Rail Track Pavements on Expansive Clay Restrained by Hybrid Geosynthetic Solution

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ABSTRACT

Large areas in Israel consist of expansive weak clay subgrades. The subgrade volume of these clays change as a result of seasonal suction fluctuations. In unpaved rail track pavement structures swelling causes severe degradation of rail alignment leading to extensive maintenance efforts and costs. The local method to deal with this phenomenon is to create horizontal and vertical moisture barriers or excavation and deep soil replacement. However, local experience in Israel indicates that only partial restraint of swell damages can be achieved by those conventional methods. Since 2005 the Israeli Rail Authority has begun to utilize a "Hybrid Geosynthetic Solution" that effectively restrains the differential heave caused by uneven swelling of the clayey subgrade. This solution combines a stiff biaxial extruded geogrid located at the subgrade surface and one or more stiff geocell layers embedded in the unbound sub-ballast granular layer. The geocell material is made of novel polymeric alloy (NPA) capable of sustaining large cyclic hoop stresses with relatively small residual long term plastic strains.

1. Introduction

Based on the author experience it is estimated that half of all new railways are founded on expansive clay soils. Expansive clay soils undergo large amounts of heaving and shrinking due to seasonal suction fluctuations. These movements lead to cracking and roughness of rail track infrastructure built on such soils, resulting in extensive damage. Local conventional methods to deal with this phenomenon consist of horizontal and vertical moisture barriers or deep soil replacement (Livne 2013). Local experience however, indicates that only partial restraint of swell damages can be achieved by those conventional methods (Kief et al. 1995). Moreover, it has been observed that at the first 2 – 4 years after the construction movements do occur despite the given solution aimed to restrain the soil volumetric changes. It is believed that moisture migration due to different suction potentials causes volumetric changes during the period prior to the formation of suction equilibrium. As a result, the facts are that the conventional, apparently, restraining methods prove to be no more than "panacea" in many cases as the mechanism of self-destruction is internally built.
The mechanism of geosynthetic restraint of pavements founded on expansive clay was analyzed more than 15 years ago (Kief 1999). Based upon the accumulated experience the Israeli Rail Authority implemented the new concept in an increasing pace of projects.
Based on those better performance and for the last decade the Israeli Rail Authority has adopted and implemented a "Hybrid Geosynthetic Solution" that effectively restrains differential heave caused by uneven swelling of the clayey subgrade.
The Hybrid Geosynthetic Solution combines a stiff biaxial geogrid located at the subgrade surface with a stiff geocell layer (one or more) embedded in the unbound granular layer. The geocell material is made of novel polymeric alloy (NPA) capable of maintaining large cyclical hoop stresses under relatively small residual long term plastic strains (Han et al. 2011). This phenomenon is depicted below (Figure 1). The Hybrid Geosynthetic Solution creates a unique composite behavior that exceeds the sum of its two components (Sitharamet al. 2013). The combined stiff biaxial geogrid and stiff geocell acts like an "I" shape steel girder. Its high resistance to the swelling phenomena significantly reduces upper track roughness. The new solution is actually unaffected by variable moisture in the expansive soil subgrade.
This semi-rigid platform acts as a flexible beam separating the weak soil from the upper track structure and smoothing the swell process by significantly reducing the differential heave. The effectiveness of the solution was verified by track monitoring measurements which have demonstrated negligible rail head settlements compared to an adjacent parallel section built with the conventional method of vertical and horizontal moisture barriers.

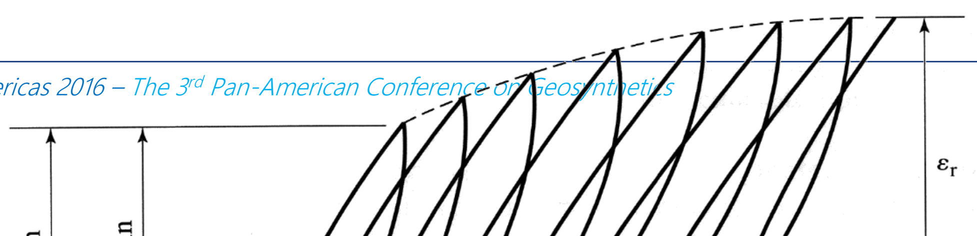

Figure 1. Lower residual cyclic plastic strains

2. NAHARIYA ACRE RAILWAY LINE

2.1 General

The Nahariya-Acre Rail line is part of the Israeli Coastal Rail main line (**Error! Reference source not found.**). In response to increased demand the Israeli Railway Authority decided to double the existing single track several years ago.

