Investigating geogrid-reinforced ballast: Experimental pull-out tests and discrete element modelling

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Abstract

This paper presents an evaluation of the interlocking behaviour of geogrid-reinforced railway ballast. Experimental large box pull-out tests were conducted to examine the interaction between ballast and a biaxial geogrid. The discrete element method (DEM) was then used to model the interaction between the ballast and the geogrid by simulating large box pull-out tests and comparing the findings with the experimental results. Four different shapes of clumps were used to represent each ballast particle in order to obtain an acceptable shape for modelling the railway ballast. The DEM simulation results were shown to provide good predictions of the pull-out resistance and to examine the effect of clump shape on both the pull-out resistance and the distribution of contact forces. Therefore, the calibrated geogrid model and the 8-ball tetrahedral clumps, used as ballast particles, hold much promise for investigating the interaction between geogrids and ballast, and thus, optimising performance.

Keywords: Pull-out test; Railway ballast; Geogrid; Clump shape; Discrete element modelling

1. Introduction

Geogrids have been successfully used as reinforcements in railway tracks for decades. A geogrid can be placed within the ballast layer to reduce ballast deformation and to extend the maintenance cycle by a factor of about 3, or it can be placed at the top of the subgrade to increase the bearing capacity of the track foundation (Tensar International, 2009). Lavasan and Ghazavi (2012) have also indicated a significant increase in the ultimate bearing capacity of neighbouring footings. Conventional geogrids are produced with high stiffness in longitudinal and transverse directions with square apertures to suit the ballast grading. The large box pull-out test is considered to be a suitable means of investigating the fundamental mechanics of ballast/geogrid interactions, as shown in Fig. 1.

Previous studies have reported that the total pull-out resistance depends on the geogrid properties, the particle size distribution and the particle density. Specifically, Jewell (1990) reported that the geogrid pull-out failure mechanism is a function of the ratio of the transverse rib spacing ($S$) and the average particle size ($d_{50}$), the compaction moisture content and the soil stiffness. Brown et al. (2007) carried out a series of experiments using biaxial geogrids to investigate the key parameters that affect the performance. They found that the optimum geogrid aperture size was 60–80 mm for ballast particles approximately 50 mm in size. Izawa and Kuwano
(2011) discovered that geogrid-reinforced soil walls showed larger shear deformation in the reinforced area after shaking, and that such deformation was influenced by the tensile stiffness of the geogrids, the pull-out resistance and the properties of the backfill material. The discrete element method (DEM) (Cundall and Strack, 1979) allows for the monitoring of the evolution of the inter-particle contact forces and the displacement of particles; this cannot be done in the laboratory. Zhang et al. (2007, 2008) presented DEM simulations of geogrid pull-out behaviour using PFC3D and compared the findings with the experimental results; some agreement was shown. The importance of modelling the ballast particle shape in DEM was investigated by Lu and McDowell (2007), in terms of the load-deformation response, and also by Lim and McDowell (2005). McDowell et al. (2006) applied DEM to model both the ballast and the biaxial geogrid, together with small box pull-out experiments to validate the simulation results. They found that the optimum ratio between geogrid aperture size and aggregate size was around 1.4.

This paper firstly presents large box pull-out test results with a biaxial geogrid. For the DEM simulations, four different shapes of clumps were used to represent each ballast particle in order to obtain an acceptable shape for modelling the railway ballast. A two-layer geogrid model using parallel bonded balls is presented. The micro-parameters of the geogrid model are calibrated in terms of stiffness and strength by performing tensile and rotational tests on the geogrid. The geogrid-reinforced system is then modelled in simulated large box pull-out tests and compared with the experimental results in order to obtain valuable insight into the interlocking mechanism of geogrid-reinforced ballast.

2. Pull-out mechanisms

The pull-out interaction mechanisms between particles and geogrid reinforcements are more complex than those between particles and sheet reinforcements. This is because the pull-out resistance of biaxial geogrids includes two main components: the passive resistance that develops against the front of the transverse ribs and the interface shear resistance that takes place along the longitudinal ribs, and also, but to a lesser extent, along the transverse ribs (Koerber et al., 1989; Teixeira et al., 2007). Although the interface shear component can be quantified using parameters obtained from direct shear tests, the passive resistance can only be evaluated using a pull-out test. Zhang et al. (2008) predicted components of pull-out resistance against pull-out displacement expressed as a percentage of ultimate resistance from DEM pull-out simulations. Fig. 2 clearly shows the tendency of the pull-out resistance components. Initially, most of the shear resistance is taken by friction along the longitudinal ribs. The component of longitudinal friction decreases as the pull-out displacement increases, whilst the component of bearing resistance, which is the same as the passive resistance, increases, and the transverse friction component is comparatively stable. All three components mobilise from the beginning of pull-out and agree well with the theoretical analysis of the mechanics of pull-out (Wilson-Fahmy et al., 1994).

