Laboratory Large-Scale Pullout Tests for Evaluation of the Application of Waste Plastic Bottles as Transverse Members on Geogrid Reinforcement

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Abstract
In recent years, the application of geogrid in reinforced soil structures, including mechanically stabilized earth walls, has remarkably increased. In earthen structures reinforced with geosynthetics, the interaction between soil and geogrid is an important criterion for designing and controlling stability. Accordingly, finding solutions to improve and strengthen the parameters of the soil–geogrid interaction is demanding. The purpose of this study is to examine the effect of using recycled bottles as transverse members on geogrid by large-scale pullout tests; the new system is called Geogrid-Bottle (GG-B). The pullout tests results have shown that sand-filled recycled bottles can provide reasonable strength in the third dimension of the reinforcement and can increase the reinforcement resistance against the pullout force. The results showed that the GG-B system increased the pullout force by more than about 69% compared to geogrid alone. In addition, it was proved that the appropriate distance between the transverse bottles attached to the geogrid was four times as large as the bottle diameter (D) under different vertical stresses. Furthermore, results showed that displacements at the geogrid end decreased with increasing the number of bottles.

Keywords Geogrid · Large-scale pullout test · Transverse member · Sand · Recycled plastic bottle

Introduction
In recent decades, the increase of pullout resistance of geosynthetic reinforcement using innovative materials has become a popular subject of interest for research purposes. The new method of reinforced soil was invented and introduced in the early 1960s by Henry Vidal. The use of reinforced soil structures has become a common solution to solve geotechnical engineering problems due to its simplicity in implementation and cost-effectiveness compared to traditional methods. In designing reinforced earth retaining walls, suitable safety factors against pullout are required to meet the strength and the deformation requirement. Therefore, the evaluation of the interaction between soil and reinforcement is necessary to achieve a safe design.

The use of geosynthetic products in various geotechnical applications such as earth retaining walls, embankments, slope protection, stabilization and foundations has increased in recent years. Geogrid is usually used for the construction of reinforced soil and reinforcement of earth retaining walls.

In coarse-grained soil (i.e., gravel), interlocking is the most important mechanism of mobilizing the shear strength at the soil–geogrid interfaces. In fine-grained soils (i.e., fine sand), the tensile strength of uniaxial geogrids includes several components, including friction between the soil and both surfaces of the geogrid. Another component includes the friction between the soil and the longitudinal ribs of the geogrid and also the friction between the soil and the transverse ribs of the geogrid. The last component is passive soil resistance against displacement of transverse ribs of

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geogrid. The soil inside the aperture of geogrid also creates bearing resistance against the displacement of the transverse ribs [1–5]. Consequently, the transverse members attached to geogrid have an essential role in the pullout resistance, since such 3D objects provide not only frictional resistance but also improve passive resistance under the pullout condition. The monotonic pullout tests conducted by Mahigir et al. [6] who indicated that adding the amount of clay to sand increased the pullout resistance at the lower effective vertical stress of 20 kPa, while at higher vertical stresses of 40 and 60 kPa, this effect was insignificant. Feng et al. [7] demonstrated that with the geogrid-reinforced and pile-supported embankments, the stability of the embankments was improved significantly. The results reported by Mekonnen and Mandal [8] showed that the failure surcharge pressure increased by 185.76% and 311.84% using bamboo geogrid strips, compared with the unreinforced model wall. The background of the research shows that the effects of various parameters on the interaction of soil and reinforcement have been investigated by performing pullout tests [9–12]. The results of study by Prashanth et al. [13] showed that the pullout behavior was sensitive to the normal stress and the type of geosynthetics in terms of its surface roughness.

Several studies have focused on discovering the effect of attaching anchors on the soil–geogrid interaction enhancement [14–16]. The anchors used were composed of 1 cm × 1 cm × 1 cm cubic elements attached to the ordinary geogrid using plastic fasteners with the capacity of automatic locking. The results of their studies showed that attaching anchors to geogrid increased the pullout resistance of the geogrid. Mirzaalimohammadi et al. [17] conducted pullout tests by attaching steel bars as transverse objects to the geogrid surface and showed that a spacing-to-height ratio of 5 for transversal elements gives the maximum pullout resistance of a polyester system in sandy soil. They also reported that with an optimum arrangement, this system can increase the pullout resistance by about 37% compared to geogrid alone. Beyranvand et al. [18] conducted pullout tests by attaching concrete cubic pieces as transverse objects to the geogrid surface. The results revealed that the pullout force increased by about 76 and 67% under 20 and 50 kPa normal stresses, respectively, compared to the geogrid alone. Shokr et al. [19] performed experiments on the tensile response of stiff fiberglass geogrid under varying temperatures and showed that the ultimate tensile strength and modulus of elasticity increased by about 24% as the room ambient temperature decreased to − 30 °C. Mahigir et al. [20] performed pullout tests under 20, 40, and 60 kPa and showed that geogrid head displacement increased as the normal stress and the load amplitude increased. Ghazavi and Bavandpour [21] developed an analytical solution for pullout of geogrid in unsaturated soils and showed that the geosynthetic–soil interaction was improved remarkably.

The results of a study performed by Mirzaalimohammadi et al. [22] showed that by increasing the frontal cross-sectional area of the reinforcements, the dilative behavior of the samples also increased during the pullout tests. Moreover, Mirzaalimohammadi et al. [23] conducted laboratory tests and showed that the efficiency of geogrid with steel bars as transverse members increased with increasing the vertical pressure.

