An experimental approach to evaluate shear modulus and damping ratio of granular material

Une approche expérimentale pour évaluer le module de cisaillement et le taux d'amortissement du matériau granulaire

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ABSTRACT: During the last few decades enormous research has been published to clarify the response of sand under cyclic loading conditions. This can be attributed to the growing concern with safety of structures subjected to similar cyclic loading patterns. The aim of the present experimental work is firstly to investigate the responses of granular materials when subjected to cyclic stressing under plane strain conditions. In particular it is to ascertain if soil eventually reaches a preferred state. In order to assess whether such a state can develop a series of tests were conducted that covered a wide range of cyclic loading conditions. It is shown that granular materials, when subjected to a large number of stressing cycles, behave elastically with a linear stress-strain relationship. Two main dynamic mechanical properties of sand, namely shear modulus and damping ratio have been evaluated.

RÉSUMÉ : Au cours des dernières décennies, énorme de recherche a été publié afin de clarifier la réponse de sable sous des conditions de chargement cycliques. Cela peut être attribué à la préoccupation croissante de la sécurité des structures soumises aux mêmes modèles de chargement cycliques. Le but de ce travail expérimental est d'abord d'étudier les réactions des matériaux granulaires lorsqu'ils sont soumis à des contraintes cycliques dans des conditions de déformations planes. En particulier, il est de savoir si le sol finit par atteindre un état préféré. Afin de déterminer si un tel état peut se développer, une série de tests ont été effectués avec une large gamme de conditions de chargement cycliques. Il est montré que les matériaux granulaires, lorsqu'elle est soumise à un grand nombre de cycles de contrainte, se comportent de façon élastique avec une relation linéaire entre contrainte et déformation.

KEYWORDS: granular, material, cyclic loading, shear modulus, damping ratio.

1 INTRODUCTION

Interest in the effects of cyclic loading on soil strength has led to increased efforts at simulation in the laboratories. The main object of almost all laboratory tests has been to study the behavior of a given material under cyclic loading (e.g. Huang Y., Huang et al. 2004). The ideal purpose of laboratory element tests is to study the behavior of soil under conditions similar to those encountered in practical situations (Springman et al. 1995), and to determine the basic mechanical properties of soil, preferably as a set of constitutive equations which can be used for design or analysis. The response of many geotechnical structures to vibration is mostly dominated by the soil dynamic properties (Sitharam et al. 2004), among which shear modulus and damping ratio are the most important. Liquefaction, as the most catastrophic failure phenomenon, is onset of instability and is governed by the stress level and shear modulus (Abdul Lahi et al. 2010). In the presents research the strength and deformation behavior of dense and loose sand samples when subjected to cyclic stressing under plane strain condition are investigated. It is shown that when sand is subjected to cyclic stressing between two equal peak stress ratios, the sand particles arrange themselves to resist the directional loading and this results in the creation of a cross anisotropic structure.

2 MATERIAL

Standard Leighton Buzzard sand (BS sieve sizes 18-25; 850-600 μm) with a specific gravity of 2.66 was used for the present investigation. Two different methods of preparing sand samples, slow raining through air and releasing a large quantity of sand from a height of 750 mm above the ground level, resulted in dense and loose samples with initial voids ratio of e_0=0.52±1 and e_0=0.72±1 respectively. The 100 mm sand cubic samples were formed in a cubic rubber membrane, supported by a perspex box. Applying a negative pressure of around 50 kPa enabled to remove and position the samples in the apparatus. Sand samples to be considered were dry and subsequently all stresses were effective stress.

3 APPARATUS

The Biaxial Tester which has been fully described elsewhere (Ogunbekun, 1988) shears soil under plane strain conditions. The boundaries of the apparatus apply principal stresses with no application of shear stress. Contact sensors detect any change in position of the centers of the stretched pressure rubber bags through which the major and minor principal stresses are applied to the sample boundaries. Boundary movement of the Biaxial Tester is achieved with the aid of a hydraulic system. Four driving pistons provide inward or outward boundary movement during deformation of a sample to just maintain or just break contacts in the automatic mode. The main novel feature of the Biaxial Tester is the changing dimensions of the flexible boundary, through which the stresses are applied.

4 STRESS PATHS

Cyclic stress-controlled tests were performed under plane strain condition (ε_z =0). After positioning in the Biaxial Tester, the specimen was biaxially loaded with σ_x=σ_y=50 kPa. The stress orthogonal to the plane of strain, σ_z was initially applied at 50 kPa via the water filled plane strain boundary. At this stage the tap of the top plane strain boundary was closed in order to record the variation of σ_z during the test. The negative pressure on the sample was then released and the test commenced by increasing σ_x and decreasing σ_y whilst the mean biaxial stress, $(\sigma_x+\sigma_y)/2$, was held constant at 50 kPa through the test. Typical stress path for this kind of test are shown in Figure 1.