The single Western track between Acre to Nahariya was fully rehabilitated about four years ago. Earthworks for the second new Eastern track began in the winter of 2013. However, when the contractor reached the bottom excavation level the clay subgrade could not be processed to the designated degree of compaction. At this point, and as a result of unsatisfactory riding quality of the rehabilitated Western Track (excessive roughness), the Railway Authority adopted the Hybrid Geosynthetic Solution for the new Eastern Track.

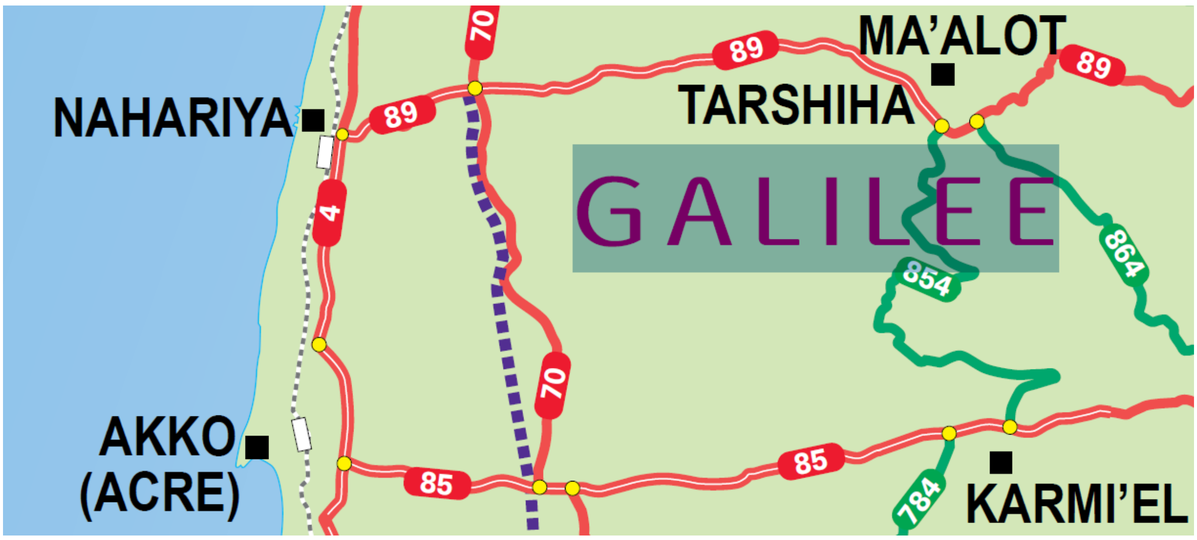

Figure 2. Location of Nahariya - Acre Rail Line

2.2 GEOTECHNICAL DATA

A comprehensive soil exploration along the track route was performed during the winter of 2003. The natural subgrade is characterized as CH (fat expansive clay) to a depth of 2.2m to over 6m. Groundwater depth is shallow along the route as a result of its proximity to the sea. The following table summarizes the consistency characteristics of the fat expansive clay along the track route:

Table 1. Basic Soil Geotechnical Data

Consistency Limits		ω/PL Ratio
Liquid Limit [%]	Plastic Limit [%]	0.80 – 2.13
40 - 103	19 - 36	

The fat expansive clay subgrade strength was evaluated from Dynamic Cone Penetrometer (DCP) and Vane Test (VT). The following table summarizes the strength characteristics of the fat expansive clay along the track route:

Table 2. Calculated Soil CBR

	CBR Calculated from VT	CBR Calculated from DCP
Minimum Value [%]	2.3	1.5
Maximum Value [%]	8.6	11.8
Average Value [%]	6.2	5.4
Standard Deviation	1.5	2.7

The design CBR value adopted for the structural calculation was 2.0%.

2.3 CLIMATIC DATA

The average annual precipitation for Nahariya is 640 mm (**Error! Reference source not found.**), which classifies it as Semi-Arid. This climatic subgroup is characterized by relatively long dry periods followed with high rainfall in short periods ("rain strokes"). These rainfall sequences create the perfect conditions to magnify damage resulting from subgrade volume changes.

