ADVANTAGES OF BIAXIAL WELDED GEOGRIDS IN RAILWAY REHABILITATION AND UPGRADE

Amir Shahkolahi1                               Jason Crase1                  Parviz Barati2
Applications Engineer                       QLD Manager                   Graduate Student
1Global Synthetics Pty Ltd, QLD, Australia      2Queensland University of Technology

SUMMARY
Improvement of the subgrade is often necessary during rehabilitation and upgrade of railway lines. In many cases, the required bearing capacity of the subgrade cannot be assured economically or achieved with traditional granular layers alone. A layer of biaxial welded geogrid with structured uniform rigid bars in combination with a nonwoven geotextile offers not only an economical solution, but also an environmentally friendly method to provide the required strength and support to the track formation. When designing railway foundations with geogrids, several design properties such as stiffness, torsional rigidity and installation damage should be considered. In this paper, traditional solutions of improving the subgrade bearing capacity are compared with this solution of track reinforcement using biaxial geogrids. Design parameters of various geogrids in regard to physical and mechanical properties are also compared and the advantages of biaxial welded geogrids are explained in detail. A technical assessment is made and various test results are presented. Results show that the biaxial welded geogrid can reduce the thickness of the required ballast layer by up to thirty percent. A biaxial geogrid can provide an economical solution for improving the bearing capacity of the weak subgrade over traditional methods of placing deep granular layers alone. Results also show that the biaxial welded geogrid with structured uniform rigid bars has enhanced design properties when compared to other geogrid types. This can lead to safer designs and greater durability without an increase in cost. A case study on the major network assets upgrade in Adelaide including two primary sections; Gawler and Noarlunga lines, from where biaxial welded geogrids were used, is also presented.

INTRODUCTION
Reinforcement of ballasted railway tracks with geogrid has been trialled in recent decades with satisfactory results leading to improved track stability and serviceability. Several theoretical studies (McDowell et al., 2006; McGown and Kupec, 2008; Chen et al., 2012), Laboratory tests (Rowe and Jones, 2000; Shin et al., 2002; Indraratna et al., 2006; Brown et al., 2007), and full-scale field measurements (Fernandes et al., 2008; Indraratna et al., 2010; Barati, 2013) have confirmed enhanced track performance when layers of geogrid are embedded within the track substructure. The track deformation/settlement and degradation can be reduced by use of geosynthetics (Rowe and Jones, 2000; Ashpiz et al., 2002; Raymond, 2002; Indraratna and Salim, 2003; Brown, 2009). The geogrid reinforcement creates a reduction in the extent of vertical settlement which adds to reduced lateral displacement of the ballast (Indraratna et al., 2010; Indraratna et al., 2013). Geosynthetics can also improve the shear strength of the ballast layer (Indraratna et al., 2010; Hussaini et al., 2012). The benefits of using geosynthetics to reduce breakage of ballast have been indicated by Indraratna et al., 2009.

The appropriateness of a particular type of geogrid embedded within the track substructure is usually determined by evaluating a number of design parameters. For instance; aperture size, grid stiffness, and junction strength are shown to be influential when selecting a geogrid for a specific track reinforcement application (Brown et al., 2007). Furthermore, in-service factors such as the potential for installation damage suffered by a particular type of geogrid should be taken into consideration.

A wide range of geogrid products are available in the market developed and produced by various manufacturers around the world. Available products vary in aperture size and shape, and manufacturing technique. The type of geogrid can affect its performance. Indraratna et al. (2013) have indicated that the lateral displacement in ballast beneath the sleeper edge, the lateral strain profile along the ballast and the geogrid influence zone are affected by the geogrid type.