Recycled bottles are municipal wastes and are necessary to be recycled to control their environmental hazards. Therefore, reusing these bottles is essential and reinforcing soils by this method may be economically and environmentally useful. High-density polyethylene (HDPE) or polyethylene high-density (PEHD) is a thermoplastic polymer produced from the monomer ethylene, which is the most common plastic used in bottle manufacturing. They have, high resistance, strength and are odorless and have very high durability.

The production and use of PET bottles in all countries around the world are increasing. According to Reuters (2018), in a single year, 481.6 billion bottles were used worldwide. By 2021, this increases to 583.3 billion bottles, according to the most up-to-date estimates from Euromonitor International’s Global Packaging Trends report) [24]. In the recent few years, due to the prevalence of COVID-19, the production and use of PET bottles for hygienic materials and disinfectants have increased considerably. Filling and reusing PET bottles may be common in some countries. According to the study results by Dimitris and Achilles [25], the reuse of PET bottles should be considered very carefully, because plastic bottles absorb more contaminants than glass. Such pollutants could be released back into food by refilling the bottles. As mentioned above, the production of recycled plastic bottles in the world is growing almost in all countries. However, as their use soars across the globe, efforts to collect and recycle the bottles to keep them from environmental pollution have been failed to keep up. Ilyas et al. [26] pointed out that such products are not mainly biodegradable. To reduce or alleviate the environmental impact of PET and mainly used bottles, disposal in landfills, reuse and recycling and incineration may be several primarily solutions each of which should be carefully considered not to cause other secondary environmental or economic problems. For example, large lands may be required for landfilling them. In addition, incineration causes toxic gases propagation, air pollution, health risks and global warming, as pointed out by Park and Kim [27]. In addition, PET bottle recycling often leads to have low quality material at every recycling stage. Moreover, as stated by Bartl [28], contaminants remaining in recycled products make recycled bottles unacceptable for further use. Furthermore, majority of PET bottles are used as containers for drink and food and refilling or reusing them may result in absorbing contaminants by inside surfaces of bottles. Such
contaminants may be released to food and drink liquids in other refilling turns.

As mentioned above, since reusing waste bottles is dangerous to people’s health, they can be reused as materials in civil engineering applications. Jalaluddin [29] studied the use of plastic wastes in civil engineering constructions and innovative decorative material (eco-friendly). The results of this study show that plastic roads mainly use plastic carry bags, disposable cups, and PET bottles, all of which have been collected from garbage dumps as important ingredients of the construction materials. Foti [30] studied the use of recycled waste PET bottle fibers for concrete reinforcement and showed that the adherence between PET and concrete facilitates to use possibly these materials in the form of flat or round bars, or networks as structural reinforcement. Chaurasia and Gangwar [31] investigated the reuse of plastic bottles as a construction material and showed that using plastic bottles can have substantial effects on saving the building’s embodied energy using them instead of bricks in walls and reducing the CO₂ emission in manufacturing the cement by reducing the percentage of cement used.

United Nations Centre Human Settlements Programme (UN-Habitat) [32] reported that an easy application is to dispose waste plastic bottles and use them in the construction of low-cost housing. Athiappan et al. [33] conducted tests to investigate the utilization of waste plastic bottles as aggregate replacement for concrete blocks and proved that sand-filled plastic bottles can be used as retaining walls or other wall structures to replace bricks and concrete blocks in the construction industry successfully. They also state that as the strength of this reinforcement technique is over than the minimum permissible strength recommended by British Standard. Bozyigit et al. [34] showed that the specimens at the same cement content tend to behave more ductile with increasing optimum amount of water bottle strips (PET bottle strips).

The PET and disposable bottles have been used for the improvement of engineering soil properties. Arpittha and Dayanandha [35] investigated land stabilization using plastic wastes and showed that the soil strength and deformation behavior of subgrade soils were substantially improved. Nadaf et al. [36] studied the use of fly ash as backfill material in slopes using waste PET bottles as reinforcement and proposed to use fly ash-filled waste plastic PET bottles for slope reinforcement. Farah and Nalbantoglu [37] used plastic wastes for soil improvement and showed that such technique led to enhance the shear strength and CBR of reinforced sand. Salimi and Ghazavi [38] showed that the reinforced dry fine sand with PET plastic sheets increased the soil friction angle and the factor of safety of slopes. The results of investigations by Thakare and Sonule [39] showed that the improvement in bearing capacity of sandy soil reinforced with plastic bottles, soil-filled bottles, and geocell had the same functions and all increased the soil bearing capacity. Moghaddas Tafreshi et al. [40] performed tests on disposable waste bottles filled with soil for improving footing bearing capacity. The results showed that the use of such soil-filled bottles as a reinforced bed is highly rigid, delivering very high bearing capacities at small soil displacements.

Most research studies in the past focused on using crushed disposable bottle chips mixed with soil to strengthen the ground. Therefore, the use of bottles filled with soil is a relatively new idea to strengthen geogrid and reinforce soil for increasing pullout resistance. The current study has been performed to evaluate the pullout performance of the geogrid connected to soil-filled bottles as a new reinforcement system. In this new system, the soil-filled recycled bottles are used as transverse members and attached to the geogrid to improve the pullout resistance. This is a new reinforcement system, and thus it needs to be investigated under pullout conditions. The current research seems to be the first contribution to increase geogrid pullout resistance by the use of bearing resistance of transverse waste bottles. This contribution may help geotechnical engineers to implement the solution for the mechanically stabilized earth walls in urban areas, where limited construction spaces are available.