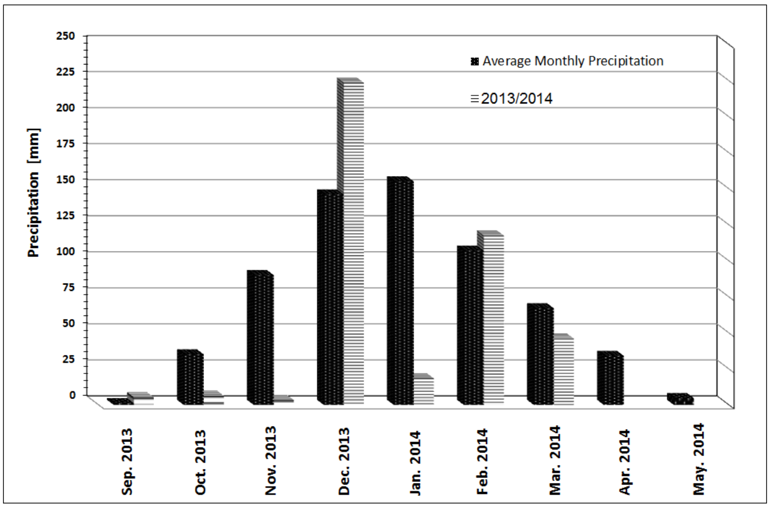

Figure 3. Average Monthly Precipitation

2.4 CONVENTIONAL DESIGN

For a design speed of 160 km/hr the track category for a major line is Category 3 (Livne 2013). The conventional pavement structure of the rehabilitated Western track is specified below:

- Steel Rails – 170 mm
- Concrete Sleepers – 220 mm
- Ballast – 300 mm
- Sub-Ballast – 750 mm
- Horizontal and Vertical HDPE Moisture Barrier
- Processed Subgrade – 400-600 mm

3. EASTERN TRACK HYBRID GEOSYNTHETIC DESIGN

3.1 General

The soil exploration survey results posse the geotechnical consultant with two major geotechnical problems: 1) Subgrade with low bearing capacity and 2) Subgrade subjected to volumetric changes.

The accumulated good experience led the Israel Rail Authority to adopt the Hybrid Geosynthetic solution for all problematic soil conditions. Within this framework, the Rail Authority decided to construct the new Eastern Track with the Hybrid Geosynthetic Solution.

The initial earthwork conditions prior to implementing the Hybrid Geosynthetic Solution were as follows:

- The contractor excavated the Eastern Track down to a depth of 1640 mm from the rail surface (1440 mm for conventional pavement structure + upper 200 mm for overall 400 mm subgrade processing).
- The contractor could not process the excavated subgrade as it was unstable ("bouncing").
- Groundwater level was in close proximity to the excavated level in several locations.

The Hybrid Geosynthetic Solution enabled the Rail Authority to keep the Western track service live while constructing the adjacent new Eastern Track (**Error! Reference source not found.**).

Figure 4. Keeping the Western track service live while constructing the adjacent new Eastern Track

3.2 Engineering Considerations

The use of stiff NPA geocells directly over weak strata is most effective with stable working platform. This provides a counter force to the compaction efforts during the geocell infilling process, while preventing infill from penetrating into the weak clayey subgrade.

The use of a stiff biaxial extruded geogrid on the smoothed subgrade surface achieved the following benefits:

- Create a working platform on the weak clayey subgrade.
- Wider distribution and reduced vertical stresses transferred into the subgrade (Han, et al. 2013).
- Interlocking mechanism of granular material inside the extruded geogrid aperture will restraint subgrade contraction cracks from reflecting upwards into the pavement structure (Zomberg 2010).

By using two layers of stiff NPA geocells the following benefits can be achieved:

- Create a relatively high modulus confined granular layer acting as a semi-rigid continuous beam [Han et al. 2012].
- A more significant reduction and wider distribution of vertical stresses transferred into the underlying granular layers (Han, et al. 2013).

The integration of all those benefits of the Hybrid Geosynthetic Solution creates a unique composite pavement, which is ideally suited to restrain the swelling damages. By creating a semi-rigid platform the differential heave resulting from the expansive clay subgrade swell is almost completely disappeared. In addition there is a basic assumption that the sawtooth-shaped differential heave produced as a result of the volumetric change short wave length will be almost totally smoothened by a significant extending of those waves lengths by the effect of the unique composite semi-rigid platform (**Error! Reference source not found.**).

