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Evaluation of the performance of sensor-enabled geobelts after cyclic loading

Xin-zhuang Cui *, She-qiang Cui, Tu Lu, Lei Zhang, Yi-lin Wang, Jun Li

School of Civil Engineering, Shandong University, Jinan 250061, PR China

HIGHLIGHTS

- A new smart geosynthetic named sensor-enabled geobelt (SEGB) was developed.
- The effects of prestrains and cyclic loads on SEGB were investigated.
- Mechanical properties of SEGB after cyclic loading were evaluated.
- A preliminary model was proposed to evaluate tensoresistivity of SEGB.

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ABSTRACT

Geosynthetics are an effective method to increase the seismic level of reinforcement soil structures. In this paper, sensor-enabled geobelts (SEGB) that performed self-measurement and reinforcement functions were developed on the strain-sensitive electrical conductivity (tensoresistivity) of the high-density polyethylene (HDPE) filled with super conductive carbon black (CB). To study the influence of seismic loads on SEGB, a series of cyclic loading tests were performed. Before cyclic loading, different prestrains were applied to simulate the deformation of SEGB in soil before earthquake. The results show that the tensile strength and elongation at break of SEGB after cyclic loading decrease with the number of loading cycles and strain amplitude of cyclic load, though the prestrains have a limited influence on the reduction of mechanical properties of SEGB. For the tensoresistivity response of SEGB after cyclic loading, the electrical conductivity of SEGB becomes more sensitive to strain by increasing number of loading cycles, amplitude of cyclic load and prestrains. Based on the test results, a preliminary model was proposed to evaluate the tensoresistivity performance of SEGB after cyclic loading.
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1. Introduction

Geosynthetic engineering has experienced tremendous growth over the past few decades. Geosynthetic reinforcements are widely used to improve the stability of many kinds of soil structures. Examples include the stabilization of highway slopes and embankments [1,2], reinforcement of foundations [3–5], and reinforcement of paved roads to mitigate cracking and rutting [6]. As geosynthetic reinforcements are used in a wide range of soil structures and these structures are subjected to various loading conditions including static and dynamic loads, more and more attention has been paid to evaluating the performance of geosynthetic-reinforced soil structures under static and dynamic loads by numerical calculations, laboratory and field tests, etc. For example, experimental studies involving field and laboratory static loading tests on geosynthetic-reinforced soil structures have been conducted [7–11]. Besides the response under static loads, there also have been many studies performed on the behaviors of geosynthetic-reinforced soil structures under dynamic loads. For instance, in order to investigate the dynamic behaviors of geosynthetic-reinforced soil structures, model tests under seismic loading had been done by some researchers [12–18]. In summary, these studies on geosynthetic-reinforced soil structures are helpful to obtain comprehensive knowledge on the behaviors of geosynthetics under static and dynamic loads, which also contribute more to the development of geosynthetics. It is also noted that these studies mostly pertain to the area wherein the soil is reinforced with geogrids, geocells, geotextiles. However, geobelt, made of polymeric materials, is one of the reinforcement materials and has also been widely used as reinforcement in embankment and

* Corresponding author.
E-mail addresses: cuixz@sdu.edu.cn (X.-z. Cui), 1914569734@qq.com (S.-q. Cui), 1033871383@qq.com (T. Lu), 837827723@qq.com (L. Zhang), eason_wyl@163.com (Y.-l. Wang), forzaapis@126.com (J. Li).

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foundation [19–21]. Some researchers have used site tests or numerical analysis to study the behaviors of geobelts-reinforced soil structures under static loads, and they confirmed the beneficial effect of reinforcement on the enhancement of bearing capacity and shear strength characteristics [22–24]. But, there is no study that has been focused on the response of soil structure reinforced with geobelts under dynamic loads.

All the studies reviewed above primarily investigated the performance of traditional geosynthetics under static and dynamic loads. Nevertheless, as geosynthetic-reinforced soil structures become more widespread globally, it becomes increasingly vital to ensure that these structures are not only safe but also offer a satisfactory level of serviceability through health monitoring. Thus, a novel concept of sensor-enabled geogrids (SEGG) has been developed based on the tensoresistivity of electrically filled polymers [25]. A self-measurement function was added to SEGG by adding a critical concentration of conductive fillers (e.g., carbon blacks and carbon nanotubes) to the polymers (e.g., polypropylene). This self-measurement function affords SEGG a unique and significant characteristic by which their tensile strain can be conveniently measured. However, an important unsolved problem remains in the referenced SEGG studies: the strain-conductivity response of SEGG materials with multiple ribs is complex, and the accuracy of self-measurement results cannot be fully ensured [26]. Therefore, to ensure the self-measurement accuracy, a new smart geosynthetic named sensor-enabled geobelts (SEGB) was developed by the authors [27]. The SEGB of high-density polyethylene (HDPE) filled with super conductive carbon black (CB) was fabricated by both industry and laboratory. In authors' previous study, a series of in-isolation tests were conducted to study its mechanical properties and tensoresistivity performance. And the pullout tests were performed using a large pullout device to investigate in-soil performance of SEGB and verify the accuracy of SEGB self-measurement.

