Study on seismic residual deformation test of reinforced soil

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Abstract. The reinforced material can increase the stability of soil material, improve its shear strength and reduce the residual deformation. In this paper, the vibration triaxial tests of coarse-grained soil under different confining pressure, consolidation ratio and dynamic stress are carried out by using the 100t electro-hydraulic servo large-scale static and dynamic triaxial testing machine of Institute of Water Resources and Hydropower Research. The results show that the average reduction ratio of the axial residual deformation of reinforced soil to that of unreinforced soil is 40%-50%, and the average reduction of the volumetric residual deformation is 30-40%. It has a good inhibitory effect. With the increase of confining pressure, consolidation ratio and dynamic shear stress ratio, the axial residual deformation and volumetric residual deformation of reinforced soil increase in varying degrees. The reinforcement effect of geogrid material on soil sample under different conditions is analyzed. The lower the dynamic shear stress ratio and the higher the consolidation ratio, the better the reinforcement effect. The lower the confining pressure is, the lower the reduction ratio of the reinforcement to the volumetric strain is.

1. Introduction

Earth-rock dam, with its advantages of convenient local materials, simple construction process, strong adaptability to foundation deformation, and low cost, has become the most widely used type of dam, accounting for more than 80% of all types of dams built in China [¹]. China is a country with frequent earthquakes, and the earthquake source is relatively shallow and the earthquake damage is relatively large [²]. Most of the earth-rock dams in China are built in the western regions with complicated geological conditions, seismic frequency and high intensity. Therefore, the safety of earth-rock dams is particularly important in these regions. In order to ensure the safe operation of earth-rock dam in seismic region, it is necessary to calculate the residual deformation of earth-rock dam under seismic conditions and evaluate the seismic stability of earth-rock dam. Therefore, it is of great significance to study the residual deformation of soil under vibration load [³].

Geotechnical reinforcement, with simple construction and low cost, can increase the stability of the structure, improve the shear strength and reduce the deformation characteristics of the structure by the interaction between reinforcement and the soil and the special meshing effect of the grid. Since the 1980s, geotechnical reinforcement technology has been applied in China widely and developed rapidly. At present, many scholars at home and abroad have done a lot of experimental model research on reinforced soil. Bao Huafu studied the stress-strain characteristics of reinforced soil with different reinforcement layers, and proposed that the reinforcement effect of gravel soil will weaken with the
increase of confining pressure \[^4\]. Through triaxial test, Wu Jinghai studied the stress-strain characteristics and reinforcement mechanism of geogrid reinforced soil \[^5\]. Bi Jing studied the dynamic characteristics of reinforced coarse-grained soil. The results show that when the dynamic shear strain is small, the reinforcement has little effect on the dynamic shear modulus and damping ratio of coarse-grained soil, and the residual volumetric deformation and residual shear deformation decrease significantly \[^6\]. Yang Shuaidong studied the dynamic elastic modulus of reinforced soil and unreinforced soil under different reinforcement layers, confining pressures and consolidation ratios. The results show that the dynamic elastic modulus of reinforced soil increases with the increase of confining pressure and consolidation ratio \[^7\].

In this paper, the vibration triaxial test is carried out with a 100t electro-hydraulic servo large-scale static and dynamic triaxial test machine of Institute of Water Resources and Hydropower Research. By changing different confining pressure, consolidation ratio and dynamic stress conditions, the residual deformation characteristics of reinforced soil and prototype soil are studied. The reinforcement effect of reinforced soil under different conditions is compared to provide solutions for engineering application.

2. Test content
In this paper, the dynamic triaxial test of saturated consolidated drainage was carried out to study the dynamic axial residual deformation and dynamic volumetric residual deformation characteristics of reinforced soil, and the axial and volumetric residual deformation values of reinforced soil under different confining pressures, consolidation ratios and dynamic stresses were obtained.