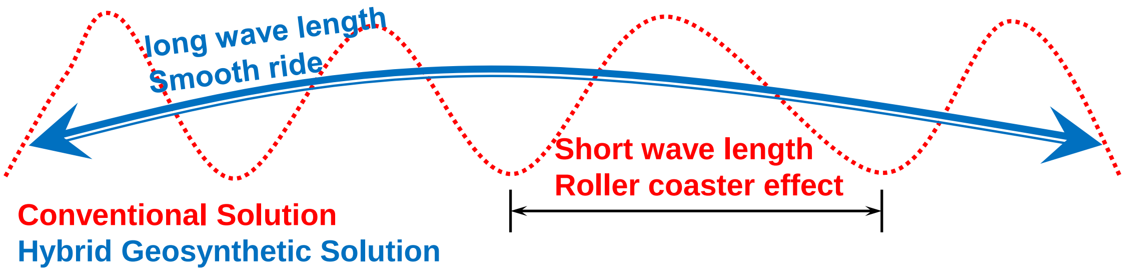

Figure 5. Swell restraint mechanism of semi-rigid Hybrid Geosynthetic Solution

3.3 Implementation of the Hybrid Geosynthetic Solution

In light of the initial earthwork conditions and the impact on the construction timetable several quick decisions had to be taken:

a. The existing excavation level was set as the lower reference point for the track pavement structure.
b. Subgrade process operations were not continued besides surface smoothing operations and watering to avoid excessive drying.
c. Immediately after the surface smoothing operations and watering, the stiff biaxial extruded geogrid was installed along the length and width of the entire excavated section.
d. The geogrid was immediately covered with sub-ballast material to avoid moisture loss.
e. Two layers of stiff NPA geocells were used as a result of stress analysis.

The "constraints" listed above led to the unique unpaved structure of the new Eastern Track as follows:

- Steel Rails – 170 mm
- Concrete Sleepers – 220 mm
- Ballast – 300 mm
- Sub-Ballast – 150 mm
- Sub-Ballast infill – 150 mm NPA geocell + 50 mm over fill cover = 200 mm
- Sub-Ballast infill – 150 mm NPA geocell + 50 mm over fill cover = 200 mm
- Sub-Ballast – 400 mm
- Stiff Biaxial Extruded Geogrid
- Smoothed Clayey Subgrade

3.4 Structural Assessment

Based upon numerous laboratory and field tests worldwide a Modulus Improvement Factor (MIF) for stiff NPA geocell confined granular layers was established several years ago (Kief and Rajagopal 2011). The MIF value evaluated from these tests is within the range of 2.5 to 5.0. For structural analysis it is accepted to use a safety multiplier factor of approx. 0.7 – 0.8. An Improvement Factor elaborated from laboratory test results performed by Sitharam and Hedge (2013) on clay subgrade with a combined geogrid and NPA geocell was within the range of approx. 4.0 to 6.0. By combining the unique composite effect the following relationship between the subgrade design CBR value and the MIF could be established (See Figure):

