Investigation on the dynamic shear modulus of fiber-reinforced sand

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Abstract: As a new type of composite material, fiber-reinforced soil has attracted much attention due to its good dispersibility, mechanical properties and durability. Based on the dynamic triaxial test, the dynamic characteristics of polypropylene fiber-reinforced sand were studied, and the effects of fiber content (w), fiber length (lf), and cyclic stress ratio (CSR) on the dynamic shear modulus (G) of polypropylene fiber-reinforced sand were systematically analyzed. The results showed that the curves of dynamic shear modulus ratio (G/G₀) and cycles ratio (N/N₀) had piecewise linear characteristics. The slope of the curves was small before the segment point, whereas was large after the segment point. The G/G₀ decreased with the increasing of the CSR, whereas the effect of w, lf and CSR on the curve was not significant. The curves of G/G₀ and dissipated energy per unit volume ratio (W/W₀) also had piecewise linear characteristics. The G/G₀ decreased rapidly as the increasing of W/W₀ until it was close to 0, and then kept stable. The decreasing rate of G/G₀ at low CSR was greater than that at high CSR, which indicated that high CSR had great affect on the G.

1. Introduction

As a new soil improvement technology, reinforced soil technology is widely used in soft soil foundation, slope and retaining wall reinforcement projects. The fiber has good dispersibility, mechanical properties and durability, and has been widely concerned by scholars [1-3]. Mohamed [4] studied the shear strength characteristics of straw fiber-reinforced soil, and concluded that with the increased of fiber content, the shear strength of fiber soil first increased and then decreased. When the fiber content was 1%, the shear strength was the largest. Chen et al. [5] studied the influences of fiber length, fiber content, water content and dry density effects on the shear strength of fiber red clay by using orthogonal test method, and established a multiple nonlinear regression model for the shear strength index of fiber red clay based on the multiple regression theory. Chu et al. [6] studied the dynamic features of fiber-reinforced loess, and analyzed the regularity of dynamic stress-strain relationship, damping ratio characteristics, dynamic strength characteristics and seismic depression. The results showed that under the same dynamic shear strain condition, the dynamic shear stress of fiber-reinforced loess was greater than that of loess; under the same failure vibration number, with the increased of fiber sand proportion, the dynamic shear stress first increased and then decreased.
Estabragh et al. [7] studied the influence of nylon fiber on the mechanical properties of clay, and concluded that adding nylon fiber could increase the shear strength and internal friction angle of the soil, and with the increased of fiber content, the pre-consolidation pressure of the reinforced soil decreased, and the expansion coefficient and compression coefficient increased. Hamidi and Hooresfand [8] obtained from triaxial test that the stress-strain characteristics of polypropylene fiber-reinforced soil showed a typical strain hardening. Patel and Singh [9] studied the effect of glass fiber on the strength of cohesive soil, and found that CBR and secant modulus increased as the increased of fiber content and fiber length. Tang et al. [10] found that the cohesion of polypropylene fiber-reinforced sand first increased and then decreased with the increased of sand content, and the internal friction angle was directly proportional to the sand content.

To date, researches mainly carried out on the fiber-reinforced soil, but relatively few researches investigated on the fiber-reinforced sand, especially on the dynamic characteristics of the reinforced sand. Based on dynamic triaxial test, the dynamic characteristics of polypropylene fiber-reinforced sand were studied in this paper. The effects of $w$, $l$, and CSR on $G$ of fiber-reinforced sand were analyzed. The results could promote the understanding of dynamic shear modulus.

2. Materials and Methods

2.1. Test Materials

After chemical treatment, polypropylene fiber may resistant to aging and highly durable in water. It is a kind of economical and convenient material. The polypropylene fiber used in the test was purchased from Jiangsu Yancheng henggu Fiber Co., Ltd. The fiber is white, round cross-section monofilament, with a length of 6 mm or 12 mm. It is distributed in bundles and can be dispersed by stirring. Its physical and mechanical properties are shown in Table 1. The test sand is ISO standard sand produced by Xiamen aiso standard sand Co., Ltd. in Fujian Province. The sand was sealed and packaged independently to ensure the uniformity. After screening the standard sand through 0.5 mm sieve, the large sand particles were removed, and the fine sands with relatively uniform particle sizes were retained, which were sealed and stored to obtain the test sand.

Table 1. Physical and mechanical parameters of polypropylene fiber

| Type                          | Fascicular monofilament |
|-------------------------------|-------------------------|
| Cross-sectional shape         | Circle                  |
| Linear density /dtex          | 7.33                    |
| Diameter /mm                  | 0.025                   |
| Specific gravity /g·cm$^{-3}$  | 0.91                    |
| Tensile strength /MPa         | 592                     |
| Elongation at break/%         | 26.4                    |
| Initial elastic modulus /MPa  | 4479                    |
| Melting point /℃              | 163                     |
| Ignition point /℃             | 590                     |
| Acidity and basicity resistance| Extremely high          |
| Dispersivity                  | Well                    |

2.2. Sample Preparation

The key of fiber sand sample preparation is to ensure that the fiber and sand are mixed evenly so as to achieve the random distribution of fiber in the sample. Preparation of fiber sand samples require repeated exploration. After repeated tests, it was found that when the water content of sand was 7~9%, the sand layer and the fiber layer were overlapped repeatedly, and then the fiber and sand could be mixed more evenly after being stirred for many times, and the sample had better homogeneity. According to the estimated number of test groups under each stress ratio, samples required for a certain fiber length and fiber content were prepared at one time, then put into plastic bags and stored in sealed boxes, so as to ensure the consistency of the samples. Considering the small fiber content, the
relative density was ignored in the calculation, and the relative density of samples was \( D_r = 0.5 \). The fiber content is the ratio of fiber mass to dry sand mass.