In this paper, the superior performance of the biaxial welded geogrids is demonstrated. Design parameters of various geogrids in relation to physical and mechanical properties are also compared and the advantages of biaxial welded geogrids are explained in detail. A technical
assessment is made and several test results are presented. A biaxial geogrid can provide a more economical solution for improving the bearing capacity of the weak subgrade when compared to traditional solutions of utilising thicker granular layers. Results also show that the biaxial welded geogrid with structured uniform rigid bars provide enhanced design properties when compared to other types of geogrid with alternate construction/aperture shapes. This can lead to safer designs and greater durability without an increase in cost. A case study from major network assets upgrade in Adelaide including the two primary sections Gawler and Noarlunga lines, where biaxial welded geogrids were used, is also presented.

DIFFERENT TYPES OF GEOGRID

Geogrids are polymeric products formed by joining intersecting ribs. They are made from polymeric materials, typically high density polyethylene (HDPE), polypropylene (PP) or polyester (PET). Geogrids are manufactured as biaxial, uniaxial or multidirectional. Biaxial geogrids are those that exhibit similar strength in both the machine and cross machine direction while uniaxial geogrids exhibit dominant strength in the machine direction with minimal strength (enough to maintain the aperture structure) in the cross machine direction. Multidirectional geogrids have bars in multiple directions.

Apart from the base polymer material, there are also varying manufacturing methods/techniques used in the geogrid construction. The first generation of geogrids used a manufacturing method consisting of extruding a flat sheet of plastic, either high density polyethylene or polypropylene, punching a controlled pattern of holes (the apertures), and stretching the sheet in both or multiple directions, orienting the polymers, to develop tensile strength. However, there is little orientation at the junctions. This type is an extruded geogrid which is rigid and can be uniaxial, biaxial or multidirectional (figure 1).

Welded geogrids are the most recent generation of geogrids. The manufacturing method for welded geogrids is to extrude flat polypropylene or polyester straps/bars that are passed over rollers, running at different speeds that stretch the bars and orientate the polymers into high tenacity flat/bars. These straps/bars are fed into the welding equipment where cross machine direction straps/bars are introduced and are welded together forming dimensioned apertures. Welded geogrids are rigid and can be uniaxial or biaxial (Figure 3).

GEOGRID DESIGN FACTORS

Apart from the subgrade, capping layer and ballast condition, the geogrid properties should be considered for designing geogrid reinforced structures in railway projects. Several laboratory and field tests have indicated properties that affect the design and performance of the geogrid reinforced track such as geogrid stiffness, geogrid aperture size, geogrid bars, applied normal stress, installation damage, geogrid type and even the location of the geogrid (Brown et al., 2007;
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Indraratna et al., 2009; Indraratna et al., 2010; Anantanasakul et al., 2012; Hussaini et al., 2012; Chen et al., 2012; Indraratna et al., 2013). One of the parameters that can affect these properties is the manufacturing method. Some of the design parameters of a biaxial welded geogrid with structured flat bars have been compared with other geogrid generations and the results have been presented in this paper.

GEOGRIDS SPECIFICATIONS

Biaxial welded geogrids with structured flat bars, biaxial woven geogrids and biaxial/multidirectional extruded geogrids were assessed in this research with the respective characteristics mentioned in the test references in each part.

ADVANTAGES OF THE BIAXIAL WELDED GEOGRID

Stiffness/Secant Stiffness (Strength at Low Elongation)

Research results have indicated that stiffness is one of the most important parameters that affect the geogrid performance in track reinforcement. The strains accumulated in geogrids are influenced by subgrade deformation, while the induced transient strains are mainly affected by the stiffness of geogrids (Anantanasakul et al., 2012). In reinforcing the ballast layer with geogrid, the stiffness of the geogrid is more effective than the tensile strength of the geogrid at low strains. Of course there is a non-linear relationship between the tensile strength and resilient stiffness (Brown et al., 2007).