5 GENERAL EXPERIMENTAL PROCEDURE

Cyclic stress-controlled tests reported in the present research, performed on dense and loose sand. Fluctuating stresses, varying between principal stress ratios $R_{1max}=\sigma_x/\sigma_y$ and $R_{2max}=\sigma_y/\sigma_x$ (where $R_{1max}=R_{2max}$), were imposed on sand samples until a repeating state of strain was achieved and no further significant volumetric change was observed (Tests NDS50-1 and NLS50-2). The peak stress ratios were then increased and the cyclic stressing repeated. This procedure was repeated several times. The tests were terminated when the imposition of a higher stress ratio caused the sand to exhibit softening behavior which eventually led to a *run away* failure. Table 1 summarizes the test conditions and program.

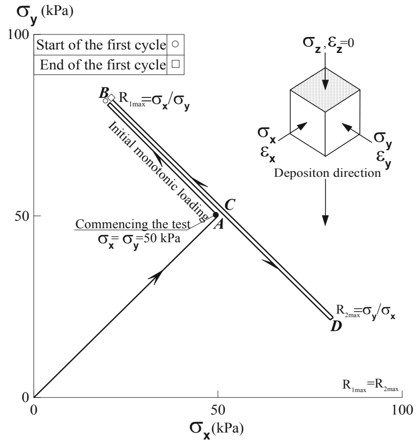


Figure 1. Stress path for cyclic stress controlled tests

6 TEST RESULTS

Following sections describe the behavior of loose and dense sand including stress strain characteristics, volume change trends, stiffening phenomenon and shear modulus evaluation.

Table 1. Test numbers and initial conditions of the cyclic tests; 90° changes of principal stress direction.

Test Number	e_0	No of total cycles	Principal stress ratio R_{max} (Number of cycles)
D-290	0.52	290	4.00 (50) 4.33 (50) 4.71 (50) 5.15 (50) 5.67 (50) 6.27 (30) 7.00 (10)
L-433	0.72	433	2.33 (100) 3.00 (25) 3.44 (25) 3.71 (40) 4.00 (40) 4.33 (60) 4.71 (60) 5.06 (70) 5.25 (10) 5.45 (3)

[1] The bracket indicates the number of cycles performed at a given stress ratio R_{max} where R_{max} is the maximum stress ratio during each stage of the tes

6.1 *Stress strain behavior*

In the course of cyclic stress loading during the first few cycles, sand exhibits significant plastic deformation accompanied by open hysteresis loops. Subsequent cycles give less plastic strain and the loops appear nearly closed, implying the development of a repeating state.

Dense Sand: Figure 2 illustrates the hysteresis loops for dense sand (for cycles 1, 5, 10, 15, and 50) in which the sand sample was subject to cyclic stressing at different maximum principal stress ratios from $R_{max}=4$ to $R_{max}=7$. It is worth mentioning that the test results are shown only for $R_{max}=4$. The Figure shows that during the first few cycles the hysteresis loops are *open* and after about 15 cycles the loops appear nearly closed. Further cyclic stressing led to a progressive stiffening of the material and resulted in apparent *elastic* behavior in which stress-strain curves follow the same path during unloading and reloading, i.e. the area within the hysteresis loop which represents the amount of dissipated energy during a cycle tends to zero.

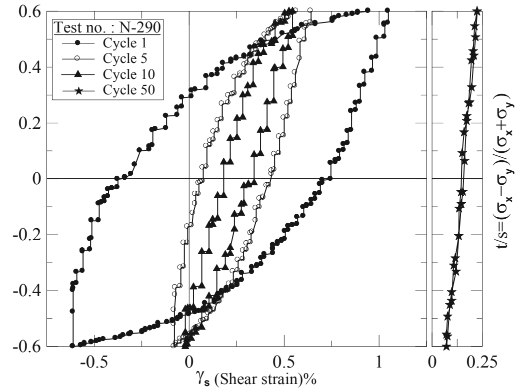


Figure 2. Hysteresis loops for dense sand (test No. N-290)

Loose Sand: The hysteresis loops for loose sand (Test L-430) in which the principal stress ratio, R_{max} varies between 2.33 and 5.45 are shown in Figure 3. The first cycle, in comparison with 10th cycle, produced a large hysteresis loop and a huge amount of unrecoverable strain. Again, repeated cyclic stressing caused sand to attain an elastic stress-strain response during unloading and reloading. It is clear that after certain of cycles, say e.g. 20, further cyclic stressing has no significant influence on the elastic behavior of material, i.e. no change in shear modulus will be observed.