3. Laboratory large box pull-out test

A typical pull-out test performed by Kwan (2006) was conducted in a small wooden box 200 mm wide × 300 mm long × 400 mm deep. However, the interpretation of the unrepeatable pull-out test results continued to be a difficult task owing to the boundary conditions of the small box and the fewer number of apertures being tested. Palmeira and Milligan (1989) also found that the internal friction angle between the soil and the reinforcement could be severely overestimated because of friction on the internal front wall of the box in the small-scale tests. They recommended lubricating the front face and increasing the scale of the tests. A critical review of the current pull-out box testing methodology and its interpretation is beyond the scope of this paper. The reader can find a useful summary of soil-geogrid pull-out test models in the paper by Miyata and Bathurst (2012).

In this paper, a larger box, 400 mm wide × 600 mm long × 400 mm deep, which is four times larger than the small box, was used in these experimental pull-out tests, as shown in
Fig. 3. Large box pull-out test set-up in laboratory.

Fig. 4. Schematic of large-box pull-out test.

Table 1

<table>
<thead>
<tr>
<th>Ballast</th>
<th>RT/CE/S006</th>
<th>BS EN 13450</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flakiness</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Elongation</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Flakiness</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Length index</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 5. Grading curve of ballast (grading limit from TR/CE/S006, Issue 3:2000).

Fig. 6. Grading curve of ballast (grading limit from TR/CE/S006, Issue 3:2000).

In these experiments, the ballast used was from the Glensanda quarry in Scotland and is a granite comprising mainly plagioclase (35%), quartz (30%) and alkali feldspar (20%). The physical properties related to the particle shape are quoted in Lim (2004); his results are presented in Table 1, where the particle shape is described according to Railtrack (2000) and the relevant British Standard (BSI 2002). The same type of ballast was used throughout the large box pull-out tests. It can generally be described as a uniformly graded, crushed hard stone which is durable, angular, equidimensional in shape and relatively non-flaky. The grading curve of the ballast specified by Railtrack (2000) is shown in Fig. 5. The ballast particle mean size is approximately 40 mm, coefficient of uniformity $C_u$ is approximately 1.4 and the initial density is approximately 1458 kg/m$^3$. The key components of polymer geogrid SSLA30 are identified in Fig. 6. The effective grid area is approximately 260 mm $\times$ 195 mm, which is equal to the area of 12 square apertures.

The pull-out tests were conducted using surcharges of 0.0 and 0.5 kN. The tests were performed with the grid being pulled horizontally at a relatively constant rate which is pumped two times per mm. The pull-out rate should be gradually increased during the initial 2 mm, because a larger pull-out rate causes a sharp increase in pull-out force at the beginning. Fig. 7(a) and (b) shows the repeated test results of small (Kwan (2006)) and large box pull-out tests, respectively, in terms of the pull-out force as a function of displacement for surcharges of 0.0 and 0.5 kN. The pull-out tests were performed three times to ensure repeatability. A better agreement was observed in the large box pull-out tests owing to the improved boundary conditions of the large box and the greater number of apertures being tested. Moreover, two lines of average pull-out forces have been added in Fig. 7(b), which reduce the oscillations and presents a clearer view of the overall behaviour.

4. Discrete element modelling of large box pull-out test

4.1. Geogrid modelling

Fig. 8 shows a new two-layer geogrid model for the biaxial geogrid with an aperture size of 65 mm, comprising 6672
parallel bonded balls. The effective geogrid area has 12 square apertures, which is consistent with the experimental tests. The model set-up was performed firstly by creating the nodes and secondly by adding the ribs between the nodes. The ribs comprise balls of different sizes, with smaller balls at the centre of the ribs to give the required geometry. All particles are bonded together by parallel bonds, which act over a circular cross-section between the two particles in contact and transmit both a force and a moment (Itasca, 2003).