The stiffness of a geogrid (Secant Stiffness) can be defined as the strength of the geogrid at low elongation. Large scale field tests as well as laboratory tests have shown that depending on the reinforcement mechanism, typical strains between 0.5% and 2% are achieved in the geogrid reinforcement. This demonstrates that the resistance of the geogrid reinforcement in the deformation range up to 2% strain is more important than the ultimate tensile strength (NAUE TN-SG 3, 2010). The secant stiffness of a geogrid is determined on the basis of a wide-width tensile test according to EN ISO 10319/ASTM D 6637 and the resulting stress-strain curve. A test has been conducted on the stiffness of various geogrids. Test results are presented in figure 4 (Secugrid Four Dimensions Technics, 2010). As it shows, the biaxial welded geogrid with structured flat bars has the highest stiffness (strength at low elongation) compared to other biaxial geogrids (extruded and woven) and the extruded multidirectional geogrid in the test. Higher secant stiffness values correspond to lower deformations inside the ballast layer which will have a positive effect on the load carrying capacity, as the loss of ballast stiffness is reduced. This leads to lower rut deformation on the surface of the ballast layer, less maintenance and a longer service life of the railway.

Radial Stiffness/Interlocking (Strength in Various Directions)

Biaxial load distribution typically takes place where the traffic flow is guided in defined directions across the installed geogrid reinforcement, such as in roads and railway applications (Figure 5). Stresses which are transferred to the ballast aggregate, lead to an outward motion of the aggregate, mainly in the direction of the train movement and perpendicular to it. Due to the shear interaction (interlocking) that is generated between the ballast aggregate and the reinforcement, the geogrid is mainly stressed in the longitudinal and transverse directions.

In applications where a defined direction of traffic flow does not exist, such as in large traffic areas like parking lots and container terminals (Figure 6), the geogrid reinforcement might also be stressed diagonally.
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For cases where a railway formation may also be subject to diagonal stresses, tensile tests according to EN ISO 10319 have been carried out at tBU Institut für textile Bau- und Umwelttechnik, Greven (Germany) that determined the radial stiffness of the biaxial welded geogrid with different polymers and tensile strengths at very low deformations of 0.5% (NAUE TN-SG 1, 2010). Results are presented in figure 7.

The test results show extremely high stiffness values of a minimum 1500 kN/m for the PP biaxial welded geogrids in the dominant biaxial directions. Importantly, high secant stiffness values of ≥ 592 kN/m and ≥ 828 kN/m can also be observed in the diagonal directions for the tested PP and PET biaxial welded geogrids with 30 kN/m ultimate biaxial strength respectively.

To compare the performance of the biaxial welded geogrid to other reinforcement products, the same tests were carried out for woven and knitted geogrids and results were compared with radial stiffness values of the multidirectional extruded polypropylene (PP) geogrid with triangular apertures (NAUE TN-SG 1, 2010). All test results of the measured radial secant stiffness values at 0.5% strain for the tested geogrids are shown in Figure 8.

The values show that the tested biaxial welded geogrid provides the highest radial stiffness values of all materials tested, even greater than the multidirectional geogrid. The multidirectional geogrid has a uniform distribution, but the minimum values of the tested biaxial welded geogrid (the two outer plots) exceed the values of the multidirectional geogrid. Test results are tabulated in table 1 (NAUE TN-SG 1, 2010). The high values for the biaxial welded geogrid are due to manufacturing technique used to produce this geogrid. The features are a flat, welded, pre-stressed polymer bar providing the desired high tensile modulus values in longitudinal, transverse and diagonal directions, especially at low strain rates.

The results also verify that this particular biaxial welded geogrid has higher stiffness in all directions compared to the multidirectional geogrid.
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### Table 1: Radial Stiffness of Various Geogrid Types

<table>
<thead>
<tr>
<th>Geogrid</th>
<th>Radial Stiffness 6% [% (N/m)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welded 6.5x6.5</td>
<td>≥ 494</td>
</tr>
<tr>
<td>Welded 5.0x6.0</td>
<td>≥ 628</td>
</tr>
<tr>
<td>Welded 6.5x5.5</td>
<td>≥ 552</td>
</tr>
<tr>
<td>Welded 5.0x5.0</td>
<td>≥ 502</td>
</tr>
<tr>
<td>Welded 6.5x4.0</td>
<td>≥ 494</td>
</tr>
<tr>
<td>Welded 5.0x4.0</td>
<td>≥ 552</td>
</tr>
<tr>
<td>Woven 4</td>
<td>≥ 544</td>
</tr>
<tr>
<td>Extruded Biaxial 7.0x7.0</td>
<td>≥ 550</td>
</tr>
<tr>
<td>Extruded Multidirectional 7.0x7.0</td>
<td>≥ 550</td>
</tr>
</tbody>
</table>