**Materials and Methods**

**Soil**

The type of soil used in this research was fine silica sand which is called broken sand in the market. According to the Unified Classification System (UCS), the soil is poorly graded sand (SP) using the procedure suggested by ASTM D2487-11 [41]. This sand was also used as the filling material for the box of large-scale pullout test apparatus. The particle size distribution of sandy soil is shown in Fig. 1. Soil characteristics were determined according to ASTM standards, as presented in Table 1.

![Fig. 1 Particle size distribution of sand](image-url)
In this study, a high-strength uniaxial geogrid, in which its tensile strength in the longitudinal direction is greater than the transverse direction, was used. The ultimate longitudinal tensile strength \( (T_{ult}) \) in the machine direction was 160 kN/m, and the ultimate transverse tensile strength \( (T_{utt}) \) in the cross-machine direction was 20 kN/m. The geogrid with black polymer coating had a rectangular network structure with aperture dimensions of 30 mm length, 25 mm width, and 2 mm thickness. The characteristics of geogrid are given in Table 2.

### Geogrid

Disposable recycled bottles chosen for this study were used for drink and had 200 mm length and 54 mm diameter. The bottles were made of polyethylene terephthalate (PET). The mass of an empty bottle was 20 g and the mass of a sand-filled bottle was 570 g. The bottles were subjected to vertical loading in a pressing machine to determine the load-deformation response. For this purpose, a hydraulic jack was used to apply the vertical load to determine the compressive strength of recycled plastic bottles. Figure 2 shows the bottles subjected to compression loads. As shown, the open-lid empty bottle, the closed-lid empty bottle, and the sand-filled closed-lid bottle were loaded. As will be stated subsequently, the soil-filled bottles can withstand the compressive load.

The results of compression tests on bottles showed that a sand-filled bottle deformed by 15 mm could withstand 100 kN vertical load (Fig. 3). The closed-lid empty bottle tolerated 2 kN vertical load at 14 mm deformation, which shows little resistance to vertical load. Finally, an empty bottle open-lid endured 1.5 kN vertical load at 14 mm deformation (Fig. 4). More resistance offered by the closed-lid empty bottle is due to the pressurized air inside the bottle.

The sand-filled closed-lid bottle has slight deformation under the vertical loading, and even if it was damaged during testing, it would be deformed slightly under

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**Table 1** Soil characteristics

| Property           | Value  |
|--------------------|--------|
| \( D_{10} \)       | 0.12 mm|
| \( D_{30} \)       | 0.22 mm|
| \( D_{60} \)       | 0.25 mm|
| Uniformity coefficient \( (C_u) \) | 2.08   |
| Curvature coefficient \( (C_C) \) | 1.61   |
| Relative density \( (D_r) \) | 80%    |
| Friction angle \( (\phi) \) at \( D_r = 80\% \) | 30°    |
| Sand–geogrid interface angle \( (\delta) \) for sand at \( D_r = 80\% \) | 22°    |
| Max. Dry unit weight \( (\gamma_{dmax}) \) | 17.6 kN/m³ |
| Min. Dry unit weight \( (\gamma_{dmin}) \) | 13.2 kN/m³ |
| Dry unit weight \( (\gamma_d) \) | 16.5 kN/m³ |

**Table 2** Geogrid characteristics provided by the manufacturer

| Description/property                     | Symbol/value       |
|------------------------------------------|--------------------|
| Trade name                               | GPGrid 160/20      |
| Type                                     | Uniaxial           |
| Raw material                             | PET                |
| Coating                                  | PVC                |
| Ultimate longitudinal tensile strength \( (T_{ult}) \) | 160 kN/m |
| Ultimate transverse tensile strength \( (T_{utt}) \) | 20 kN/m |
| Longitudinal strain at \( T_{ult} \)     | 11%                |
| Transverse strain at \( T_{utt} \)      | 11%                |
| Width of longitudinal members            | 10 mm              |
| Width of transverse members              | 4 mm               |
| Thickness                                | 2 mm               |
| Ratio of geogrid solid area/total area   | 36%                |
| Ratio of geogrid open area/total area    | 64%                |
| Mass per unit surface area               | 530 g/m²           |
| Geogrid aperture dimensions             | 30×25 mm           |

__Fig. 2__ Compression load test on: a open-lid empty bottle; b closed-lid empty bottle; c sand-filled closed-lid bottle
the vertical pressure. During the pullout test, the bottles attached to the geogrid are subjected to vertical stress. It may be argued that waste bottles may be different in different geographical regions, and therefore, the performance of soil-filled bottles under pullout condition may be different. It is noted that the behavior of soil-filled bottles fastened to geogrid under pullout loading may be dependent on the initial materials used for bottle production, initial bottle production technology, bottle geometries, bottle thickness, bottle material stiffness, etc. However, the present study is a comparative investigation and in fact, it compares the pullout behavior of geogrid alone and sand-filled bottles fastened to geogrid. Therefore, even there are some differences in material properties of bottles alone in various geographical regions, sand-filled bottles certainly offer better resistance under pullout conditions, compared with empty bottles alone. This is because soil-filled bottle compressive load due to tension stress tolerated by bottle shells. This tensile stress resistance increases due to confinement of bottles associated with overburden pressure in pullout tests. This is supported by the fact that sand-filled bottles did not experience apparent damage after performing tests in the current study. Therefore, in this study, soil-filled recycled bottles were used as transverse members for strengthening the geogrid.