It should be noted that the parallel bonds along the transverse direction (black) differ from the parallel bonds along the longitudinal direction (red), as shown in Fig. 6(c). According to Konietzky et al. (2000, 2004), the parameters for the geogrid are calibrated by three different tests: a single rib test, a single junction test and an in-plane rotation test. The force at failure for a single rib test is 1.37 kN at a failure strain of 10.5% and the force at failure for a single junction test is 1.26 kN at a failure strain of 9.2%. Table 2 shows the calibrated set of parameters in PFC3D (Chen et al., 2012b).

4.2. Particle shape modelling

Particle shape plays a key role in the behaviour of railway ballast. It influences not only the physical state of the assembly (grain structure and porosity), but also the particle interaction (interparticle friction, contact force and coordination number). In the past, various attempts were made to characterise particle shape for railway ballast. However, due to the complexity and irregularity of the particle shapes, universally accepted effective shape characteristic parameters could not be established. In the railway industry, various shape characteristics (i.e., flakiness, elongation, roughness, angularity and surface texture) are used.

Barrett (1980) reviewed various approaches for analysing particle shape in geology and sedimentology and expressed the shape of a particle in terms of three independent properties, namely, form (overall shape), roundness (large-scale smoothness) and surface texture, as shown in Fig. 9. It should be noted that each of these aspects of shape can itself be represented by more than one dimension. Form reflects variations in the particle scale, while roundness reflects variations at the corners. Surface texture is a property of particle surfaces between and at the corners. To model the angular shapes of ballast particles and to investigate the effect of particle shape on performance, four different shapes of clumps were created, as shown in Fig. 10. The 2-ball clump is the same as that used by Chen et al. (2012a, 2012b). The 4-ball tetrahedral clump is rounder than the 2-ball clump. The surface texture of the 8-ball tetrahedral clump is rougher than that of the 4-ball tetrahedral clump. The 8-ball flaky clump represents the particle of rectangular form. The dimensions of these clumps are shown in Table 3. It should be noted that the volumes of these four clumps are the same as a single sphere with a radius of 20 mm.

4.3. Modelling of particle-pouring test

Kwan (2006) showed that for an experimental test in which one flat ballast particle surface was sheared past another, a particle-particle friction coefficient of approximately 0.6 (tan 31°) was obtained. Fig. 11 shows a heap of 736 2-ball clumps deposited from a hopper with a 25-cm-square aperture, 0.7 m above the base wall. The spreading of the simulated material demonstrates the realistic physical behaviour of the clumps. The critical state angle of the shearing resistance or the angle of repose is a function of the ball–ball coefficient of friction and the particle shape. Fig. 12 shows the ballast heaps
using different particle shapes. The heap of spheres with a radius of 20 mm was simulated for comparison. The coefficients of friction for the balls are all set to be 0.6 in order to be able to ignore the influence of the ball–ball friction coefficient. The coefficient of friction for the base wall is also set to be 0.6.

For the heap of spheres or 2-ball clumps, it was possible to calculate the porosity directly using a measurement sphere in PFC3D. However, no facility is available in PFC3D for calculating the porosity of a sample of clumps comprising more than two particles within each clump. Therefore, the porosities of the heaps were estimated using a 3-D grid of 9 x 10^6 small cubes, each with sides of 0.5 mm, in the column directly below the top of the heap (Fig. 12(b)). By comparing the porosities of a heap of spheres calculated by PFC3D and MATLAB, it is estimated that the percentage error in the porosity was less than 4%. This was deemed acceptable.

Table 3 lists the angles of repose and the porosities of the heaps for each aggregate of clumps. There are no results available for the particle pouring tests. It is to be noted that even recycled ballast exhibits a basic friction angle of approximately 40°. If the slope is not constant, a visual estimate is made for the particles over the surface of the sample. The angles of repose resulting from the numerical simulations with the 2-ball clumps and the 4-ball tetrahedral clumps show agreement with the angle of shearing resistance of real ballast (typically around 40°). In the case of the 8-ball tetrahedral clumps and the 8-ball flaky clumps, the angle of repose (43–44°) is a little higher. There are some large voids in the middle of the heaps resulting from the interlocking of the complex, angular clumps.