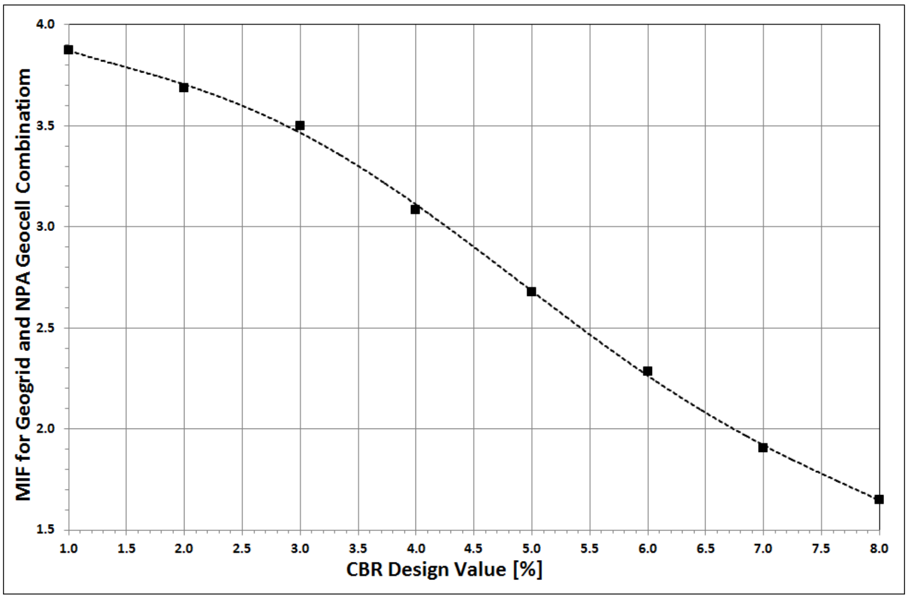

Figure 6. MIF Value vs. CBR Value

For the current project a MIF value of 3.7 was set for design CBR value of 2.0%.
The different layer moduli can be defined as each consequent layer is dependent on the layer underneath it, as listed below (Israel Road Authority 2003):

	Elasticity Parameters	Notes
Base	$E_b = E_{ab}$ x (1+0.0067 x h_b [mm]) υ_b = 0.35	E_b [MPa] ≤ 700
Sub-base	$E_{sb} = E_{sg}$ x (1+0.003 x h_{sb} [mm]) υ_{sb} = 0.35	E_{sb} [MPa] ≤ 300
Subgrade	E_{sg} [MPa] = 14 x CBR [%] υ_{sg} = 0.40	2 < CBR [%] < 12

Where:

h_{sub}	-	Subbase layer thickness [mm]
h_b	-	Granular base layer thickness [mm]
E_{sg}	-	Subgrade elastic modulus [MPa]
E_{sub}	-	Subbase elastic modulus [MPa]
E_b	-	Granular base elastic modulus [MPa]

The Subgrade modulus (for CBR value of 2%) is 28 Mpa
The Sub-ballast modulus is calculated as follows: E_{sb} = 28 x (1+0.003 x 950) x 3.7 = 400 MPa.

The cross section view of the Hybrid Geosynthetic Solution (Eastern track) versus the conventional Western track cross section is illustrated in Figure :

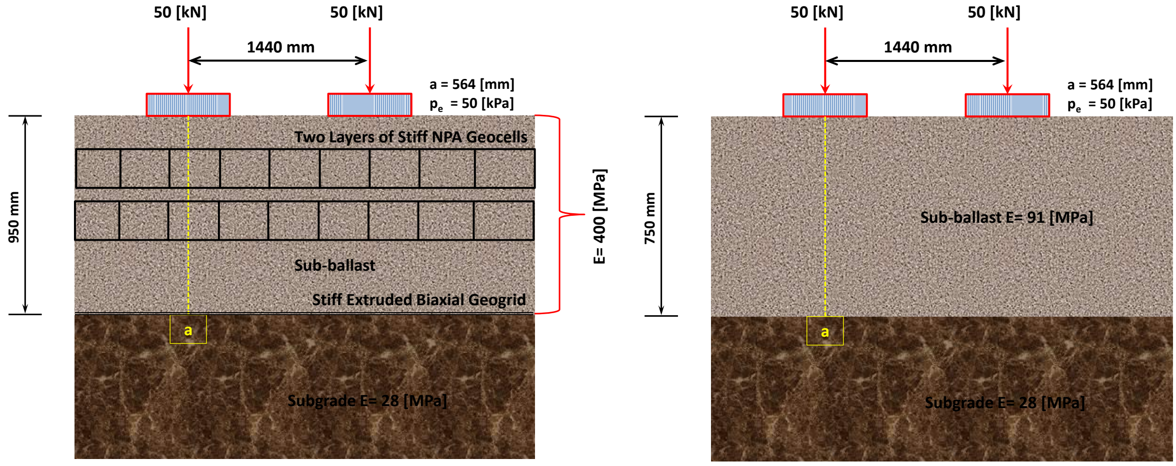

Figure 7. Cross Section of Hybrid Geosynthetic Solution of the Eastern Track (left) and for the existing Western Track (right)

The vertical settlement on the sub-ballast surface and the vertical stress on the subgrade surface at point "a" were calculated for both tracks using mePADS® stress/strain software. The results are listed in the table below:

Table 5. Settlement and Stress: Hybrid Geosynthetic Solution Vs. Conventional Solution