**New Reinforced Soil System**

The new system consists of uniaxial geogrid-reinforced with recycled soil-filled bottles. Compared to the geometry of the geogrid aperture and bottles diameter, the tested sand appears to be too fine. The purpose of this study is to provide solutions that improve soil–geogrid interaction parameters, especially in the case of fine-grained soils, which may usually be available at the project site. The sand-filled bottles used as transverse members attached to geogrid were named GG-BN, in which N stands for the number of bottles attached to geogrid. For example, GG-B4 represents 4 sand-filled bottles that were attached to geogrid (Fig. 5). The bottles were fastened to some knots along the transverse geogrid ribs with plastic fasteners with the capacity of automatic locking. These plastic fasteners have high strength. The waste bottles filled with soil can strengthen the geogrid. To have the same compaction for sand filling bottles, all bottles were chosen to be the same and of the same mass. Several measurements were made to ensure that the same amount of sand mass was poured in each bottle to have the same density. After filling bottles with sand, the mass of each sand-filled bottle was measured to ensure that the same compaction for infilled sand was achieved. The benefit of this system is to use geogrid as a longitudinal member as well as to increase the soil bearing wedge resistance against the displacement of the soil-filled bottles as the transverse members.

**Testing Procedure**

**Pullout Test Apparatus**

The pullout test apparatus consists of a pullout box, holder bases, hydraulic jack, airbag, load cell, and an LVDT (Fig. 6). The pullout box has 1.2 m length, 0.6 m width, and 1 m height, and is made of steel sheets with a thickness of 15 mm. Some stiffeners were welded to sheets of box peripheries to prevent buckling and distortion of the box walls. The suggestions proposed by ASTM D6706-01 [42] Standard were considered in the construction of the pullout device. These included the minimum distance between the reinforcing edge and the friction-free walls, which was 75 mm, and also the creation of the sleeve in the pullout box.

**Fig. 3** Variation of load-deformation of a sand-filled closed-lid bottle

**Fig. 4** Comparison of load-deformation variation of close-lid and open-lid empty bottles

**Fig. 5** Arrangement of sand-filled bottles fastened to the geogrid surface and subjected to pullout force T
The vertical pressure was applied to the soil surface by airbag located on the top of the pullout box. The pressure inside the airbag was provided by an air compressor. Since the airbag inside the box is surrounded by the door and walls of the box during the tests, the airbag pressure is applied as vertical stress to the soil surface inside the pullout box. The airbag pressure was varied depending on the desired vertical stress. The schematic view of the pullout test box, airbag, sleeve, geogrid, and bottles attached to it is shown in Fig. 7. During the experiment, a can was placed inside the soil and the soil was compacted. The soil density was measured from the soil inside the can. The relative density of soil samples in all laboratory tests was about 80% and the compaction degree was about 90%. In mechanically stabilized earth walls, usually compacted soil with relative compaction of about 90% is used. A value of $\gamma = 16.5$ kN/m$^3$ was measured for the soil dry unit weight in this research. Three normal stresses of 7, 27, and 57 kPa, represent depths of 0.43, 1.64, and 3.45 m, respectively, if $\sigma = \gamma z$ is used, where $z$ represents the depth. The reason for choosing such normal pressures is that they may be applicable in road construction, where reinforcement layers are under pullout conditions. The system of applying horizontal pullout force to the reinforcement is located outside the pullout box. This force was applied to the geogrid by one clamp under the displacement control by a hydraulic jack with 50 kN capacity. The distance of geogrid from the box side walls was 150 mm, and tests were performed under the constant loading speed of 1 mm/min.

Farrag et al. [43] demonstrated that the use of a sleeve inside the pullout test box reduced the effect of the front wall of the pullout test box on the pullout resistance of the reinforcement. Therefore, the sleeve composed of two metal sheets with 60 cm length, 20 cm width, and 1 cm thickness on the front wall of the box was installed to reduce the friction between the soil and the front of the pullout box. The distance between the two metal sheets was 16 mm, covered with cotton to prevent the sand particles from outpouring while performing the pullout test.

The pullout test ends when a rupture occurs in the geogrid or the displacement in front of the geogrid becomes 10 cm. Because the maximum amount of displacement of the hydraulic jack course length was 10 cm.

**Sample Preparation and Test Procedure**

The soil was poured into the pullout box in 9 cm layers, each of which was compacted with blows of handcrafted metal hammer with a size of 20×20 cm. The weight of the handmade metal was 85 N. After pouring and compacting five soil layers, the surface of the soil became smooth and flat. Subsequently, a geogrid (GG) sample, with a length of 100 cm and width of 20 cm, or the geogrid-bottle system as a new reinforcement layer (GG-B) was placed on the soil surface and attached to the clamp. In the next step, after placing the reinforcement on the compacted soil inside the pullout box, the soil was poured on the reinforcement and compacted, similar to what was done for the lower half of the pullout box. After the pullout box was filled with compacted sandy soil, a 120 × 60 cm rectangular steel plate with 2 mm thickness was placed on the soil and under the airbag. The steel plate facilitates the airbag to apply uniform vertical pressure on the soil surface in the pullout box. The door of the pullout box was closed by steel bolts, and then the applied pressure inside the airbag was supplied by an air compressor.

**Experimental Plan**

In this study, 20 large-scale pullout tests were performed under normal stresses of 7, 27, and 57 kPa. The variables that were studied involved vertical stress, geogrid alone, the number of sand-filled bottles attached to the geogrid layer, and the horizontal distance between the bottles. In tests with a sand-filled bottle attached to the end of geogrid, the distance from the center of the bottle to the box’s sleeve was 973 mm. In other tests, the distance of the first bottle attached to the geogrid to the box’s sleeve was 150 mm, and the distance of the first bottle from the clamp was 350 mm. The minimum and maximum
distances between the center to the center of the bottles were 132 mm and 796 mm, respectively. Table 3 outlines the details of the 20 tests conducted in the current research.