4.4. Numerical modelling procedure

Fig. 13 shows the numerical model for the large box pull-out tests and the specimen of the 2-ball clumps with the embedded geogrid under a surcharge of 0.5 kN. Single-sized clumps were used even though the size distribution plays an important role
in the mechanical behaviour. This can be considered satisfactory as ballast is usually reasonably uniformly graded ($D_{60}/D_{10} ≈ 1.4$) to provide large enough voids to facilitate good drainage. The dimensions of the pull-out box and the geogrid, as well as their positions, are the same as those used in the laboratory experiments. The DEM sample preparation procedure followed the experimental sample preparation. At the beginning, an initial sample of spheres was generated within the top of the box without overlapping; the spheres were then expanded to their final size (40 mm). After that, the position of each sphere was found, and the spheres were replaced by the 2-ball clumps or other clumps with the same volume, which were given random orientations. The clumps were directly deposited in the pull-out box and cycled to equilibrium under a changing gravitational acceleration which was reduced gradually from 98.1 m/s$^2$ to 9.81 m/s$^2$ followed by monotonic compaction with a horizontal wall to densify the sample. The clumps located higher than the centre of the slot were then deleted. Afterwards, the remaining sample below the slot was compacted using cyclic loading by a horizontal wall. The geogrid specimen was then installed at the centre of the slot, with the geogrid protruding outside of the slot. Two frictionless walls were generated near the slot above and below the grid (Fig. 13(a)) to prevent the geogrid layer from overlapping with the right-hand walls above and below the aperture during pull out. In PFC$^{3D}$, balls and walls overlap to give contact forces and it is possible for balls to penetrate through walls

<table>
<thead>
<tr>
<th>Ballast particle shape</th>
<th>Radius of balls in clump (mm)</th>
<th>Angle of repose</th>
<th>Porosity in middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single sphere</td>
<td>$R = 20$</td>
<td>15–16°</td>
<td>0.409</td>
</tr>
<tr>
<td>2-Ball clump</td>
<td>$R_1 = 18.8$</td>
<td>38–39°</td>
<td>0.426</td>
</tr>
<tr>
<td></td>
<td>$R_2 = 12.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-Ball tetrahedral clump</td>
<td>$R = 14.1$</td>
<td>39–40°</td>
<td>0.447</td>
</tr>
<tr>
<td>8-Ball tetrahedral clump</td>
<td>$R_1 = 13.6$</td>
<td>43–44°</td>
<td>0.499</td>
</tr>
<tr>
<td></td>
<td>$R_2 = 6.8$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-Ball flaky clump</td>
<td>$R = 11.7$</td>
<td>43–44°</td>
<td>0.499</td>
</tr>
</tbody>
</table>

Fig. 10. Clumps tested in simulations: (a) 2-ball clump, (b) 4-ball tetrahedral clump, (c) 8-ball tetrahedral clump and (d) 8-ball flaky clump.

Fig. 11. Numerical model of the ballast-pouring test using PFC$^{3D}$ two-ball clumps.

Fig. 12. Ballast heap simulations using different particles: (a) sphere, (b) 2-ball clump, (c) 4-ball tetrahedral clump, (d) 8-ball tetrahedral clump and (e) 8-ball flaky clump.
according to the contact law. This would artificially increase the pull-out resistance if the “membranes” above and below the grid were not installed to prevent particles from becoming trapped around the aperture. The upper half sample was again generated using the same expansion method, replaced by the clumps. After that, the whole sample was compacted and cycled to equilibrium. In the experimental pull-out tests, a wooden block slightly smaller than the internal dimensions of the box was placed to distribute the surcharge. Similarly, a simulated block that consists of 600 parallel bonded balls was used at the top surface to apply a vertical load, as shown in Fig. 13(a). The parallel bond stiffness (uniformly distributed over the bond area) is 600 Mpa/m. The normal strength and the shear stiffness of the particles were $1.0 \times 10^8$ N/m and the stiffnesses of the walls were set to have the same values as the particles. The ball, box and geogrid friction coefficients were all set to be 0.6. The density of the ballast particles was 2600 kg/m$^3$. A horizontal pull-out rate of 5 mm/s was given to

The initial porosity of the sample in the lab is approximately 0.44. The numbers and sizes of the particles for the four simulated samples are listed in Table 4. The porosity of the sample of 8-ball clumps is a bit higher, but shows good agreement with the lab tests. Moreover, the porosity in the particle-pouring test (Table 4) may be larger than the initial porosity of the pull-out test specimen after compaction. However, in the 2-ball clump model, the porosity in the particle-pouring test is smaller than the initial porosity of the pull-out test specimen after compaction. That is because of the interlocking effect of the geogrid in the pull-out specimen, which leads to more voids in the geogrid/ballast interaction zone.