According to Seed research, when the initial stress state and the dynamic stress condition are the same, the dynamic residual axial strain and the residual volumetric strain are related to the number. When analyzing the seismic dynamic residual strain, the random seismic load needs to be converted into an equivalent cyclic number under the cyclic load, the equivalent magnitude of the seismic load depends on the magnitude of the earthquake \[^8\]. The results of the 12th, 20th, and 30th magnitudes of the triaxial vibration test correspond to the magnitudes of 7, 7.5, and 8.

2.1 Test equipment
In this paper, the dynamic residual deformation of reinforced soil was tested by a 100-ton electro-hydraulic servo triaxial testing machine. The large triaxial testing machine has the characteristic of vertical excitation load, and can conduct static and dynamic tests through the triaxial pressure chamber to study the static and dynamic properties of soil and rock samples. The instrument is sensitive, accurate and has a clear display. Static and dynamic tests are controlled by two independent hydraulic units, which make the operation very convenient.

Representative soil samples were selected for the test. The dry density was controlled to be $\rho_d = 2.2\text{g/cm}^3$, and the relative density was 80%. The grain size accumulation curve of the soil is shown in Figure 1.

![Figure 1. Grain size accumulation curve of the soil.](image-url)
2.2 Test plan
The test uses three groups of control tests to explore the residual deformation characteristics of reinforced soil with seismic strengthening measures under different confining pressures, consolidation ratios, and dynamic shear stress ratios under vibration loading. The control group is Series 1-2. The vibration triaxial tests of reinforced soil and unreinforced soil under the conditions of a confining pressure of 500 kPa, a consolidation ratio of 2.0, a dynamic stress of 50 kN, and a dynamic shear stress ratio of 0.4716 were performed.

2.2.1 Dynamic shear stress ratio. The dynamic shear stress ratio test group is series 3-4, and the test chooses 60kN dynamic stress, maintains 2.0 consolidation ratio, and 500kPa confining pressure and explores the residual deformation characteristics of soil samples with and without geogrid material.

2.2.2 Consolidation ratio. The consolidation ratio test group is series 5-8. The test uses 2.5 consolidation ratio to investigate the residual deformation characteristics of soil with and without geogrid material at two dynamic shear stress ratios at a confining pressure of 500 kPa.

2.2.3 Confining pressure. The confining pressure test group was series 9-13. The confining pressure condition of 1000kPa was selected for the test to explore the residual deformation characteristics of reinforced and unreinforced soil with two dynamic shear stress ratios of consolidation ratio 2.0.

| Series | confining pressure (kPa) | consolidation ratio | dynamic stress (kN) | reinforced | Dynamic shear stress ratio | Test name |
|--------|--------------------------|---------------------|---------------------|------------|--------------------------|-----------|
| 1      | 500                      | 2.0                 | 50                  | No         | 0.4716                   | unreinforced 500 2.0 50kN |
| 2      | 500                      | 2.0                 | 60                  | No         | 0.5659                   | unreinforced 500 2.0 60kN |
| 3      | 500                      | 2.0                 | 50                  | Yes        | 0.4716                   | reinforced 500 2.0 50kN  |
| 4      | 500                      | 2.0                 | 60                  | Yes        | 0.5659                   | reinforced 500 2.0 60kN  |
| 5      | 500                      | 2.5                 | 45                  | No         | 0.3638                   | unreinforced 500 2.5 45kN |
| 6      | 500                      | 2.5                 | 65                  | No         | 0.4850                   | unreinforced 500 2.5 65kN |
| 7      | 500                      | 2.5                 | 45                  | Yes        | 0.3638                   | reinforced 500 2.5 45kN  |
| 8      | 500                      | 2.5                 | 65                  | Yes        | 0.4850                   | reinforced 500 2.5 65kN  |
| 9      | 1000                     | 2.0                 | 75                  | No         | 0.3537                   | unreinforced 1000 2.0 75kN|
| 10     | 1000                     | 2.0                 | 95                  | No         | 0.4480                   | unreinforced 1000 2.0 95kN|
| 11     | 1000                     | 2.0                 | 75                  | Yes        | 0.3537                   | reinforced 1000 2.0 75kN |
| 12     | 1000                     | 2.0                 | 95                  | Yes        | 0.4480                   | reinforced 1000 2.0 95kN |
| 13     | 1000                     | 2.0                 | 105                 | Yes        | 0.4951                   | reinforced 1000 2.0 105kN|