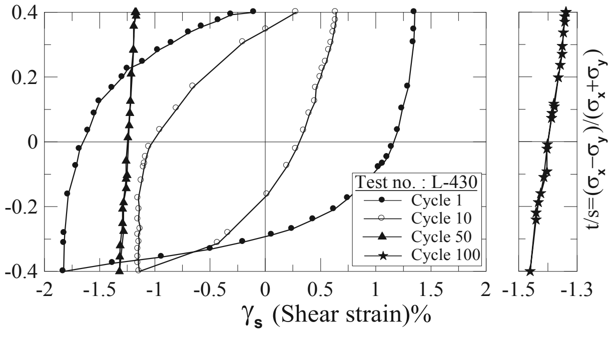


Figure 3. Hysteresis loops for Loose sand (test No. L-430)

6.2 *Overall Volume Change Behavior*

When dense or loose sand samples are subjected to cyclic stressing at constant stress ratio amplitude, irrecoverable or plastic strain during each successive cycle tends to reduce with increasing number of cycles until the induced shear strain over a cycle remains roughly constant, implying that elastic response dominates. However, the magnitudes of volume change after 100 cycles are considerably different for the dense and loose sands. The small densification of 0.6% which was observed for the dense sand is attributed mainly to the high initial density of the sample. For the loose sand sample there is a significant reduction in voids ratio leading to a densification of 5.5%

6.3 *Effects of increasing peak stress ratio*

Cyclic stressing with 90° changes in the principal stress directions on granular materials, described in the previous Sections, suggested that the granular media behaves as a linear and elastic material after a large number of cycles (e.g. 100).

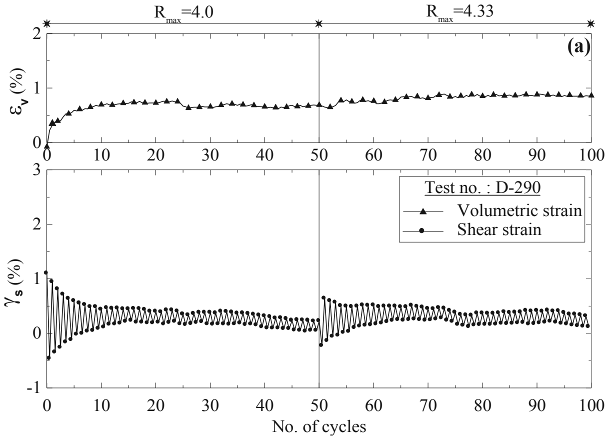


Figure 4. Effect of increasing the peak stress ratio on shear sand and volumetric change (dense test).

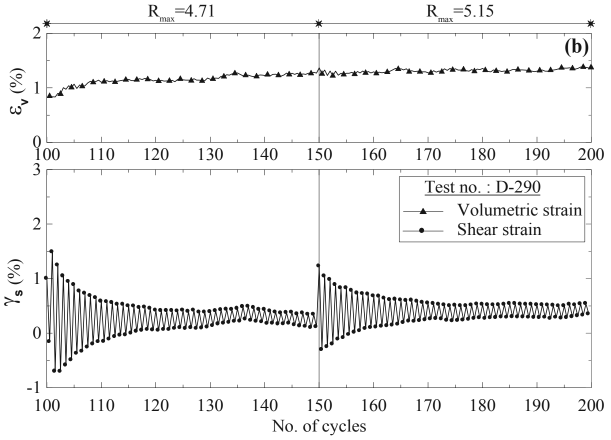


Figure 4. (Continued)

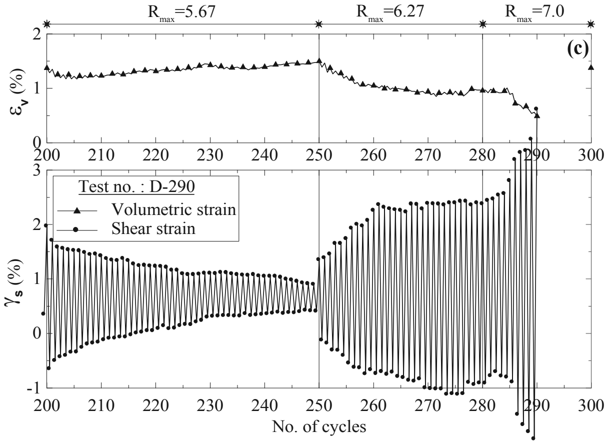


Figure 4. (Continued)

At this stage, if the sample experiences a higher peak stress ratio, it again behaves hysterically and plastic strain develops. The magnitude of the induced plastic strain and also the number of cycles required for the sample to again attain an elastic state are dependent on the magnitude of the new peak stress ratio.