For each sample, two different vertical loads were considered: 0.0 and 0.5 kN. For these simulations, the normal and the shear stiffness of the particles were $1.0 \times 10^8$ N/m and the stiffnesses of the walls were set to have the same values as the particles. The ball, box and geogrid friction coefficients were all set to be 0.6. The density of the ballast particles was 2600 kg/m$^3$. A horizontal pull-out rate of 5 mm/s was given to

$$n = 1 - \left( \frac{V_{cl}}{V_{tot}} \right)$$

(1)

Fig. 13. DEM of large box pull-out test: (a) embedded geogrid specimen and simulated surcharge and (b) specimen of two-ball clumps under 0.5 kN surcharge.

![Diagram](image)

Fig. 14. Comparison of DEM with laboratory experiment: (a) pull-out force against displacement without surcharge and (b) pull-out force against displacement for surcharge of 0.5 kN.

Table 4

<table>
<thead>
<tr>
<th>Ballast particle shape</th>
<th>Number of clumps</th>
<th>Initial porosity (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 2-Ball clump</td>
<td>1605</td>
<td>0.44</td>
</tr>
<tr>
<td>Sample 2 4-Ball tetrahedral clump</td>
<td>1624</td>
<td>0.43</td>
</tr>
<tr>
<td>Sample 3 8-Ball tetrahedral clump</td>
<td>1573</td>
<td>0.45</td>
</tr>
<tr>
<td>Sample 4 8-Ball flaky clump</td>
<td>1507</td>
<td>0.47</td>
</tr>
</tbody>
</table>
the spheres at the right-hand end of the geogrid. To avoid any
dynamic effects, the pull-out rate was gradually increased
linearly with time from zero to the final rate after an initial
displacement of 2 mm. The simulation was terminated at a
total pull-out displacement (i.e., the displacement at the right-
hand end of the geogrid) of 60 mm for comparison with
experiments. During the simulation, the pull-out force, the
pull-out displacement and the vertical displacement of the
surcharge (shown in Fig. 13(b)) were recorded.

4.5. Results and discussion

Selig and Waters (1994) reviewed the experimental data for
granular materials and pointed out that increasing both angularity
and particle surface roughness increases the shear strength of the
assembly. In order to evaluate the influence of particle shape on the
aggregate-geogrid interlock, four clumps with different shapes
were simulated. Compared to the 8-ball tetrahedral clump, it can be
seen from Fig. 10 that the 2-ball clump is less angular and that the
4-ball tetrahedral clump is more round. Fig. 14 shows the
development of pull-out force for all four samples under different
loading conditions. It clearly shows that up to a displacement of
approximately 20 mm, the pull-out force is well predicted by the
DEM simulation and the peak force is larger for a greater
surcharge. Moreover, the particle shape seems to have little effect
during the initial 20-mm displacement. However, it appears that the
DEM simulations for Sample 1 and Sample 2 underestimate the
pull-out force after the approximately 20-mm displacement. It is
believed that, due to the lower angularity of the 2-ball clumps and
the roundness of the 4-ball tetrahedral clumps, interlocking
between the particles and the geogrid is reduced compared to the
real experiments comprising more angular and rougher particles. In
the case of the 8-ball tetrahedral clumps and the 8-ball flaky
clumps, the pull-out forces are closer to the experimental results.
However, the flaky ballast is not considered to be good quality
ballast. After having conducted a set of triaxial ballast tests to
investigate the ballast shape on ballast performance, Roner (1985)
found that randomly placed flaky material had a higher deviator
stress and angle of internal friction than nonflaky material at the
same void ratio. Similarly, Selig and Waters (1994) concluded that
any quantity of flaky particles, either randomly oriented or oriented
other than generally parallel to the failure plane, increases the shear
strength of the granular specimen. This offers a possible explana-
tion as to why the pull-out force was higher than expected. In
addition, orientation parallel to the failure plane, when a signifi-
cant proportion of the particles are flaky, will cause a substantial
reduction in strength. The disadvantage of increased flakiness
appears to be increased abrasion, increased breakage, increased
permanent strain accumulation under a repeated load and decreased
stiffness. Therefore, for the four alternative clumps presented here,
the 8-ball tetrahedral clump seems to be the most representative of
real ballast. For the sample of 8-ball tetrahedral clumps, the
displacement at the peak pull-out force (approximately 47 mm) is
associated with the maximum rate of dilation for the sample given
by the average vertical displacement of the loading spheres, as
shown in Fig. 15. Each average is the mean displacement of the
central sphere and the two adjacent transverse spheres on either
side, at the left-hand end, the centre and the right-hand end of the
surcharge (Fig. 13(b)). It should be noted that volumetric strain
cannot be obtained for these clumps including more than two balls
using measurement spheres in PFC³D. Fig. 15 also indicates that
the dilative behaviour is more obvious in the reinforced zone at the
right-hand end of the sample. This can also be seen in Fig. 16. It is
clear in Fig. 16 that the upwards displacement is noticeably greater
at the right-hand end after pull-outs of approximately 30 mm and
50 mm, respectively.