These studies on SEGB and SEGG are solely focused on the performance under static loads. However, compared to the traditional geosynthetics, SEGB can be subjected to seismic loads during service life and more studies are needed to obtain comprehensive knowledge on SEGB. There are few evaluations on the performances of SEGB after earthquake. Though Yazdani et al. [28] studied the influence of cyclic loading on SEGG, the frequency of cyclic loading is too low to simulate seismic loads. In this paper, to simulate the seismic behavior of SEGB, a series of cyclic loading tests were performed. The factors including the prestrains, number of loading cycles and strain amplitude of cyclic load were investigated. This work aims to improve the knowledge related to the effects of earthquake on the mechanical properties and tensoresistivity performance of SEGB.

2. Materials

The materials used for SEGB included high-density polyethylene (HDPE) and the super conductive carbon black (CB). The physical properties of HDPE are shown in Table 1. Because the components of CB masterbathes and their contents are disclosed by the supplying companies, the filler content of the CB-filled SEGB in this paper was the mixing ratio of the conductive masterbatch to the HDPE instead of the actual contents. In the fabrication of SEGB, HDPE was filled with the conductive masterbatch (CB) by different weight. In factory, the masterbatch of CB was firstly mixed with HDPE until the polymer beads appeared to be evenly distributed in the mix. The mixture in the batch should be kept dry before being poured into the extruder and then be preheated and melted completely and uniformly. The temperatures in the working zones of the extruder were set to 180 °C, 185 °C, 190 °C, 200 °C, 213 °C, 205 °C, 212 °C. The compounding procedures started after reaching the target temperatures, and the pellets melted in the working zones. Once extruded, SEGB was extrusion molded.

Table 1
Physical properties of HDPE.

Density (g/cm^3)	Tensile strength (MPa)	Elongation at break (%)
0.954	26	500

Rectangle SEGB specimens (16 cm × 11 cm) with a thickness of 4 mm were molded. The specimens were wiped clean and then adhered by conductive tapes as measuring points. The surface resistance was measured with a FLUKE insulation tester. The surface resistivity is defined as follows:

$$\rho_s = R_s \frac{l}{d} \tag{1}$$

where ρ_s is the surface resistivity; R_s is the surface resistance; d is the electrode distance perpendicular to the two conductive adhesive tapes; and l is the electrode length.

Fig. 1 shows the variation curve of the surface resistivity of SEGB with the CB content [27]. It is seen that the surface resistivity of SEGB gradually decreases with the concentration of conductive fillers CB and eventually tends to stability at a critical concentration (i.e., 47.5% in Fig. 1). Based on the percolation theory [29,30], a CB conductive network which allows the electrons to be able to "flow across the polymer barrier" or "travel through a disordered network of conductive fillers" is formed at this critical concentration. At the point of 47.5%, small changes in the CB conductive network structure (e.g., due to tensile strain) can dramatically change the conductive pathways in the SEGB, which in turn can cause large changes in conductivity. Hence, in this study, the tests were performed on the SEGB with the filler concentration of 47.5%, which was the optimum CB content value.

3. Cyclic loading tests

3.1. Simulation of seismic loads

According to the previous studies [31–35], the number of significant uniform loading cycles can be considered equivalent to repetitive loads on site caused by an earthquake that has irregular stress-time history. This can be explained with the aid of Fig. 2. Fig. 2(a) shows the irregular pattern of stress with time for an earthquake. The maximum stress induced is σ_{max}. Because the effect of the irregular stress-time history shown in Fig. 2(a) is the same as the uniform stress cycles shown in Fig. 2(b), the stress-time history of earthquake can be equivalent to uniform strain–time history of cyclic stress with the maximum magnitude equal to $\beta\sigma_{max}$. Seed et al. [32] presented the relationship between the earthquake magnitude and the equivalent number and duration of loading cycles, shown in Table 2. In this study, changing the number and duration of cyclic loading simulated the five kinds of earthquake magnitudes in Table 2.

During earthquake, dynamic stress was applied on geosynthetics by the transformation of soil. Wang et al. [36] investigated the behaviors of geosynthetic-reinforced embankment during an earthquake by using centrifuge model tests. It was found that the peak strain of geosynthetics induced by earthquake was around 2%. Therefore, based on their studies, there were two strain amplitudes (i.e., 1% and 2%) used in the tests to simulate the intensity of earthquake.

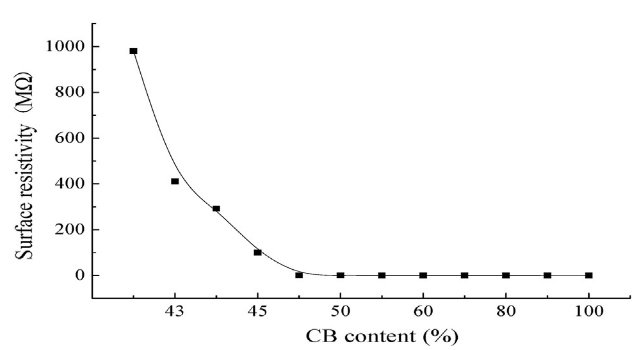

Fig. 1. Variation curve of the surface resistivity of SEGB.

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