Results and Discussion

Interaction of Soil–Geogrid

The pullout force of the geogrid generally depends on various factors including soil type, soil density, geotechnical properties of soil, geometric shape and dimensions of the geogrid aperture, mechanical specifications of the geogrid, contact surface roughness, vertical stress, and the speed of force application to the reinforcement. In fine-grained soils (i.e., fine sand), the tensile strength of uniaxial geogrids includes several components, including friction between the soil and both surfaces of the geogrid. Another component includes the friction between the soil and the longitudinal ribs of the geogrid and also the friction between the soil and the transverse ribs of the geogrid. The last component is passive soil resistance against displacement of transverse ribs of geogrid. The contribution of geogrid in soil–reinforcement characteristics depends on the load extension behavior of longitudinal and transverse members and geogrid stiffness [44]. To assess the pullout force of geogrid, Jewell [45] suggests:

\[ P_R = 2f_b L_R \sigma_n \tan \phi \]  

(1)

where “2” shows two frictional surfaces above and below geogrid surfaces.

Equation (1) may be re-written as

\[ P_R = 2L_R \sigma_n \alpha F^* \]  

(2)

where \( P_R \) is the pullout force per unit width of the geogrid, \( f_b \) is the coefficient of the soil–geogrid interaction, \( L_R \) is geogrid length, \( \sigma_n \) is vertical stress, \( \phi \) is the soil friction angle, \( F^* \) is pullout strength coefficient, and \( \alpha \) is the correction factor for scale effect by considering the nonlinear reduction of stress for flexible reinforcements.

The correction factor of scale effect is considered for nonlinear stress reduction, which is 0.8 for geogrid, as suggested by FHWA-NHI-00-043 [46].

The apparent friction coefficient at the sand–geogrid contact surface, \( f^* \), is computed from

\[ f^* = \frac{P_R}{2L_R \sigma_n} \]  

(3)

The total pullout force in the new system consists of the frictional force of the solid surface on both sides of the geogrid, the bearing force inside the geogrid aperture, and passive resistance of soil against sand-filled bottles attached to geogrid. The value of \( f^* \) in Eq. (3) is estimated by performing large-scale pullout tests. The effect of longitudinal and transverse ribs in Eq. (1) is determined from pullout force. Equation (3) suggested by ASTM D5321 [47] may be used to calculate the pullout force of geogrid to obtain the interaction coefficient of the soil–reinforcement interface or the apparent friction of soil–reinforcement. The relationship suggested by ASTM D6706-01, [42] was used to compute the increased percentage of the pullout force in the new GG-B system.

Repeatability of Tests

To ensure the functionality of the pullout apparatus and the testing procedure, three tests were repeated three times under the same conditions. The results are shown in Fig. 8. The repeatability of pullout test results for geogrid with 50 cm length under 7 kPa vertical stress is shown in Fig. 8. As seen, the results are in good agreement, demonstrating that they are indicative and repeatable.

Table 3 Details of performed tests

| Type of reinforcement | N | L (cm) | S (cm) | Geogrid width (cm) | Vertical stress (kPa) | Number of experiments |
|-----------------------|---|--------|--------|--------------------|----------------------|----------------------|
| GG                    | – | 50, 100| –      | 20                 | 7, 27, 57            | 6                    |
| GG-B1                 | 1 | 100    | –      | –                  | 27, 57               | 2                    |
| GG-B2                 | 2 | 79.6   | 20     | 27, 57             | 7, 27, 57            | 2                    |
| GG-B3                 | 3 | 39.4   | 20     | 27, 57             | 7, 27, 57            | 2                    |
| GG-B4                 | 4 | 26.4   | 27, 57 | 2                  |                      | 2                    |
| GG-B5                 | 5 | 19.9   | 27, 57 | 2                  |                      | 2                    |
| GG-B6                 | 6 | 15.9   | 27, 57 | 2                  |                      | 2                    |
| GG-B7                 | 7 | 13.2   | 27, 57 | 2                  |                      | 2                    |

\( N \) Number of sand-filled bottles, \( L \) Geogrid length, \( S \) Distance of center to center of bottles
Three experiments were performed with geogrid alone and the results are shown in Fig. 9. In the pullout test, the length of the geogrid placed between the compacted soil and the part beginning of geogrid length has attached to the clamp. By applying tensile force by the hydraulic jack, the pullout force is applied to clamp, after that geogrid between in sleeve is first stretched and then the geogrid layer buried in the soil is stretched. This results in gradual increase in the pullout force. With relative movement between the geogrid and soil, passive strength is created against transverse ribs of geogrid. Consequently, with increasing the pullout force, the geogrid tends to be pulled out from the box.

Figure 9 shows the variation of pullout force versus the displacement of the beginning of geogrid length. As seen, by increasing the vertical stress, more displacement is required to mobilize the maximum pullout force. The results showed that under vertical stresses of 7, 27, and 57 kPa, the pullout forces are 3.78, 7.77, and 10.33 kN, respectively. These forces are obtained for front geogrid displacements of 13, 16, and 16 mm, respectively. The results show that the pullout force gradually decreases with increasing the geogrid displacement after reaching peak points. This reduction of soil–geogrid interface strength is due to the displacement of soil particles in the movement path of geogrid and reduction of the soil resistance against the movement of the transverse ribs of geogrid. This is caused by the interference of transverse ribs of geogrid. Table 4 summarizes the results of the geogrid pullout tests.