The multidirectional geogrid may have better results compared to some other geogrids assessed, but it does not necessarily outperform all other biaxial geogrids. This indicates that the aperture shape and the direction of the bars do not affect the performance of the geogrid.

### Torsional Rigidity/Aperture Stability

As a load is transferred to a granular aggregate layer such as ballast layer, which is installed over a geogrid, a shear stress develops in the aggregate in the plane of the grid. This shear stress changes in magnitude and direction as the load continues. The direction is important because the change in direction causes a twisting motion in the geogrid. The main motion of the aggregate is outward, but the stress on an individual particle during this migration changes from predominately forward to predominantly outward, to predominantly backward. The magnitude is the highest in the outward direction and the stress may not be high enough to cause slippage in all directions, but the stress and the potential for movement change in direction, results in a twisting stress in the base reinforcement geogrid (NAUE TN-SG 4, 2010).

The strains measured in the plane of the geogrid are indicating very low stresses in the geogrid. It was thus concluded by Kinney and Xiaolin (1995) that the main effect improving the bearing capacity is related to the stiffness of the geogrid and its ability to interlock with the soil aggregates. Several tests were attempted to simulate this; in particular, the so called “Geogrid Aperture Stability by In-Plane Rotation”-Test (a.k.a. Torsional Rigidity or Torsional Stiffness, figure 9). Kinney and Xiaolin (1995) interpreted from their test results that geogrids with high torsional rigidity behaved better than geogrids with less torsional stability due to more effective interlock and lateral restraint of the granular material.

### Installation Damage/Robustness

Potential for on-site damage during the installation process by machinery, poor handling or lack of proper site preparation are issues consider. Whilst one always designs with long-term goals of a project in mind, protecting the product during installation is very important. This protection can be safe guarded in the geogrid product selection. The subtle imperfections that installation damage can cause may be the difference between success and failure in the long-term, since a weakened grid may yield to later stresses. Robustness plays a key role. The robustness of a geosynthetic is crucial not only to its long-term performance but its ability to properly perform its engineered function. Geogrids, in particular, must be able to withstand site installation damage potential.

A test has been carried out by British Textile Technology Group (BTTG) in the UK on ERA Installation Damaged Samples based on BS 8006-1:2010 for the welded biaxial geogrid “S-Q1-30” and the extruded multidirectional geogrid “T-16”. It
was conducted with three different aggregate sizes and three compaction levels (figure 11).

Figure 11: Compaction Levels for Installation Damage Test

The results of the installation damage factor measured in the test are shown in figure 12 (Secugrid Four Dimensions Quality, 2010).

Figure 12: Installation Damage Reduction Factor for Two Geogrid Types

As it shows, the installation damage reduction factor is lower for the welded biaxial geogrid with the structured flat bars compared to the extruded multidirectional geogrid in this test. This is because of the uniform flat bars and uniform joints of this welded geogrid. This leads to a safe design and long term serviceability for this type of geogrid.

Pull-Out Resistance

Numerous tests have revealed the durability of geogrids. Pull-out tests, for example, permit the calculation of the coefficient of interaction. This helps investigate the differing behavior between a geosynthetic and a soil. In pull-out tests, the pull-out resistance of a geogrid is largely dependent on the product's structure. Despite the same tensile strength and aperture size, geogrids may have different relative soil contact surfaces.

A pull-out test has been carried out at the University of Munich on three different geogrids with the same strength, a welded biaxial geogrid with structured flat bars, an extruded biaxial geogrid and a woven biaxial geogrid shown in figure 13 with two soil types: sand and crushed gravel.