2.3 Test operation
The large-scale dynamic triaxial test project is carried out in accordance with the relevant requirements of the "vibration triaxial test" in the geotechnical test regulations. The specific operation process of the test is as follows.

2.3.1 Sample preparation. Prepare the sample by dry packing. Place a piece of filter paper on the sample base, cover the rubber film on the sample base, and fasten the rubber film on the sample base with a rubber rope to avoid the existence between the base and the rubber film. Gap. Install the split mold, seal the contact seam with rubber clay, turn on the vacuum pump to extract the gas between the split mold and the rubber film to make the two fit together. Load the sample according to the control dry density, and load it in five layers (see Figure 2). A geogrid (see Figure 3) is installed between each two layers, and the sample cylinder is sequentially filled and compacted using the layered vibration method. Pay attention to prevent coarse and fine particles from separating during the filling of the sample, and keep the coarse and the fine soil is mixed evenly. After the sample is installed, put a piece
of filter paper on the top of the sample, install the sample cap, and fasten the rubber film and the sample cap with a rubber rope.

2.3.2 Sample saturation. After the sample is installed, the air in the sample is evacuated under vacuum to apply negative pressure to the sample. Check the air tightness of the sample and remove the split mold. Lift the pressure chamber to the base of the triaxial instrument and tighten the bottom of the pressure chamber fixing screw. Pass in degassing water from the bottom of the sample, and saturate the sample from bottom to top. If necessary, combine the method of applying reverse pressure to saturate the sample. The saturated pore water pressure coefficient of the sample is required to be above 0.97.

2.3.3 Sample consolidation. After the sample is saturated, drain the consolidation under the corresponding consolidation stress. Adjust the confining pressure to 500kPa and 1000kPa, remove the top support screw. Connect the consolidation circuit and start the consolidation load. Use grading loading method, each level 100kPa, 10 minutes a level.

2.3.4 Confining pressure. According to the requirements of the geotechnical test specification, set the cyclic vibration cycle and cyclic load amplitude on the computer control interface, and then apply dynamic stress to the sample for testing. Computer sensors are used to collect test data during the test.

3. Analysis of test results
Based on the results of the dynamic residual deformation test of the reinforced soil, the changes of the axial residual strain and the volumetric residual strain with the vibration cycle, the consolidation confining pressure, the consolidation stress ratio, and the dynamic shear stress ratio were studied.

3.1 Influence of seismic reinforcement measures on residual deformation
Comparing the test results of series 1 and series 3, the two series maintain the same confining pressure, consolidation ratio, and dynamic stress, and the test variable is whether or not a geogrid material is applied. The test results are shown in Figure 4. From the axial strain to cyclic number curve, it can be seen that the axial deformation of the reinforced soil is not significantly reduced during the first 5 weeks, and the effect of reducing the axial strain of the reinforced soil after 5 weeks is increased, with the highest reduction ratio reaching 32%. It is stable, and the volumetric strain increases steadily with the increase of vibration frequency, which conforms to the law of volumetric strain. The effect of reducing the volumetric strain is obvious, and the reduction ratio is about 25%.