The specimen used in the test was 61.8 mm in diameter and 125 mm in height. The weighed fiber sand was loaded into the mold four times, and compacted evenly layer by layer. Before compaction, the fiber sand was fully stirred to eliminate the interference caused by uneven density, and sufficiently scraping treatment between layers to ensure the connection effect.

2.3. Calculation of \( G/G_0 \)

The \( G \) can be calculated by the equation (1):

\[
G = \frac{E}{2(1+\nu)}
\]  \hspace{1cm} (1)

Where \( E \) is the dynamic elastic modulus; \( \nu \) is Poisson's ratio, which is 0.5.

The initial dynamic shear modulus \( G_0 \) is the dynamic shear modulus when the dynamic shear strain is 0.

The \( G \) represents the axial stress-strain relationship of the specimen and is calculated from the average slope of the hysteresis loop.

\[
E = \frac{\sigma_d}{\varepsilon_d}
\]  \hspace{1cm} (2)

Where \( \sigma_d \) and \( \varepsilon_d \) are the dynamic stress and strain at the apex of hysteresis loop.

3. Results and Discussion

3.1. Influence of Fiber Content

Figure 1 shows the relationship between \( G/G_0 \) and \( N/N_L \) when \( w \) changes with \( D_r = 0.5 \); \( CSR = 0.203, 0.230 \); \( l_f = 6\text{mm}, 12\text{mm} \). It can be seen from Figure 1 that the \( G/G_0 \sim N/N_L \) curves generally present a downward trend, which are consistent with the attenuation property of dynamic shear modulus. The curves are piecewise linear and can be approximately regarded as two straight lines. When the \( N/N_L \) is less than a certain value, the slope of the curve is small, and the dynamic shear modulus decreases gradually; While the \( N/N_L \) is greater than a certain value, the slope of the curve is larger, and the \( G \) decreases rapidly until liquefaction. As \( CSR = 0.203 \), the segment point values of the curve are relatively close, and the influence of fiber content on the curves are not significant; As \( CSR = 0.230 \), the segment point values of the curves are significantly different. When the length of 12mm fiber is mixed, the lower the fiber content is, the greater the value of curve segmentation point is.
3.2. Influence of Fiber Length

The influence of $l_f$ on $G/G_0$ vs. $N/N_L$ curves under $D_r=0.5$; $CSR=0.203, 0.230$; $w=0.2\%, 0.4\%, 0.6\%$ as shown in Figure 2. The law of $l_f$ on the curves is similar to that of $w$ on the curves, and the curves show a downward trend as a whole, which can be approximately two straight lines, and the segment point values are close, the influence of $l_f$ on the curves is not significant. When $CSR=0.230$ and $w=0.2\%$, the segment point value of the curves are significantly different, and the $l_f$ had a significant impact on the curve.

Figure 1. Relationship between $G/G_0$ and $N/N_L$ under different $w$
3.3. Influence of Cyclic Stress Ratio

Figure 3 shows the relation curves of $G/G_0$ vs $N/N_L$, and $G/G_0$ vs $W/W_L$ under different CSR with $D_r=0.5$; $w=0.2\%$, $0.4\%$, $0.6\%$; $l_f=6$mm, 12mm. Under the condition of low CSR (CSR=0.203), the $G/G_0$ changes approximately, and decreases steadily with the increase of $N/N_L$ at the initial stage. When the $N/N_L$ is greater than 0.8, the $G/G_0$ decrease rapidly and finally approach to 0. While, at high CSR (CSR=0.230), the initial decrease rate of dynamic shear modulus is greater than that of low stress ratio. When the $N/N_L$ is greater than 0.7, the $G/G_0$ begins to decline rapidly.

It can be seen from the curves of $G/G_0$ vs $W/W_L$ that the attenuation of dynamic shear modulus can be divided into two stages. In the initial stage, with the increase of $W/W_L$, the attenuation of $G/G_0$ decreases rapidly, and when it drops to close to 0, it maintains a stable state. Under CSR=0.203, the $G/G_0$ reach stability when $W/W_L=0.7$, and under CSR=0.230, the $G/G_0$ reached stability at $W/W_L=0.6$, indicating that the high stress ratio has a greater impact on the weakening of the dynamic shear modulus.
Figure 3. Relationship between $G/G_0$ and $N/N_L$, $G/G_0$ and $W/W_L$ under different CSR

4. Conclusions

(1) The curves of $G/G_0$ and $N/N_L$ under different $w$, $l_f$ and CSR all have attenuation and piecewise linear characteristics. The slope of the curve before the segment point is small, and the $G/G_0$ decrease slowly. The slope of the curve after the segment point is larger, and the $G/G_0$ decrease faster. At low stress ratio, the influence of $w$ and $l_f$ on the curve is insignificant. In the case of high stress ratio, the value of segment point is obvious.

(2) The curves of $G/G_0$ and $W/W_L$ have piecewise linear characteristics. With the increase of $W/W_L$, the $G/G_0$ decrease rapidly. When it is close to 0, it keeps stable with the increase of $W/W_L$.

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