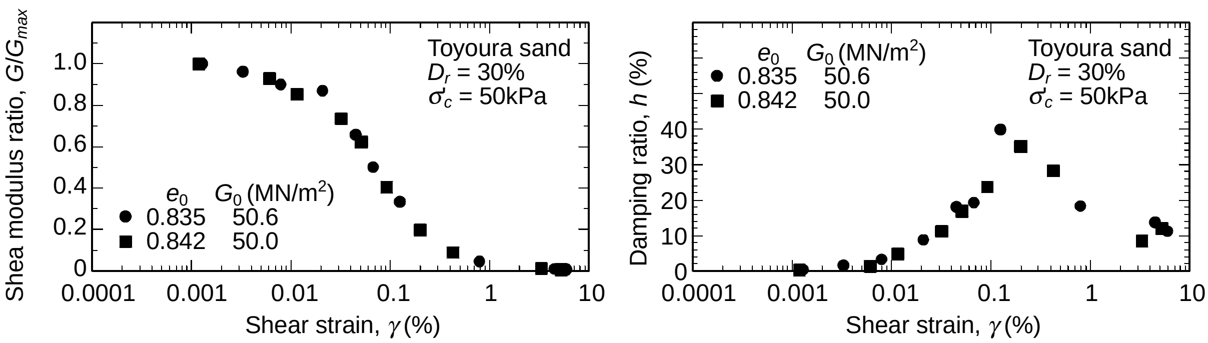


Figure 6: *G*-γ and *h*-γ relationships

DISCUSSION

Figure 7 shows stress-strain relationships derived from the G-γ relationships in Figure 8. Shear stress reaches peak value at strain of about 1×10^{-3} (0.1 %), then begins to decrease. It, however, again start increasing at strain of 3×10^{-1} (3 %). This behavior resembles stress-strain behavior obtained by monotonic loading test in which softening and hardening behaviors occur due to negative and positive dilatancy effect.

Then monotonic loading test is conducted under the same condition under which dynamic deformation characteristics test was conducted. The only difference is loading speed; monotonic test is conducted at strain rate of 10 %/min, whereas cyclic loading tests are conducted under 0.1 Hz. The comparison is shown in Figure 8. Stress-strain relationships obtained by monotonic loading test agrees with the ones obtained by cyclic loading test.

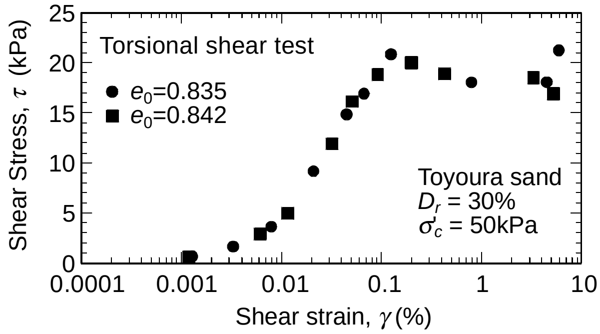


Figure 7: Stress-strain relations derived from *G*-γ relationships

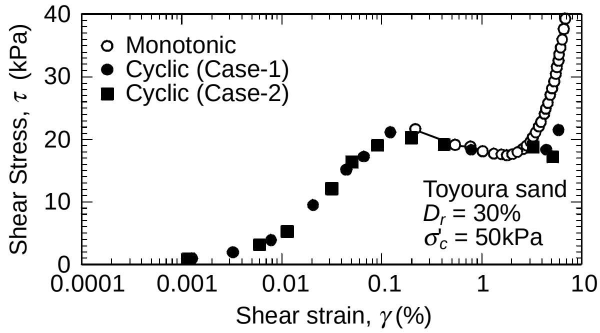


Figure 8: Comparison of stress-strain relations under cyclic and monotonic loading

Suetomi and Yoshida [1996] examined on various empirical equations on the frequency dependent damping characteristics by comparing the response of the ground by dynamic response analysis. One of their conclusions is that peak acceleration is not affected by the damping ratio very much. Yoshida et al. [1998], examined the effect of constitutive models on the nonlinear dynamic behavior in which constitutive models that have the same *G*-γ relationships but different hysteretic characteristics are used. They found that acceleration response spectrum is nearly the same in the frequency range less than 10 Hz although large difference is seen in the acceleration time history. These numerical analyses indicate that, if peak acceleration is or primary interest, the comparison shown in Figure 8 gives necessary data.

Their calculation, however, is limited to one case study. Moreover, knowing the *G*-γ relationships is far from the complete understanding of the soil behavior. Therefore, further research will be necessary. The future test and data processing method should be the one that can reproduce the stress-strain relation necessary in the nonlinear dynamic response analysis. This means that predominant factors controlling the behavior at large strains should be made clear, but is not at present.

Attention should also be paid on the current dynamic deformation characteristics test procedure, i.e., stage test procedure. This procedure assumes that loading in the previous cycles does not affect the subsequent loading. As described before, significant generation of excess porewater pressure is observed in the quasi-liquefaction state. Generated excess porewater pressure is drained at the end of loading in each cycle. This obviously results in the densification of test specimen.

CONCLUDING REMARKS

We first pointed out that soil behavior in the strain range between a little less than 1% and several percents is not known because this strain range lies between the conventional dynamic deformation characteristics test and dynamic strength test. Cyclic loading test that follows the procedure in the conventional dynamic deformation characteristics test made the features of the soil behavior in this strain range clear. Degradation of stress-strain curve is observed, which comes from excess porewater pressure generation under cyclic loading. In other words, soils enters quasi-liquefaction state. Therefore, conventional dynamic deformation characteristics test is shown to be difficult to apply in this strain range.

In this preliminary study, we compared stress-strain behavior obtained by monotonic and cyclic loading tests and showed that they agrees with each other. This information may be sufficient to obtain peak acceleration of ground by dynamic response analysis because effect of damping ratio on the peak acceleration seem small based on the past research. However, whole behavior at this strain range cannot be obtained by this comparison. Indices to represent the behavior in this strain range should be developed and test method to find them should also be developed.

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