Fig. 17(a) and (b) shows the development of the contact
force chains under a surcharge of 0.5 kN for Sample 1 and
Sample 3, respectively (geogrid is shown in red). It should be
noted that the contact forces are all drawn at the same scale. These figures show the strong increase in contact forces in the geogrid area due to aggregate-geogrid interlock. This is in agreement with simulations by McDowell et al. (2006). It can be seen from Fig. 17(c) that the clump ballast particles have arched around the transverse ribs during the pull-out. Comparing Fig. 17(a) and (b), the magnitude of the average contact force for the 8-ball clumps in Sample 3 is less than that for the
2-ball clumps in Sample 1 due to the higher number of contacts for the 8-ball clumps (20,845 compared to 18,831 for the 2-ball clumps) leading to a more homogeneous stress distribution.

In a mechanically stabilised layer, ballast particles interlock within the geogrid and are confined within the apertures, creating an enhanced composite material with improved performance. The structural properties of the mechanically stabilised layer are influenced by the depth of the confined zones. As shown in Fig. 18, the interlocking effect is largest for approximately 75 mm on both sides of the geogrid, decreases during the transition zone and then vanishes at a distance greater than about 150 mm. For the case without surcharge, the contact forces below the geogrid are larger than those above the geogrid due to the non-confinement on the top (i.e., gravity). For the case with surcharge, the contact forces above and below the geogrid are relatively symmetrical due to confinement at both the top and the bottom (gravity is negligible in comparison). This can explain why the peak of the contact force is below the geogrid for the case without the surcharge and approximately at the geogrid level for the case with the surcharge.

The deformations of geogrids under a surcharge of 0.5 kN in the laboratory experiment and simulation (the sample of two-ball clumps) are shown in Fig. 19, which clearly displays the extensive deformation of the grid, and the deflection of the ribs can be seen in the side view. The geogrid in the simulation seems to have more evident deformation compared with the experimental geogrid sample. This is because the geogrid deformation in the simulation was captured during the pull-out tests, whereas it is not possible to view the whole deformed geogrid during the pull-out tests in the laboratory, but only after the tests when the geogrid has been removed.

5. Conclusions

Laboratory large box pull-out tests have been performed on typical geogrids embedded within a ballast sample. The pull-out force has been measured as a function of the displacement under different surcharges. A new DEM model for the geogrid has been developed by bonding two layers of small balls together to form the required geometry using parallel bonds, and calibrated by simulating standard tests. Four kinds of clumps, namely, 2-ball, 4-ball tetrahedral, 8-ball tetrahedral and 8-ball flaky, were used to represent the real ballast particles. All four kinds of clumps have been shown to give acceptable angles of repose, compared with real ballast. The DEM simulations have been shown to provide good predictions of the pull-out force as a function of displacement, especially for the initial 20-mm displacement. The particle shape was shown to have little effect on the initial development of the pull-out force. The simulations have also given valuable insight into the interaction between ballast and geogrids under different surcharges, although the DEM simulation using the 2-ball or the 4-ball tetrahedral clumps underestimates the pull-out force after a displacement of about 20 mm. This is thought to be a function of the uniform particle size, angularity and roundness of the simulated clumps, compared to the well-graded, angular ballast particles in the laboratory tests. Considering the four kinds of clumps, the 8-ball tetrahedral clump, which has more angularity and roughness, seems the most representative of real ballast. The
fully reinforced zone lies approximately 75 mm above and below the geogrid.

References