Figure 13: Geogrids Used in the Pull-Out Test

The test results are shown in figure 14 (Secugrid Four Dimensions Technics, 2010). These tests verify that the pull-out resistance of a geogrid is largely dependent on the product's structure.

Figure 14: Pull-Out Test Result for Different Geogrid Types

Figure 14 shows that the surface friction for the woven and extruded geogrid (A and B respectively) is less than that of the welded one with structured flat bars (C). Extruded geogrids mobilise their pull-out resistance mainly by way of their transverse ribs. They require larger displacements to mobilise the same pull-out resistance as the welded biaxial geogrid C. Conversely, for a given low displacement, the extruded ones develop less force absorption capability despite having thicker ribs.

On the other hand, the low junction strength (mainly achieved by the coating) exhibited in woven geogrids allows large displacements between the machine direction yarns (longitudinal) and cross-machine direction yarns (transverse) and therefore a potential damage of the coating. The bonding between machine direction and cross-machine yarns suffer local damage such that, for the same displacement, a significantly lower pull-out resistance is mobilised than in the case of the welded geogrid with flat structured bars.

In contrast, greater displacements of the welded biaxial geogrid C caused the cross machine direction bars to tilt in the middle along their axis such that pull-out resistance actually increased (figure 15).

The structure of geogrid C causes a considerably large soil area to become involved in the absorption of force because its transverse ribs
torque/twist slightly on their axis toward their midpoints between junctions (figure 15).

**Figure 15: Welded Biaxial Geogrid After the Pull-Out Test**

The strong junction shear strength of the welded geogrid C prevents torqueing/twisting under soil coverage from occurring at the junctions. One of the important things with junctions is to consider the realistic conditions for the geogrid. When a geogrid is installed, the junctions are under confinement from top and bottom and there are normal forces on the junctions from above and below (figure 16). Without considering this, the junction strength tests may not represent realistic results. The high junction strength and efficiency of the welded biaxial geogrid C contributing to high pull-out test results testifies this point.

**Figure 16: The Loading on the Geogrid Junction Area under Installed Conditions**

Additionally, the interlocking effect restrains the aggregate laterally and transmits tensile forces from the aggregate to the geogrid. As the geogrid is much stiffer in tension than the ballast aggregate, lateral stresses and strains in the reinforced ballast aggregate are reduced and less vertical deformation can be expected.

In addition, the structured surface of the flat bars in the welded geogrid C creates more friction between the geogrid and aggregates. This rib surface friction as well as the stiffness of the geogrid is important in the performance of the geogrid in reinforcing the ballast layer especially at low strains (Brown et al., 2007).

**CASE STUDY**

**Project Information**

In 2012, Tracksure Pty Ltd, a joint venture between John Holland, Coleman Rail and York Civil, were awarded the Adelaide Metropolitan Rail Revitalisation project by the Department of Planning, Transport and Infrastructure in South Australia (DPTI). The revitalisation forms the centrepiece of a $2 billion investment and will transform the metropolitan passenger rail network. The project involved a major upgrade of several of the network assets including two primary sections, the Gawler and Noarlunga lines. This large and complex project required a similarly complex formation design which necessitated subgrade improvements where marginal soils had deteriorated. Furthermore, the excavation and imported material had to be minimised to reduce the project costs.

CBR testing along the track had determined in-situ subgrade strength values of between 1% and 10% (Drechsler et al., 2010). On top of the formation level a minimum CBR of 10% was required. In those areas, where 10% CBR subgrade strength could not be achieved, it was planned to improve the in-situ strength by lime/cement stabilisation to reach 10% CBR on the formation level. Figure 17 shows a typical scenario of the railway track where vertical alignment of the rail height is constrained and new, thicker concrete sleepers were to be installed to replace old, thinner timber or steel sleepers. This required ballast material to be removed down to the subgrade level and additional excavation to a nominal depth of 100 mm to provide the design ballast depth (typically 250 mm).