From Eq. (3), the values of 1.38, 0.72, and 0.45 were determined for $f^*$, which correspond to vertical stresses of 7, 27 and 57 kPa, respectively. This demonstrates that $f^*$ decreases with increasing the vertical stress due to decreasing the dilatation of compacted sandy soil. This is consistent with findings of former studies [48].

**Table 4** Summary of pullout test results under three vertical stresses

| Type of reinforcement | $\sigma$ (kPa) | Displacement (mm) | $F_{\text{max}}$ (kN) | $P_{\text{Rmax}}$ (kN/m) | $f^*$ |
|-----------------------|---------------|-------------------|------------------------|---------------------------|-----|
| CG                    | 7             | 12                | 3.87                   | 19.33                     | 1.38 |
|                       | 27            | 16                | 7.77                   | 38.83                     | 0.72 |
|                       | 57            | 16                | 10.33                  | 51.6                      | 0.45 |

**Geogrid Alone Pullout Tests**

Pullout Force of Geogrid-Bottle with One Transverse Member (GG-B1)

The passive resistance of soil to geogrid transverse ribs and the transverse bearing members are the most important parameters in the increased pullout force. The maximum pullout force of reinforcing transverse members was influenced by various factors, including soil dilation, boundary conditions, and the interference between bearing elements [49]. In the present experiments, recycled bottles filled with soil were transversely attached to geogrid to improve the pullout force. Figure 10 shows two samples of the sand-filled bottles attached to the geogrid end.

The results for the bottle attached to the end of the geogrid were compared with those for the geogrid alone under two vertical stresses in Fig. 11. As seen, the attached
bottle at the end of the geogrid offers a greater pullout force than the geogrid alone, but the peak pullout force is mobilized at a greater displacement compared with the geogrid alone.

The results in Fig. 11 indicate that the pullout force increases with increasing the geogrid displacement until it reaches its peak point and then gradually decreases. The maximum pullout force for attaching a bottle at the end of the geogrid under 27 kPa vertical stress is 8.62 kN, representing 11% increase. For GG-B1, the required displacement to reach the peak force increases with increasing the vertical stress. The results of pullout tests on the GG-B1 system are summarized in Table 5.

The apparent friction coefficient ($f^*$) value under 27 kPa vertical stress for the GG-B1 system located at the end of geogrid is 0.79. For vertical stress of 57 kPa, the apparent friction coefficient ($f^*$) accounts for 0.49 for a bottle attached to the geogrid end. The results show that increasing the vertical stress results in decreasing the value of $f^*$. Increasing the geogrid length alone does not have a significant effect on the amount of pullout force, but attaching a bottle to the end of the geogrid can increase the pullout force. Such reinforcement systems may be used in practice, for example, in mechanically stabilized walls, covers, and liners of landfills, especially when space limitations are encountered. Thus, providing sufficient anchorage length for reinforcement layers is challenging. The bottle attached to the end of geogrid acts as an anchor and can hold a geogrid sheet for better performance.

**Pullout Force of Geogrid-Bottle with Different Transverse Members (GG-BN)**

For the optimal design of reinforced soil structures, the interaction behavior and the efficiency of soil reinforcement systems consisting of soil and transverse members attached to geogrid are necessary to understand under pullout conditions. The soil–geogrid interface friction angle and the bearing capacity of transverse members attached to geogrid are important parameters in the design of mechanically stabilized earth structures under pullout conditions. This new method could generally reduce the geosynthetics material consumptions, since soil-filled bottles could be attached to the geogrid and thus its effective length will be reduced. Moreover, the abundance and availability of disposable bottles exist in large numbers and enter the environment daily. Such applications can, to some extent, reduce the environmental impact. To increase the pullout force, there would be two main options: The length of the reinforcement can be increased, or the transverse members can be attached to it. In the current research, soil-filled bottles were used as transverse members. In some civil engineering projects, there is no possibility of increasing the length of the reinforcement. Thus, increasing the number of transverse reinforcement members may be the best option. To achieve the optimal number of bottles, as transverse members, the spacing between the bottles and the number of bottles in the experiments can be varied. In all experiments, the spacing between the first bottle attached to the geogrid and the sleeve of the pullout box was 15 cm. Figures 12 and 13 show the results of pullout tests of the GG-BN system with various numbers of the soil-filled bottles under 27 kPa vertical stress. As seen, the GG-B system increases the pullout force by increasing the displacement until reaching the peak force and then gradually decreases with the continuation of the test. The numbers of bottles and the spaces between the bottles have both pronounced effects on the pullout force. The finding in this research is in agreement with other studies that use other types of transverse members to provide increased pullout force [50, 51].

According to the results of the tests, under vertical stress equal to 27 kPa, bottles 2, 3, and 4 filled with soil attached

![Graph showing variation of pullout force versus front displacement of GG-B1 under 27 and 57 kPa vertical stresses](image)

**Fig. 11** Variation of pullout force versus front displacement of GG-B1 under 27 and 57 kPa vertical stresses

| Table 5 | Summary of pullout test results for the single-bottle system (GG-B1) under 27 and 57 kPa vertical stresses |
|---------|-------------------------------------------------|
| Type of reinforcement | $N$ | Situation of bottle | $\sigma_v$ (kPa) | F.d (mm) | $F_{max}$ (kN) | $P_{R_{max}}$ (kN/m) | $f^*$ | $I.P_{R}$ (%) |
| GG-B1 | End of geogrid | 27 | 47 | 8.62 | 43.1 | 0.79 | 11 |
| | | 57 | 50 | 11.23 | 56.15 | 0.49 | 8.7 |

*F.d* The amount of displacement front of the geogrid
to the geogrid increased the maximum pullout force (IPR) by about 27%, 32%, and 69%, respectively.