To investigate the influence of increasing the peak stress ratio on stiffening behavior and volume change the results from tests D-290 (dense sand) and L-433 (loose sand see Table 1) are compared. In the case of dense sand, Figure 4, the test started at a peak stress ratio of t/s=0.6 (R_{max}=4) and it was increased when an elastic state was observed. The values of ε_v=-0.08% and γ_s=1.1% when N=0 for dense sand (Test D-290, Figure 4) are the corresponding values at the end of the initial monotonic shear loading before commencing the cyclic stressing.

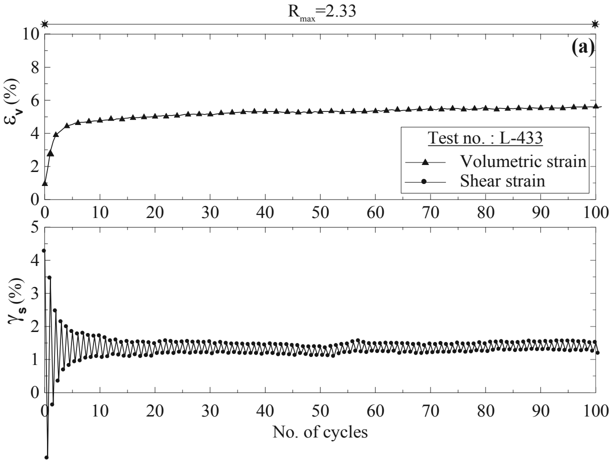
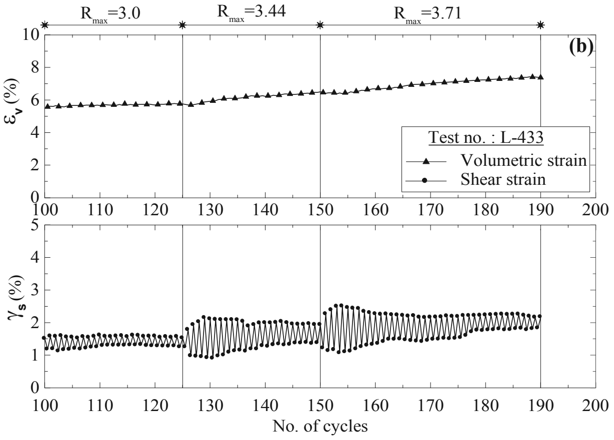


Figure 5. Effect of increasing the peak stress ratio on shear sand and volumetric change (loose test).



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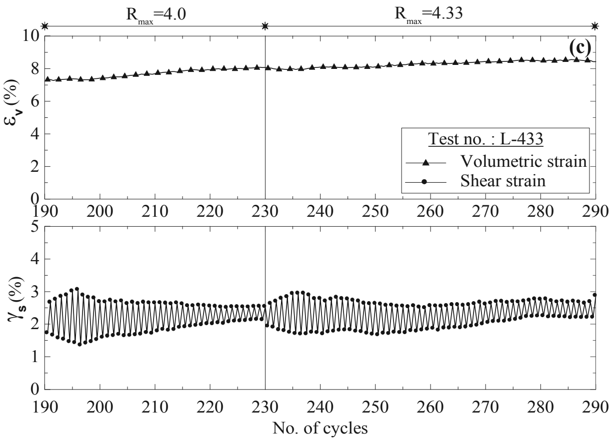

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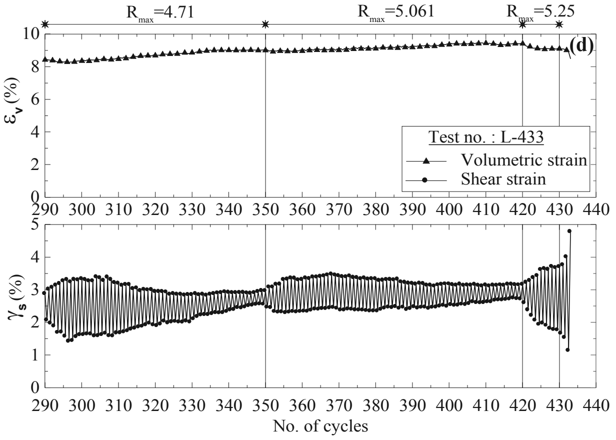

Figure 5. (Continued)

The initial peak stress ratio for the loose sand, Figure 5, started at t/s=0.40 (R_{max}=2.33) in order to prevent premature failure prior to densification. When sans attains a form of elastic behavior, R_{max} was again increased. It is clear that even at high stress ratio (R_{max}=5.061), the sand tends to reach a steady state.