**Figure 17: Typical Project Cross Section**

It was planned to achieve an allowable bearing pressure of 290 kPa on top of the ballast layer immediately beneath the sleepers. According to correlations given in Doyle, 1980, a target CBR of 40% can be correlated to the defined bearing pressure. To achieve the required bearing capacity under the railway, a geogrid reinforcement layer was proposed at the interface between formation and ballast layer.
Geogrid Selection

As mentioned in the previous sections, higher modulus/stiffness values correspond to lower deformations within the reinforced aggregate/ballast layers, which will have a positive effect on the long-term load carrying capacity, and the less reduction of aggregate stiffness. This leads to lower deformations on the surface of the aggregate/ballast layers and furthermore, lower maintenance costs and provide longer service life of railway tracks. Interlocking of the aggregates and the geogrid as well as the installation damage are other important parameters to be considered.

Based on test results for the welded biaxial geogrid with structured flat bars presented above indicating a high stiffness, high torsional rigidity/aperture stability, high interlocking effect and low installation damage, this type of geogrid called Secugrid® was selected over a range of other geogrids considered for the project. As the subgrade CBR was 10%, the strength of biaxial 30kN/m was considered appropriate according to design charts.

Final Design

According to the provided boundary conditions and Secugrid® design charts, an approximate 250 mm thick Secugrid reinforced ballast layer was proposed to achieve the required 40 % CBR. The result showed that the planned ballast depth of 250 mm (with only 100mm excavation into subgrade) was sufficient where this type of geogrid was used at the interface between formation and ballast layer. A layer of nonwoven geotextile was adopted below the geogrid for separation purposes. Without this geogrid, the excavation and the new ballast layer thickness would have been at least 30% more. Figure 18 shows the final cross section.

CONCLUSION

Different generations of geogrids including extruded, woven and welded geogrids were introduced in this paper. Several tests on some important and most effective geogrid design properties such as stiffness, radial stiffness/interlocking, torsional rigidity, installation damage and pull-out resistance have been reviewed and the results have been compared and tabulated.

Test results indicate that the welded biaxial geogrid with pre-stressed structured flat bars have the highest stiffness, more than extruded biaxial and multidirectional geogrid and the woven style. This leads to lower deformations of the reinforced aggregate/ballast layers, offering a positive effect on the long-term load carrying capacity, and reduced loss of aggregate stiffness. This leads to lower deformations on the surface of the aggregate/ballast layers and furthermore lower maintenance costs providing longer service lives of roads or railway tracks.

Tests show that this type of welded biaxial geogrid has higher stiffness in all directions, even higher than the extruded multidirectional one in diagonal directions. Although the stiffness of the extruded
multidirectional geogrid is more uniform, it is not higher than all biaxial geogrids, even in diagonal directions. This verifies that the aperture shape is not a relevant parameter in the geogrid stiffness in different directions (radial stiffness). Some biaxial geogrids such as the welded biaxial geogrid in this test have higher values and better performance even in diagonal directions when compared with the extruded multidirectional one.

Other tests indicate that the welded biaxial geogrid in this test has higher torsional rigidity/aperture stability than extruded biaxial and multidirectional and woven biaxial geogrids.

Another important consideration is installation damage. Tests show that the welded geogrid had lower installation damage reduction factors when compared with the extruded multidirectional geogrid due to the uniform flat bars and joints. This leads to safer installation and long term serviceability and performance of the geogrid.

In summary, this welded biaxial geogrid exhibited higher pull out resistance than the biaxial extruded and woven geogrids despite having thinner bars. This is due to its structured flat bars and strong junctions. These bars have the ability to rotate under confinement which enables them to bond with a broad range of interface stone sizes. This gives the benefit of greater interlocking between the geogrid and the ballast layer. Lateral stresses and strains in the reinforced ballast aggregate are reduced and less vertical deformation can be expected when adapting a welded biaxial geogrid with structured uniform flat bars.

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