The results in Fig. 13 show that under 27 kPa vertical stress, the use of $N=5$, 6, and 7 sand-filled bottles attached to geogrid increase the maximum pullout forces (IPR) by about 67%, 66%, and 61%, respectively. In these cases, 5, 6, and 7 bottles were spaced at 199, 169, and 132 mm center to center, respectively.

Equation (4) is used to calculate the percentage of increase for geogrid pullout force in the geogrid-bottle system with respect to the geogrid alone:

$$I.P.R(\%) = \frac{P_{\text{max}}(GG-BN) - P_{\text{max}}(GG)}{P_{\text{max}}(GG)} \times 100$$  \hspace{1cm} (4)

where $P_{\text{max}}(GRG-BN)$ is the maximum pullout force for the geogrid-bottle system and $P_{\text{max}}(GG)$ is that for the geogrid alone.

Figure 14 shows the results of pullout tests of the GG-BN system with different numbers of sand-filled bottles under 57 kPa vertical stress. As illustrated, with increasing the vertical stress, the pullout resistance increases. The values of the pullout forces for GG-B2, GG-B3, and GG-B4 are 12.3, 13.69, and 16.68 kN, respectively. Thus, the attached bottles increase the maximum values of IPR by about 19.1%, 32.5%, and 61.5%, respectively, compared to that offered by the geogrid alone.

Figure 15 depicts the variation of pullout force versus front displacement of GG-BN with $N=5$, 6, and 7 bottles under 57 kPa vertical stress. As observed, the values of the pullout forces for GG-B5, GG-B6, and GG-B7 systems are 16.69, 16.57, and 16.35 kN, respectively. Thus, the attached bottles increase the maximum IPR values by about 61.56%, 60.4%, and 58.27% for $N=5$, 6 and 7 bottles, respectively, compared with the geogrid alone. For 4 bottles attached to the geogrid, the soil is locked between the bottles and acts as a block in the pullout test mode. This block action is like a thick reinforcement layer that is more resistant to pullout force.

In the current study and similar studies, it may be said that in the extensible materials, such as geogrid and geotextile, with increasing the reinforcement length and the amount of vertical stress, more displacement is required to achieve
the maximum pullout resistance. In addition, by attaching transverse members to the geogrid, the greater amount of displacement than the geogrid alone is required to reach the maximum pullout resistance due to the passive resistance associated with the transverse members. In general, it may be said that the amount of displacement required to achieve the maximum pullout force depends on the reinforcement stiffness and type, soil type, soil geotechnical properties, soil–reinforcement interface properties, transverse objects attached to reinforcements, scale effects, boundary effects, overburden pressure and so on.

During the pullout tests, by increasing the front displacement of the geogrid, the rupture mode started to form in the transverse ribs near the horizontal force clamp. The next transverse ribs were cut by increasing the front displacement of the geogrid in pullout tests. The review of the samples at the end of experiments showed that the geogrid transverse ribs between the bottles attached to geogrid were not damaged, but the geogrid transverse ribs at a little distance from the horizontal force clamp were rupture. The plastic bottles were slightly rotated. The geogrid longitudinal strips had no rupture. The bottles were not deformed under the vertical stress because of the presence of fully compacted soil and additionally because of the confinement provided by the soil inside the pullout box. A summary of pullout test results for the system (GG-BN) for \( N = 2 \) to 7 under 27 and 57 kPa vertical stresses presented in Table 6.

According to the results obtained from pullout experiments under vertical stresses of 27 and 57 kPa, the GG-B4 system with 264 mm bottle spacing offers the maximum pullout force. In the new GG-BN system, the spacing between the bottles, the number of bottles, and the vertical stress were the most effective factors in increasing the pullout resistance.

Figure 16 illustrates the variation of pullout force as a function of the number of bottles under 27 and 57 kPa vertical stresses. As seen, as the number of bottles increases to \( N = 4 \) and the vertical stress increases, the pullout force increases. The pullout force decreases with increasing the bottle numbers from 5 to 6 and then to 7, compared with the GG-B4 system. As a result, due to the slight difference between the results obtained for \( N = 4, 5, 6 \) and 7 soil-filled bottles, the use of four bottles seems to be the optimum number. The percentage of increase in pullout force with the \( S/D \) ratio (\( S = \) space between bottles and \( D = \) bottle diameter) is shown in Fig. 17. The greatest pullout force is achieved in pullout tests under 27 and 57 kPa vertical stresses with \( S/D = 4.88 \) and \( S/D = 3.68 \), respectively. Therefore, the GG-B4 system seems to be the most efficient.

For the soil-filled bottles as transverse members, the range of \( 3.68 \leq S/D \leq 4.88 \) offers the most efficiency in the pullout tests. This range is compatible with \( S/D = 3.68 \) in former studies in which other transverse members were used [52–55]. It is noted that in these studies, angle steel members attached to geogrid were used.