6.4 *Evaluation of shear modulus and damping ratio*

Most experimental investigations have implied that the shear modulus-shear strain relations are mainly affected by voids ratio and mean confining stress (e.g. Alarcon-Guzman et al, 1989).
Sand under cyclic stressing exhibits non-linear hysteretic stress-strain behavior. The equivalent linear shear modulus, G, can be defined by the slope of the chord passing through the ends of hysteresis loop. As mentioned earlier after many cycles the open stress-strain hysteresis loop transforms almost into a unique line during reloading and unloading (Figures 4 and 5). It is evident with increasing number of cycles the hysteresis loop of stress-strain becomes gradually narrower and the line whose slope shows the equivalent shear modulus cannot be separated from a single stress-strain path during unloading and reloading. This implies that the sand essentially behaves elastically.

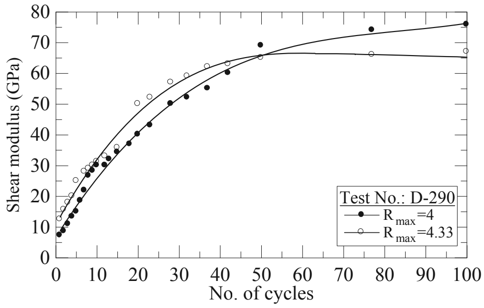

Figure 6. Variation of shear modulus with number of cycles

Shown in Figure 6 are the variations of shear modulus with number of cycles. It is clear that after many cycles the magnitude of shear modulus tends to remain constant, implying an elastic behavior. The following table summarizes the magnitudes of shear modulus as evaluated after several cycles at each of eight different stress ratios. The derived magnitudes of shear modulus for dense test, indicate that for all stress ratios below R_{max}=5.15 the sand attains a form of elastic deformation as the number of cycles approaches 50. An average magnitude of G=70 MPa for all stress levels below R=5.15 implies that if sand behaves elastically at any maximum principal stress ratio, R_{max}≤5.15, then there exists a unique value for shear modulus which is independent from the stress level and current voids ratio. However, when the maximum stress ratio is as high as R_{max}=5.67, the magnitude of G=32.9 MPa, is considerable lower than the average magnitude, G=70 MPa, obtained earlier.

Table 2. Evaluation of shear modulus for dense and loose sand at several peak stress ratios.

Test Number	R_{max}	No of cycle	G (GPa)
D-290	4.00	50	75.8
	4.33	100	67.8
	4.71	150	69.3
	5.15	200	71.2
	5.67	250	32.9
	6.27	270	4.53
	7.00	275	4.52
L-433	2.33	100	45.2
	3.00	124	38.7
	3.44	149	20.0
	3.71	189	35.2
	4.00	229	30.8
	4.33	289	28.8
	4.71	349	36.7
	5.06	419	34.7

The damping ratio for dense test is shown in Figure 7. The damping ratio decreases with increasing number of cycles. After a large number of cycles, damping ratio tends to becomes zero, again indicating an elastic behavior.

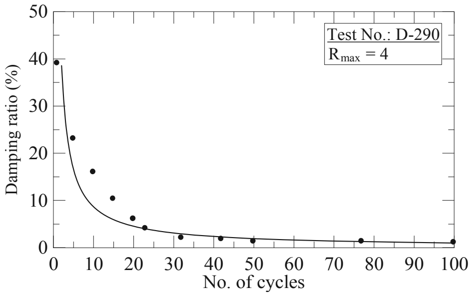

Figure 7. Variation of shear modulus with number of cycles..

7 CONCLUSIONS

The following points have been raised in this research:
When sand is subjected to cyclic stressing between two equal peak stress ratios, the sand particles arrange themselves to resist the directional loading.
Ideally true elastic response can only be achieved when the soil reaches its densest possible state. However, a strong induced structure may give the same shear modulus even though the soil is not at densest state.

There is a unique stress ratio below which cyclic stressing causes sand to attain an elastic state and above it cyclic stressing results in a softening response which eventually leads to a *run away* failure.

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