To verify the effect law of the reinforced soil on the residual deformation under a consolidation ratio of 2.5, a comparative test was carried out in series 6 and 8. The test results are shown in Figure 5. Comparing the test results of working conditions 6 and 8, the two conditions maintain the same confining pressure, consolidation ratio, and dynamic stress, and the test variable is whether or not a geogrid material is applied. The test results are shown in Figure 5. Similar to the result of consolidation ratio of 2.0, it also showed that the reinforced soil has the characteristic of inhibiting residual deformation under the condition of a consolidation ratio of 2.5. It can be seen from the axial strain—cyclic number curve that as the vibration order increases, the axial residual deformation inhibits obviously. The reduction rate of axial residual strain reaches 60%. The volumetric strain—cyclic number curve also shows a good law, and the reduction rate of volumetric residual strain reaches 45%.
To verify the effect law of the reinforced soil on the residual deformation under confining pressure of 1000kPa, a comparative test was carried out in series 9 and 11. The test results are shown in Figure 6.

Comparing the test results of condition 9 and condition 11, the two conditions maintain the same confining pressure, consolidation ratio, and dynamic stress. The test variable is whether or not a geogrid material is applied. The test results are shown in Figure 6. Compared to the 500kPa confining pressure test results, when the confining pressure is 1000kPa, the reinforced soil also plays a role in reducing the residual deformation. From the axial strain-vibration number curve, it can be seen that as the vibration number increases, the difference between the axial residual deformation of the unreinforced soil and the reinforced soil is relatively stable, and the average reduction of the axial residual strain under the entire working condition is 50% on average. The volumetric strain-vibration curve in the first 5 weeks of the reinforced soil to suppress the volumetric residual deformation is not obvious. After 5 weeks, the effect of reducing the residual volumetric of the reinforced soil increased, and the reduction of the residual volumetric strain reached 40%.

3.2 Influence of dynamic shear stress ratio on residual deformation in reinforced soil
The influence of dynamic shear stress ratio on residual deformation in reinforced soil was investigated. The test results are shown in Figure 7.
Comparing the test results of series 11, 12, and 13, the three series maintain the same confining pressure and consolidation ratio, and they are all reinforced with geogrid materials. The test variables are different dynamic stresses of 75kN, 95kN, and 105kN. The test results are following Figure 7. In reinforced soil, when the confining pressure, consolidation ratio and geogrid material are the same, the axial strain increases significantly with the increase of dynamic stress. The volumetric residual strain also shows similar conclusions and the increase is more Stable, showing the same research conclusions as the prototype soil sample.

![Figure 8](image)

Figure 8. Influence of seismic reinforcement measures on residual strain——high consolidation ratio.

The test results of series 9-12, calculated under the same confining pressure, consolidation ratio, and dynamic stress conditions, the reduction ratio of residual deformation compared to reinforced soil and unreinforced soil, the processing results are shown in Figure 8. Deformation mutations at 4 weeks have a greater impact, so the processing data is discarded from the first 4 weeks of strain data. As the cyclic number increases, the reduction ratio of the axial strain and the volumetric strain decreases. Under the condition of low dynamic shear stress ratio, the reduction ratio of axial strain and volumetric strain is higher, which is stable at more than 40%, and the effect of geogrid material is better than that of high dynamic shear stress ratio.

### 3.3 Influence of consolidation ratio on residual deformation in reinforced soil

The influence of consolidation ratio on residual deformation in reinforced soil was investigated by comparing test series 4 and series 8. The test results are shown in Figure 9.

![Figure 9](image)

Figure 9. Influence of consolidation ratio on residual strain of reinforced soil.
Comparing the test results of series 4 and series 8, the two conditions maintain the same confining pressure and the dynamic shear stress ratio are similar, and both are applied with geogrid materials for reinforcement. The test variables are different consolidation ratios of 2.0 and 2.5. As shown in Figure 9. In the reinforced soil, as the consolidation ratio increases, the axial residual deformation increases significantly, and the volume residual strain also increases. This shows that for the reinforced soil, the axial residual deformation is affected by the consolidation ratio larger, the residual volume strain is less affected by the consolidation stress ratio.

![Figure 9](image)

Figure 10. Residual strain reduction ratio in reinforced soil with different consolidation ratio.