Sub-ballast Surface Settlement at Point a [mm]		Subgrade Surface Vertical Stress (σ_{zz}) at Point a [kPa]	
Western Track	Eastern Track	Western Track	Eastern Track
1.124	0.574	19.8	8.0

The sub-ballast surface vertical settlement and the subgrade surface vertical stress (σ_{zz}) of the Hybrid Geosynthetic Solution of the Eastern Track are approx. half comparing to the Conventional Solution of the Western Track. The stress strain characteristic of a railway substructure is dependent on the frequency and the size of the individual axle load applications. Profillidis (2000) has suggested that Dormon's rule established in highway engineering can be implemented for railways as well. Accordingly, the loading on the subgrade is inversely proportional to the number of loading cycles raised to a power λ, given by:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{N_2}{N_1}\right)^{\lambda}$$

Where:

σ_1, σ_2	Stresses corresponding to N_1, N_2 loading cycles respectively
λ	An exponent with a mean value of 0.2

For constant axle loadsthe equation above becomes:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{T_2}{T_1}\right)^{\lambda}$$

Setting the stresses from the conventional and alternative solution into this equation results in:

$$\frac{\sigma_{zz1}}{\sigma_{zz2}} = \frac{19.1}{8.0} = \left(\frac{T_2}{T_1}\right)^{\lambda} = 2.39$$

$$\left(\frac{T_2}{T_1}\right) = 77.6$$

The conclusion of the above equations is that the calculated allowed daily traffic tonnage of the Hybrid Geosynthetic Solution is far greater than the allowed daily traffic tonnage of a conventional solution. This implies that the periods between each successive maintenance operations needed in the Eastern Track will be significantly prolonged compared to the conventional Western Track (see Figure 8).

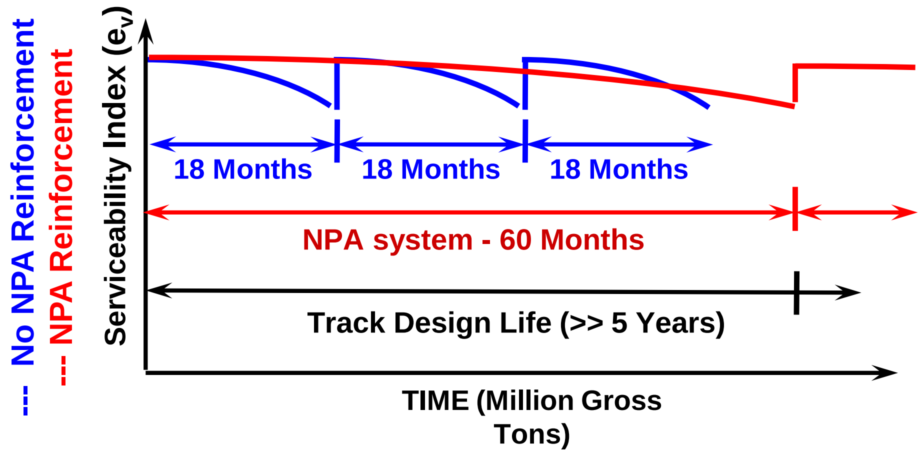

Figure 8. Increasing the time between successive maintenance operations

4. Conclusions

More highly engineered solutions are required for railway substructure than current soil treatment practices to prevent expansive clay soils from impacting track performance. A Hybrid Geosynthetic Solution was implemented in a new track foundation in Northern Israel over weak expansive clays. This composite solution combines a biaxial stiff extruded geogrid layer at the clayey subgrade surface with two stiff NPA geocell layers that reinforce the sub-ballast layer. The stiff biaxial extruded geogrid provides a working platform for the stiff NPA geocell layers, resulting in an "I" beam over the problematic soil. This semi-rigid platform acts as a geosynthetic substructure separating the weak soil from the upper track structure and smoothing the swell process by significantly reducing the differential heave. Now, after more than 3 years in service and undergoing severe and harsh semi-arid climatic effects the effectiveness of the solution was verified by track monitoring measurements which demonstrated negligible rail head settlements compared to a parallel unreinforced section. The resulting reduction in maintenance cycles and costs show the efficacy of the Hybrid Geosynthetic Solution for many rail and road soil stabilization and reinforcement applications.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contribution of Dr. Arkady, Rabinovitz, of the Israeli Railway Authority for his vision led to the implementation of the Hybrid Geosynthetic Solution.

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