Table 6  Summary of the pullout test results for GG-BN system

| Type of reinforcement | \( N \) | \( S \) (mm) | \( \sigma_u \) (kPa) | F.d (mm) | \( F_{\text{max}} \) (kN) | \( P_{\text{Rmax}} \) (kN/m) | \( f^* \) | \( I_{PR} \) (%) |
|-----------------------|-------|-------------|-----------------|----------|----------------|----------------|---------|-------------|
| GG-B2                 | 2     | 796         | 27              | 26       | 9.89           | 49.45         | 0.915   | 27.28       |
| GG-B3                 | 3     | 394         | 27              | 27       | 10.27          | 51.35         | 0.95    | 32.17       |
| GG-B4                 | 4     | 264         | 27              | 30       | 13.14          | 65.7          | 1.21    | 69.11       |
| GG-B5                 | 5     | 199         | 27              | 37       | 13.69          | 68.45         | 0.6     | 32.52       |
| GG-B6                 | 6     | 169         | 27              | 35       | 12.94          | 64.7          | 1.198   | 66.53       |
| GG-B7                 | 7     | 132         | 27              | 34       | 12.54          | 62.7          | 1.16    | 61.38       |

\( F.d \) Front displacement of geogrid

\( \sigma_u \) Front displacement of soil

\( I_{PR} \) Percentage of increase
Effect of Interference of Soil-Filled Bottles

Evaluating the interaction of soil and transverse members attached to geogrid is essential for achieving an improved and cost-effective design in soil reinforcement structures. The interference effect between the transverse members is an essential factor in changing the reinforcement pullout force. The results show that when the number of soil-filled bottles attached to the geogrid increases to \( N = 1, 2, 3, \) and 4, the pullout force increases significantly. By increasing the number of bottles attached to geogrid, the spacing between the bottles decreases and the amount of the pullout force decreases slightly due to the interference effect. A schematic view of the effect of the interference of transverse soil-filled bottles attached to geogrid with one to seven bottles in Fig. 18. For extensible reinforcement, extrapolation of pullout test results to the reinforcement of different dimensions requires a careful evaluation of the scale effect [48]. For extensible reinforcements, such as geogrid in pullout tests, it is placed between two layers of soil, and a pullout force is applied by the clamp. Then, the horizontal force applied to the beginning of the geogrid is gradually transferred along the length of the geogrid. In the GG-BN system, the first bottle is first exposed to pullout force, and therefore, its pullout resistance is mobilized earlier than subsequent bottles. Then, the pullout force is transferred to the second bottle and its pullout resistance is mobilized. This procedure continues from row to row of soil-filled bottles. Depending on the amount of vertical stress and the tensile strength of the geogrid layer, this load-transfer procedure continues to reach a full mobilization of soil against the geogrid-bottle system. The interference between transverse members occurs for two reasons:

Fig. 17 Variation of pullout force versus bottle spacing (S/D) for soil-filled bottles under vertical stresses of 27 and 57 kPa

Fig. 18 Schematic view of the effect of the interference of transverse soil-filled bottles attached to geogrid with various spaces
(1) The increase in stress and rotation of the principal stresses was due to the mobilization of passive soil resistance against transverse members [56]. Observation of the condition of the bottles at the end of the experiments showed that the bottles attached to geogrid experienced a slight rotation under the effect of lateral soil pressure.

(2) By movement of each transverse member under pullout condition, a low-stress area (softened area) is created behind it. When the next transverse member enters this area, its final resistance decreases. In the low-stressed zone, the amount of frictional force at the soil–geogrid interface also decreases.

In the GG-BN system with using $N=1, 2, 3$ and $4$ soil-filled bottles, a low-stressed zone is created behind the transverse bottles, but because the distance between the bottles is greater than the low-stress area length, transverse members do not enter the low-stressed area (Fig. 18). However, geogrid transverse ribs are affected by interference, because the distance between them is smaller than the amount of geogrid displacement.

An investigation of the effect of soil-filled bottles attached to the geogrid indicates that there is an optimum spacing between bottles. If the bottle spacing is less than the optimal value, the bottle–bottle interference causes to decrease in the pullout resistance. In the GG-BN system with $N=5, 6$, and $7$ soil-filled bottles, since the bottle spacing is less than the optimal distance, the effect of interference between the bottles reduces the pullout force. As the S/D ratio decreases, the interference effect increases. By increasing the S/D ratio, the effect of bottle–bottle interference decreases. The three-dimensional resisting zones created by transverse members attached to geogrid have greater passive resistance than those created by geogrid alone. The measured displacement of the front and end of the geogrid showed that due to the expandability of the geogrid, the amount of displacement at the end of the geogrid is less than that at the front of the geogrid. In addition, the size of the soil softened region at the rear of each transverse member due to the movement of the transverse members was varied along the geogrid length.

Conclusions

The current study aimed to use waste drink water bottles filled with soil and attached to geogrid for strengthening the geogrid under pullout conditions. Large-scale pullout tests were performed in the laboratory to evaluate the performance of the GG-BN system. Based on the results of the performed tests, the main results may be summarized as:

1. The soil-filled bottles attached to geogrid as transverse members increased the pullout force. The largest pullout force for the system was obtained for the GG-B4 configuration, resulting in 69% increase in the pullout force, compared with a comparable system with geogrid alone.

2. For better performance of the GG-BN system, it was found that the optimal distance between the bottles attached to the geogrid are about four times as great as the bottle diameter ($S/D = 4$, where $S =$ distance between bottles and $D =$ bottle diameter). The new GG-BN system reaches the peak pullout force with greater displacement compared to the geogrid alone under pullout conditions.

3. Increasing the number of bottles (or decreasing the bottle spacing) reduces the pullout force due to the interference effect. To reduce the negative effect of interference, a value of $S/D = 4.88$ should be used.

4. The length of reinforcement required for resistance to the pullout force specified in the GG-BN system is less than that for the geogrid alone. Therefore, the new system is efficient, and such a system is recommended for places with space limitations.

5. Creating the third dimension by attaching disposable soil-filled bottles to geogrid is an effective solution to improve the soil–geogrid interaction. Thus, to achieve the required pullout capacity, the use of the GG-BN system results in reducing geogrid consumption.

Data Availability All data and models that support the findings of this study appear in the submitted article.

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