The test results of series 1, 3, 6, and 8 are calculated, and the reduction ratio of residual deformation compared with reinforced soil and unreinforced soil under the same confining pressure, consolidation ratio, and dynamic stress is calculated. The data from the previous 4 weeks is also discarded, on the condition of high consolidation ratio, and the reduction ratio of axial strain is higher than that of low consolidation ratio, indicating that the higher the consolidation ratio, the better the reinforcement effect. Under the condition of consolidation ratio 2.0 The reduction ratio of the axial strain fluctuates around 25%, and the reduction ratio of the volumetric strain is about 30%. At the consolidation ratio of 2.5, the reduction ratio of the axial strain is 60%, and the reduction ratio of the volumetric strain is about 40%.

3.4 Influence of confining pressure on residual deformation in reinforced soil

The influence of confining pressure on residual deformation in reinforced soil was investigated by comparing test series 3 and series 12. The test results are shown in Figure 11.

![Figure 11](image)

Figure 11. Influence of confining pressure on residual strain of reinforced soil.
Comparing the test results of series 3 and series 12, the two conditions maintain the same consolidation ratio, the dynamic shear stress ratio is approximately equal, and both are applied with geogrid materials. The test variables are 500kPa and 1000kPa with different confining pressures. The test results are shown in Figure 11. In the reinforced soil, when the dynamic shear stress ratio, consolidation ratio and geogrid material are the same, with the increase of the confining pressure, the axial residual deformation and volumetric residual deformation all increase significantly, showing the research conclusions consistent with the unreinforced soil.

![Figure 11. Residual strain reduction ratio in reinforced soil with different confining pressure.](image1)

The test results of series 1, 3, 10, and 12 calculate the reduction ratio of residual deformation of reinforced soils with different confining pressures and unreinforced soils under the same consolidation ratio and similar dynamic shear stress ratio. The processing results are shown in Figure 12. After discarding the data for the first 4 weeks, it is concluded that the reduction ratio of volumetric strain is higher in low confining pressure conditions than in high-confining pressure conditions, indicating that the smaller the confining pressure, the better the reinforcement effect. The reduction ratio of the axial strain fluctuates around 25%, and the reduction ratio of the volumetric strain is about 30%. Under the confining pressure of 1000 kPa, the reduction ratio of the axial strain is about 25%, and the reduction ratio of the volumetric strain is about 20%. Due to the weak shear expansion potential of the sample under high confining pressure, the lateral movement of the soil material between the grids is restricted, so the reinforcement effect is reduced.

4. Conclusion
As a seismic reinforcement measure, geogrid material is important to study the residual deformation characteristics of reinforced soil for the seismic safety performance of earth-rock dams. This paper reviews the results of large-scale dynamic triaxial tests on reinforced and unreinforced soil. The main conclusions obtained from the analysis are as follows,

1. Under the same consolidation ratio, confining pressure and dynamic shear stress ratio, the axial residual deformation and volumetric residual deformation of the soil samples with geogrid in the test materials are reduced in varying degrees. The average reduction of axial residual deformation is 40% - 50% of that of unreinforced soil, the maximum is 60%, and the average reduction of volume residual deformation is 30-40%. The geogrid material has a good inhibition effect on the residual deformation of coarse-grained soil.

2. Under the same confining pressure and consolidation ratio, the seismic residual deformation of reinforced soil increases with the increase of dynamic shear stress ratio. Under the same confining pressure and dynamic shear stress ratio, the axial residual deformation and volume residual strain of reinforced soil increase with the increase of consolidation ratio. Under the same consolidation ratio and dynamic shear stress ratio, with the increase of confining pressure, the axial residual deformation and volume residual deformation of reinforced soil increase significantly. All the above results are consistent with the unreinforced soil.
(3) The reinforcement effect of geogrid material on soil sample under different conditions is analyzed. The results show that the lower the dynamic shear stress ratio and the higher the consolidation ratio, the better the reinforcement effect. The lower the confining pressure, the lower the volumetric strain reduction ratio of the reinforced soil, and the axial strain reduction ratio is about 25%.

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